Parry, Brian

The provenance of the norber erratics, and the formation of post-devensian-deglaciation pedestal rocks with carboniferous limestone pedestals in England, Ireland and Wales

THE PROVENANCE OF THE NORBER ERRATICS, AND THE FORMATION OF POST-DEVENSIAN-DEGLACIATION PEDESTAL ROCKS WITH CARBONIFEROUS LIMESTONE PEDESTALS IN ENGLAND, IRELAND AND WALES

BRIAN PARRY

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

September 2007

The University of Huddersfield

ABSTRACT

This study investigates a Devensian glacial conundrum, the provenance of the Norber erratics in North Yorkshire, and the origins of a post-Devensian-deglaciation landform, pedestal rocks with Carboniferous limestone pedestals in England, Ireland and Wales.

Investigations to determine the provenance of the Norber erratics were undertaken in a study area of about 2000ha. Mapping erratic dispersal and measuring striae strike revealed that the provenance is Crummackdale, and that Devensian ice crossed over only the Crummack, Sowerthwaite and Austwick formations *en route* to Norber. Petrographical and physical surveys further revealed that the erratics are derived from the Austwick Formation only, and that provenance is a glacially-plucked 'amphitheatre' in the vicinity of the Old Limekiln (SD 770707).

Investigations to determine the formation of post-Devensian-deglaciation pedestal rocks with Carboniferous limestone pedestals were undertaken at 19 sites in England, Ireland and Wales, where 162 pedestal rocks and a pedestal rock field were examined. The study was divided into two, the formation of perched and mushroom pedestal rocks. An examination of weathering and erosion processes at Norber, where only perched pedestal rocks with vertical sidewalls are found, revealed that lowering of the inter-pedestal limestone surface has taken place primarily in a sub-regolith karstic environment, and that little or no pedestal formation occurred prior to ca.10000BP. In contrast, the lowering of the inter-pedestal limestone surface about perched pedestal rocks with sloping sidewalls, such as at Scales Moor (North Yorkshire) and the Burren (County Clare), has taken place primarily in a subaerial environment. Moreover, pedestal formation commenced in ca.14500BP in England and Wales, and ca.13700BP in Ireland. The pedestals of mushroom pedestal rocks have formed due to lateral dissolution under regolith that has largely been eroded, probably following deforestation in ca.3000BP.

FOREWORD

Norber in North Yorkshire (SD 763698) is celebrated for its erratics and limestone pedestals (Plate F.1), which is why I initially became acquainted with the site, my first visit taking place in 1967 on an A-Level geology field trip from Cambridgeshire. I still have my field notes and I wrote (Parry, 1967: 29) that the greywacke erratics have been moved "…two miles from Silurian rocks at Crummack Dale Head…[which are]…part of the Austwick Grits and Flags". I also wrote that some of the blocks are "…perched on stools of Carboniferous Limestone, which are a foot or two above the ordinary base-level of the limestone. This indicates the amount of erosion by solution of the limestone since the blocks had been emplaced."

In 1973 I took up a post as a teacher of geology and geography at Foxwood Comprehensive in Leeds. The school owned an outdoor centre at Horton-in-Ribblesdale and using it as a base I accompanied various groups to Norber, not only from Foxwood but also later from Lawnswood Comprehensive, likewise in Leeds. During the visits I was informed that the erratics originated from a variety of sites. These were one kilometre to the north in Crummackdale, two kilometres to the east in the valley of Wharfe Gill Syke and thirty kilometres distant in the Howgill Fells. The Lake District was also mentioned (in the same breath that the erratics were composed of granite). On asking where the party leaders had acquired their information, it emerged that most, like me, had obtained it from a third party. Some, however, did not know where provenance was, so had made it up, although in all cases there was some logic behind their thinking. The reason why the leaders were not familiar with erratic provenance was simply because bookshops were almost bereft of texts and field guides on Norber. The only up-to-date book I knew of was 'Geology explained in the Yorkshire Dales and on the Yorkshire Coast' by D. Brumhead (1979). It was explained (p. 37) that the erratics were "…once in situ on the western slopes of Crummack Dale, half a mile away and 400 feet [121 metres] lower where the basement rocks outcrop beneath the limestone". No evidence was offered as to why this particular spot was provenance, and when I attempted to locate the site on a map I discovered that the western slopes of Crummackdale are at best little more than 40m lower than Norber, a discovery that did not inspire confidence in the claim. In 1987 Norber was featured in a BBC television series for schools, 'The Geography Programme: What Ice did to the Land', in which erratic provenance was moved to "…a hundred kilometres away." The erratics also figured in a newly published book by A. Goudie and R. Gardner (1992) 'Discovering Landscapes in England and Wales'. Goudie and R. Gardner (1992) wrote (p. 31) that the huge boulders were "…fairly local in origin…[and are]…often composed of Yoredale or Millstone Grit." The latter comment not only added to erratic composition, but through implication signified that some of the erratics must have originated from outside of Crummackdale since neither Yoredale nor Millstone Grit crops out in the dale. An inspection of the site revealed that none of the huge boulders were composed of Yoredale or Millstone Grit, which again did not inspire confidence in the claim.

Although most party leaders had their own views on erratic provenance, they always knew that the pedestals at Norber had formed due to the erratics protecting the underlying limestone surface from the dissolving action of falling rain. This hypothesis is known as the 'Umbrella Theory' and its source was either student days or word of mouth. In the early 1990s a number of texts affirming the theory became available in bookshops. A typical account occurred in 'The Yorkshire Moors and Dales' by R. Talbot and R. Whiteman (1991), who explained (p.151) that the "…surrounding softer limestone – unprotected by the umbrella effect of the harder boulders – has been dissolved away by 10000 years of rainfall." Yet in spite of the universal belief in the 'Umbrella Theory' I had always been somewhat mystified by its easy acceptance, primarily because on my first visit to Norber I wrote that most erratics did not, in fact, have pedestals below them at all. In addition, I noticed during subsequent visits that the girth of some pedestals was much narrower than that of the erratic that straddled them, a phenomenon that seemed to be puzzlingly at odds with the theory. Thus, when I retired from teaching in 1996 it was small wonder that I had little sense of where the erratics had originated, and although I had always felt there was something 'wrong' with the 'Umbrella Theory' I had no idea what the 'right' alternative might be. Therefore, I had it in mind to attempt to discover myself, by thesis, the provenance of the Norber erratics and the formation of the limestone pedestals beneath them.

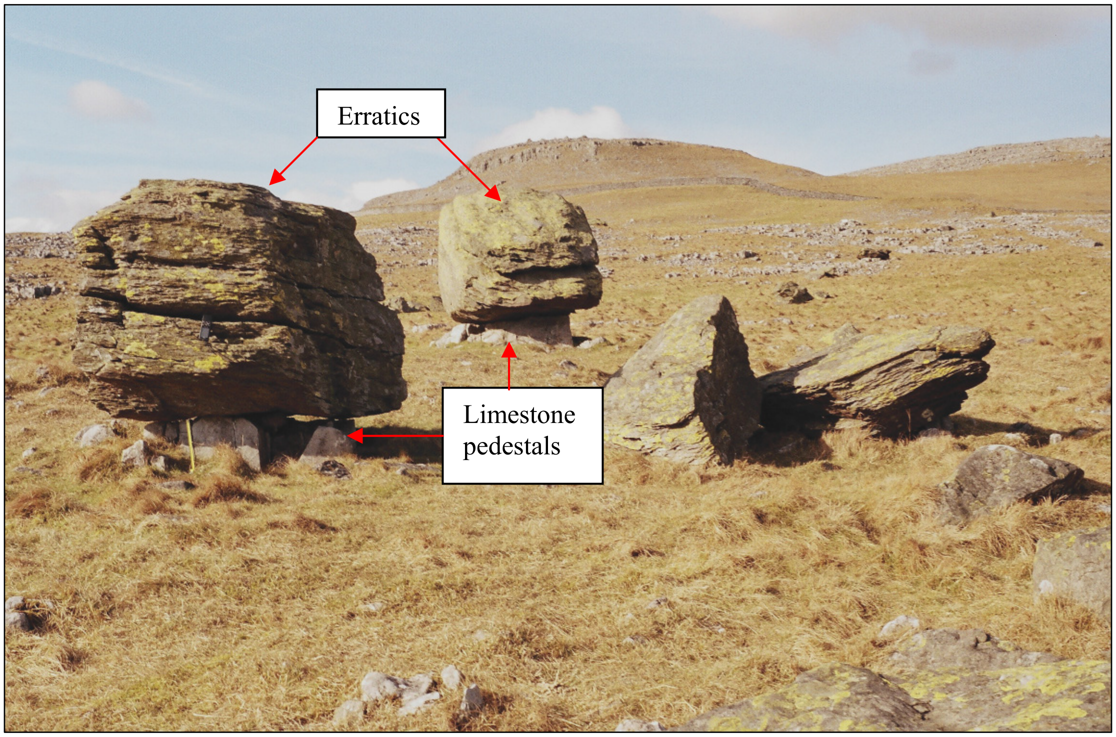

Plate F.1: General scene at Norber

Most of Norber, which extends as far as the dry-stone wall in the distance, consists of erratic-strewn rough pasture, although relatively small islands of pavement and even smaller limestone residuals also occur. The vegetation consists primarily of grasses and herbs, and trees are absent except for a few growing in scree, and on scars and erratics. Norber inclines generally to the south-east, i.e. towards the viewer, with scar and step topography in the south and east, and a gently sloping plateau to the north and west. There is no surface water at the site and neither is there any evidence of its presence in the past. Despite the fact that there is a jumble of perhaps thousands of erratics, which come in all shapes and sizes, only a few have pedestals beneath them, two of which are evident above (N28 foreground and N12 background). The caps of the pedestals are all erratics composed of Silurian grit, as above, apart from two that are composed of Carboniferous limestones. Caprocks range in volume from approximately 0.25 to 12m³ and pedestal height from about 30 to 50cm; all pedestals are vertically-walled. (The metal tape in front of N28 is extended by 27cm.)

ACKNOWLEDGEMENTS

I would like to thank Professor John Gunn at the University of Huddersfield and Dr David Lowe at the British Geological Survey at Nottingham for providing invaluable help, guidance and advice during the nine years it took to complete this thesis. Also, many thanks to Phil Murphy at the University of Leeds for his encouragement and for sharing his knowledge of the Yorkshire Dales, Rhys Davies at Malham Tarn Field Centre for supplying meteorological data and Dave Ryan at the University of Huddersfield for his time spent Desktop Publishing. Thanks, too, to Ibrahim George at the University of Huddersfield, and Kirk Handley and Dave Hatfield at the University of Leeds for their assistance in the laboratory. Finally, I would have been unable to complete the thesis if many farmers, especially Peter Haw of Crummack Farm and George Huck of Sowerthwaite Farm in Crummackdale, had not allowed me to walk over their land at will.

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CHAPTER 1: INTRODUCTION

1.1: Foreword

Although Norber is celebrated for its erratics and its Carboniferous limestone pedestals, neither feature is unique to the landscape of the British Isles. Nevertheless, they appear to have captured the 'public imagination' more here than at other locations. Thus, they are mentioned in principal university set-books (e.g. Holmes, 1978), in laymen's books on the Yorkshire Dales (e.g. Duerden, 1986), in geology guides (e.g. Scrutton, 1994), in school textbooks (e.g. Cook *et al*., 2000) and in academic journals (e.g. Waltham, 2005). They have also appeared in television programmes made for schools (The Geography Programme, 1987) and the general public (British Isles: A Natural History, 2004), which was watched by 6.77 million viewers (Fenyoe, A. personal communication. 21 January 2006), and are referred to online (e.g. Cragface, 2006). Norber is also sometimes regarded as a 'type' site re pedestal formation against which other sites are compared (e.g. Goldie, 2005). Furthermore, Waltham and Tillotson (1989) have recorded that the Ingleborough area, which includes Norber, is one of the country's most visited locations for fieldwork.

References in the thesis are not restricted to articles that have appeared solely in 'serious' texts, since there are many sources of 'non-serious' information that need to be examined if conclusions appropriate to today re the provenance of the Norber erratics are to be reached. This is because although articles in serious texts, e.g. by Dunham *et al.* (1953), are likely to be better informed, sources of non-serious information, e.g. British Isles: A Natural History (2004), are likely to reach a wider audience.

1.2: Aims and objectives

1.2.1: The provenance of the Norber erratics

In spite of the interest shown in the Norber erratics their provenance is unknown. Thus, it has been proposed, for example, that the erratics have originated from 1km away in Crummackdale (Arthurton *et al.*, 1988) and from 160km away in Northumberland (British Isles: A Natural History, 2004). Consequently, the main aim of this section of the thesis is to determine the provenance of the Norber erratics, and in order to fulfil this aim the following specific objectives are outlined:

1. To map the dispersal of erratics and determine the geographical provenance of the Norber erratics

2. To measure the trend of striae and determine the Lower Palaeozoic lithostratigraphical unit(s) Devensian ice crossed in Crummackdale *en route* to Norber

3. To compare and contrast the Norber erratics with strata of the Sowerthwaite, Crummack and Austwick formations in western Crummackdale in terms of their petrography, and determine which of these lithostratigraphical unit(s) is/are the provenance of the Norber erratics

1.2.2: The formation of post-Devensian-deglaciation pedestal rocks with Carboniferous limestone pedestals in England, Ireland and Wales

The formation of post-Devensian-deglaciation Carboniferous limestone pedestals is also unknown. Thus, although the lowering of the inter-pedestal limestone surface at Norber is most often attributed to karstic erosion by rainwater (e.g. Raistrick and Illingworth, 1965; Penny, 1974; Bell, 1996), it is also attributed, for example, to karstic erosion in a sub-regolith environment (e.g. Hughes, 1886), wind erosion (Wood, 1985) and step-retreat erosion (Goldie, 2005). Post-Devensian Carboniferous limestone pedestals occur at sites other than at Norber in England (e.g. Scales Moor, North Yorkshire (Sweeting, 1966)), and also in Ireland (e.g. the Burren, Co. Clare (Drew, 2001)) and Wales (e.g. Twyn Du, Powys (Thomas, 1970)). It is apparent from descriptions/illustrations that some pedestals and sites are similar to those at Norber (e.g. Cunswick Tarn, Cumbria (Hughes, 1886)) whereas others are dissimilar (e.g. Gait Barrows, Cumbria (Goldie, 2004)). The lowering of the inter-pedestal limestone surface at these sites is likewise most often attributed to karstic erosion by rainwater (e.g. Drew, 2001), but Hughes (1886) has argued that karstic erosion in a sub-regolith environment has occurred at Cunswick Tarn, for example. Moreover, Dunne and Feehan (2003) have argued that some pedestals in the Republic of Ireland have formed due to dissolution in lake water. Consequently, the main aim of this section of the thesis is to determine the formation of post-Devensian-deglaciation Carboniferous limestone pedestals, and in order to fulfil this aim the following specific objectives are outlined:

1. To investigate which erosion/weathering environments are lowering the inter-pedestal Carboniferous limestone surface

2. To determine whether Carboniferous limestone fabric and composition have played a role in pedestal formation

3. To investigate the evidence for post-Devensian-deglaciation periglacial tundra and temperate arboreal environments at Norber

4. To resolve the formation of post-Devensian-deglaciation Carboniferous limestone pedestals of perched pedestal rocks through time

5. To resolve the formation of post-Devensian-deglaciation Carboniferous limestone pedestals of mushroom pedestal rocks through time

The formation of the caprocks is, however, not disputed. Thus, caprocks of perched pedestal rocks are erratics (e.g. Hughes, 1886; Drew, 2001), whereas the formation of caprocks of mushroom pedestal rocks is attributed to preferential erosion (Goldie, 1994 and 1996; Dunne and Feehan, 2003).

1.2.3: The amount and rate of post-Devensian deglaciation Carboniferous limestone surface lowering in England, Ireland and Wales

Measuring the height of Carboniferous limestone pedestals beneath Devensian erratics in England, Ireland and Wales has been used to determine the amount of post-Devensian-deglaciation surface lowering (e.g. Goldie, 2005). Sites are often compared (e.g. Williams, 1966), even though past deglaciation-date differences and environmental changes are not taken into account. Consequently, the aim of this section of the thesis is to assess the amount and rate of post-Devensian deglaciation Carboniferous limestone surface lowering in England, Ireland and Wales, and in order to fulfil this aim the following specific objective is outlined:

1. To measure the height of Carboniferous limestone pedestals beneath Devensian erratics

1.3: Thesis layout

Subsequent to the introduction, the thesis continues with an account of physical aspects of the Norber area (Chapter 2) in order to set the scene and to familiarize the reader with the site. Determining the provenance of the Norber erratics (Chapters 3 to 5) is embarked upon prior to determining the formation of their underlying Carboniferous limestone pedestals (Chapters 6 to 11), since erratic deposition, which occurred when Devensian ice ablated, precedes pedestal formation. The two ‘sections’, i.e. Chapters 3 to 5 and Chapters 6 to 11, begin with a literature review so that a framework for follow-up fieldwork and laboratory work could be pieced together.

The Norber Erratic literature review (Chapter 3) reveals that potential sites of provenance are not always specifically named. Nevertheless, nine sites are identified, all to the north of Norber (Fig. 1.1). In Chapter 4 the boundaries of a survey area (Fig. 1.2), which extends some 4km to the north of Norber, are drawn up and the dispersal of lithologically-different erratics is mapped in order to delete potential sites of erratic provenance. In Chapter 5 provenance is narrowed further still by mapping glacial striae, examining thin sections, and comparing the characteristics of erratics and *in situ* rock outcrops, until the whereabouts of provenance is brought to a successful conclusion. The literature review in Chapter 6 and field observations indicate that processes operating in seventeen different environments might be responsible for pedestal formation at Norber. These are split into erosion and modification environments, and the two groups are respectively examined in Chapters 7 and 8. This procedure is adopted because it is possible that once erosion of the inter-erratic limestone surface has led to pedestal formation the pedestals might be subsequently modified, either in erosion environments additional to those outlined in Chapter 7 or in weathering environments. It is also possible that the fabric and/or composition of the limestone have played a role in pedestal formation, and these criteria are examined in Chapter 9. Each environment/criterion is examined alphabetically by section so as not to presume that one is of greater importance than another, and each section contains aims, methods and results where appropriate, to maintain coherence. A conclusion is drawn at the end of each section and an overall conclusion is marshalled at the end of each chapter. The conclusions relate mostly to the extant environment, but as climate, soil and vegetation changes have occurred since the erratics were deposited, an account of previous post-Devensian deglaciation environments is presented in Chapter 10. Finally, an account of pedestal formation at Norber is proposed in Chapter 11 drawing on appropriate information from the preceding five chapters. The thesis is then expanded to consider the formation of post-Devensian-deglaciation Carboniferous limestone perched pedestal rocks at seventeen sites in England, Wales and Ireland in addition to Norber (Chapter 12). No post-Devensian-deglaciation Carboniferous limestone pedestal rocks are known to occur in Scotland. This expansion is undertaken in order to place the perched pedestal rocks at Norber within a regional context, and subsequently the pedestals at Norber are regarded as 'type' pedestals against which those at other sites are compared and contrasted. The first site examined is Scales Moor, in North Yorkshire, as a greater range of pedestal form and surroundings is found here than at any other site. Thereafter, sites are considered alphabetically. It is argued that pedestals at Scales Moor which are similar in form and setting to those at Norber have formed in a similar manner, whereas those that are different in form and setting have formed in a different manner. The latter pedestals are consequently regarded as 'type' pedestals against which those at other sites are compared and contrasted. Scales Moor does not contain all pedestal types, however, and the formation of pedestals unlike those at this site is considered in subsequent sites as they arise. They too are regarded as 'type' pedestals. The layout of Chapters 6-12 and the methods employed to determine pedestal formation are summarised in Fig. 1.3. The formation of mushroom pedestal rocks is considered in Chapter 13, and the amount and rates of post-Devensian-deglaciation Carboniferous limestone surface lowering in England, Ireland and Wales in Chapter 14. The conclusions of the research are presented in Chapter 15.

1.4: What are the Norber erratics?

Four lithologically-different types of erratic are found at Norber, and they are Silurian grit and siltstone, and Carboniferous grit and limestone (refer to Section 4.3.5.2). Almost all published 'popular' and 'academic' references to the erratics, whether in the form of text, photographs or film, are of clasts composed of Silurian rock. Erratics comprised of Carboniferous grit and limestone are rarely mentioned. Nonetheless, the question arises as to what are the Norber erratics, i.e. are they erratics comprised of just Silurian rock or are they erratics comprised of Silurian and Carboniferous rock? Accordingly, in order to avoid confusion the term 'the Norber erratics' in the thesis is applicable only to erratics composed of Silurian rock, i.e. they are the Norber erratics '*sensu stricto*', and it is their provenance that is pursued. If reference is made to all erratics at Norber, i.e. those composed of Silurian and Carboniferous rock, it is qualified by the term '*sensu lato*'. The provenance of erratics composed of Carboniferous rock is not pursued in the thesis, except where relevant to determining the direction of ice flow.

1.5: Definition of the term 'erratic'

In a narrow sense the term 'erratic' refers simply to clasts that have been eroded, transported and deposited by moving ice. Saarnisto (1990) has pointed out that erratics are not solely confined to transport by glaciers, though. Thus, material of the clastic nature, total volume, and individual size and weight of the Norber erratics has been moved about the earth's surface by volcanic activity and/or man and/or gravity and/or natural agents of erosion. There is no evidence whatsoever of post-Silurian vulcanism in the area, and there are no grounds to suppose that the boulders have been transported by man – as one local farmer suggested. Nor is it possible for the erratics to have been moved by gravity since they are composed of rock (greywacke) that does not occur at higher altitude than the Carboniferous limestone at Norber. Consequently, the Norber erratics must have been transported either by one or by a combination of the four agents of erosion – namely wind, marine currents and/or waves, rivers and ice. The bulkiest complete erratic found at Norber (N3) is some 12m^3 in volume and as it weighs in excess of 30000kg (the mean bulk density of the greywacke erratics at Norber is 2.56t/m^3) this immediately precludes movement by aeolian processes. There is no geological evidence to suggest a recent incursion by the sea, either at Norber or within the regional vicinity, thus transport by marine currents and/or waves can also be discounted. Movement by fluvial processes can likewise be rejected since the erratics are found on the brow of a spur rather than in a river valley, and because Norber and Long Scar are both lacking in surface water. In any case, the lack of boulder sphericity does not lend itself to transport by moving water, whether marine or fluvial. Menzies (2002) has pointed out that boulders which have been plucked or quarried by ice from a bedrock substrate typically have an angular shape and that ice has immense power to transport material. The former comment is confirmed by field observation at Norber (Plate 1.1), and the latter by Embleton and King (1968) who have recorded a grit erratic 180m long near Abergavenny, one from Canada weighing 18,150 tons (in excess of 18 million kg) and erratics of Torridonian sandstone that have been carried 450m uphill in western Scotland. Furthermore, Wilson (1948) cites rhomb-porphyry erratics occurring in glacial till along the Yorkshire coast that have been carried a distance of approximately 1000km from near Oslo in Scandinavia. Therefore, as the erratics at Norber fall well within these ranges of size, weight, and alleged vertical and horizontal displacement, and as their shape is indicative of glacial plucking or quarrying, they were moved by ice. It is commonly accepted that the Norber erratics have originated in this way, as noted in Hughes (1886) and Waltham *et al.* (1997), for example, and one erratic still bears the 'scars' of glacial transport in the form of striae incised into it (Plate 1.2). Accordingly, for the purposes of this study the term 'erratic' is restricted only to clasts that owe their formation, transport and deposition to glacial processes.

There are many definitions of the term 'erratic'.

"A large pebble, cobble or boulder which has been transported some distance from its source. The term is commonly applied to glacially transported blocks." (Whitten and Brooks, 1972: 159).

"A large rock fragment that has been transported, by moving ice, away from its place of origin and deposited in an area of dissimilar rock types." (Whittow, 1984: 178).

"A mass of rock or a boulder transported by a glacier or an ice sheet and deposited in an area remote from its place of origin." (Clark, 1985: 199).

"Glacially transported stones and boulders." (Lapidus and Winstanly, 1990: 195).

"An erratic is a term applied to a particle of any size contained in drift or lying free on the surface. It is used mainly for particles transported by glaciers but is not confined to these alone." (Saarnisto, 1990: 1).

"Glacial boulders are rock fragments that have been transported over variable distances by glaciers or ice sheets; it is generally understood that the glacial boulders originate mainly as a result of glacial erosional processes such as quarrying and plucking. They are called erratics, when deposited at some distance from the outcrop from which they were derived." (Bouchard and Salonen, 1990: 87-88).

"A rock fragment that has been transported a great distance by glacier ice, and differs from the bedrock on which it rests." (Parker, 1997: 90).

Most of the definitions provide some indication of distance the erratics have been transported, their size and the agent of erosion responsible for their movement; they may also mention bedrock and the provenance of the erratic. None of the definitions, however, can be applied specifically to the Norber erratics (*sensu lato*) or to erratics found within the vicinity of Norber.

The definitions of Whittow (1984), and Whitten and Brooks (1972) are not applicable due to the fact that they both require erratics to be 'large' in size. Clark (1985) and Lapidus and Winstanly (1990) likewise require that an erratic be of a particular dimension. Benn and Evans (1998) note, however, that erratics do not have to be of any specific size, and that they include a complete range of sediment size, from erratic blocks down to the fine-grained matrix of till.

The definitions of Clark (1985) and Parker (1997) cannot be applied to the Norber erratics as they respectively require an erratic to have been deposited in an area 'remote from its place of origin' or 'transported a great distance'. Whitten and Brooks (1972) and Bouchard and Salonen (1990) similarly require movement of 'some distance'. However, if the erratics at Norber are of Silurian age and if they have originated from the Austwick Formation in Crummackdale as Brumhead (1979), Arthurton *et al.* (1988) and Scrutton (1994), for example, have suggested, then they may have been moved by as little as 1km.

The definitions of Parker (1997) and Saarnisto (1990) are of limited applicability as they restrict erratics to rocks moved by glaciers. Yet it is likely that the erratics in the Norber area were moved by ice sheets (Section 5.2.6).

The definitions of Whitten and Brooks (1972), Whittow (1984), Clark (1985), Lapidus and Winstanly (1990), Saarnisto (1990) and Parker (1997) all lack any information about the erosional processes leading to the formation of the erratics. Dreimanis (1990) has pointed out, however, that glaciers derive their material not only from *in situ* bedrock but also by recycling older sediment. Yet only Bouchard and Salonen (1990) require that glacial boulders should originate as a result of glacial erosional processes, such as quarrying and plucking, a necessary prerequisite if the erratics at Norber are to be used for glacial indicator tracing.

None of the definitions mentions that erratics may undergo post-depositional movement due either to geomorphological or, more likely, anthropogenic processes. Lawson (1990) suggests, however, that clasts finer than boulder size, in an area free of drift cover, are more likely to have been redistributed by geomorphic processes subsequent to deposition than clasts greater than boulder size. In addition, Mitchell and Buggie (1991) note the appearance of erratics in stone walls, as being proof of anthropogenic post-depositional movement.

As none of the cited definitions is considered to be wholly adequate, an erratic is defined as ‘a clast of any size if contained wholly or partially within *in situ* till, or greater than boulder size (>256mm on the Wentworth Scale) if lying free on the surface, which has been transported over any distance by moving ice. It is generally understood that the clast originates as a result of glacial erosional processes such as quarrying and plucking’.

1.6: Definition of the term ‘pedestal rock’

A number of the Norber erratics (*sensu lato*) rest on pedestals of the underlying limestone, the erratic, which forms a caprock, and the pedestal together comprising a pedestal rock. Pedestal rocks occur world-wide in a variety of environments in lowlands and highlands from the equator to the poles, and although few are smaller than a metre in height the largest can be ten times this size. They are confusingly cloaked in a plethora of names such as pedestal boulders (Hughes, 1886), hoodoo rocks (Bryan, 1923), champignons calcaires (Corbel, 1957), rocking stones (Fairbridge, 1968) and wave stones (Dunne and Feehan, 2003) depending on locality, caprock origin, structure and rock type. The pedestals are also known as socles (Bögli, 1961) and karrentische (Ford and Williams, 1989) if composed of limestone. Pedestal rocks are grouped into two types based on geological structure: perched pedestal rocks where there is a structural break between the overlying boulder and the rock mass below (Plate 1.3): and mushroom pedestal rocks where the shaft is structurally contiguous with the rock masses above and below (Plate 1.4).

There are a number of definitions of the term ’pedestal rock’, and some of the more recent ones are:

“A residual columnar mass of weak rock capped with a harder rock. Opinions differ as to whether it is formed by weathering helped by rainwash, or by wind abrasion.” (Clark, 1985: 456).

“A land feature (most common in desert environments) sculpted by wind.” (Lapidus, 1987: 373).

“An unstable, mushroom-shaped land-form found typically in arid and semi-arid regions. The undercut base was formerly attributed to wind abrasion but is now believed to result from enhanced chemical weathering at a site where moisture would be retained longest.” (Allaby and Allaby, 1990: 273).

“A pillar made of weak rock capped with a more resistant rock.” (Mayhew and Penny, 1992: 72).

Most pedestal rocks are “…two-stage forms. Thus, preferential weathering by soil moisture beneath the land surface produces the pedestal, which is subsequently exposed by erosion of the regolith. (Twidale and Campbell, 1992: 2).

“A rock mass supported on a rock pedestal.” (Geller, 2003: 268)

The definitions of Clark (1985), Lapidus (1987), and Allaby and Allaby (1990) are dismissed on the grounds that the environments of formation are too prescriptive. Thus the literature review (Chapter 6) revealed that processes acting in seventeen environments might be responsible for pedestal rock formation. The literature review also revealed that some pedestal rocks are composed of homogeneous rock throughout, which means that the definition of Mayhew and Penny (1992) is also dismissed. The definition of Twidale and Campbell (1992) is set aside on the grounds it implies that the girth of the pedestal is narrower than that of the caprock, which is not always the case. Although the definition made by Geller (2003) is rather broad, its very simplicity overcomes most of the shortcomings of the above definitions. Nevertheless, it was felt that something more specific was required for the thesis. This is because the thesis is concerned with the formation and evolution of only post-Devensian-deglaciation pedestal rocks whose pedestals are composed of Carboniferous limestone. In addition it became apparent from the literature review that caprocks might or might not have protected their pedestals from weathering/erosion, in which case the pedestals have formed due to preferential weathering/erosion, and that caprocks might or might not be contiguous with their pedestals. Finally, the literature review brought to light the fact that caprocks are composed of different rock types, and as it is unknown whether this might have any bearing on pedestal formation it was felt that mention of this fact had to be included in any proposed definition. Accordingly, but only for the purpose of the thesis, the following definition is used.

‘A pedestal rock is comprised of an overlying caprock consisting of any type of rock supported by a pedestal composed of Carboniferous limestone that has formed since ablation. The caprock and pedestal may be separated by a structural break (a perched pedestal rock) or the two may be structurally contiguous (a mushroom pedestal rock). The girth of the pedestal may be narrower or broader than that of the caprock and the caprock might or might not have protected its pedestal from weathering/erosion. The pedestal rock can have formed in a wide diversity of weathering and/or erosional environments.’

1.7: Ethical considerations

Every attempt was made to follow the country code when carrying out fieldwork. Permission was sought to enter private land if ownership was known; otherwise the use of binoculars was substituted for access. Attempts were also made to be as non-invasive as possible of the natural environment. Thus, all plant species were identified *in situ*, and the removal of soil and rock samples for testing in the laboratory was kept to a minimum.

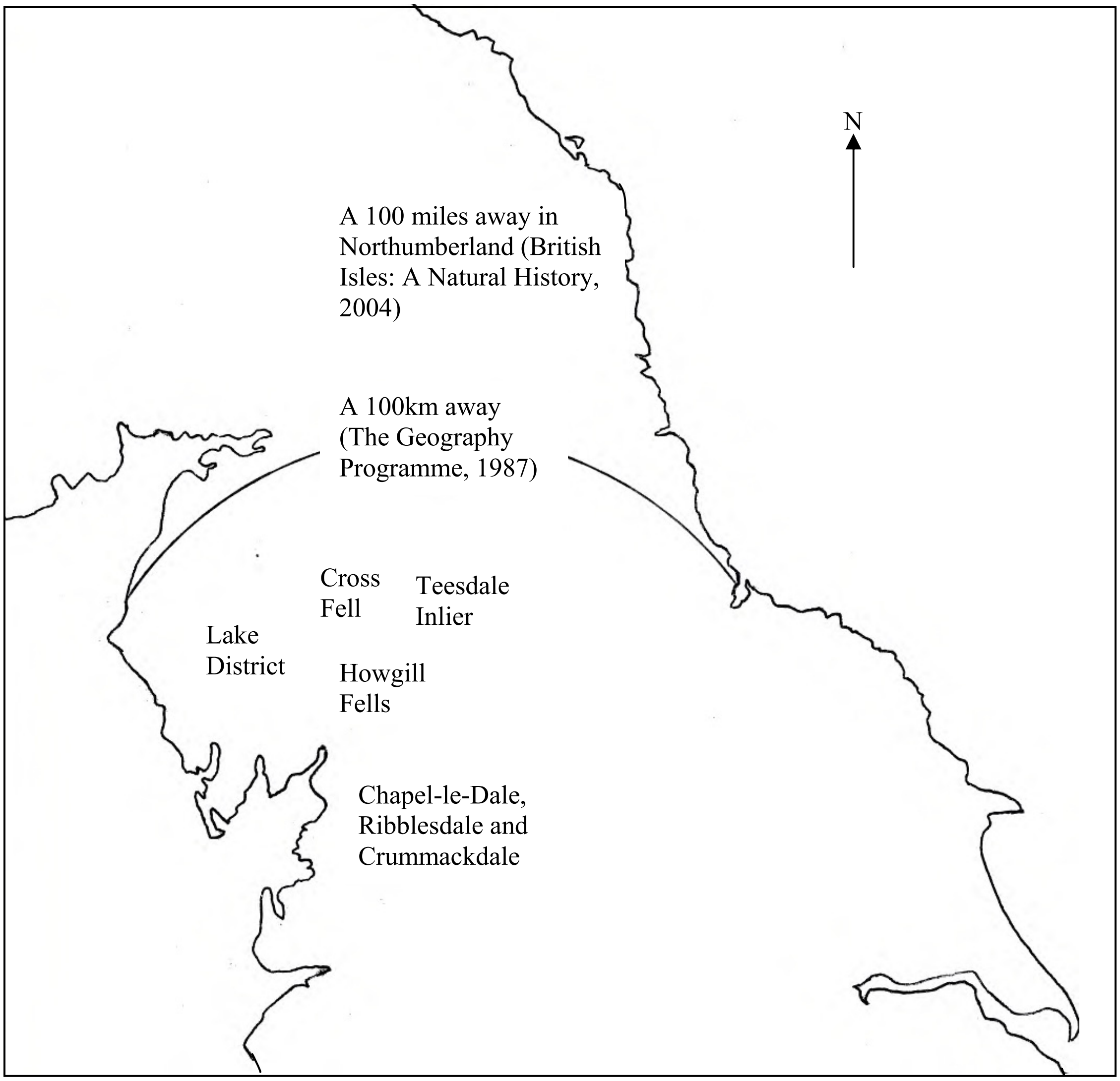


Fig. 1.1: The nine potential sites of Norber Erratic provenance

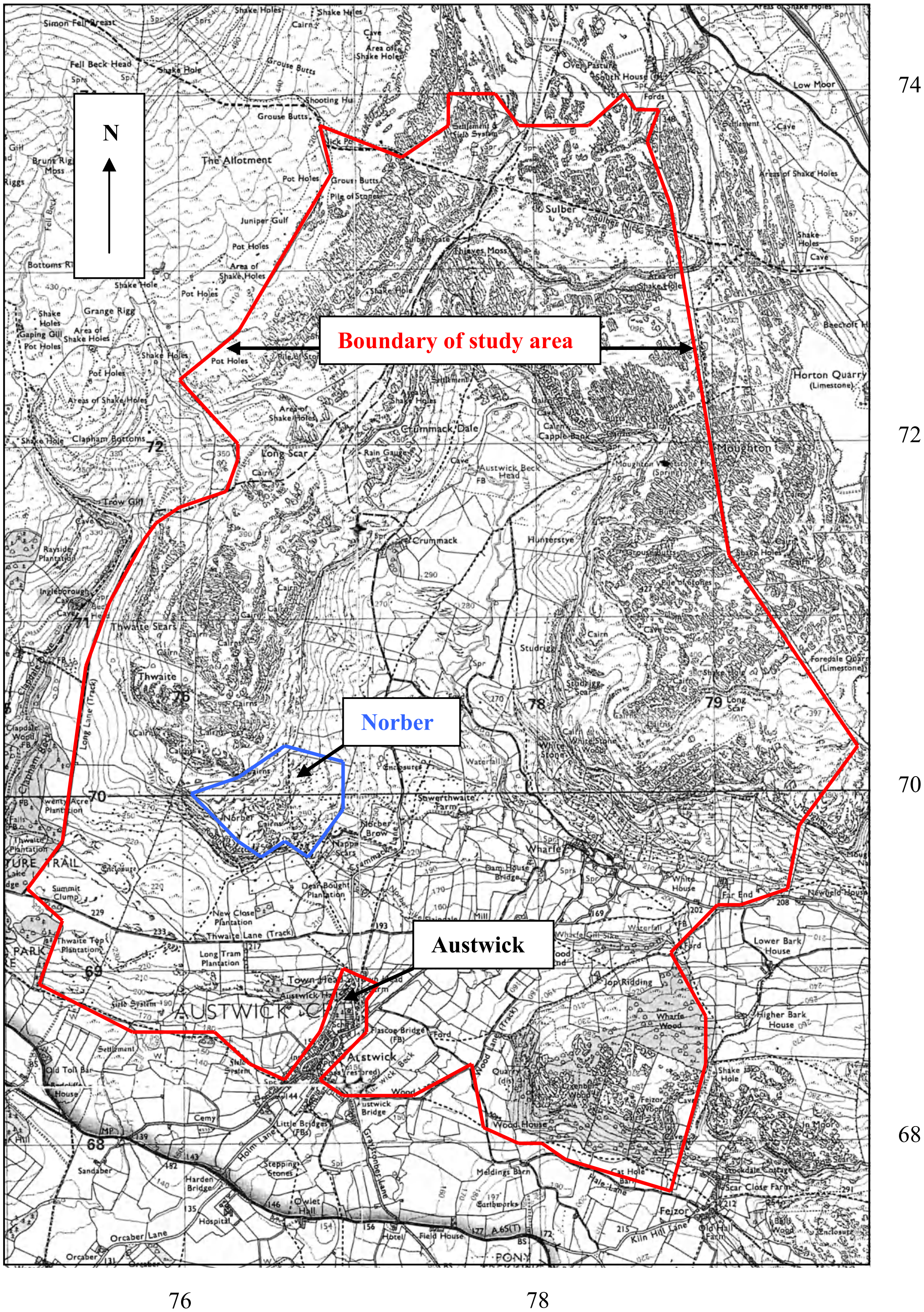


Fig.** Error! No text of specified style in document..1: Norber and the study area (courtesy of the Ordnance Survey, Southampton) (Scale given by National Grid coordinates)***

Fig.* Error! No text of specified style in document.*.2: Thesis layout and methodologies re pedestal formation in Chapters 6-12

Chapter 6: Literature review
17 environments identified that might have contributed to pedestal formation at Norber

Chapter 7: Erosion environments

Environment	Methods
Aeolian	Vegetation height survey Soil sieving
Fluvial	Landform survey
Glacial	Pedestal-height measurements
Karstic (sub-regolith)	Soil pH analysis Limestone tablet weight loss Karst landform survey
Lacustrine	Map study
Marine	Clast-roundness survey
Poaching	Landform survey
Soil creep	Soil-depth measurements
Step retreat	Climate analysis

Chapter 8: Modification environments

Environment	Methods
Biogenic	Algal/lichen survey
Freeze-thaw	As step retreat
Hydration	Thin-section analysis
Induced fracture	Stress and UCS determination
Insolation	Climate analysis
Karstic (subaerial)	Rain/dripwater analysis Limestone tablet weight loss
Salt crystallisation	Climate analysis
Sidewall failure	Landform survey

Chapter 9: Limestone fabric and composition at Norber
Discontinuity and thin-section surveys

Chapter 10: Past environments at Norber
Literature review
Vegetation and landform surveys

Chapter 11: Formation of post-Devensian-deglaciation Carboniferous limestone pedestals at Norber
Formation determined by drawing on information from Chapters 6-10

Chapter 12: Formation of post-Devensian-deglaciation Carboniferous limestone pedestals at seventeen extra-Norber sites in England, Ireland and Wales
Formation determined by drawing on information from Chapters 6-11 and by comparing 'type' pedestals

Plate** Error! No text of specified style in document.**.1: Erratics in south Norber

The angular shape and relatively large size of the erratics, which are all comprised of Silurian grit, are indicative of erosion and transport only by ice (Section 1.5). Their abundance, especially in the foreground, shows why it was impossible to plot each and every one onto a base map (Section 5.4.4). Their abundance, and size, also shows only too well why it was also impossible to excavate thirty pits by hand in order to bury limestone tablets at rockhead (Section 7.6.5). It is likely that ice flowing southwards off Moughton Scar (not in the photograph) would have been deflected westwards by the wooded, relatively high ground (Oxenber) in the left middle distance (Section 5.2.6). The 'improved' meadows in the left middle distance, which separate Norber from Oxenber, occupy the lower reaches of Crummackdale and are some 2km in width. Oxenber is partly covered in semi-natural woodland, and it is the nearest extant site to Norber where arboreal plants such as wood anemone, herb robert, wood sorrel, dog's mercury and primrose grow, plants that are also found growing in the grykes at Norber. The seed of these under-canopy species are not spread by the wind or by animals but by discard, which means it is not considered possible for progeny to have spread from Oxenber to Norber across the livestock-browsed meadows. Consequently, it is believed that the arboreal plants in the grykes at Norber are a relict flora of the Wildwood that covered Craven from ca.10000-3000BP, as outlined in Section 10.3.6.

Plate** Error! No text of specified style in document.**.2: Striae on N23

The striae dip at a steep angle (red arrow) and are not to be confused with cleavage planes or the joint sets that are also present. (For purposes of scale the long axis of N23 is about 1.5m.)

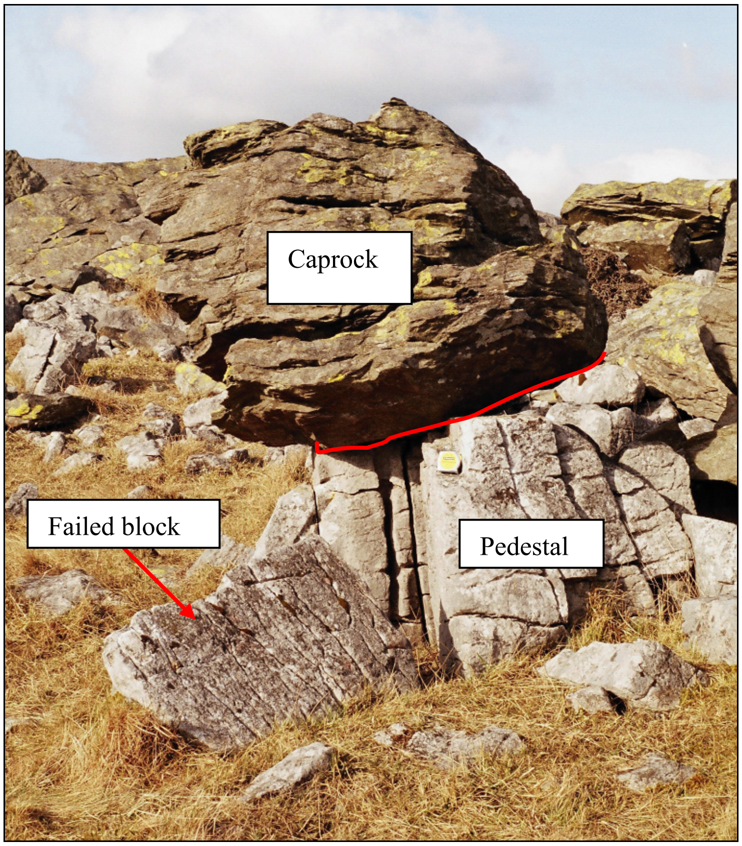


Plate** Error! No text of specified style in document.**.3: Perched pedestal rock N10 at Norber

N10 is a perched pedestal rock since there is a structural break between the cap rock, which is composed of Silurian grit, and the pedestal, which is composed of Carboniferous limestone (the approximate junction between cap rock and pedestal is marked by the red line). Note that the limestone block in the foreground can be 'jig-sawed' back into the pedestal, the block having failed due to undercutting of the pedestal by dissolution below the pasture-covered regolith (re Section 8.10). For purposes of scale, the tape-measure case is 5x5cm.

Plate *Error! No text of specified style in document.* ***.4: Mushroom pedestal rock B47 on the Burren***

B47 is a mushroom pedestal rock since the cap rock and pedestal, which are both composed of Carboniferous limestone, are structurally contiguous (the approximate junction between cap rock and pedestal is marked by the red line). For purposes of scale, the tape-measure case is 5x5cm.

CHAPTER 2: NORBER

2.1: Location

Norber (SD 763698) is located in the western Pennines of North Yorkshire, and is the name given to the south-eastern extremity of Long Scar/Thwaite Scars, an interfluve that extends northwards to Ingleborough some 5km distant (Fig. 2.1). Crummackdale, in which Austwick Beck flows, lies to the immediate east of Norber, while Clapdale, in which Clapham Beck flows, is found to the west, on the far side of the interfluve. Norber overlooks the Craven Lowlands, in which the River Wenning flows, to the south. The village of Austwick is located 1.5km to the south of Norber and the market town of Settle is situated some 6.5km to the south-east. Refer to Appendix 1 for a full list of localities and Appendix 2.1 for a glossary.

For the purpose of this study 'Norber' is defined as the walled field containing the word 'Norber' at SD 763699 on the 1:25000 OS sheet Outdoor Leisure 2: Yorkshire Dales – Southern and Western areas (1997) (Fig. 1.2). The definition also applies to the 1:10000 OS sheets SD 76 NE (1994) and SD 77 SE (1979). Two rights of way cross this field, one from Robin Proctor's Scar (SD 763697) to Nappa Scars (SD 769698) in an east-west direction and the other northwards from Nappa Scars to SD 766702, which means that the site is readily accessible to the public. The erratics in this field are the only ones that are regarded as 'the Norber erratics' *sensu lato*. Some authors, for example Dunham *et al.* (1953), Jones (1965) and Penny (1974) refer to the erratics as occurring on Norber Brow, which is an area some 100m to the east of Norber that is not open to the public.

2.2: Geology

To the north of Norber lies the peak of Ingleborough that rises to a height of 724m. The summit consists of a gently dipping and rhythmically alternating series of limestones, shales and sandstones, which comprise part of the Yoredale Group (formerly Wensleydale Group or Yoredale Series) of Upper Carboniferous age. The lower slopes of Ingleborough Fell, which includes Norber, consist of relatively pure and massive near-horizontal limestones of Lower Carboniferous age that were deposited some 320Ma ago. The following brief descriptions of the limestones at Norber are taken from the Geological Survey 1:50000 map, Sheet 60 – Settle (1989).

> 3. Gordale Limestone Formation (Malham Formation) – well-bedded packstones, wackestones and subordinate grainstones.
>
> 2. Cove Limestone Formation (Malham Formation) – a sequence of massive light grey, pure packstones and grainstones.
>
> 1. Kilnsey Limestone Formation (Kilnsey Formation) – well-bedded, partly muddy limestones.

Refer to Appendix 2.1 for abbreviations and Appendix 3TS.4 for a more complete description of the three limestones.

The Carboniferous limestones of Ingleborough form a plateau whose surface lies at an approximate altitude of 400m that stretches to the west as far as Chapel-le-Dale and to the east as far as Ribblesdale. During the Devensian glaciation the ice that flowed southwards along Crummackdale cut down through the southern flank of the plateau to expose highly-folded Lower Palaeozoic basement rocks. These consist largely of grits (greywackes), flags and shales of Silurian and Ordovician age that were deposited in excess of 400Ma ago. The basement rocks of the Crummackdale Inlier have been divided by Arthurton *et al.* (1988) into six lithostratigraphical units in Crummackdale, and the succeeding brief descriptions are again taken from the Geological Survey 1:50000 map, Sheet 60 – Settle (1989).

Silurian:

4. Horton Formation – mainly comprising laminated siltstones, but also including a turbiditic sandstone.

3. Arcow Formation – comprising calcareous siltstones.

2. Austwick Formation (formerly the Austwick Flags and Grits) – comprising alternations of turbiditic sandstones and siltstones that become thicker and more arenaceous southwards.

1. Crummack Formation – comprising impersistent mudstones.

Ordovician:

2. Sowerthwaite Formation – a sequence of tuffs and of sandstones below overlain by mudstones that include a conglomerate above.

1. Norber Formation – comprising calcareous siltstones.

Refer to Section 5.3.2 for a more complete description of the lithostratigraphical units that are relevant to the thesis.

The Carboniferous limestone succession of Norber and the Lower Palaeozoic succession of Crummackdale are terminated to the south by the North Craven Fault, which is the most northerly major fault of the Craven Fault Zone. The land is downthrown to the south of the zone and this has resulted in rocks of Upper Carboniferous age appearing at the surface. The fault zone separates the Craven Lowlands to the south from the Askrigg Block to the north. The geology of Norber and its environs is outlined in Fig. 2.2.

2.3: Geomorphology

The Norber-Ingleborough landscape is essentially Quaternary in age, since most surface features were carved by ice during the Pleistocene, and subsequently modified by more temperate fluvial and karstic processes in the Holocene. The Pleistocene epoch, or 'Ice Age', began some 2Ma ago, and ice sheets scoured the Yorkshire dales on at least four occasions (Waltham *et al.,* 1997). The final glaciation, which occurred in the Devensian, lasted from ca.24000 to 14500BP reaching an acme at ca.18000BP (Brandon *et al.,* 1998). The only local above-ground features that may pre-date Devensian glaciation are old erosional surfaces at approximately 400m (Sweeting, 1950) and at 700m (King, 1969) as well as the main valleys such as Ribblesdale (Raistrick, 1930). During the Devensian ice swept in from the north, the valleys of Chapel-le-Dale and Ribblesdale acting as iceways beneath the ice sheets (Waltham and Tillotson, 1989), and covered the entire area reaching a thickness of perhaps 300m over the summit of Ingleborough Fell during its maximum (Boulton *et al*., 1977). The ice not only stripped the hills and the limestone plateaux of superficial deposits, but also plucked long lines of crags such as Moughton Scars and deepened valleys such as Crummackdale. By ca.14500BP the Pennines had become ice-free more due to a lack of supply of fresh snow than to amelioration, and it seems that the ice shrank into the valleys (Dunham *et al.*, 1953; Waltham and Tillotson, 1989) where it stagnated and melted away (Carruthers, 1948). The ablating ice sheet dumped extensive veneers of till up to about 490m above OD (Arthurton *et al.,* 1988), including the till and erratics at Norber. The deposits still cover much of the lower ground where they locally attain a thickness of 20m, but over the uplands they are patchy. The following 1500 years witnessed periglacial/tundra conditions, which saw the formation of the many scree deposits that envelop the steep valley sides of Crummackdale. During this period it is likely that frost action caused some of the erratics at Norber to split into several portions. The Devensian Stadial ended ca.13000BP and was followed by a period of relative warmth, the Windermere Interstadial, and for the ensuing ca.2000 years the climate, weathering and erosion were broadly similar to that of nowadays. A climatic deterioration at ca.11000BP shepherded in the Loch Lomond Stadial when glaciers reappeared in Britain, though none is thought to have formed on Ingleborough (Manley, 1959). Freeze-thaw was widespread (Berglund, 1986) and may have added to the formation of the extensive drapes of scree found at the foot of plucked scars. The Pleistocene came to an end ca.10000BP with a climatic amelioration that marshalled in the Holocene, and for the past ten millennia the climate has remained broadly comparable to that at present. Karstic processes became dominant and the maturation of such features as clints and grykes on the glacially stripped limestone benches led to the formation of limestone pavements, such as those at Thieves Moss.

2.4: Climate

Wheeler and Mayes (1997) has described Ingleborough Fell as being of sufficient altitude to create a harsh local environment of low temperatures, high rainfall and frequent cloud cover, and this is borne out by meteorological data. There is no local weather station in the immediate neighbourhood of Norber, the nearest being Malham Tarn Field Centre, which is some 16km to the east-south-east of Norber. Daily measurements of temperature and precipitation have been recorded at the Field Centre since 1961, and sunshine hours since 1983. An analysis by the author of figures for 1961-2003 provided by the Field Centre shows that Malham has a mean diurnal temperature range of 6.0ºC (mean minimum-maximum range of 3.8-9.8ºC) with a mean frequency of seventy-eight days of frost per annum. Mean annual precipitation rates are 1501mm and the mean daily incidence of sunshine is 3.2 hours per day. Both Malham and Norber have similar aspects with relatively high ground to the north and lowlands to the south. Malham, though, is of a greater altitude than Norber the respective heights of the two localities being approximately 400m and 300m above OD. Consequently, it is likely that Norber has slightly higher temperatures given that the environmental lapse rate is 0.6ºC for every 100m of ascent, and perhaps a little less precipitation and a few more sunshine hours than Malham. Measurements of wind speed are not recorded at Malham, but the mean annual wind speed in the western Pennines was 17.3-18.4kph (4.8-5.1m/sec), with gusts of over 100kph recorded, for the years 1961-1990 (Barrow *et al.,* 1993). Wind direction is likewise not recorded at Malham, but figures are at hand for High Bradfield (SK 2694) in the Peak District Pennines, some 90km to the south-east of Norber, which is described by Briffa and Atkinson (1997: 221) as a "…typical exposed upland site." The wind blows from all quarters with a mean of 22% of winds originating from the west-south-west (windward) octant and 7% from the east-north-east (leeward) octant. The mean wind speed is greater from the windward (approximately 9m/sec) than from the leeward (approximately 6m/sec). It is not known whether winds at Norber differ from those at High Bradfield, but speeds may be marginally less since the altitude of the latter site is 81m greater. It is supposed that the climate of Norber is typical of the localities given, notwithstanding some differences of site.

2.5: Vegetation and soils

In view of the fact that Devensian ice covered the entire local area (Boulton *et.al.*, 1977) no soils (apart from those in deep grykes – if, indeed, the latter existed) or plants can have survived from a time prior to deglaciation ca.14500BP. In fact, it is likely that the vegetation and soils, although since much man-modified, date from the Holocene as the vegetation of the Loch Lomond Stadial consisted of tundra and scrub communities interspersed with ground covered in snowfields, while soils were thin, mineralic and contained mull humus. The dramatic global warming that ushered in the Holocene resulted in a great expansion of trees on the initially base-rich and shallow soils, which were low in organic content. Once established, the natural vegetation of oak/hazel woodland created its own soil (Waltham and Tillotson, 1989) so that by ca.5000BP much of Britain was covered by dense, mixed deciduous forest (the Wildwood) growing on fertile brown earths (Berglund, 1986). At ca.5000BP retrogressive vegetational changes came about caused by a combination of progressive leaching of nutrients under a cool, moist climate and by the anthropogenic removal of vegetation (Hockey, 1969). The changes led to mor humus replacing mull, and also to much soil loss and to the laying bare of limestone pavements. Most of the land in the environs of Norber is now treeless comprising a degraded vegetation of established grassland with underlying rendzina soils on limestone pasture and peaty podsols on the more acidic sandstones. At Norber itself, soils mainly comprise brown earths developed on till. Nearly all of the pre-ca.5000BP plant cover has now been lost, although some man-modified remnants can still be found locally, such as Colt Park Wood in Ribblesdale.

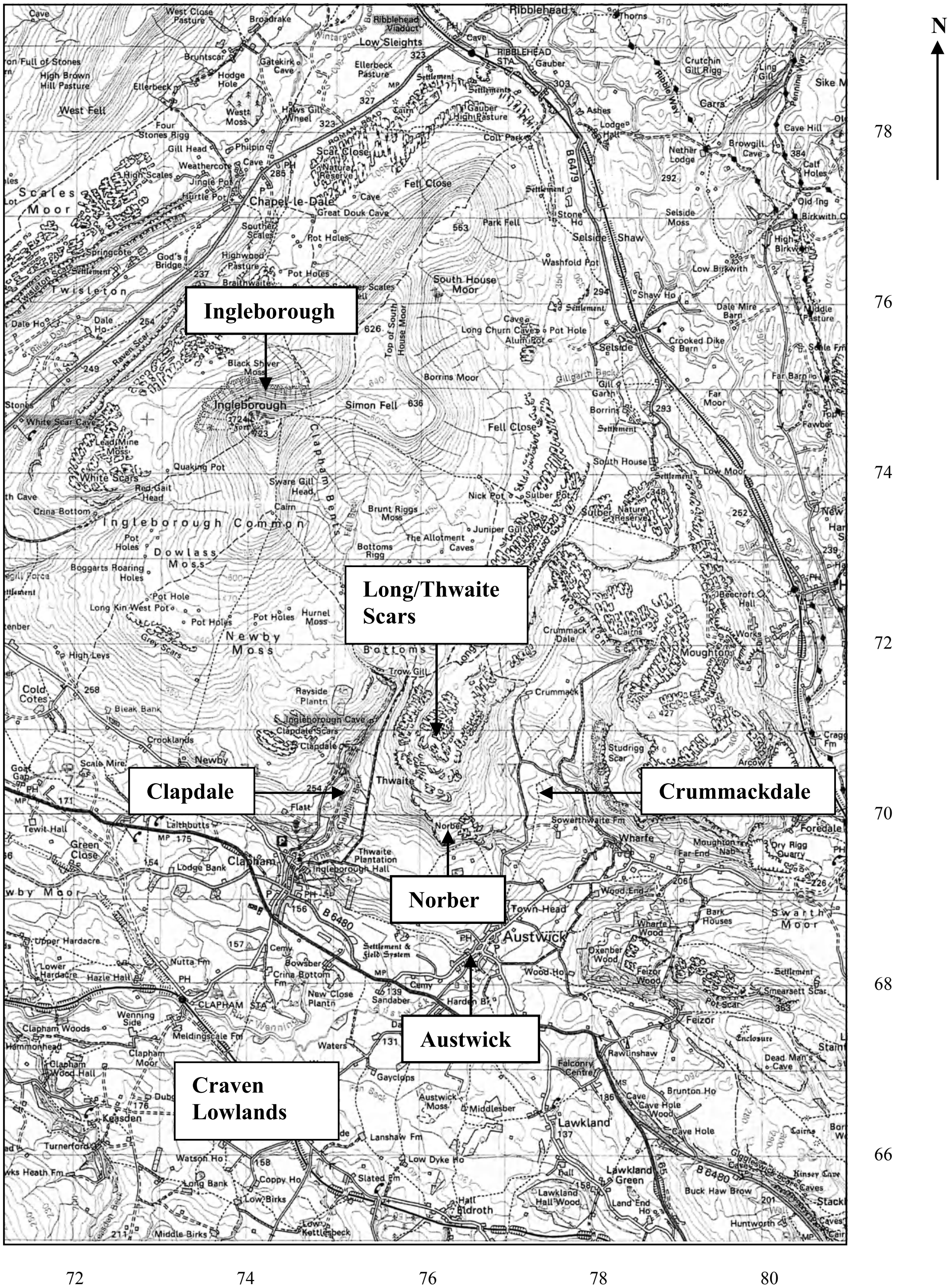
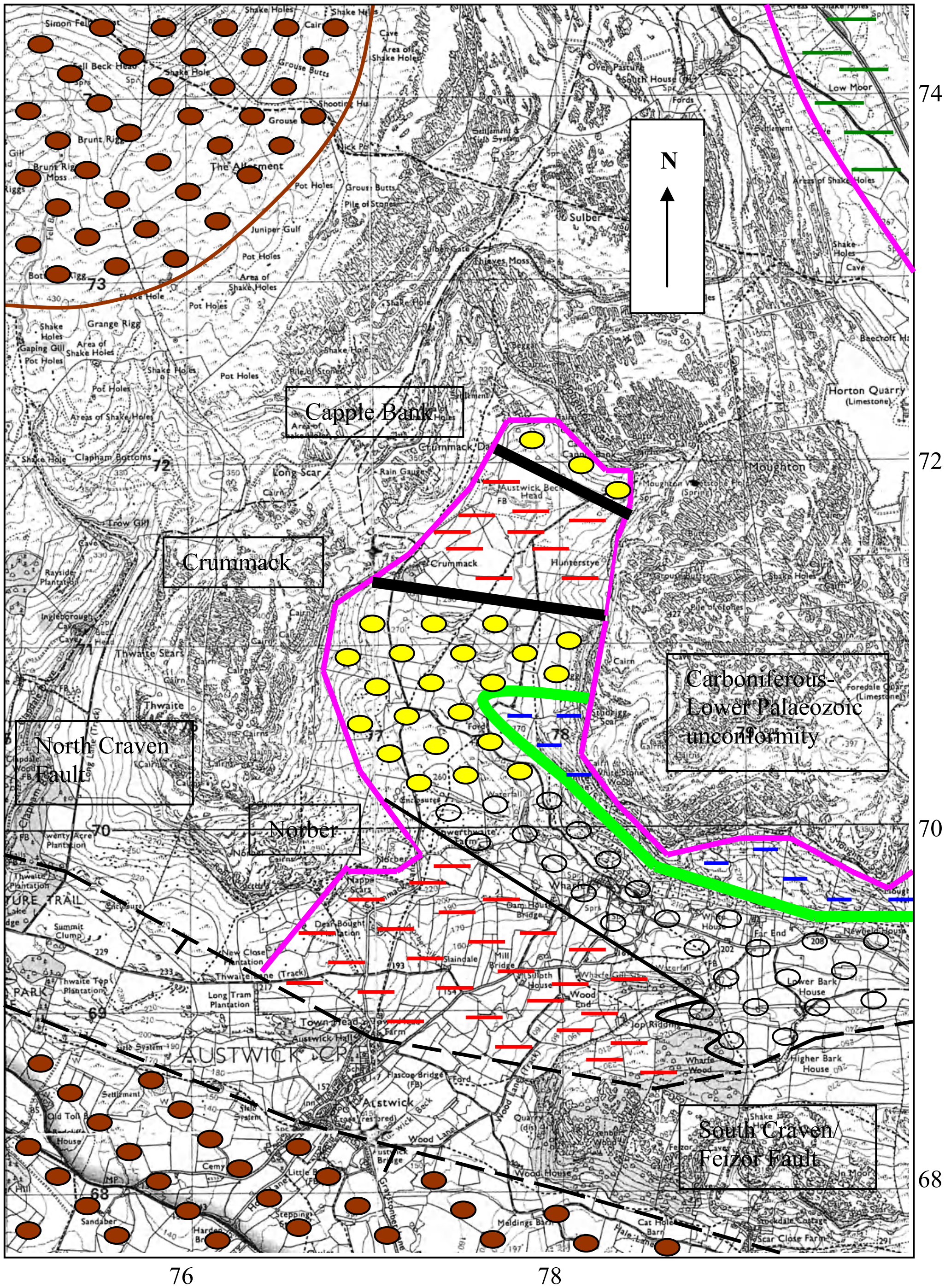


Fig. *Error! No text of specified style in document.**.1: The location of Norber, near Austwick and Ingleborough, in North Yorkshire (courtesy of the Ordnance Survey, Southampton)***

Norber (SD 7669) is located about 1.5km to the north-north-west of Austwick (SD 7768) and about 5km to the south-south-east of Ingleborough (SD 7374). Scale given by National Grid coordinates.



KEY:

Carboniferous
Carboniferous sandstone
Carboniferous limestone (blank)

Silurian
Crummack Formation
Austwick Formation
Arcow Formation
Horton Formation

Ordovician
Coniston Limestone Group (includes the Sowerthwaite and Norber formations)
Ingleton Group

Fig. *Error! No text of specified style in document.*.***2: Geology of Norber and its environs (after Dunham et al. (1953) and Arthurton et al. (1988)) (Scale given by National Grid coordinates)***

CHAPTER 3: THE NORBER ERRATICS – LITERATURE REVIEW

3.1: Introduction

The literature review is not restricted to articles that have appeared solely in 'serious' texts, since there are many sources of 'non-serious' information that need to be examined if conclusions appropriate to today re the provenance of the Norber erratics are to be reached. This is because although articles in serious texts, e.g. by Dunham *et al.* (1953), are likely to be better informed, sources of non-serious information, e.g. British Isles: A Natural History (2004), are likely to reach a wider audience. Both sources of information are likewise examined in Chapter 6 re the formation of post-Devensian-deglaciation pedestal rocks for the same reasons.

3.2: Literature review

The earliest-known record of the Norber erratics is in Phillips (1827 and 1855) (cited in Hughes, 1886). Phillips (1855) (cited in Hughes, 1886: 530) wrote that calliard (=hard, smooth and flinty) masses of the slaty rock have been drifted "...to the south-west, south, and south-east, not merely or mainly by the valleys, but over the high ground, so as to rest on the limestone hills...above Ingleborough House and Austwick. The greatest elevation reached by the slaty rock *in situ* in the district is about 1160 feet under the bare limestone of Long Scar...[which]…is covered by very many of these blocks brought from below, and scattered on the surface to a height of no less than 1260 feet. The blocks...show no marks of abrasion; no other drift matter is with them; they are collected sometimes into small groups; and they may be regarded as having been uplifted and floated by ice, and dropped on surfaces which have been swept by currents clear of other loose matter." Davis and Peck (1878: 200-201) made illustrations of the erratics (Fig. 3.1) and also wrote an account of them, stating that the most magnificent example of ice-transported blocks in the West Riding "…is at Norber. They occur in great numbers on the Limestone Escarpment about half way between Clapham and Moughton Scar above the village of Austwick. In the low part of the valley of Crummack Dale, the Silurian Grits are exposed at the base of the Limestone Scars and are inclined at a considerable angle. The glacier which descended this valley has torn away huge fragments of the grits and carried them in a westerly or south-westerly direction." Hughes (1886: 531) likewise drew attention to the erratics. "About a mile north of Austwick…Resting on the mountain-limestone plateau of Norber, there are a number of large blocks of Silurian grit…These have been forced along from beds at a lower level, in Crummack valley, and left often on a bare table of limestone." Hughes (1886) also pointed out (p. 535) "…that they have all obviously travelled in the direction of the furrows on the rock on which they rest, from rock in place close by to the north of them." Kendall and Wroot (1924: 942) mentioned the erratics only briefly, writing that blocks of Ordovician and Silurian rocks (Austwick Grits) "…strew the surface of the limestone." Dunham *et al.* (1953: 110-111) provided more detail as they wrote that erratic blocks "…of limestone and sandstone are common, but the most spectacular examples occur in a wide train of blocks, many of them perched, on Norbert Brow. Occurring between 1,000 and 1,200 feet they consist of Austwick Grit transported from the lower ground of Crummack Dale (769707)". Jones (1965: 429) explained that the erratics were "…dragged out of Crummack Dale and deposited on Norber Brow as the ice skirted Thwaites Scar. They now lie, an untidy collection over a great field of rough pasture." Raistrick and Illingworth (1965) appear to suggest, however, that the erratics may have come from slightly farther afield. They wrote (p. 28) that the limestone area of Norber and Moughton "…is scattered with large erratic boulders of green slates and grits carried by the ice out of Crummockdale (sic) and Ribblesdale, and dropped here on melting."

Embleton and King (1968: 304) concentrated more on the processes involved, as they stated that a good example of the prising off of erratics by ice "…is seen in north-west Yorkshire where Silurian boulders lie on Carboniferous Limestone at Norber Brow. The beginning of the process is seen in enlarged rectangular cracks developed in the Silurian bedrock as the prising process (along bedding planes or joints in many instances) started to operate." Rodgers (1978: 78) wrote that the Norber scenery "…is characterised by the blocks of sandstone that lie upon and indeed litter the limestone surface. The sandstone is of Silurian age and is therefore older than the limestone on which it sits. These blocks were, in fact, deposited here by the ice sheets of the last glaciation which came to an end around 10000 years ago." Brumhead (1979) gave a full account of the origin of the erratics. He wrote (p. 37) that the Norber Rocks (SD 766697) are "…glacially transported angular boulders of dark grey grits of the Austwick Formation (Silurian) littering the surface of a wide limestone shelf. These boulders were once *in situ* on the western slopes of Crummack Dale, half a mile [1km] away and 400 feet [120m] lower where the basement rocks outcrop beneath the limestone. They have been torn from their position, transported, and deposited by ice which once filled the dale." In complete contrast to an origin from as little as 1km distant, the presenter of The Geography Programme (1987) declared that the erratic boulders at Norber belong to a rock type "…which comes from a completely different area, a hundred kilometres away." Arthurton *et al.* (1988: 89) prefer a more local provenance as they stated that on the west side of Crummackdale "…are the famous Norber erratics. These blocks of Austwick Formation sandstones and siltstones have been plucked from outcrops (SD 770704) north-west of Sowerthwaite Farm, glacially transported and strewn over the limestone pavements on Norber." Waltham (1990: 14) was somewhat less precise about the provenance of the erratics, mentioning only that the

Crummack ice "…plucked greywacke blocks from the basement slope just south-west of Crummack Farm…[and that they]…have even been carried slightly uphill." In 2005 Waltham expanded and refined this viewpoint somewhat, stating (p.145) that the erratics had been carried south by the Crummack Dale ice, and are now "…stratigraphically higher than their source". Waltham (2005) added it was clear that the popular concept of the erratics being glacially transported uphill from the floor of Crummack Dale was inaccurate "…as they are derived largely from the crags at higher level in the basement rise". Goudie and Gardner (1992: 31) portrayed the Norber erratics as one of the finest groups in Britain. In disparity with all of the preceding authors, however, a Carboniferous age is ascribed to the rock that comprises some of them as it is stated that the boulders are "…often composed of Yoredale or Millstone Grit." Scrutton (1994: 27) concurred with Arthurton *et al.* (1988) re provenance writing that the limestone pavement is strewn with blocks of dark Austwick Formation sandstones and laminated siltstones. The blocks were plucked by the ice "…from outcrops (SD 770704) 1 kilometre to the north in Crummack Dale. The source of the erratic blocks can be seen in the small crags on the left-hand side of Crummack Lane (heading north) before the junction at SD 772706." Huddart and Glasser (2002) are a little less specific about provenance, mentioning that the erratics have been transported across the limestone for more than 1km and more than 120m uphill from Austwick Formation outcrops to the north. A much more far-flung provenance is proposed in British Isles: A Natural History (2004), as the commentator stated that some of the stones at Norber came from "…Northumberland, a hundred miles away." In the most recent account Goldie (2005) writes that the erratics are Austwick Formation grit/greywacke boulders placed on Carboniferous limestone by ice that moved them mostly about 1km, and uphill about 120m, from their original outcrop.

3.3: Summary of literature review

The general consensus is that the erratics found at Norber were transported from a northerly direction and were then deposited at the end of the Late Devensian Glaciation. It appears that they are composed of sedimentary rock since they are described as grits or sandstones or laminated siltstones or greywackes and that this rock is of Silurian age. It also appears that the erratics have been plucked from the Austwick Formation and that their provenance is rocky outcrops that occur approximately 1km away on the west side of Crummackdale. Nonetheless, there is much disharmony with regard to this generalized viewpoint, especially when the site of provenance is considered. Hence the direction of movement of the ice that transported the boulders may have been from the east or north-east (Davis and Peck, 1878), while the geological age of the rock comprising the erratics may be Ordovician (Kendall and Wroot, 1924) or, by implication, Carboniferous (Goudie and Gardner, 1992). It is possible, too, that the rock comprising the erratics may be metamorphic, as Phillips (in Hughes, 1886) and Raistrick and Illingworth (1965) use the terminology 'slaty' and 'slates' (the latter also use the additional term grits) in turn when describing it. Raistrick and Illingworth (1965) propose an origin from Ribblesdale in addition to Crummackdale, and a source from outside of Crummackdale is implied by Goudie and Gardner (1992), given that neither Yoredale beds nor Millstone Grit occur in Crummackdale. The differences of lithological opinion pale into insignificance when provenance is considered, however, as an origin from a hundred kilometres away (The Geography Programme, 1987) and from even farther afield a hundred miles distant in Northumberland (British Isles: A Natural History, 2004) is proposed.

3.4: Discussion

3.4.1: Evidence that the Norber erratics have been transported and deposited by Late Devensian ice

Northern England suffered several advances and retreats of the ice during the Pleistocene, but Rodgers (1978:78) was the first to suggest that the Norber erratics were deposited by ice "…of the last glaciation", i.e. the Devensian. Arthurton *et al.* (1988) offer confirmatory evidence for this suggestion, as they point out that the last glaciation during late Devensian times in the Settle area was so intense that all deposits from earlier Pleistocene events other than some occurring underground were destroyed. Moreover, Mitchell (1994), working in the Western Pennines immediately to the north of Ribblesdale, discovered that Ice Flow Event 2 in the Devensian had destroyed all evidence of previous ice sheet flow direction. Brandon *et al.* (1998) likewise suggest that although the Lancaster district was very probably glaciated on several occasions, its Quaternary deposits (with the possible exception of minor cave sediments) date mainly from the later parts of the last, or Late Devensian, glacial stage. More generally, Williams (1966) points out that limestone pavements were swept clear of weathered residue during the last glaciation and that no pre-glacial or inter-glacial deposits have been found on them, although such deposits may be sealed within caves or joints. Ballantyne and Harris (1994) have written that it is not really clear when the ice sheet finally melted but date ablation at about 14000BP. Most authors more-or-less agree with this date, e.g. about 15000-14000BP (Soffer and Gamble, 1990), 14500BP (Pentecost, 1992), retreating from most areas by 14500BP (Williams *et al.*, 1998), and approximately 14000BP (Robinson and Henderson-Sellers, 1999). Accordingly, for the purpose of this study a date of 14500BP is adopted.

Subsequent to the melting of Devensian ice, a period of climatic amelioration (the Windermere Interstadial) occurred but this was followed by a climatic deterioration, the Loch Lomond Stadial. According to Mitchell (1991) this latter event was marked in the Western Pennines by the re-establishment of five small cirque glaciers, the nearest to Norber being found on Whernside. This was the largest of the Loch Lomond Stadial glaciers in the Western Pennines, but it was nevertheless very limited in size and only covered an area of 0.4km^2. There is no evidence for the establishment of a glacier on Ingleborough, although Manley (1959) suggested that a persistent snowbed might have existed to the north of the summit plateau and that if so, this was the southernmost outlier of the Loch Lomond Stadial in north-west England. Therefore, the Norber erratics must have been deposited when Devensian ice ablated.

3.4.2: Evidence that Devensian ice moved from the north

At its maximum extent Devensian ice covered all of Scotland, a very substantial area of Ireland and Wales, and large parts of northern England (Fig. 3.2). According to Lowe and Walker (1997) the greatest areas of ice accumulation and dispersal in Britain were the highlands of western Scotland, and here ice flow was essentially radial. Thus flow from the southern parts of this major ice sheet, such as in the Loch Lomond area, was generally to the south. Consequently great masses of ice advanced southwards into the Irish Sea Basin and also down the western margins of the North Sea basin. There is much evidence to support this regional southerly movement of ice in the Late Devensian, including pebbles derived from Ailsa Craig in the Firth of Clyde occurring in South Wales (Pringle and George, 1948), and, rocks from the Cheviots found in till along the coast of Lincolnshire (Wilson, 1948). At a more local level, Goodchild (1875: 59) verifies the southerly flow of ice as he noted that the Silurian areas of Chapel-le-Dale, Crummackdale and Horton-in-Ribblesdale "…have yielded no boulders that have traveled to the north." In addition, Raistrick (1930: 240) observed that the pre-Carboniferous slates and grits from Ribblesdale "…are traceable in the drift southward through Lancashire, and eastward through Airedale for considerable distances." This is confirmed by Arthurton *et al.* (1988) who showed that the major drumlin field that fills the Craven lowlands to the south at Settle indicates that that the ice that crossed the Ribblesdale Inlier flowed either south into Lancashire or south-east along the higher reaches of Airedale. Furthermore, Mitchell (1994) identified a north to south-trending ice divide to the east of the Dent Fault that bifurcated on Rise Hill immediately to the north of Dent (Fig.3. 3). This shows that ice flowed to the south from Rise Hill into the northern part of the Ribble catchment and then down-valley towards the Ingleborough area and beyond. Therefore, it would appear that the Norber erratics originated from the north.

3.4.3: Evidence that the Norber erratics are composed of sedimentary rock

There is no record of a full petrographical description of either a hand specimen or a thin section of a sample taken from an erratic at Norber. In addition most of the field descriptions are rather short, refer largely to grain size and make little or no reference to other textural features or mineralogy or structure. Most of the field descriptions do, however, imply that the rock that comprises the Norber erratics is sedimentary. This is due to the use of such terminology as grits (e.g. Brumhead, 1979), greywacke (e.g. Waltham and Tillotson, 1989), sandstones (e.g. Arthurton *et al*., 1988) and siltstones (e.g. Scrutton, 1994). Nevertheless, some metamorphic terminology has also been introduced into the descriptions, as the words 'slaty' and 'slate' are used respectively by Phillips (cited in Hughes, 1886) and by Raistrick and Illingworth (1965). The use of these metamorphic terms can almost certainly be explained by the fact that most Lower Palaeozoic rocks, including those in Crummackdale, have suffered some degree of deformation such as folding, faulting and compression, and as a result any relatively fine-grained sedimentary strata present have developed poor cleavage. Thus Dunham *et al.* (1953: 93), when describing a section of the Austwick Grits in Crummackdale, write that the lower division of the grits "…is massive and thick bedded but contains narrow bands of flaggy mudstone in which excellent examples of refraction of cleavage can be seen." Thus, the terms slaty and slate are applicable in this situation. Therefore, it would appear that the Norber erratics are composed of sedimentary rock.

3.4.4: Evidence that the Norber erratics consist of rock that is of Silurian age

Although it is generally accepted that the rock that comprises the Norber erratics is Silurian in age, this fact appears to be based solely on the assumption that the erratics have been derived from the Austwick Formation in Crummackdale. There is no doubting the age of the Austwick Formation itself, since it contains a Silurian fauna that includes the graptolites *Monograptus priodon* and *Pristiograptus dubius* (Arthurton *et al*., 1988), but there is no record of any fossils having been found in the erratics themselves. It is thus not possible to prove on palaeontological grounds whether the rock that comprises the erratics is of Silurian or Ordovician or Carboniferous or indeed any other age; nor have the erratics been subjected to any radiometric dating tests. Nonetheless, since the rock that comprises the erratics has undergone low-level deformation and has also been described as greywacke, it cannot post-date the Silurian as strata with these characteristics do not appear higher in the geological column to the north of Norber. Sedimentary rocks of a similar description are, however, found in older strata in the Ordovician and in the Cambrian, but rocks of the latter age do not occur to the north of Norber until the Highland Boundary Fault is crossed. Therefore it would seem likely that the rock that comprises the Norber erratics is either of Silurian and/or Ordovician age (i.e. they were deposited in the Lower Palaeozoic).

3.4.5: Evidence that the provenance of the Norber erratics is approximately 1km away on the west side of Crummackdale

It would appear that erratic provenances could be one of several localities occurring approximately 1km from Norber on the west side of Crummackdale, and that of these the most precisely indicated is that of Dunham *et al.* (1953). They write (p.93) that to the west the lower groups of the Austwick Grits extend across Crummack Dale and that their outcrops "…are seen lying in the core of the syncline on the western slopes below the Carboniferous rocks. Here they provide the material for the famous glacier-carried "Norber boulders" (769707)." This locality has been photographed by Dunham *et al.* (1953) who state (p. 102) that blocks "…may be seen in process of being riven off by the glacier that traveled down the dale from north to south. Blocks that have been removed litter the ground to the south of the crag and form a trail up the hill onto the Carboniferous Limestone of Norber." Arthurton *et al.* (1988), however, suggest a provenance approximately 0.5km to the south at SD 770704, a site which is also favoured by Scrutton (1994). The latter author somewhat confusingly adds (p. 27), though, that the source of the blocks can be seen "…in the small crags on the left-hand side of Crummack Lane (heading north) before the junction at SD 772706." This is somewhat perplexing since the grid references are not only 0.5km apart but also because the small crags in question are a segment of the same suite as those at SD 769707. Waltham *et al.* (1997) produced a geomorphological map of the Ingleborough area that shows a boulder train originating from a plucked scar on the western side of Crummackdale and which includes the erratics found at Norber. The origin of the boulder train would seem to be more in the vicinity of SD 769707 than of SD 770704. Brumhead (1979) also prefers a provenance that is approximately 1km (half a mile) away on the western slopes of Crummackdale, but adds (p. 37) that these boulders "…were once in situ… 400 feet lower [than Norber]". The latter figure is inaccurate as there are no locations in western Crummackdale that are 120m (400 feet) lower than Norber; the only point which is 120m lower and 0.8km (0.5 mile) away from Norber is at SD 777 696 directly to the east of Norber.

Although it seems that the provenance of the Norber erratics is 1km away on the west side of Crummackdale, Raistrick and Illingworth (1965) recorded that the limestone area of Moughton is also scattered with large erratic boulders of green slates and grits. The view of a limited area for the source of the Norber erratics is further muddied by the only recorded observations of striae made in the area. These were made by Tiddeman (1872), who measured 7 striae in the vicinity of Norber (Table 3.1) and who produced a map showing the strike of 4 striae in Crummackdale. Tiddeman (1872) utilized glacial indicator tracing to show that ice-flow was from the north and using the striae as evidence deduced that ice flow varied from toward the south-east (i.e. 135° azimuth) to 20° west of south (i.e. 200° azimuth). The direction of ice movement based on Tiddeman's (1872) results can be seen in Fig. 3.4. This indicates that the erratics found at Norber could have been derived from outcrops other than in western Crummackdale, as his south-easterly stria, which is located in Clapham Burn, suggests a possible provenance for the Norber erratics from Chapel-le-Dale. The statement by Goudie and Gardner (1992) that the erratics are often composed of Yoredale or Millstone Grit also implies that they do not originate from Crummackdale, since rocks of this type do not crop out in the valley itself. In fact, the nearest outcrops are several kilometres to the north on the southern flanks of Ingleborough.

The proposal in The Geography Programme (1987) that provenance is 100km away from Norber is not backed up by any evidence. Its credence is also lacking, since no Lower Palaeozoic rocks actually crop out 100km to the north of Norber, the closest to 100km occurring at some 90km distance near Bewaldreth in the northern Lake District. In theory, it is possible for the erratics at Norber to have been derived from this location as Ordovician mudstones, siltstones and sandstones of a turbiditic origin that belong to the Skiddaw Group (Jackson, 1978) crop out here. The regional movement of ice would, however, suggest otherwise. Thus, flow from the northern Lake District was initially westwards and then southwards into the Irish Sea basin (Fig. 3.2), as witnessed by the occurrence of Buttermere and Ennerdale granophyres, and Eskdale Granite in the lowlands of Lancashire and Cheshire (Wright, 1937). Hence, ice from the Bewaldreth area would have by-passed Norber well to the west.

It is also possible in theory for the Norber erratics to have originated from Northumberland, as proposed in British Isles: A Natural History (2004), since two Silurian inliers crop out at about 100 miles (160km) from Norber in the Cheviots. The inliers, which are comprised of grits, greywackes and shales (Robson, 1976), are found in the immediate proximity of the Scottish border, the larger of the two occurring in the headwaters of the River Coquet and the smaller 0.5km to the south of Ingram. Two other inliers containing greywackes, which are respectively 130km (80 miles) and 190km (120 miles) rather than 160km (100 miles) from Norber, also crop out in Northumberland. These occur at Caddroun Burn near Saughtree to the west of Kielder Water (Scrutton, 1995) and immediately to the north of Berwick-upon-Tweed on the North Sea coast (Robson, 1965). The regional movement of ice would again suggest that Northumberland is not the source of the erratics, though. This is because ice-flow in the Scottish Borders was eastwards from the Cheviots towards the North Sea basin, and then southwards along the North Sea coast (Pringle, 1948), as seen in Fig.

3.2 and as shown by the presence of Cheviot erratics on Holderness (Eastwood, 1963). This means that Northumbrian ice would have by-passed Norber well to the east.

Three further Lower Palaeozoic outcrops that are more local than those found in the northern Lake District and in Northumberland also occur to the north of Norber. Of the three localities, the Cross Fell Inlier, which occurs some 75km distant from Norber, contains greywacke siltstones and sandstones (Burgess and Wadge, 1974) as do the Howgill Fells (Rickards, 1978), which occur some 35km to the north of Norber. The third outcrop, the Teesdale Inlier, which occurs some 70km distance from Norber, is comprised mostly of fine-grained rocks (Johnson, 1961) that are not akin to the Norber erratics. Eastwood (1963) has shown, however, that ice from Cross Fell (and Teesdale) swept south-eastwards/eastwards across the northern Pennines, before turning southwards when it met Scottish ice along the margin of the North Sea basin, consequently by-passing Norber to the east. Ice from the Howgill Fells, on the other hand, by-passed Norber to the west, since Moseley and Walker (1952), and Brandon *et al.* (1998) have made clear that it flowed southwards down Lunedale. Further verification that ice did not move from any of these outcrops of Lower Palaeozoic rocks towards Norber from the north has been compiled by Mitchell (1994), who used the evidence of drumlin orientation to reconstruct former ice sheet movement in the western Pennines. Here, a north to south-trending ice divide was identified to the east of the Dent Fault, which bifurcated on Rise Hill near Dent, the offshoot trending south-east and approximately following the line of the Wensleydale-Dentdale interfluve. From these two divides ice flowed largely into the upper reaches of Ribblesdale and then proceeded to the south. Hence the ice that plucked, transported and deposited the Norber erratics originated from no farther away than Rise Hill, just 10km to the north of Norber. Therefore, it would seem extremely unlikely that the Norber erratics have originated from outside of the Ingleborough area, although this assertion can not quite be dismissed out of hand since Arthurton *et al.* (1988) mention that erratics from beyond the Pennines, however rare, occur in the Settle area.

3.4.6: Evidence that the source of the Norber erratics is the Austwick Formation

It has been stated, for example, by Hughes (1886), Kendall and Wroot (1924), Brumhead (1979) and Scrutton (1994), that the Norber erratics are derived from the Austwick Formation, yet these authors have given brief field descriptions only of the erratics and not of the Austwick Formation itself. In contrast, King and Wilcockson (1934) and McCabe and Waugh (1973) have given petrological descriptions of the Austwick Formation (but only of arenaceous units), whereas Dunham *et al.* (1953) have given an account of its discontinuities. No similar account of the Norber erratics has, however, been undertaken by any of these latter authors. The only authors to have described both the erratics and their putative source rock, the Austwick Formation, are Arthurton *et al.* (1988), and here the only words common to both descriptions are sandstones and siltstones.

If the provenance of the Norber erratics is from Crummackdale, then those erratics composed of sandstone/greywacke can have originated only from the Austwick Formation, since this is the only lithostratigraphical unit in the valley to contain arenaceous rock. Those erratics composed of siltstone (or slate) could, however, have been derived from any one, or more, of the five lithostratigraphical units that outcrop to the north of Norber, namely the Sowerthwaite, Crummack, Austwick, Arcow and Horton formations, depending on the direction of ice-flow. If, however, the provenance of the Norber erratics is from Chapel-le-Dale or Ribblesdale, then those erratics composed of sandstone/greywacke could have originated from the Ingleton Group in either valley or from the Studfold Sandstone Member, the Austwick Formation or the Neals Ing Formation in the latter valley. No siltstones occur in Chapel-le-Dale, but two units of siltstone, the Arcow Formation and the Horton Formation, are found in Ribblesdale. Furthermore, there are other Lower Palaeozoic outcrops in the Lake District, at Cross Fell and in the Howgill Fells, where arenaceous and argillaceous lithostratigraphical units crop out together to the north of Norber.

Therefore, although it is quite feasible that the Norber erratics have been derived from the Austwick Formation in Crummackdale, it is not clear whether some or indeed all of the erratics have been derived from other outcrops either in Crummackdale itself or from farther afield to the north.

3.5: Conclusion

On the basis of published literature it can be concluded that the Norber erratics are glacial clasts, composed largely of arenaceous rock that have been plucked from Silurian or Ordovician strata and then transported by ice moving from a general northerly direction during the Devensian. They might, or might not, have been derived from outcrops of the Austwick Formation located 1km to the north of Norber in western Crummackdale. This conclusion is scrutinized in the following two chapters.

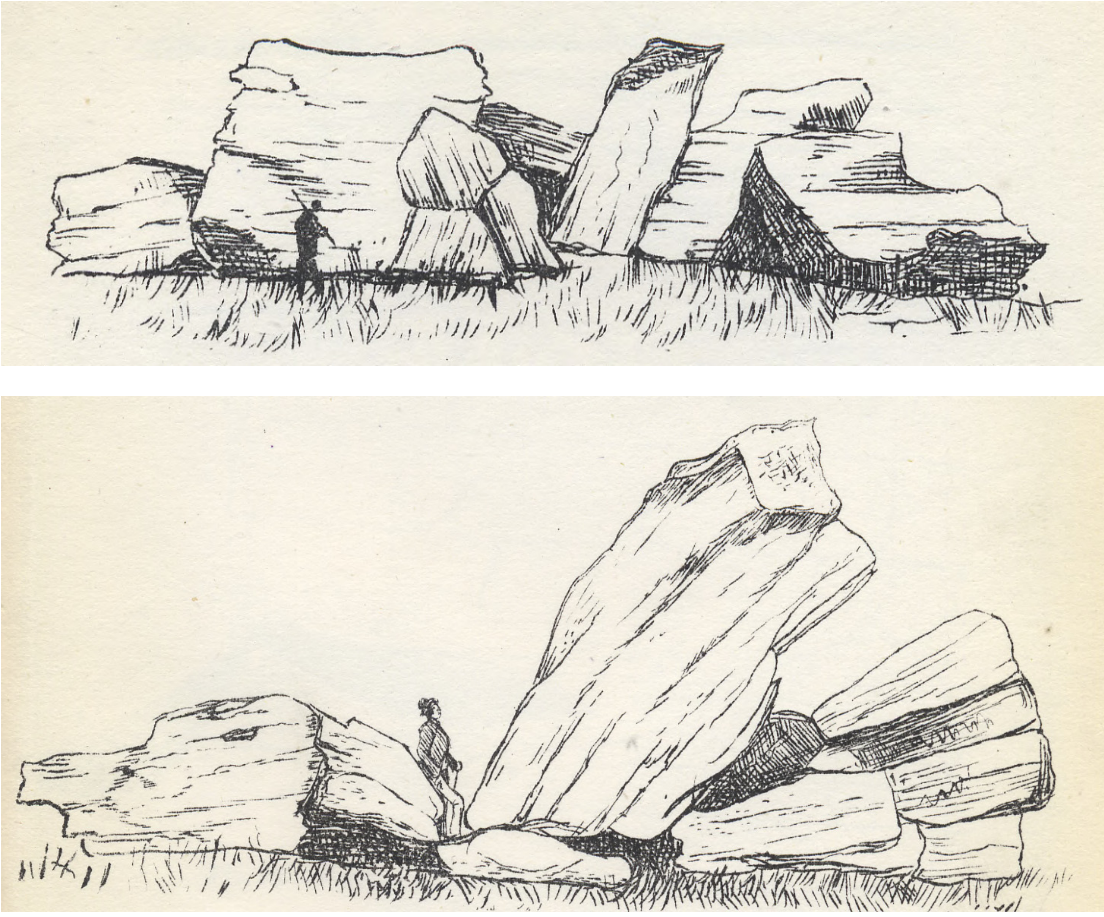


Fig. *Error! No text of specified style in document.****.1: Erratic blocks at Norber (Davis and Peck, 1878, Figs. 41 and 43)***

For purposes of scale, the two figures give an indication of the large bulk of some of the erratics at Norber.

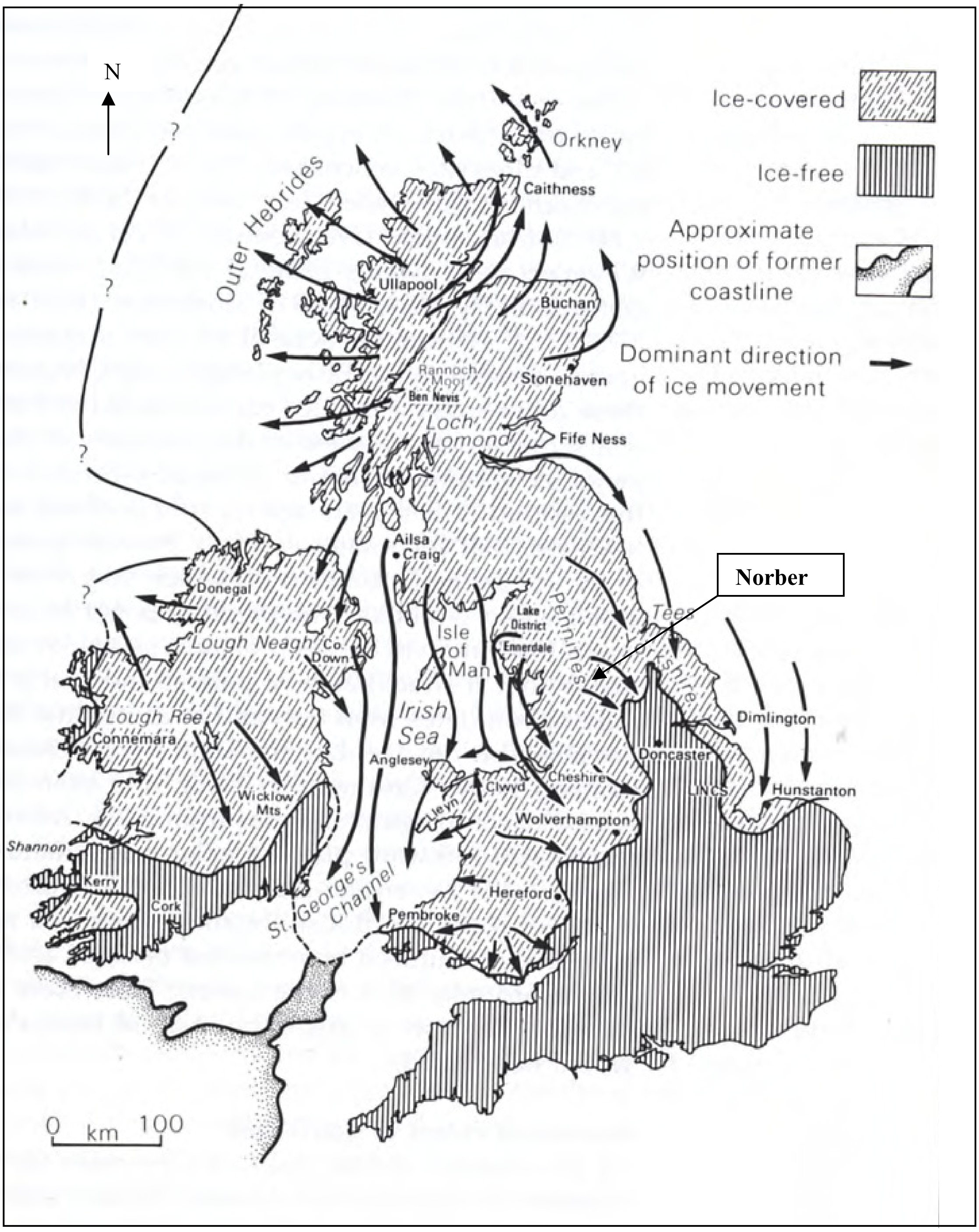


Fig. *Error! No text of specified style in document.****.2: The position of Norber, and the extent of ice-covered and ice-free land, principle paths of ice movement and the approximate position of the coastline at the maximum extent of Devensian glaciation (Lowe and Walker, 1984)***

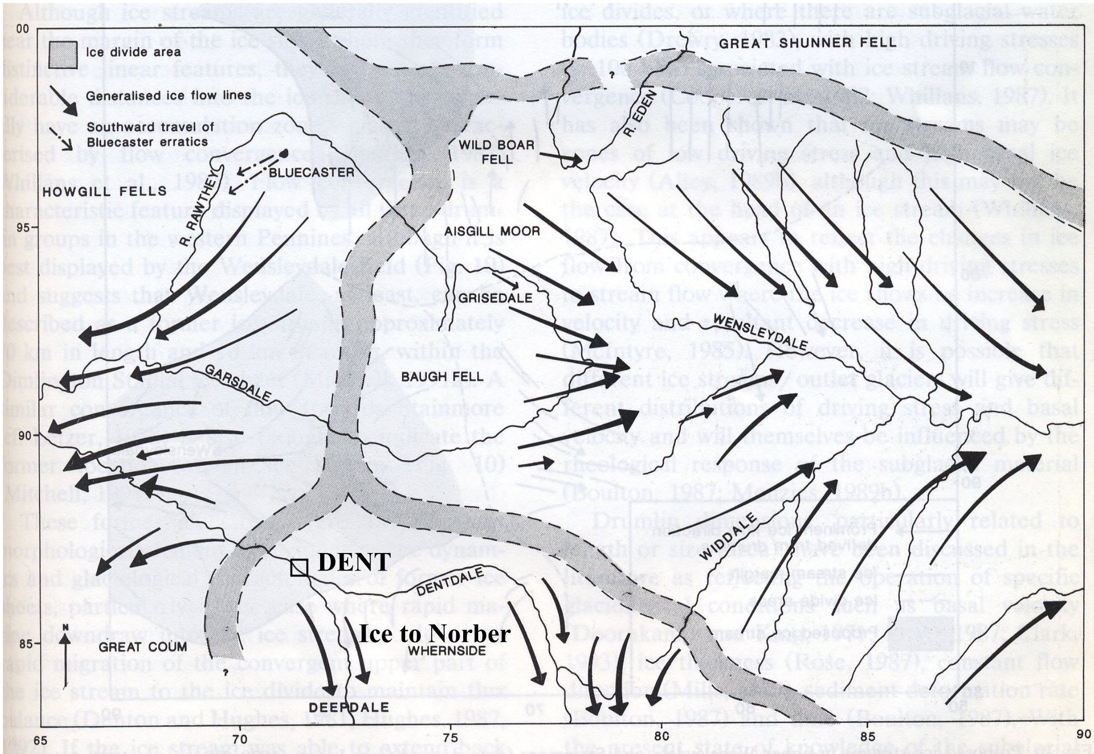


Fig.** Error! No text of specified style in document.**.3: Ice flow directions and location of ice divides in the Western Pennines during Ice Flow Event 2 (Mitchell, 1994) (Scale given by British National Grid coordinates at 5km intervals)

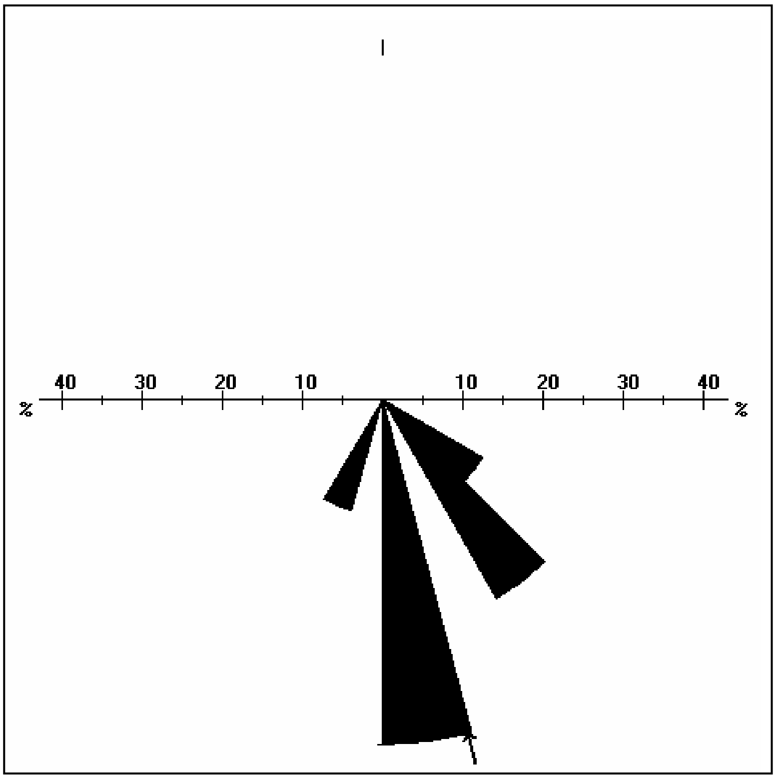


Fig. *Error! No text of specified style in document.**.4: Rose diagram of the direction of Devensian ice flow in the Crummackdale area (from seven measurements of striae made by Tiddeman (1872)) (sector size 15° azimuth)***

Striae Localities	**Direction**
W. side of Clapham Burn [3]	S.E.
Norber [1]	S. 20° W.
Wharfe Mill-Dam [2]	S. 30° E.
W.S.W. of Crummack [1]	S.
¾ mile S. of Crummack [1]	S.
200 yards E. of last [1]	S. 10° E.
Newby Cote [3]	S. 35° E.

[1] In Crummackdale and in the survey area
[2] Not in Crummackdale but in the survey area
[3] Not in Crummackdale or the survey area

Table** Error! No text of specified style in document.**.1: Location and strike of striae for Sheet 113 (Crummack Dale) (after Tiddeman, 1872)

CHAPTER 4: THE GEOGRAPHICAL PROVENANCE OF THE NORBER ERRATICS

4.1: Introduction

As it is unclear whether the provenance of the Norber erratics is Crummackdale or other Lower Palaeozoic outcrops occurring to the north of Norber, the aim of the work described in Chapter 4 is to establish which outcrop(s) they have been derived from. The chapter opens with a preliminary survey that delineates the boundaries of the study area within which evidence was to be collected for analysis. After the completion of the survey the dispersal of erratics within the designated area was mapped, largely following procedures outlined by Lawson (1990). The distribution of three tracer erratics was then scrutinised in order to determine the general direction from which Devensian ice moved into Crummackdale. Once this had been established it then became possible using the dispersal of all erratic types found within the study area to conclude which Lower Palaeozoic outcrop is the geographical provenance of the erratics at Norber.

4.2: Preliminary survey

Prior to the commencement of the preliminary survey the OS maps outlined in Section 2.1 were scrutinised in order to gain familiarity with the terrain and rights of way. A thorough preliminary examination of ground was then undertaken in order to reconnoitre natural phenomena such as erratics, landforms and outcrops of strata, and anthropogenic features such as fields and dry stone walls, and to delineate the area to be studied. Although the boundaries of the study area are determined by accessibility, they were mainly chosen to allow sufficient clear ground between them and Lower Palaeozoic outcrops both in and beyond Crummackdale in order to determine whether or not the Norber erratics had been derived from outside of Crummackdale. The study area encompasses some 20km² (2000 hectares) of rough moorland, limestone pavement and enclosed fields (Fig. 1.2). The boundaries are as follows:

Western boundary. This approximates to easting SD 75 and is roughly 1km to the west of Norber and the Carboniferous-Lower Palaeozoic unconformity in the vicinity of Crummack (SD 7771). The boundary encloses erratics found to the west of the unconformity on Long Scar (SD 7671) and Thwaite Scars (SD 7570), including those at Norber, and it is pertinent to geographical provenance as the Lower Palaeozoic outcrop at Chapel-le-Dale is found to the west.

Northern boundary. This approximates to northing SD 74 and is about 4km to the north of Norber and some 2km to the north of the Carboniferous-Lower Palaeozoic unconformity in the vicinity of Capple Bank (SD 7872). The boundary encloses erratics on Sulber (SD 7873) to the north of the unconformity, and it is pertinent to geographical provenance as the Lower Palaeozoic outcrops of Northumberland, the Lake District and the Howgill Fells are found to the north.

Eastern boundary. This approximates to easting SD 79 and it is around 3km to the east of Norber and 1km to the east of the Carboniferous-Lower Palaeozoic unconformity in the vicinity of Studrigg (SD 7870). The boundary encloses erratics found to the east of the unconformity on Moughton (SD 7971), and it is pertinent to geographical provenance as the Lower Palaeozoic outcrop at Ribblesdale is found to the east.

Southern boundary. This approximates to northing SD 685 and it is some 3.5km to the south of the Carboniferous-Lower Palaeozoic unconformity in the vicinity of Capple Bank. It is also 1.5km to the south of Norber and 0.5km to the south of the North Craven Fault in the vicinity of Thwaite Lane (SD 7669) at the 207m spot height. The boundary encloses erratics to the south of the Crummackdale Inlier, which are pertinent to the survey in terms of establishing/confirming the direction of Devensian ice flow.

4.3: The dispersal of erratics

4.3.1: Introduction

According to Shakesby (1978), examining the dispersal of erratics has for long been cited as tangible evidence of former ice-flow direction and erratic provenance. The technique of investigating the distribution of erratics is known as glacial indicator tracing, and Benn and Evans (1998) add that it provides glacial geologists with a powerful tool for reconstructing the patterns and history of ice movement. Thus Dakyns (1873: 161) was able to prove that Silurian erratics discovered in Wharfedale had not been transported from the direction of Ribblesdale by traversing the countryside between the rivers Wharfe and Ribble. "For I quite satisfied myself, that these boulders had not come direct over the Fells from the Silurian strata of Ribblesdale; I felt sure of this, because I carefully examined the ground, and not a boulder of Silurian rock could I find any where on the fells." Furthermore, Dakyns (1873) was able to pin down their (concealed) provenance by tracing the erratics and observing (p. 162) "…that all the Silurian boulders occur south of…Kilnsey Crags. I would suggest that somewhere in the lower part of Upper Wharfedale Silurian rocks exist…beneath the covering of deposits…and that it was from this outcrop of rock that the Silurian boulders…were derived."

4.3.2: Aim and objectives

The aim of the work undertaken in Chapter 4 is to discover the geographical provenance of the Norber erratics. The objectives are to map the dispersal of erratics, noting any that may be of use as indicator erratics, and to determine the direction of Devensian ice-flow.

4.3.3: Method

A number of erratic dispersal mapping methods have been employed in order to determine ice-flow direction and/or erratic provenance:

1. Geochemical analyses of erratics (e.g. Dilabio, 1981), geochemical anomalies of drift (e.g. Shilts, 1996) and geophysical surveys (e.g. Puranen, 1990); these techniques have been used to trace ore-rich, magnetic or radioactive clasts back to their source.

2. The distribution of erratics in random sections of dry stone walls: Shakesby (1978), and Mitchell and Bugie (1991) used this procedure to trace the former direction of ice-flow respectively in Scotland and the western Pennines during the Devensian.

3. The examination of ground: Lawson (1990), when resolving ice movement in Assynt, Sutherland, systematically 'examined the ground' by traversing across the assumed former ice-flow direction by approximately following the Ordnance Survey eastings, where the topography allowed, mapping the distribution of distinctive erratic boulders. The 1km spacing of eastings was subsequently reduced in those areas of particular interest, for example to clarify the edges of boulder trains leading from their source outcrops. The distribution of erratics was plotted onto 1:10560 field maps and where scale allowed, individual erratics were shown. He also delineated where the occurrences of specific erratics were not found.

4. Aerial photography: Saarnisto (1990) recorded that aerial photographs may be used as a mapping resource although no specific examples of their employment are quoted.

There is no literature evidence for the presence of any ore bodies or mineralised zones in Crummackdale or its environs, thus neither geochemical nor geophysical surveying methods were considered. In contrast, dry stone walls abound in the survey area, and as it is recognised, for example by Raistrick (1970), and Mitchell and Bugie (1991), that such walls are normally built of clearance stones picked up *in situ* from the ground nearby this method was utilised to determine the direction of ice flow. Shakesby (1978), though, noted that it is important to discover whether the indicator rock in question has been quarried. Consequently, it was decided not to use this technique in Crummackdale (with just one exception) as Dunham *et al.* (1953) and Arthurton *et al.* (1988) mention the occurrence of several abandoned and overgrown quarries in the valley. The presence and/or absence of 'anthropogenic' erratics was, however, noted in the dry stone walls of the moorland, limestone pavements and enclosed fields surrounding Crummackdale above the Carboniferous-Lower Palaeozoic unconformity where quarrying has not taken place. A study of aerial photographs of the Norber area (Meridian Airmaps Sheets 48 68 029/030/031: 1968) revealed that erratics are of insufficient stature and density to be readily discernible; tree crowns also fog the overall picture. Therefore, the main technique employed in order to determine the dispersal of erratics was an 'examination of the ground', as the appearance and lithology of Lower Palaeozoic rocks contrasts strongly with those from the Carboniferous. The survey was largely restricted to logging boulder-sized erratics that are exposed at the surface, since such boulders are relatively abundant throughout the survey area, but clasts of all sizes incorporated in regolith were also noted.

The location of erratics and rock outcrops/exposures (and also glacial features in Chapter 5) to ten grid reference figures was obtained using Magellan Promark X Global Position System (GPS) equipment that uses post-processing GPS technology to achieve an accuracy to within one metre. Essentially this requires two logging GPS hand sets: one logging continuously as a base station which must remain stationary, the other as a mobile unit used to locate and log features in the field. After all data has been collected the two units are downloaded and then processed by Magellan's Mstar software. The software compares the mobile files to the base control file by taking into account the wander inherent in GPS location; it processes the data and produces corrected positions. Prior to use the equipment was checked for accuracy against known locations of height and position, such as bench marks and triangulation pillars.

4.3.4: Limitations

It was initially planned to conduct the survey along the lines described by Lawson (1990), but a number of methodological limitations soon became apparent as the systematic mapping progressed.

1. It was intended to map the dispersal of erratics along grid lines that were 0.5km apart, but this proved impossible in the enclosed areas within Crummackdale and farther to the south, as this would have necessitated major detours in order to avoid clambering over dry-stone walls.

2. It was aimed to map the entire survey area, but it soon became apparent that many farms, especially in southern areas, consisted of split holdings. Permission to gain access to all fields was not therefore always sought due to the difficulties of locating the relevant landowner, and such fields were not entered.

3. It was planned to map all erratics, but their sheer abundance at certain localities (as seen in Plate 1.2, for example) made this a meaningless task. Thus, attempting to mark tens of the same erratic type next to each other onto a base map was not only impossible but was also thought not to be of any greater worth than marking just one.

Consequently the methodology used was modified as follows:

1. Unenclosed areas (largely open moorland) with access. Erratics were plotted onto the base map along the boundaries of the survey area, along grid lines 0.5km apart and in areas of particular importance, such as erratic boundaries and along the Carboniferous-Lower Palaeozoic unconformity. Erratics were plotted as accurately as possible where they were encountered, providing numbers were not overwhelming.

2. Enclosed areas (mostly fields) with access. No attempt was made to plot the position of erratics accurately except in specific instances, such as to clarify erratic boundaries. Otherwise it was felt sufficient to define the entire field as containing erratics of a particular type or types once an individual of that type had been located within it.

3. Enclosed areas (principally fields) without access. Erratics were surveyed using binoculars (Optolyth Alpin 10x40) and their lithology was deduced from their structure, colour and shape, as these properties were judged sufficient for diagnosis. No attempt was made to plot the position of erratics accurately as it was not believed that this could be achieved from afar. Thus the entire field was defined as containing erratics of a particular type or types once an individual of that type had been diagnosed within it.

4.3.5: Results

4.3.5.1: Tracer erratics

Three distinctive types of erratic rock were encountered that were regarded suitable for glacial indicator tracing purposes. They are derived from:

1. Lower Palaeozoic strata of the Crummackdale Inlier in general, as they are totally surrounded by outcrops of Carboniferous limestones.

2. The Wharfe Conglomerate (a member of the Sowerthwaite Formation), which consists of rounded or sub-rounded pebble-sized clasts set in a grey-green sandy matrix. It occurs in the northern limb of the Austwick Anticline near Sowerthwaite Farm (SD 7769) and also in the Crummack Anticline near Austwick Beck Head (SD7770).

3. Conglomeratic basal units of the Kilnsey Formation that contain angular Lower Palaeozoic lithoclasts, which are commonly pebble-sized, embedded in a calcareous matrix. They crop out immediately above the Carboniferous-Lower Palaeozoic unconformity in south-eastern Crummackdale, and between Robin Proctor's Scar (SD 7669) and the North Craven Fault; they are particularly well exposed at Nappa Scars (SD 7669) and at the head of Norber Syke (SD7669).

4.3.5.2: Erratic types and their distribution

All erratics are composed of clasts derived from rocks of Carboniferous or of Lower Palaeozoic ages (Fig. 4.1), and both types are present in till, on the surface of the ground and in dry stone walls. The Carboniferous erratics generally comprise either rounded clasts of grey or brownish-grey orthoquartzite or arkose (Carboniferous sandstones) or tabular/blocky clasts of pale-grey limestone (Carboniferous limestones). Most of the sandstone erratics are less than 30cm in size, although one reaches almost 1m in diameter on Sulber. Most of the Carboniferous limestone erratics are also less than 30cm in size, but two sub-spherical boulders at Norber, several on Sulber and a dozen or so slabs on Thwaite Top (SD 7569) reach a metre or more in diameter or in length. The precise provenance of the Carboniferous erratics is unknown, with the exception of the slabs occurring on Thwaite Top which are composed of the conglomeratic Kilnsey Limestone (Fig. 4.2). Erratics composed of Carboniferous sandstones and limestones are unevenly dispersed throughout the entire survey area, including Norber.

The Lower Palaeozoic erratics consist of angular clasts of arenaceous rock, and occasionally of argillaceous and rudaceous rock, which is dark grey and in some cases well-cleaved. The usage of the metamorphic terms 'slaty and slate' (Section 3.4.3) by Phillips (in Hughes, 1886), and by Raistrick and Illingworth (1965) when describing the erratics is thus not entirely misplaced. There is a complete range in grain size (to the naked eye) from sand-sized particles to a boulder as voluminous as approximately 56m^3 that occurs in the vicinity of the Old Limekiln (SD 770707). All the erratics at Norber that are larger than 1m in length are composed of Lower Palaeozoic rock except for the two that consist of Carboniferous limestone. This shows that Goudie and Gardner (1992: 31) are incorrect when stating that the huge boulders resting at Norber "…are often composed of Yoredale or Millstone Grit." Unlike the erratics of Carboniferous age, the Lower Palaeozoic erratics do not occur throughout the survey area, as can be seen in Fig. 4.1. They are totally absent on the limestone pavements of Sulber to the north of Crummackdale, on Long Scar to the west except in the vicinity of Norber and on Moughton to the east except in limited numbers under Studrigg Scar (SD 7870) (Figs. 4.1 and 4.3). The latter observation is somewhat at odds with the statement by Raistrick and Illingworth (1965: 28) that the limestone area of Moughton "…is scattered with large "erratic" boulders of green slates and grits." Unless, that is, they are alluding to similar erratics found to the east of the Moughton interfluve in Ribblesdale. Lower Palaeozoic erratics appear within a metre or so to the south of the approximate location of the Carboniferous-Lower Palaeozoic unconformity (it is largely covered by scree (Plate 4.1)), on Capple Bank, at Crummack and at Wharfe (SD 7869). They also occur throughout Crummackdale, at Oxenber (SD 7868), in the neighbourhood of Austwick (SD 7668) and on Thwaite Top southwards to the extremity of the study area. They were also observed (through binoculars) as isolated 'sentinels' in some of the fields to the south of the study area and were noticed in dry stone walls at SD 74701 69119 to the east of Clapham (SD 7469). Thus, apart from the exceptions at Norber and under Studrigg Scar, Lower Palaeozoic erratics occur only on Lower Palaeozoic strata or on the Carboniferous limestones to the south of the North Craven Fault. They are not evenly distributed, being most numerous on the western fringes of Crummackdale to the south of the Old Limekiln and to the south of Moughton Scar (SD 7971). They reach their greatest elevation at 380m above OD on Long Scar immediately to the north of Norber at SD 76384 70526. The bulk of the Lower Palaeozoic erratics are clasts whose precise provenance is unknown, but they include a sparse collection of Wharfe Conglomerate erratics at SD 77602 69686 to the south of Sowerthwaite Farm (Fig. 4.3) and at SD 77786 71806 east of Austwick Beck Head. In addition, the shape of a few clasts occurring in the vicinity of the Old Limekiln indicates that their provenance is nearby cliffs, since they can visually be 'jig-sawed' back together.

4.3.6: Limitations

No erratics are exposed over some relatively large tracts of the survey area, especially in the vicinity of Austwick, due to the relatively thick covering of regolith and to the agricultural 'improvement' of pastureland. Erratics are, however, usually exposed on the fringes of these areas thus enabling the overall picture of dispersal to be viewed, the one possible exception being in the vicinity of the Carboniferous-Lower Palaeozoic unconformity to the west of Crummack.

The use of binoculars in areas where access was not sought was deemed to be a 'necessary evil' as it follows that the lee of slopes, sheep walks and stream banks becomes 'blind ground' when using this survey method; it is thus possible that some erratics may not have been noted. Binoculars were, though, used only in the myriad of fields to the south of Crummackdale where the accurate mapping and identification of erratics was not considered critical to the survey.

The base of the scars and cliffs that largely surround the valley floor of Crummackdale are commonly mantled in scree or have fallen blocks of rock below them (Plate 4.1), and their presence led to difficulties in determining whether some blocks were *in situ* erratics or whether they were clasts that had undergone post-glacial mass movement. Nevertheless, it was possible to resolve their mode of formation in most cases. Accordingly, blocks that were more rounded than nearby scree or that had a different lithology when compared with exposures in nearby cliffs were deemed to be erratics. In contrast blocks resting on regolith were judged to owe their origin to mass movement, since scree formation post-dates till (regolith) deposition (Section 7.11.2), as were blocks that had obviously ploughed into the regolith.

4.3.7: Analysis

The dispersal patterns of the three indicator erratics in the survey area all show that the passage of Devensian ice was towards the south. Thus, the occurrence of Lower Palaeozoic erratics to the south of the Carboniferous-Lower Palaeozoic unconformity and to the south of the North Craven Fault (outcrops occur only to the north of the fault) show that the ice which transported them moved from the north (Fig. 4.1). The southerly movement of ice is also confirmed by the presence of conglomeratic Kilnsey Formation limestone erratics on Thwaite Top some 1km to the south-south-west of exposed outcrops at Nappa Scars/Norber Syke (SD 7669). Furthermore, these erratics occur to the south of the North Craven Fault even though basal units of the limestone crop out only to the north of it (Fig. 4.2). (The Kilnsey Formation also occurs at depth in the vicinity of Austwick to the south of the North Craven Fault, but the basal beds are not exposed because they have been faulted out by the Feizor Fault.) Erratics of the Wharfe Conglomerate occurring near Sowerthwaite Farm likewise occur to the south of their outcrop, having been transported some 200m by the ice (Fig. 4.3); they also appear in a dry stone wall approximately 100m farther south. The latter occurrence is the one exception where 'anthropogenic' erratics have been used to determine ice-flow direction in Crummackdale. There is, though, no evidence that the Wharfe Conglomerate has ever been quarried and it was observed that the phenoclasts readily weather out, which would render it a poor building stone. Wharfe Conglomerate erratics are also found to the south of their outcrop near Austwick Beck Head, although those found alongside the watercourse of Austwick Beck or occurring in loose piles are likely to have been moved by flood water or bulldozed by man. The southerly movement of ice is additionally verified by the presence of a particularly large (4mx4mx3.5m) Austwick Formation erratic in the vicinity of the Old Limekiln. The erratic is juxtaposed with a plucked cliff that has an approximate north to south strike, but as the erratic has been moved by only a few metres it is possible visually to 'jigsaw' it back into the cliff it was quarried from. This reveals that the northern edge of the erratic has moved approximately a metre further than its southern edge, which suggests that the erratic has been rotated in a southerly direction. The observation that Crummackdale is a U-shaped valley with a general north to south strike and with a floor that slopes to the south assists in confirming that Devensian ice moved in a general southerly direction. A little caution, though, must be exercised when making this assumption, since Waltham and Tillotson (1989) have pointed out that the overall pattern of hills and valleys in the Ingleborough area pre-date the Devensian Stadial. The deduction that ice-flow was from a northerly direction is in agreement with most views outlined in the literature, for example as proposed by Stephens (1990), Scrutton (1994) and Waltham *et al.* (1997), but is at slight variance with Davis and Peck (1878) who suggest flow from the east or north-east.

As it has been established from field evidence that Devensian ice moved to the south, it follows that the Norber erratics can have been derived only from Lower Palaeozoic outcrops that occur to the north of Norber. The complete absence of Lower Palaeozoic erratics on Sulber (SD 7873) immediately to the north of the Crummackdale Inlier conclusively shows, however, that erratic provenance is not 100km away as proposed in The Geography Programme (1987) or 100 miles distant in Northumberland as advocated in British Isles: A Natural History (2004). Nor, for the record, is it the inliers at Berwick-upon-Tweed and at Saughtree in Northumberland, nor the Lake District, the Cross Fell Inlier and the Howgill Fells in Cumbria, nor the Teesdale Inlier in County Durham. This assumption is confirmed by the total absence over the entire study area of erratics that are 'foreign' to the Ingleborough/Craven district, such as igneous or Devonian rocks that are found in association with the greywacke siltstones and sandstones at the above localities. Thus, ice emanating from these distant outcrops (Fig. 1.1) must have circumvented the Ingleborough/Craven area to the west or east (Fig. 4.4).

Lower Palaeozoic erratics do, however, occur under Studrigg Scar (SD 7870) on Moughton (SD 7971) on the east side of the Crummackdale Inlier (Fig. 4.1). The erratics rest on outcrops of the Malham Formation, *in situ* exposures of this formation and the underlying Kilnsey Formation cropping out for a minimum distance of about 2km to the east and north-east before the inlier at Ribblesdale is reached. Yet the Lower Palaeozoic erratics barely extend a hundred metres towards the north-east in the direction of Ribblesdale, and beyond them erratics composed only of Carboniferous rock occur. Thus, although ice moved from Ribblesdale into Crummackdale (over Sulber, Waltham *et al.* (1997)) the absence of Lower Palaeozoic erratics on Moughton discloses that the ice did not cross Lower Palaeozoic outcrops farther to the south in Ribblesdale prior to reaching Norber. Consequently, the Ribblesdale Inlier cannot be the provenance of the Norber erratics. This finding is in agreement with several authors from Dakyns *et al.* (1891) to Stephens (1990) who all envisaged ice moving south-south-eastwards down the length of the Ribblesdale Inlier into the Craven Lowlands, thus by-passing Crummackdale to the east. Accordingly, the (somewhat ambiguous) assertion made by Raistrick and Illingworth (1965: 28) that Norber and Moughton are scattered with erratics "…carried by the ice out of Crummockdale [sic] and Ribblesdale…" cannot be correct.

Lower Palaeozoic erratics also occur on Long Scar (SD 7671) at Norber to the south-east of the Chapel-le-Dale Inlier. The erratics rest on limestone outcrops of the Kilnsey and Malham formations, yet *in situ* exposures of these two formations crop out for a minimum distance of about 7km to the west and north-west before the inlier at Chapel-le-Dale is reached. Nonetheless, the erratics barely extend one kilometre towards the north-west in the direction of the Chapel-le-Dale Inlier, and beyond them erratics composed only of Carboniferous rock occur. Consequently, ice did not move from Chapel-le-Dale to Norber, which reveals that the Chapel-le-Dale Inlier cannot be the provenance of the Norber erratics. This concurs with the opinions of several authors from Goodchild (1875) to Waltham *et al.* (1997), who envisaged ice moving south-westwards down the full extent of Chapel-le-Dale into the Craven Lowlands, thus by-passing Crummackdale to the west. Accordingly, as it has been shown that the provenance of the Norber erratics is not from the Chapel-le-Dale Inlier, Tiddeman's (1872) south-east (135° azimuth) stria measurement on the west side of Clapham Burn (Table 3.1, Section 3.4.5) must represent a local rather than a more regional movement of Devensian ice.

A number of other, local, Lower Palaeozoic inliers can also be discounted as the provenance of the Norber erratics given the absence of Lower Palaeozoic erratics on Long Scar and Moughton other than at Studrigg Scar and at Norber. These comprise the two small Craven inliers at Clapham Beck and Jenkin Beck, which are respectively some 1.5km west and 6.5km west-by-north of Norber, and the larger Neals Ing/Malham Inlier, which is an east-south-east continuation of the Ribblesdale Inlier. An origin from the concealed Wharfedale Inlier which is some 22km east of Norber can also be rejected, not least because Dakyns (1873) found no Lower Palaeozoic erratics on the fells between Wharfedale and Ribblesdale.

4.3.8: Conclusion

Mapping the dispersal of glacial indicator erratics shows that ice flowed into the survey area from a general northerly direction and that it brought with it glacial clasts derived solely from Carboniferous strata. Consequently, a provenance for the Norber erratics from Lower Palaeozoic outcrops to the north of Crummackdale as well as from the Ribblesdale and Chapel-le-Dale Inliers that lie respectively to the north-east and north-west can be precluded. Therefore, the geographical provenance of the Norber erratics is the Crummackdale Inlier, or, more precisely, Lower Palaeozoic rocks that crop out to the north of Norber within that inlier. Moreover, an examination of the juxtaposition of the Norber erratics with the Lower Palaeozoic outcrops in Crummackdale, as seen in Fig. 4.1, reveals that the direction of ice movement to Norber can only have been from between north-by-east and east-by-north. The conclusion that the Norber erratics have been derived from Lower Palaeozoic outcrops in the Crummackdale Inlier to the north of Norber is in agreement with proposals made by, for example, Davis and Peck (1878), Hughes (1886), Dunham *et al.* (1953), Arthurton *et al.* (1988), Waltham (1990) and Scrutton (1994).

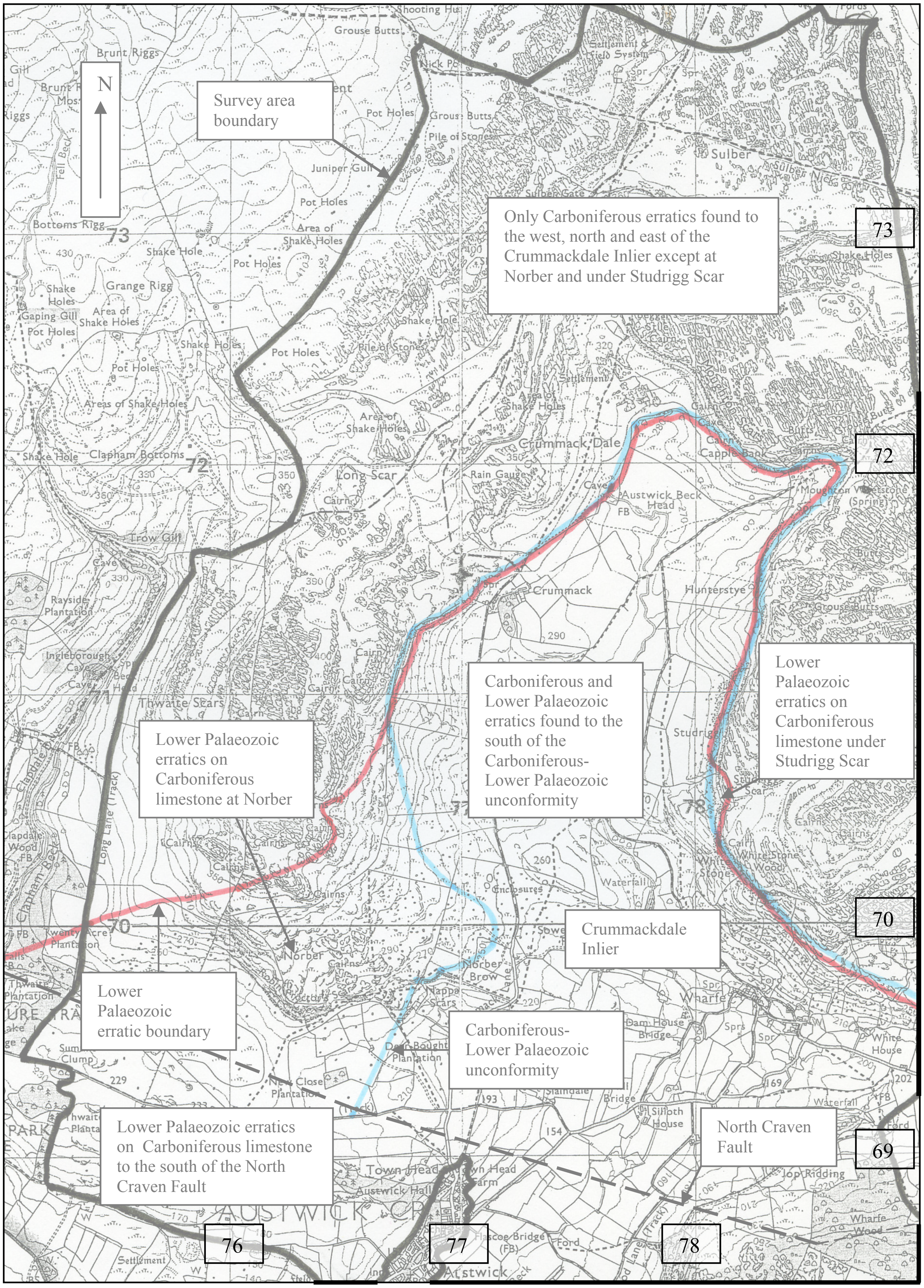


Fig. 4.1: The distribution of erratic types within the study area (courtesy of the Ordnance Survey, Southampton) (Scale given by National Grid coordinates)

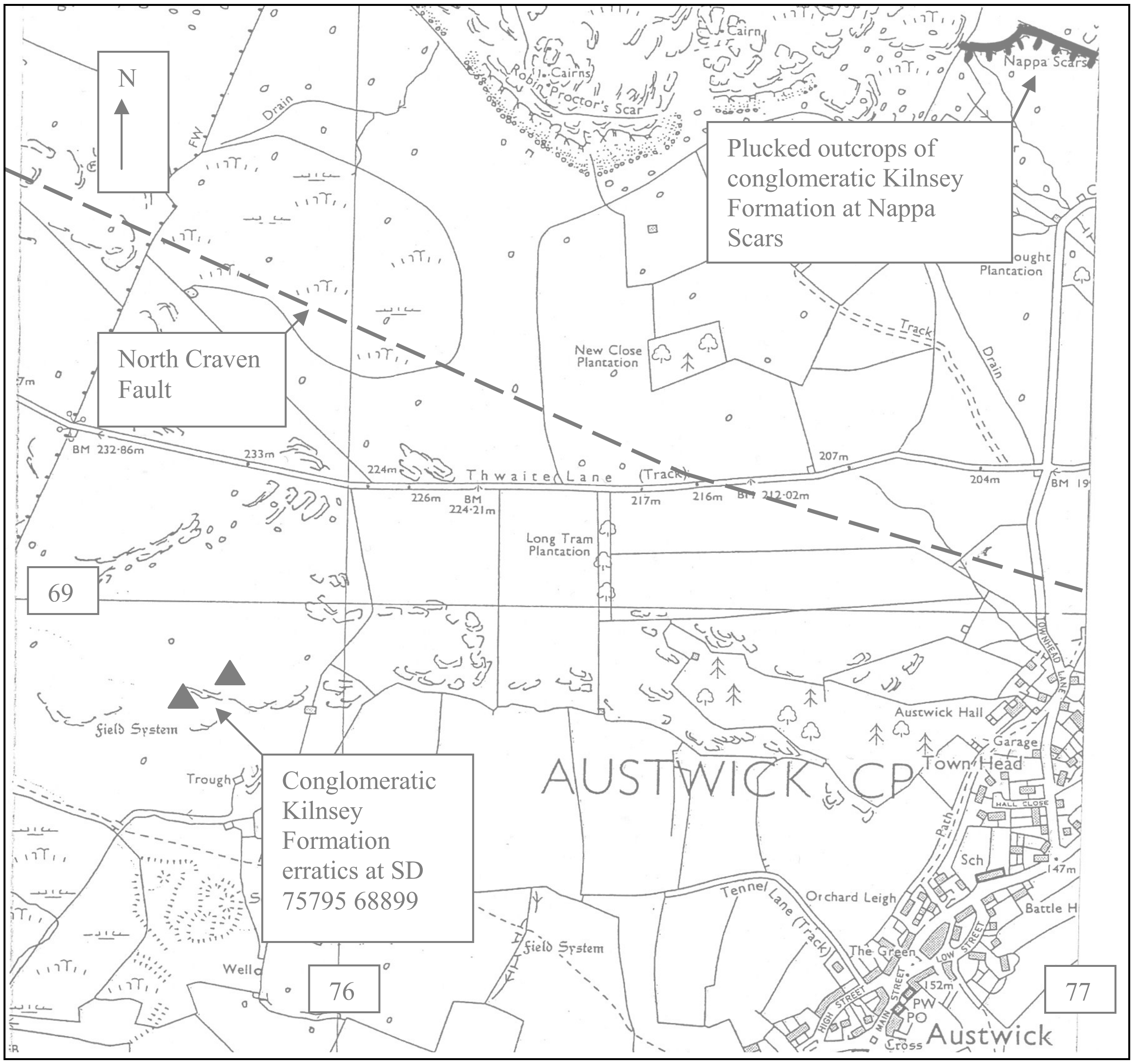


Fig. 4.2: Conglomeratic Kilnsey Limestone erratics on Thwaite to the south-west of their putative provenance at Nappa Scars (courtesy of the Ordnance Survey, Southampton) (Scale given by National Grid coordinates)

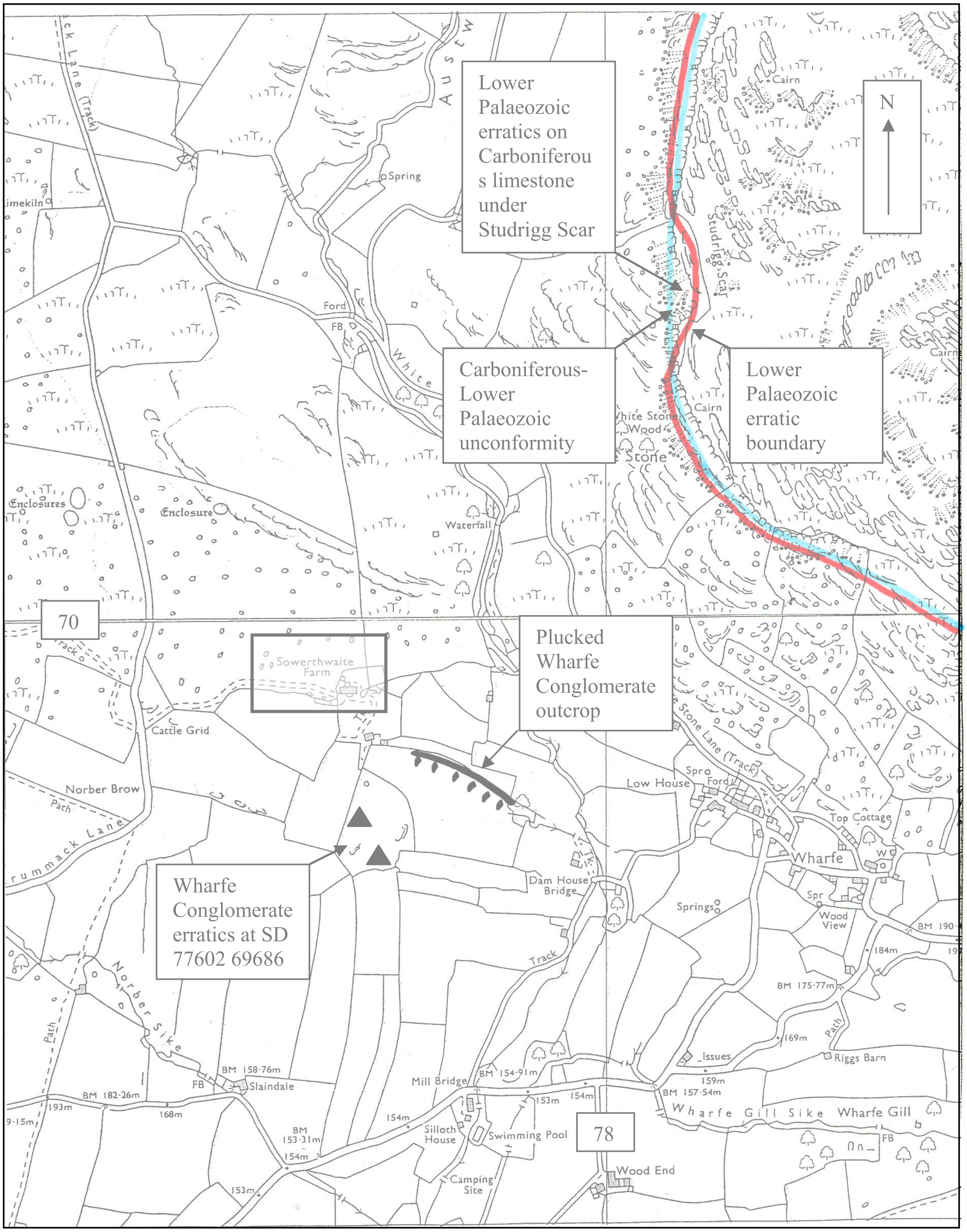


Fig. 4.3: Lower Palaeozoic erratics on Carboniferous limestone under Studrigg Scar, and Wharfe Conglomerate erratics to the south-west of their provenance at outcrops near Sowerthwaite Farm (courtesy of the Ordnance Survey, Southampton) (Scale1:10000)

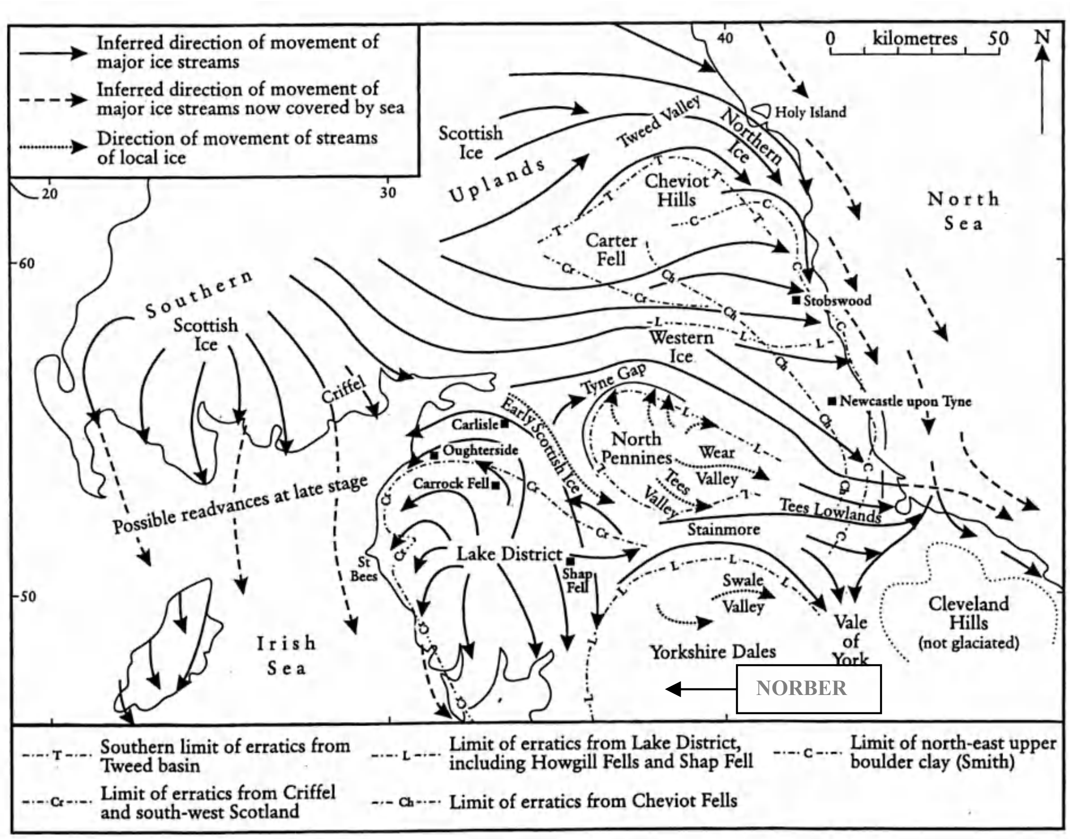


Fig. *Error! No text of specified style in document.**.4: The position of Norber, and suggested Late Devensian ice movements in southern Scotland and northern England (Huddart and Glasser, 2002)***

Plate *Error! No text of specified style in document.**.1: Scree slopes on the eastern flank of Crummackdale***

The Carboniferous-Lower Palaeozoic unconformity, which occurs somewhere below the line of limestone scars (red arrow), is masked by scree (Section 4.3.5.2), that largely formed in the Late Devensian between ca.14500 and 13000BP (Section 7.11.2). Note that the scree is partly overgrown with vegetation, which means that little material is being added to it in the present temperate clime.

CHAPTER 5: THE PROVENANCE OF THE NORBER ERRATICS IN THE CRUMMACKDALE INLIER

5.1: Introduction

Although it has been proved that the geographical provenance of the Norber erratics is the Crummackdale Inlier to the north of Norber, the actual site(s) of glacial plucking remain unknown. The two most clear-cut locations in the literature occur in the Austwick Formation in western Crummackdale at SD 769707 (Dunham *et al*., 1953) and at SD 770704 (Arthurton *et al*., 1988). Waltham *et al*, (1997) also appear to favour a site in the vicinity of SD 769707, whereas Scrutton (1994) supports SD 770704. Other less specific sites include a lower level (Hughes, 1886), lower ground (Kendall and Wroot, 1924), half a mile away and four hundred feet lower (Brumhead, 1979), just south-west of Crummack Farm (Waltham, 1990) and within the core of the basement rise (Waltham, 2005). With several sites to choose from it was decided to attempt to solve the conundrum of erratic provenance by progressively narrowing down the area from which the erratics could have been plucked. The first step undertaken to accomplish this was to determine more accurately the course of ice flow other than 'from a general northerly direction'. Once this had been established, a petrographical comparison of the Norber erratics with *in situ* Lower Palaeozoic lithostratigraphical units occurring up-ice from Norber determined which unit was provenance. Following detection of the source unit, a spatial and physical survey of erratics at Norber and of the unit, and of unit outcrops was used to bring the search for the whereabouts of provenance to a successful conclusion.

5.2: The direction of devensian ice flow

5.2.1: Introduction

A number of glacial landforms such as drumlins, roches moutonnées and striae can be employed to reconstruct past directions of glacial movement more accurately than glacial indicator tracing. Only striae occur within the study area, but as Lundqvist (1990: 61) has pointed out that striae give "…a most precise picture of glacial movement" this is not considered to be a drawback. Striae are scratches or grooves found on the surface of an ice-abraded rock that have been produced by the scoring action of rock fragments frozen into the base of a moving glacier or ice sheet. They are usually less than 1cm in depth and width but can be of almost unlimited length. The long axis of the stria parallels ice-movement, but as striae are symmetrical in long section it is not possible to deduce the bearing of flow unless they are used in conjunction with other directional evidence. It is known from the dispersal patterns of the three indicator erratics in the survey area, however, that the passage of Devensian ice in Crummackdale was towards the south (Section 4.3.7).

5.2.2: Aim and objectives

The aim of the work undertaken in Section 5.2 is to discover which Lower Palaeozoic lithostratigraphical unit(s) the ice crossed *en route* to Norber. The objectives are to measure the direction of striae and determine the specific bearing of movement of Devensian ice flow in the study area.

5.2.3: Method

Striae were located by a ground survey and their direction was measured in degrees azimuth using a Silva Ranger 15T compass (Plate 5.1) that had been adjusted to grid north (in 1999 magnetic north was estimated to be 5° west of grid north (Ordnance Survey)) for ease of plotting purposes. The software programme GEOrient 4.1 (1995): Stereographic Projections and Rose Diagram plots: The Department of Earth Sciences, University of Queensland, Australia, was used to plot rose diagrams of striae direction and to calculate the mean circular stria direction in degrees azimuth.

5.2.4: Results

The direction of ninety striae was recorded at thirteen separate locations (Fig. 5.1). All but twelve striae are found in Crummackdale to the north of Norber, the exceptions comprising nine occurring at a single locality near Wharfe (SD 7869) and one each at three separate locations at Norber itself. Eight of the locations occur on outcrops of the Austwick Formation, two on outcrops of the Horton Formation and three on outcrops of the Malham Formation. Four of the striae present at Location 4 can be seen in Plate 5.2. The circular mean for all ninety striae is 020-200° azimuth (Table 5.1, bottom row). The results from individual locations indicate that there are minor differences in striae strike over the survey area from east to west. Thus, the mean direction near Wharfe is 036-216° azimuth (Location 10), in east, central and west

Crummackdale it is respectively 028-208° (Location 9), 023-203° (Location 6) and 016-196° azimuth (Locations 1-5 and 7-8), and at Norber it is 039-219° azimuth (Locations 11-13). The bearing from *in situ* exposures of conglomeratic Kilnsey Formation at Nappa Scars/Norber Syke (SD 7669) to the conglomeratic Kilnsey Formation erratics on Thwaite Top (SD 7569) is approximately 220° azimuth. The direction of the ninety striae are represented in Fig. 5.2. Refer to Appendix 3S for strike of striae measurements and statistics, rose diagrams and ice flow cursors.

5.2.5: Limitations

Striae definition is poor at some locations due to the degree of surface weathering and/or to the amount of lichen cover, as is clearly evident in Plate 5.2. Thus in some cases it was necessary to introduce external aids, such as water on worn rock or angled torchlight under the erratics at Norber, to increase contrast between striae and the surrounding bedrock. In addition, it was physically impossible to view the compass face when *in situ* below two of the Norber erratics, so a rule was placed alongside the stria and a reading taken from that. Therefore, striae direction results may be subject to a degree of sampling error in some instances.

5.2.6: Analysis

Tiddeman (1872) recorded the direction of five striae within the survey area (Table 3.1). The four recorded in Crummackdale, including one at Norber, have a mean circular direction of 166-346° azimuth, which does not match well with the survey mean of 020-200°. The remaining striation, recorded at Wharfe Mill-Dam has a direction of S. 30° E. (i.e. 150° azimuth), which is even more at odds with the survey mean of 036-216° azimuth logged at Wharfe close by. Neither does it compare favourably with the ice-flow direction illustrated by Waltham *et al.* (1997) in the same vicinity. The reasons behind these differences are unknown, although movements in the magnetic pole since 1872, and the fact that it is unclear whether Tiddeman's measurements are for magnetic, true or grid north might, in part, offer an explanation.

The minor differences in ice-flow direction within the survey area are attributed to small variations in the relief and the terrain, as Embleton and King (1975) have pointed out that the movements of ice sheets are affected by local topographic irregularities. Thus, it is probable that the spur at White Stone (SD 7770) may have affected ice-flow in eastern and central Crummackdale, and the valley side may have constricted ice-flow in western Crummackdale. It also seems plausible that ice emerging from the constrictions of Crummackdale onto Norber would spread out laterally, i.e. to the west, due to the open east to west trending lower ground of Thwaite Top (SD 7569) and the Wenning valley beyond. The conglomeratic Kilnsey Formation limestone erratic slabs on Thwaite Top help confirm the direction of ice-flow at Norber, as their bearing of approximately 220° azimuth from *in situ* exposures at Nappa Scars/Norber Syke (SD 7669) is almost identical to the mean strike of striae at Norber, which is 219°. It must be pointed out, though, that the errratics may be derived from beds of the conglomeratic Kilnsey Formation that skirts Norber Brow and which are masked by superficial deposits. Even so, the bearing from Norber Brow to Thwaite Top is to the south-west.

The occurrence of the bulk of striae on surfaces of the Austwick and Horton Formations is almost certainly a result of these strata being well bedded, well indurated and relatively resistant to weathering. The absence of striae on Carboniferous limestone surfaces open to the elements is due to the relative solubility of the rock, as Sweeting (1966) discovered that striae on newly exposed limestone surfaces are removed by weathering within about 13 years. Several authors, such as Hughes (1886), Jones (1965) and Rodgers (1978), have noted the presence of striae under some of the Norber Erratics, and they suggest that the erratics have protected the surface of the limestone from weathering since Devensian deglaciation.

If taken in isolation, the ice-flow cursors in Fig. 5.1 reveal only the direction of ice movement at Norber, in lower Crummackdale and at Wharfe (SD 7869), as striae are absent elsewhere. Nonetheless, it is possible to deduce the overall direction of flow, since it can be shown that ice generally moved independently of topography and with a degree of uniformity in the survey area. Tiddeman (1872), Raistrick (1930), Dunham *et al.* (1953) and Waltham *et al.* (1997) have suggested that an ice sheet covered the Ingleborough area. This is substantiated by the distribution of erratics in the survey area, as Carboniferous limestone and sandstone glacial clasts occur both in Crummackdale and on surrounding interfluves alike. (Devensian ice was at least 190m thick over Norber, as Arthurton *et al.* (1988) have noted the presence of till up to about 490m above O.D. on the flanks of Ingleborough.) It is well documented by Virkalla (1951) and Mitchell (1994) that ice sheets flow independently of topography, and the presence of striae occurring at oblique angles relative to the strike of up-ice cliffs at Crummack (SD 7771) and Wharfe show that this was so in the survey area (Fig. 5.1). Virkalla (1951) also found that the Fenno-Scandinavian ice sheet moved with a degree of uniformity, since 83% of striae had a strike within 15° of either side of an east-west azimuth. These figures are almost replicated in the survey area, as 78% of strike values are within 15° of either side of the 015-195° azimuth. Consequently, the direction of ice flow can be projected up and down ice from the ice-flow cursors with a degree of confidence. It follows, therefore, that Norber was by-passed by ice moving from Moughton (SD 7971) over Wharfe because it flowed towards Oxenber (SD 7868). It was also by-passed by ice moving over the more easterly parts of Moughton Scars/Capple Bank (SD 7872) because it flowed down central and eastern Crummackdale towards Austwick (SD 7668). Norber ice, on the other hand, crossed the Carboniferous limestone benches of Crummack Dale (SD 7772) (which is distinct from Crummackdale) and western Moughton Scars (SD 7872) prior to dropping into Crummackdale in the vicinity of western Capple Bank (SD 7872)/Austwick Beck Head (SD 7770). It then hugged the western flanks of Crummackdale before flowing onto the Malham Formation/Kilnsey Formation limestones of Norber/Norber Brow (SD 7769), spreading slightly westwards as it did so. The ice next cascaded over the vertical Robin Proctor's and Nappa scars (SD 7669), crossed the North Craven Fault and streamed south-westwards over Thwaite Top (SD 7569) into the Craven Lowlands.

5.2.7: Conclusion

The Norber erratics have been derived from Lower Palaeozoic lithostratigraphical units that crop out only in western Crummackdale between the Malham Formation outcrop of Moughton Scars (SD 7872) and the Kilnsey Formation outcrop of Norber Brow (SD 7769). This conclusion concurs with, for example, Dunham *et al.* (1953), Arthurton *et al.* (1988) and Waltham (1990), who all favour western Crummackdale as the provenance of the erratics. It does not, though, concur with assertions made by Brumhead (1979), Huddart and Glasser (2002), and Goldie (2005) that provenance is 120m lower than Norber, since Lower Palaeozoic outcrops at this height are found only to the east-south-east, some 1.6km distant near Wharfe. A provenance from this locality is out of the question as transportation of clasts to Norber would require ice-movement to the west-north-west, a direction that is at right angles to flow as deduced from measurements of striae.

5.3: A petrographical comparison of the Norber erratics with Lower Palaeozoic lithostratigraphical units cropping out in western Crummackdale

5.3.1: Introduction

There are many examples of erratic provenance being procured through a field survey of erratics and their putative source rock, for instance by Bird (1881), Knetchel (1942) and Shakesby (1978). Thus Bird (1881: 174) was able to recognise Shap Granite clasts at Holderness in east Yorkshire due to their "…well marked" appearance. Neither the Norber erratics nor the lithostratigraphical units of western Crummackdale are 'well marked', however, since all are more-or-less of a uniform texture and grey colour. Consequently, an examination based on their petrographical characteristics was utilised in order to narrow down erratic provenance within western Crummackdale. No similar surveys are recorded in the literature, although Grip (1953) and Dreimanis (1990) both used geochemical analysis to identify erratic source, the latter author emphasising the importance of lithology in solving the problem.

5.3.2: The lithostratigraphical units of western Crummackdale

The Lower Palaeozoic strata of the Crummackdale Inlier (Fig. 2.2) have been grouped by Arthurton *et al.* (1988) into five lithostratigraphical units. Of these units, only three, the Sowerthwaite, Crummack and Austwick Formations, crop out in western Crummackdale between Moughton Scars and Norber Brow. The descriptions below are those of Arthurton *et al.* (1988) unless stated otherwise.

SILURIAN

3. Austwick Formation (formerly the Austwick Flags and Grits). This crops out in the Studrigg-Studfold Syncline between Norber Brow and Crummack, as well as on the northern limb of the Crummack Anticline at Capple Bank (SD 7872). The Formation is about 400m thick in the Studrigg-Studfold Syncline, where the basal part of the succession comprises laminated argillaceous siltstones up to 80m thick, the remaining beds consisting of units of turbidites (greywacke-sandstones) alternating with units of laminated siltstones. Dunham *et al.* (1953) point out that the lower division of the turbidites is also massive and thick bedded, that it extends across Crummackdale and that its outcrops can be seen in the core of the syncline on the western slopes of Crummackdale in the environs of SD 769707. King and Wilcockson (1934) note that the Austwick Formation thins to the north, which according to McCabe and Waugh (1973) is due largely to a reduction in the thickness of the turbidite units (Fig. 5.3). A petrographical description of the arenaceous beds of the Austwick Formation has been given by McCabe and

Waugh (1973: 448) who state that the fine- to medium-grained greywacke sandstones "…consist mainly of quartz with subordinate feldspar, muscovite and rock fragments in a calcareous clay matrix." A very similar account has been given by Arthurton *et al.* (1988: 14) who write that the sandstones "…are fine- to medium-grained, and consist of an ill-sorted assemblage of quartz, feldspar and rock fragments in a clay matrix."

2. Crummack Formation. This crops out in both limbs of the Crummack Anticline in the vicinities of Crummack and Capple Bank, and is mostly obscured by regolith. It consists of 15m of locally present black graptolitic mudstone below (the Hunterstye Member) and up to 20m of calcareous siltstones above (the Capple Bank Member).

ORDOVICIAN

1. Sowerthwaite Formation. This crops out in the Crummack Anticline between Crummack and Capple Bank. It comprises a varied succession of deposits some 60m thick, which include argillaceous limestones below and laminated sandy siltstones above, separated by a rudaceous deposit, the Wharfe Conglomerate; strata are poorly exposed.

5.3.3: Aim and objective

The aim of the work undertaken in Section 5.3 is to determine which lithostratigraphical unit(s) is/are the provenance of the Norber erratics. The objective is to compare and contrast the Norber erratics with strata of the Sowerthwaite, Crummack and Austwick formations in western Crummackdale in terms of their petrography.

5.3.4: Method

The 1:50000 B.G.S. maps for Hawes (sheet 50, solid and drift: 1997) and for Settle (sheet 60, solid: 1989, and sheet 60, solid and drift: 1991) were scrutinised prior to the commencement of field work in order to ascertain the location of boundaries between the different lithostratigraphical units. The geological maps of Dunham *et al.* (1953) and Arthurton *et al.* (1988) were also examined. Unweathered samples were removed from eight widely scattered erratics at Norber, to ensure that the provenance of each was distinct; six were comprised of arenaceous rock and two of argillaceous rock, since the former outnumber the latter roughly in this proportion. Unweathered samples were also taken from eight widely separated exposures of the Austwick Formation between Crummack and Norber Brow (SD 7769) in the same ratio. It was intended to sample the two sites (both located using GPS) that were designated as the provenance of the erratics by Dunham *et al.* (1953) at SD 769707, and by Arthurton *et al.* (1988) and Scrutton (1994) at SD 770704. SD 769707 was sampled, but as no exposures occur at SD 770704 a sample was removed from the nearest outcrop to this location (at SD 77100 70451) some 100m to the north-east. It was also intended to sample the more westerly outcrops of the Austwick Formation on Capple Bank (SD 7872), but this proved out of the question as exposed strata consisted solely of rock that is so well-cleaved and weathered it proved impossible to obtain samples suitable for thin-sectioning. Instead, two samples were removed from an east to west-striking plucked and more competent arenaceous bed a little to the east. The only outcrops of the Sowerthwaite Formation that lie immediately up-ice from Norber are in the vicinity of Austwick Beck Head (SD 7770), and two samples were removed from this location, one from an abraded cliff and the other from the bank of Austwick Beck. The Wharfe Conglomerate was not sampled as erratics composed of it are not found at Norber. Strata of the Crummack Formation are not exposed up-ice from Norber due to a covering of regolith. Thus exposures that crop out along the strike 1km to the east from Crummack in the vicinity of King and Wilcockson's (1934) trench were sampled, one from a rivulet bed (Hunterstye Member) and one from a well-weathered and presumably plucked cliff (Capple Bank Member).

Examination of thin sections (prepared by the BGS, Nottingham) was undertaken using a petrographical microscope. The degree of sorting was determined using visual estimation sorting charts and grain shape using visual roundness charts (both Pettijohn *et al.*, 1987). The constituent percentages were determined using Terry and Chilingar visual percentage estimation comparison charts (1995) and grain sizes using the Wentworth-Udden Scale (1972), both cited in Hunt (1999). Birefringence colours were resolved using a visual birefringence chart (MacKenzie and Guilford, 1980). The naming of individual specimens of wackes conforms to Pettijohn *et al.*'s (1987) classification of sandstones and Tucker's (2001) description of mudrocks. The results are presented in a north to south order, i.e. from the Austwick Formation at Capple Bank to the erratics at Norber, since Devensian ice moved in this direction. Analyses usually begin with thin section scrutiny, typically in the order of texture, mineralogy and structure.

5.3.5: Limitations

There are many hundreds of erratics at Norber, while McCabe and Waugh (1973) noted a total of 149 individual greywacke sandstone turbidite units in the Austwick Formation alone, each presumably separated by a unit of siltstone and/or mudstone. The description of only twenty-two samples cannot be fully representative of the range of rocks present, yet the sampling and describing of all erratics and units is clearly not expedient. The location of sampling also merits a degree of concern as samples removed from outcrops of the Austwick Formation on Capple Bank are probably east of down-ice to Norber, which means they may be atypical of strata that are up-ice from Norber. Samples removed from the Crummack Formation may also be atypical of down-ice to Norber as Arthurton *et al.* (1988) have noted that the Crummack Formation shows some degree of lateral variation. The technique of using visual charts to determine constituent content percentages and textural features also leaves something to be desired, since it is open to a measure of human error. Nonetheless, it would seem that petrographical descriptions are typical of the three lithostratigraphical units as portrayed in the literature (Section 5.3.2).

5.3.6: Results

Sampled outcrops of the Austwick Formation at Capple Bank consist of well-indurated sandstone (Table 5.2, Samples 17 and 18). The rock is grey in colour and a few percent of mica is visible to the naked eye, as is also the case with unsampled argillaceous beds to the west. In thin section the rock consists of a homogeneous yet very poorly sorted mixture of grains that are mostly angular in shape (Fig. 5.4, Sample 18). The three most abundant constituents are quartz (mean 60%), muscovite mica (mean 9%) and matrix (mean 20%). Other constituents include rock fragments, opaque minerals, plagioclase feldspar, biotite mica and chlorite. Both samples are wackes.

Exposures of the Hunterstye Member of the Crummack Formation are composed of friable rock that is black in colour, and that has relatively good cleavage and fissility (Table 5.3, Sample 21). In contrast, the Capple Bank Member of the Crummack Formation is grey in colour and well indurated (Table 5.3, Sample 22). The rock at both exposures is fine-grained and no identifiable minerals are visible to the naked eye. In thin section neither specimen is homogeneous, as the Hunterstye Member is banded (Fig. 5.4, Sample 21) while the Capple Bank Member contains patches of slightly coarser grain size (Fig. 5.4, Sample 22). The grain sizes also differ as the Hunterstye Member is bi-modally sorted while the Capple Bank Member is moderately sorted. Both samples are argillaceous, and their fine grain size and degree of alteration mean that few individual grains are evident in thin section, although those that are discernible tend to be angular in shape. The matrix (mean 89%) comprises the bulk of both rocks; subordinate quartz (mean 9%) is also present, as are traces of opaque minerals, rock fragments, muscovite mica, biotite mica and plagioclase feldspar; both samples are mudrocks.

Sampled outcrops of the Sowerthwaite Formation are grey in colour and well-indurated (Table 5.4, Samples 19 and 20). No identifiable minerals are visible to the naked eye and both rocks are argillaceous; the stratum from which sample 20 was taken is laminated. In thin section neither sample is homogeneous as both are graded; the sorting within the coarser fraction of individual graded beds is poor and constituents tend to be angular (Fig. 5.4, Sample 20). The matrix (mean 91%) comprises the bulk of both samples; subordinate quartz (mean 7.5%) is also present, as are traces of opaque minerals, rock fragments and muscovite mica. Sample 19 is a graded wacke and sample 20 is a graded mudrock.

The Austwick Formation between Crummack and Norber Brow is comprised of both argillaceous (Fig. 5.4, Sample 15) and arenaceous beds (Fig. 5.4, Sample 9) (Table 5.5, Samples 9-16). Strata are grey in colour, mostly well indurated and have a fine to medium grain size; a few percent of mica is discernible to the naked eye. In thin section the rock consists mostly of angular grains the majority of which are either very poorly or poorly sorted, the only exceptions being samples 15 and 16, which are moderately well-sorted. Most samples are homogeneous, although sample 15 is lineated and sample 16 contains a band of matrix. The three most abundant constituents are quartz, muscovite mica and matrix, with quartz being the most common detrital mineral in all samples. Other constituents include rock fragments, opaque minerals, plagioclase feldspar, biotite mica and chlorite. The sampled outcrops fall into two grain-size classification groups, arenaceous (samples 9-14) and argillaceous (samples 15-16). The groups contrast in their mean constituent contents, which are respectively 49% and 35% for quartz, 7% and 11.5% for muscovite mica, and 35% and 51% for the matrix; there is some inter-group content overlap of muscovite mica. All samples are wackes.

The rock that composes the erratics at Norber is grey in colour, is generally well-indurated and is fine- (Fig. 5.4, Sample 7) to medium-grained (Fig. 5.4, Sample 1) (Table 5.6, Samples 1-8). A few percent of mica is visible to the naked eye. In thin section the rock consists mostly of angular grains that are either very poorly or poorly sorted, with the sole exception of sample 7, which is moderately well-sorted. Most samples are homogeneous, though samples 1, 2 and 8 respectively contain a quartz-rich band, a lens of finer material and bands/lenses of matrix. The three most abundant constituents are quartz, muscovite mica and matrix, with quartz being the most common detrital mineral in all samples except for sample 8 where muscovite mica is more plentiful. Other constituents include rock fragments, opaque minerals, plagioclase feldspar, biotite mica, chlorite, calcite and augite. The samples fall into two grain-size classification groups, arenaceous (samples 1-6) and argillaceous (samples 7-8). The two groups contrast in some of their constituent contents, and the respective means for quartz are 48% and 35%, and for muscovite mica are 6% and 12.5%, though there is some inter-group overlap of both minerals. The mean matrix content of the groups is not significantly dissimilar as it comprises 43% of samples 1-6 and 46% of samples 7-8. All samples are wackes. Refer to Appendix 3TS.1 for full thin-section descriptions of the Norber erratics and Appendix 3TS.2 for *in situ* lithostratigraphical units.

5.3.7: Analysis

As the Sowerthwaite Formation is argillaceous, it follows that erratics 1-6 cannot have been derived from it since they are composed of arenaceous rock. The textural differences between Norber erratics 7-8 and strata of the Sowerthwaite Formation are not clear-cut, as all the samples are composed of rock that is fine-grained. Nevertheless, as the erratic samples contain noticeably higher percentages of quartz (35% compared to 7.5%) and muscovite mica (12.5% compared to trace) but appreciably less matrix (46% compared to 91%) they too are not derived from it. Disparities in internal structure are also apparent as graded bedding typifies both formation samples while the erratic samples are comprised of rock that is either homogeneous, or contains bands or lenses of matrix. In addition, the presence of a few percent of lustrous muscovite mica in erratic hand specimens and its absence in Sowerthwaite Formation hand specimens further demonstrate that erratic provenance is not the latter.

A derivation of any of the Norber erratics from the Crummack Formation Hunterstye Member can be ruled out because the erratics consist of wackes that are grey in colour and the Member of shales that are black. Nor can erratics 1-6, which comprise arenaceous rock, be derived from the Crummack Formation Capple Bank Member since it is argillaceous. The textural differences between Norber erratics 7-8 and strata of the Capple Bank Member are not quite as unequivocal, since all samples are argillaceous. All the same, major mineralogical dissimilarities occur between them, as the erratic samples contain considerably higher mean percentages of quartz (35% compared to 10%) and muscovite mica (12.5% compared to 1%), and appreciably less matrix (46% compared to 88%). In addition, the presence of a few percent of lustrous muscovite mica that is noticeable to the naked eye in erratic hand specimens and its absence in Crummack Formation hand specimens further demonstrates that erratic provenance is not the latter. The percentage constituent content differences of Norber erratics samples 7-8 in comparison to those of the Sowerthwaite and Crummack Formations are clearly evident in Fig. 5.5.

Mica, however, is clearly visible to the naked eye in all Austwick Formation samples and its presence strongly suggests that erratic provenance is this formation. Its presence does not discriminate between a provenance at Capple Bank or at Crummack-Norber Brow, though. Neither are there any distinguishing textural characteristics, such as sorting or grain shape, to link the erratics with one outcrop or the other. Nor is the classification of samples into wackes, feldspathic wackes and lithic wackes diagnostic of source area, as no geographical pattern of the various wacke types is apparent. A mineralogical comparison does favour one site at the expense of the other, however. This is best elicited in chart form rather than in plain script. Thus, Fig. 5.6 reveals that erratics 1-6, which consist of arenaceous rock, have a closer mineralogical affinity with arenaceous Austwick Formation outcrops at Crummack-Norber Brow (columns 1 and 2 of each constituent) than at Capple Bank (columns 1 and 3 of each constituent). Further, Fig. 5.5 shows that the mineralogies of Norber erratics 7-8 and Austwick Formation outcrops 15-16 at Crummack-Norber Brow (columns 1 and 2 of each constituent), all of which consist of argillaceous rock, are almost identical. No comparative figures for Norber erratics 7-8 and argillaceous Austwick Formation outcrops at Capple Bank are available, for reasons outlined in Section 5.3.4.

5.3.8: Conclusion

Of the three lithostratigraphical units cropping out in western Crummackdale, there is no doubting that petrographical evidence shows that the Norber erratics have not been derived from the Sowerthwaite and Crummack formations. Accordingly, provenance is the Austwick Formation, and this is substantiated by the fact that both erratics and the formation share mutual petrographical characteristics, the most obvious being the presence of mica that is visible to the unaided eye in hand specimens. The Austwick Formation crops out at two quite separate sites, however, and although mineralogical evidence favours Crummack (SD 7771)-Norber Brow (SD 7769), an origin from Capple Bank (SD 7872) cannot be ruled out. This is because it proved impossible to sample argillaceous strata at the latter site for thin-section examination. In addition, King and Wilcockson (1934), Dunham *et al.* (1953), McCabe and Waugh (1973), and Arthurton *et al.* (1988) have all shown that the Austwick Formation has lateral and vertical changes in mineral content, rock type and structure. Many authors, such as Dunham *et al.* (1953), Arthurton *et al.* (1988) and Scrutton (1994) have proposed that the Austwick Formation is the provenance of the Norber erratics.

5.4: Erratic source in western Crummackdale: Capple Bank or Crummack-Norber Brow?

5.4.1: Introduction

Several authors, for instance Embleton and King (1968), Sugden and John (1976), and Bouchard and Salonen (1990), have written that erratics might suffer comminution during down-ice transport. This is supported by Shakesby (1978), who noted that erratics (of essexite) with closely spaced jointing readily underwent crushing during glacial conveyance. Consequently, erratics at the site(s) of provenance ought to be more abundant than and some ought to be of greater dimensions than those at Norber, especially as discontinuities are present in all potential source rocks. Of no less importance, Puranen (1990) and Evans (1996) have pointed out that angular and rounded glaciated cliffs are, by and large, respectively indicative of pre-ablation histories of plucking and abrasion. Thus angular cliffs ought to be present at the site(s) of provenance, since the Norber erratics are a product of plucking. In addition, the site(s) must also include an arenaceous bed at least 2m thick as the very largest erratic at Norber is composed of grit and measures approximately 3x2x2m. Accordingly, a field survey of the two Austwick Formation outcrops at Capple Bank and at Crummack-Norber Brow, and of the erratics emanating from them and of those occurring at Norber was undertaken in order to determine which site(s) best meets the physical requirements of erratic provenance. It is not thought that post-Devensian weathering and erosion regimes have affected the landforms unduly (apart from the frost-shattering of erratics perhaps) since the presence of Devensian striae on exposed strata of the Austwick Formation bears witness to a general lack of post-ablation degradation.

5.4.2: Aims and objectives

The aims of the work undertaken in Section 5.4 are to establish whether erratic provenance is one or both of the two Austwick Formation outcrops and to isolate the actual site(s) of erratic provenance. The objectives are to compare and contrast the Norber erratics with erratics derived from the two Austwick Formation outcrops in terms of size and distribution, and to compare and contrast the size and shape of the Norber Erratics with bed thickness and shape of the two Austwick Formation outcrops.

5.4.3: Method

Measurements of only the most bulky erratics at the three sites, and only of maximum bed thickness and height of glacially eroded cliffs at the two outcrops were undertaken, since evidence points to a decrease in erratic size down ice. Subjective note only was made of erratic numbers and of cliff roundness or angularity. The results of previous surveys are incorporated into the findings where applicable.

5.4.4: Results

Erratics are sparsely distributed on and to the south of western Capple Bank; they are angular in shape, are composed solely of arenaceous rock and have long axes that range up to approximately 1m in length. Only a few outcrops are exposed and they consist mostly of plucked near-vertical cliffs up to a metre in height composed of arenaceous rock; some well-weathered outcrops of argillaceous rock are also present. The paucity of erratics and cliffs is evident from an examination of Plate 5.3.

Erratics are also scarce between Crummack and Norber Brow apart from four ‘hotspots’ that occur in association with plucked cliffs. Three are found in easterly parts on lower ground at SD 76860 71232, SD 76973 71018 and SD 76899 70777/SD 77090 70652, the latter occurring in the vicinity of the Old Limekiln (SD 770707), and one in westerly parts on higher ground at SD 76743 71002 (Fig. 5.7 and Plate 5.4). Most of the erratics are angular in shape and consist of arenaceous rather than argillaceous rock; their long axes range up to about 4m. The Austwick Formation, which comprises both argillaceous and arenaceous beds, includes a massive sandstone unit that forms several intermittent lines of plucked cliffs with sheer vertical faces that reach a maximum height of approximately 3.5m. The sandstone is best exposed in the near-horizontal core of the syncline in the vicinity of the Old Limekiln close to Crummack Lane (SD 7769) where it undoubtedly forms the thick-bedded turbidite of Dunham *et al.* (1953). From here it strikes uphill to the north-north-west where it is exposed in the core of the eroded anticline at SD 76743 71002, close to the Carboniferous-Lower Palaeozoic unconformity. It then forms a series of east-facing vertical cliffs directly below the unconformity as shown in Fig. 5.1. Striated pavements customarily occur above the sandstone cliffs. Other Austwick Formation beds rarely reach a metre in thickness and although they commonly form cliffs they are generally less precipitous and more abraded when compared with the massive sandstone. The relative abundance and bulkiness of the erratics as well as the line of comparatively tall plucked cliffs near the Old Limekiln are clearly discernible in Plates 5.5 and 5.6.

Erratics occur throughout Norber but are not evenly distributed being more numerous in eastern than in western parts. The greatest erratic long axis is about 3m and the bulkiest is approximately 12m³ in volume; most erratics are angular in shape. Erratics comprised of arenaceous rock greatly outnumber those comprised of argillaceous rock. Their abundance and relative bulkiness in eastern Norber is plainly apparent in Plate F1.

5.4.5: Analysis and conclusion

The reality that the largest erratic occurring at Crummack Norber Brow and on Capple Bank is respectively some five times greater and some twelve times smaller in size than the largest at Norber is sufficient in itself to show that the former site is the provenance of the Norber erratics. The respective maximum thickness of arenaceous beds, which is some 3.5m at Crummack-Norber Brow and 1m on Capple Bank, also favours the former site. Further support for a Crummack-Norber Brow provenance is provided by maximum cliff height, which is some 3.5m between Crummack-Norber Brow and only 1m on Capple Bank, the former height, but not the latter, easily being of sufficient stature to have spawned the largest erratic at Norber. In addition, a comparative wealth of erratics, usually composed of both arenaceous and argillaceous rock, is present at four locations between Crummack and Norber Brow, and at Norber itself. In contrast, erratics are scarce on and to the south of Capple Bank, and are composed solely of arenaceous rock. There is no doubting, therefore, that the provenance of the Norber erratics is between Crummack and Norber Brow, which is also the site favoured on mineralogical grounds (Section 5.3.7). The geomorphological evidence confirms petrographical findings that the Sowerthwaite and Crummack formations are not the provenance of the Norber erratics, since outcrops are mostly abraded while cliffs rarely reach 1m in height. Erratics to the south of Sowerthwaite and Crummack formation outcrops are also uncommon and only reach a maximum of 1m in section.

5.4.6: Where within Crummack-Norber Brow?

It is clear from thin-section evidence that none of the sampled Norber erratics have been derived from any of the sampled outcrops in Crummack-Norber Brow, since no one erratic sample can be wholly matched with any one outcrop sample. Lawson (1990) has pointed out that the liberation and removal of rock by ice leads to a reduction in the size of outcrops being quarried, which means it will not be possible to sample the original sites of glacial quarrying since such sites will have been removed to Norber. Nor can any of the erratic samples be wholly matched with each other, which signifies that each must have been derived from a different site rather than from just one. It is not possible, either, wholly to match samples derived from the same outcrop due to the fact that the Austwick Formation is not uniform in character, as shown in Table 5.5. Accordingly, petrography is of no use in narrowing down the site(s) of provenance between other than pinpointing that erratics composed respectively of arenaceous and argillaceous rocks are derived from like strata.

Several authors, such as Knetchel (1942) and Lawson (1990), have discovered erratic provenance by tracing/mapping boulder trains up-ice to their source. The erratics at Norber do not form a distinctive enough train to be followed up-ice in the field, as they are just a small portion of a much larger number of clasts of Lower Palaeozoic age that occur in parts of the survey area (Section 4.3.5.2). Nor does a train show up on aerial photographs (Meridian Airmaps Sheets 48 68 029/030/031: 1968). If western Crummackdale is viewed from Studrigg Scar (SD 7870) high up on the opposing side of the valley, however, four erratic trains can be seen between Crummack-Norber Brow. Three occur in lower ground, two some 0.4km to the north of the junction of Wharfe and Crummack lanes (SD 772707) and one some 0.2km to the west, and one on upper ground. The two to the north of the junction and the one on upper ground peter out after a few tens of metres at most, which suggest that they are unlikely to be the source of the erratics at Norber. In contrast, the train to the west of the junction is much more substantial, fanning out in a south-south-west direction before breaking up into disconnected erratic fields on the slope leading up to Norber Brow some 0.4km from source. Unfortunately, Norber is in dead ground to the south so it is not possible to view its relationship with the train.

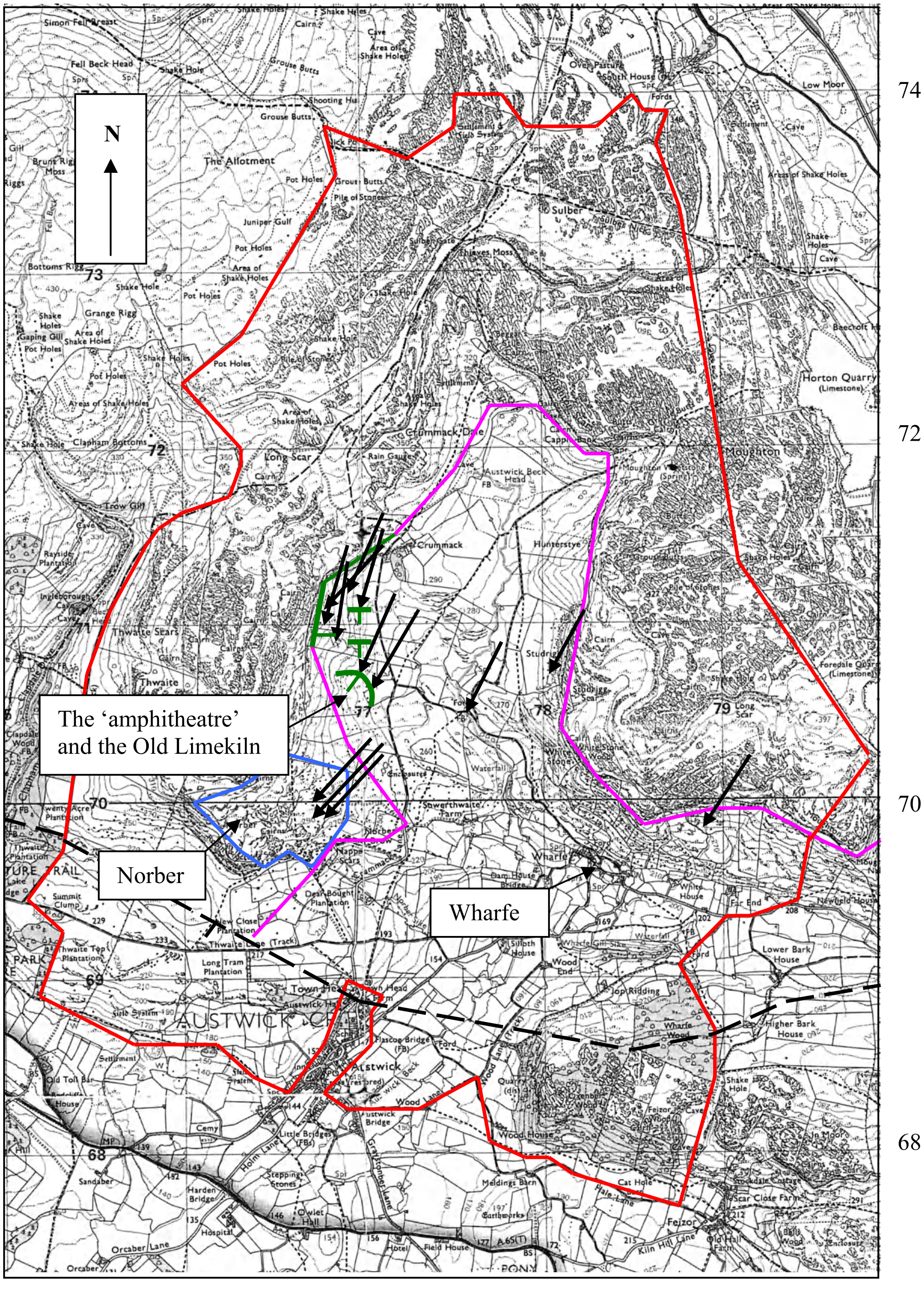
This observation was confirmed, at least in part, by a north to south ground survey from Crummack to Norber Brow of erratic distribution, morphology and size, and of bed morphology and thickness. The northern parts of Crummack-Norber Brow south to northing 710 are relatively bereft of erratics so it is assumed that this zone is not the source of many erratics at Norber. The small numbers of erratics that are present are composed of arenaceous rock, are angular in shape, reach almost 1.5m in section and are found mostly on upper, western slopes. It would seem certain that they have been quarried from plucked east-facing sandstone cliffs some 2.5m in height that occur below the Carboniferous-Lower Palaeozoic unconformity. At northing 710 two plucked sandstone cliffs that are about 0.7m and 1.5m in height occur on lower, eastern slopes and from them a fair quantity of moderately sized erratics trail to the south. The erratics form the two trains visible from Studrigg Scar that occur some 0.4km to the north of the junction of Wharfe and Crummack lanes, and their numbers and bulk indicate that they may well have contributed to the overall sum of erratics at Norber. Farther to the south at northing SD 708 near the Old Limekiln a dramatic increase in erratic size and number occurs to the immediate south of plucked cliffs composed of the near-horizontal 3.5m sandstone. The cliffs occur in the core of the syncline outlined in Section 5.4.4 and they form the up-ice end of the erratic fan that is plainly visible from Studrigg Scar. The ground drops vertiginously 3-4m from cliff top to base, the cliffs forming the northern back-wall of an ‘amphitheatre’ of some 6ha extent that is bordered by intermittent sheer cliffs to the east, by Crummackdale valley flank to the west and by Norber Brow to the south. The ‘amphitheatre’ is clogged with a multitude of mostly angular erratics ranging up to a leviathan some 4mx4mx3.5m in size, and a dense array of many hundreds more clasts (thousands even) strike south towards Norber parallel with the direction of ice-flow (Plate 5.7). The vast majority of the erratics are composed of arenaceous rock, but some comprising argillaceous rock also occur, the latter almost certainly originating from strata exposed in the north-western sector of the ‘amphitheatre’ where plucked cliffs, which are overgrown, weathered and a good metre in height, are discernible. No further plucked cliffs of any stature occur at any altitude between the ‘amphitheatre’ and the Carboniferous limestone outcrops of Norber Brow. Consequently, it is assumed that few of the Norber erratics have been derived from farther south. Therefore, although several sites of angular cliffs comprised of an arenaceous bed at least 2m thick occur between Crummack and Norber Brow, only one, the void bounded by the ‘amphitheatre’ walls near the Old Limekiln, meets the requirements of provenance. This is because it is the only site where erratics emanating from it are present in greater concentrations than at Norber and where some erratics are of greater bulk than the largest at Norber. This claim is backed up by the preponderance of erratics composed of arenaceous rock over those composed of argillaceous rock at both locations. It is also corroborated by the distribution of erratics at Norber and in Crummack-Norber Brow, as the greater concentration at both localities occurs in eastern parts and the lesser in western parts.

The back-wall of the ‘amphitheatre’ is the site photographed by Dunham *et al.* (1953) at SD 769707 as Norber erratic provenance, and it would also seem that it forms the up-ice end of the erratic train that envelops Norber as illustrated by Waltham *et al.* (1997). The site would also appear to be the “basement slope” of Waltham (1990) and the “crags within the core of the basement rise” of Waltham (2005), although as no grid references are provided this cannot be taken as read. Arthurton *et al.* (1988), on the other hand, nominate a provenance at SD 770704, which is found approximately 0.5km to the south of the ‘amphitheatre’. There is no field evidence to link this site with the Norber erratics at all, since erratics are scarce and plucked outcrops are lacking, as can readily be seen in Plate 5.8. No explanation for its nomination springs to mind other than that the grid reference number is erroneous. Scrutton (1994) also suggested that provenance is SD 770704 but goes on to write that the source of the blocks can be seen in the small crags on the left-hand side of Crummack Lane (heading north) before the junction at SD 772706 (Plate 5.6). Somewhat confusingly the small crags are the very same cliffs designated by Dunham *et al.* (1953) at SD 769707 as the site of erratic provenance; they are also the cliffs of the ‘amphitheatre’. Did Scrutton (1994) therefore re-use SD 770704 without re-evaluating the spot in the field?

As the ‘amphitheatre’ cliff-top backwall is about 280m above OD and as Norber is between about 290-320m above OD, it follows that the majority of Norber erratics have been carried uphill by some 10 to 30m. Some of the erratics, however, might have originated from the plucked cliffs at SD 76973 71018 and SD 76860 71232, which are about 320m above OD, and at SD 76743 71002, which are about 360m above OD. If so, any of the erratics at Norber originating from the former two sites have been moved downhill by up to 30m and any from the latter site by between 40-70m (Fig. 5.7). It was noted in Section 5.2.7 that Brumhead (1979), Huddart and Glasser (2002), and Goldie (2005) asserted that provenance of the Norber erratics was 120m lower than Norber. Clearly, this is not the case. Could it be that Huddart and Glasser (2002), and Goldie (2005) re-used Brumhead’s (1979) claim without re-appraising it in the field?

5.4.7: Conclusion

The provenance of the Norber erratics is unquestionably the Austwick Formation that crops out between Crummack and Norber Brow some 1.1 and 0.3km to the north of the northern boundary of Norber. This means that the erratics are confirmed as being composed of rock of Silurian age, since they are indisputably derived from outcrops of the Austwick Formation. Provenance is not necessarily a single site, though, as erratic trains strike towards Norber from several lines of plucked cliffs, especially from the glacially eroded void enclosed by the ‘amphitheatre’ walls in the vicinity of the Old Limekiln (SD 770707). Therefore, it follows that the provenance of the bulk of the Norber erratics is this site. It follows, too, that as the cliff top near the Old Limekiln is some 280m above OD that the majority of erratics at Norber have been carried uphill (by some 10 to 30m), which concurs with Hughes (1886), Kendall and Wroot (1924), and Waltham (2005).



KEY:

Boundary of the study area — Boundary of Norber

The Carboniferous-Lower Palaeozoic unconformity — North Craven Fault

Plucked cliff and face of slope — Direction of Devensian ice flow

Fig. *Error! No text of specified style in document.****.1: The direction of Devensian ice flow and the location of plucked cliffs re the provenance of the Norber erratics (Courtesy of the Ordnance Survey, Southampton) (Scale given by National Grid coordinates)***

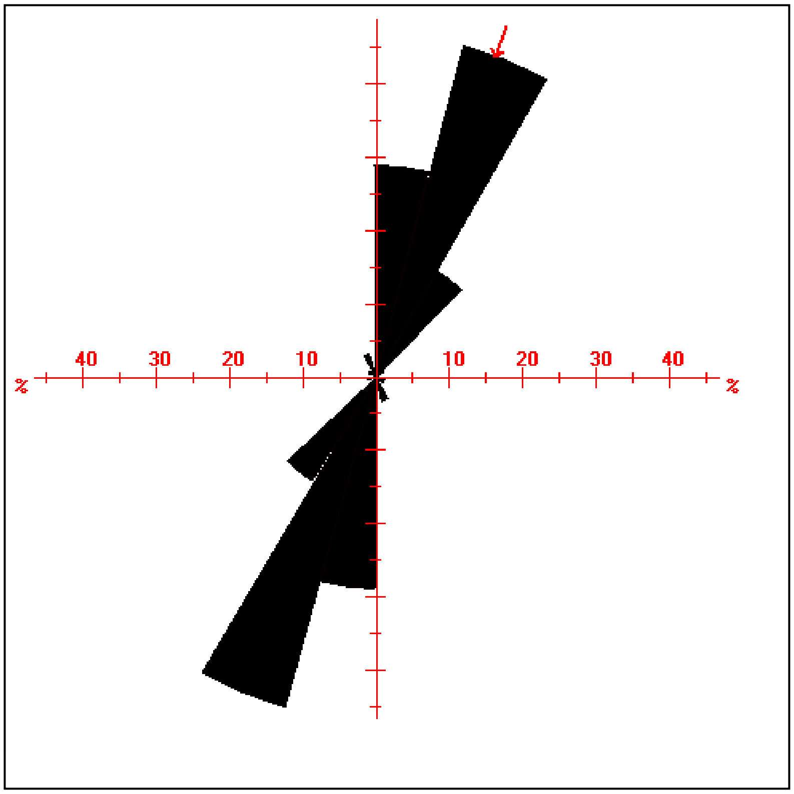


Fig. *Error! No text of specified style in document.****.2: Rose diagram of the direction (Grid North) of 90 striae (sector size 15° azimuth)***

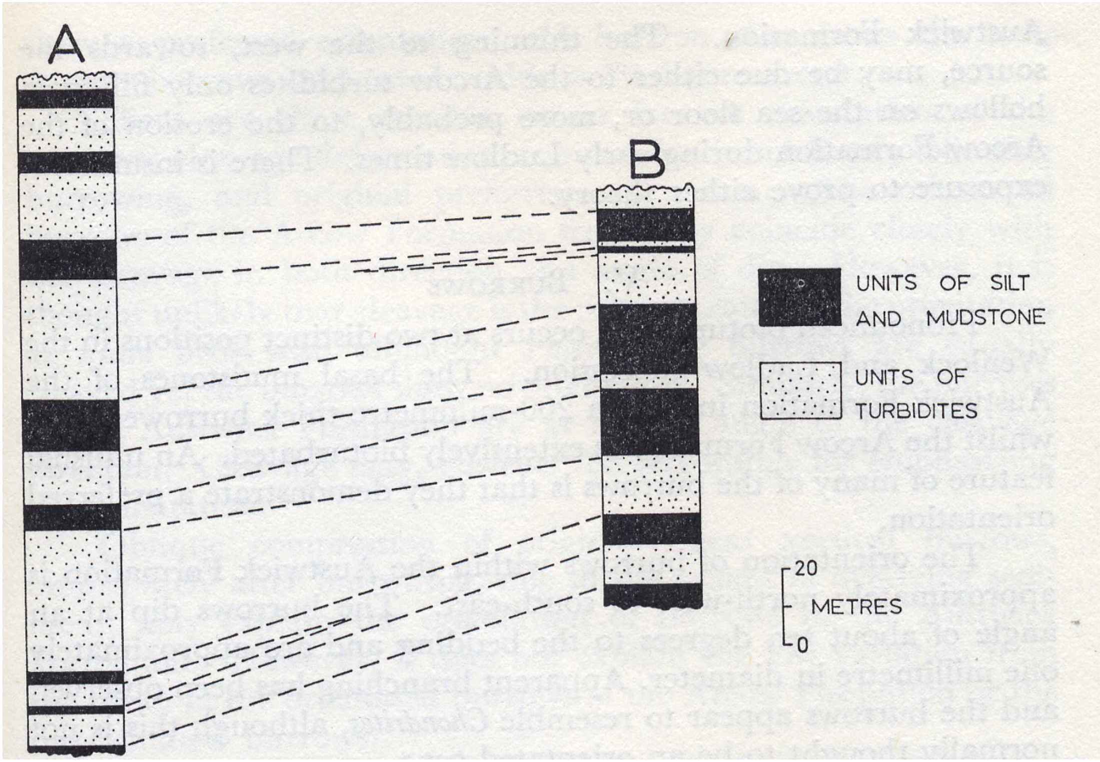


Fig. *Error! No text of specified style in document.***.3: Lithological thickness variations in the Austwick Formation: traverse A, south Crummackdale; traverse B, north Crummackdale (from McCabe and Waugh, 1973, Fig. 2)***

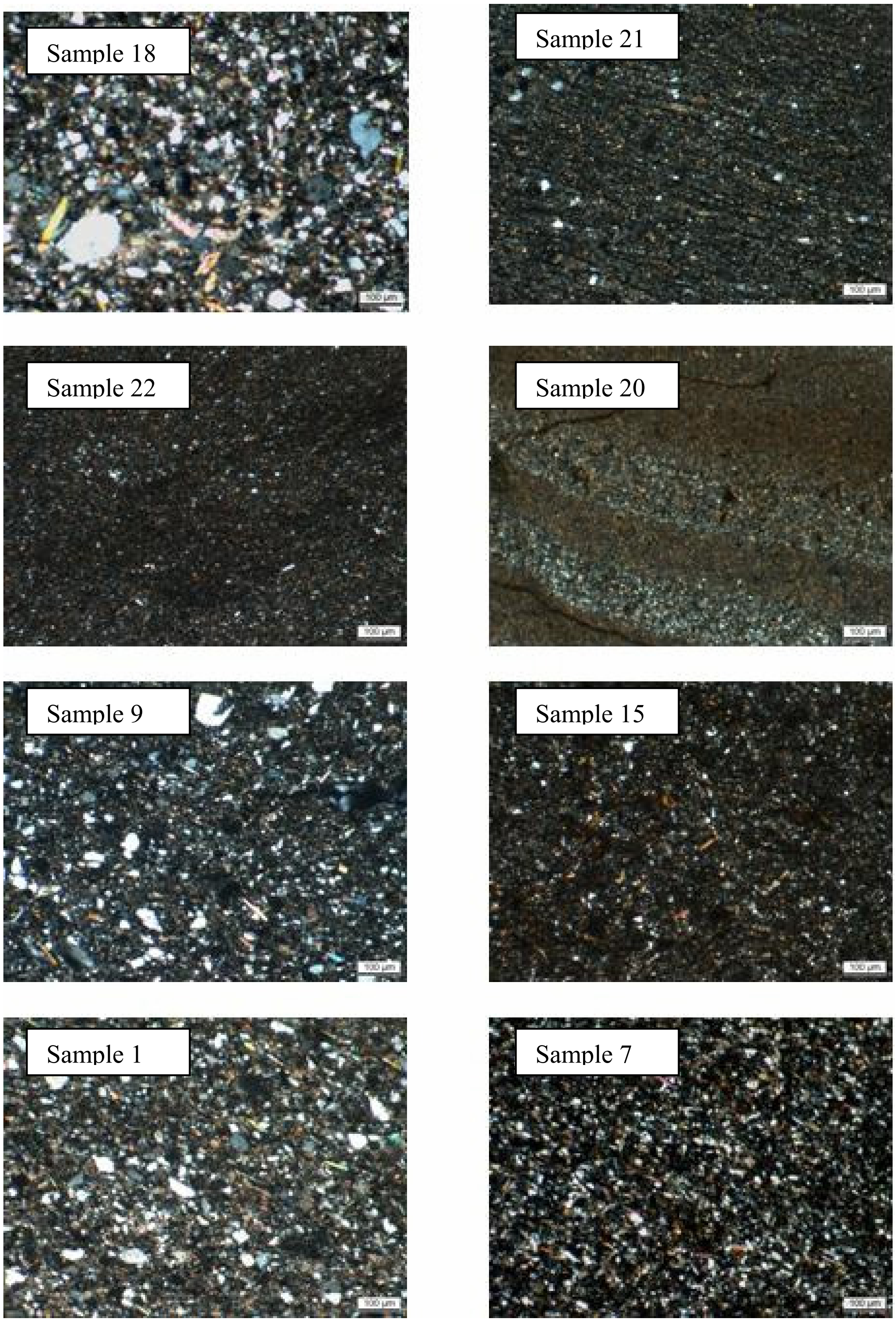


Fig.* Error! No text of specified style in document..*4: Thin sections of samples 18, 21, 22, 20, 9, 15, 1 and 7

The thin sections are presented in a single page for ease of comparison. They are: Sample 18 the Austwick Formation (arenaceous) (Capple Bank), Sample 21 the Crummack Formation (Hunterstye Member), Sample 22 the Crummack Formation (Capple Bank Member), Sample 20 the Sowerthwaite Formation, Sample 9 the Austwick Formation (arenaceous) (Crummack-Norber Brow), Sample 15 the Austwick Formation (argillaceous) (Crummack-Norber Brow), Sample 1 Norber Erratic N1 (arenaceous) and Sample 7 Norber Erratic N7 (argillaceous).

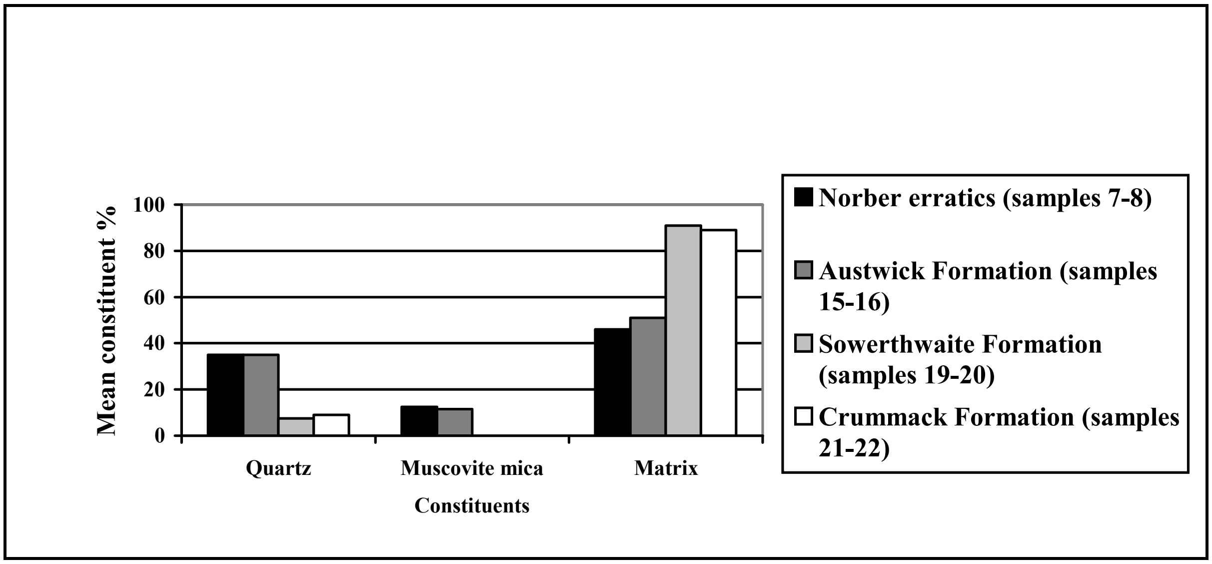


Fig. 5.5: Mean percentages for the three main constituents in argillaceous samples of the Norber erratics, and the Austwick, Sowerthwaite and Crummack formations

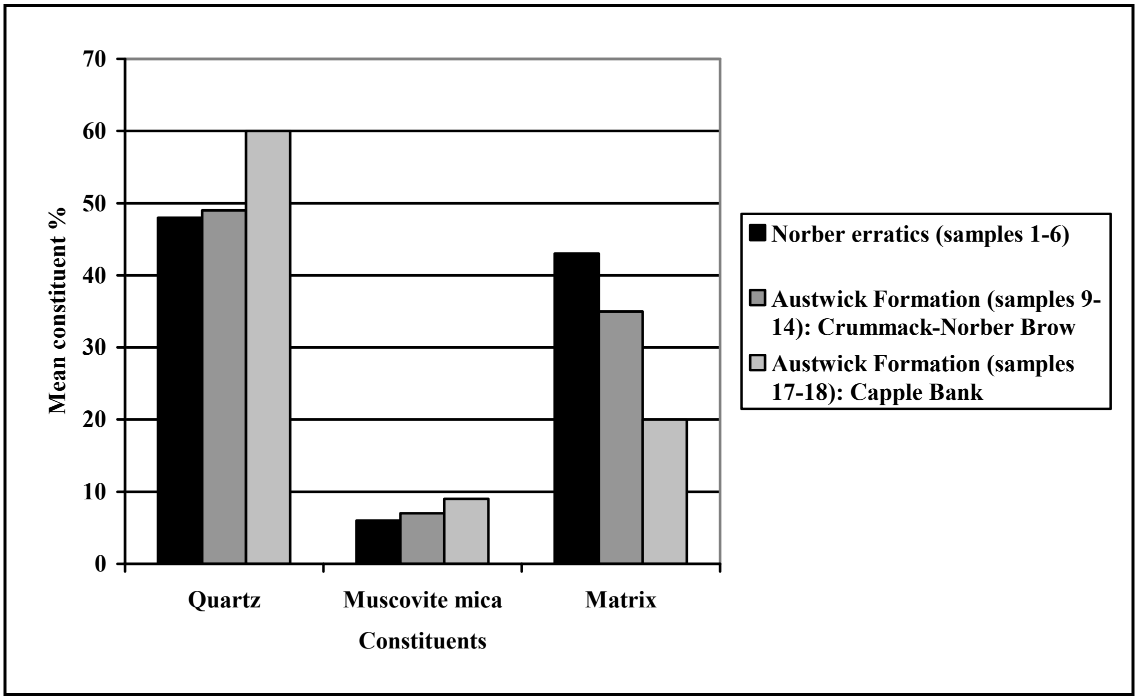


Fig. 5.6: Mean percentages for the three main constituents in arenaceous samples of the Norber erratics, and the Austwick Formation at Crummack (SD 7771)-Norber Brow (SD 7769) and Capple Bank (SD 7872)

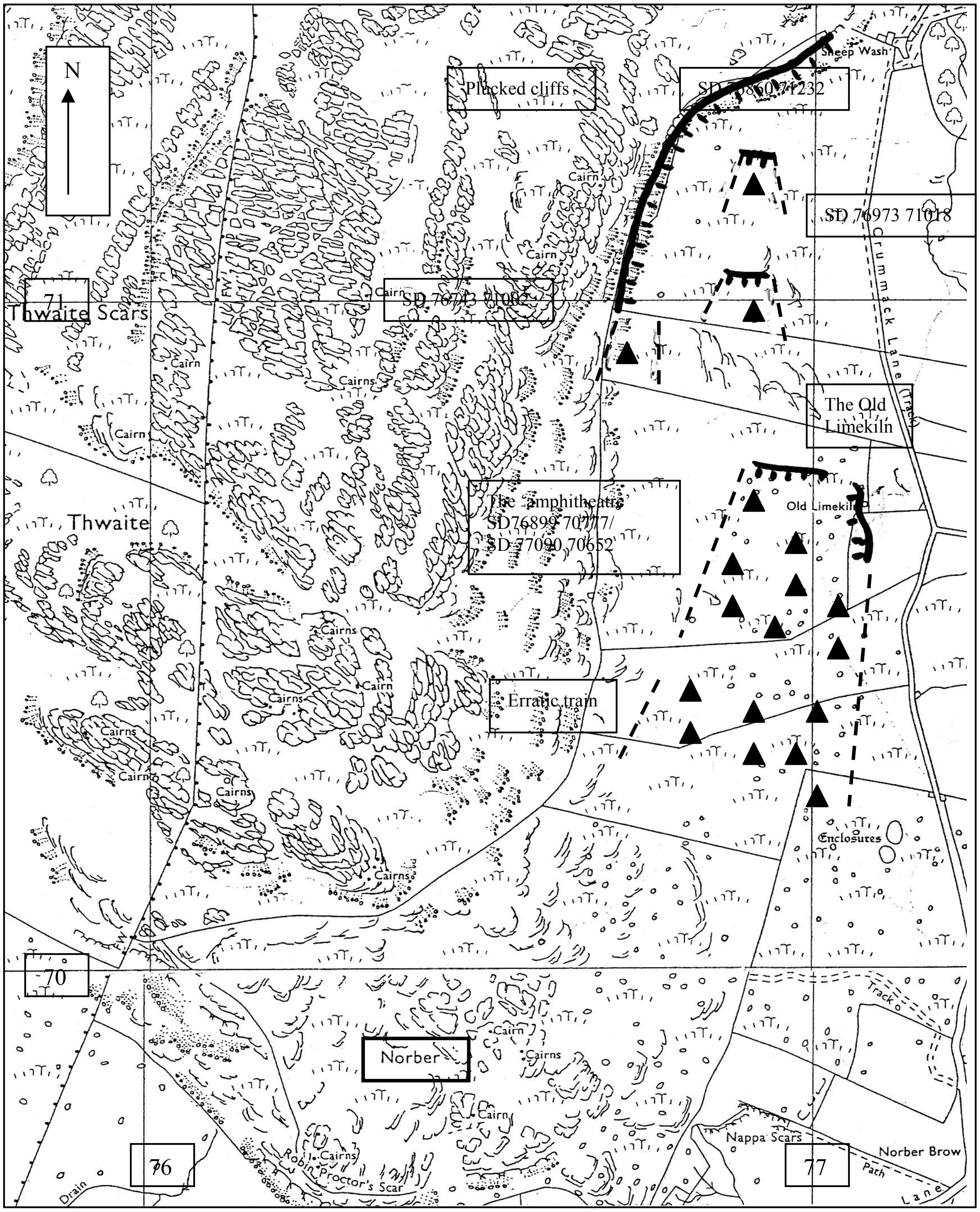


Fig. 5.7:Crummack-Norber Brow: the four source areas of the Norber erratics, and Austwick Formation plucked cliffs and erratic trains. (Courtesy of the Ordnance Survey, Southampton) (Scale given by National Grid coordinates)

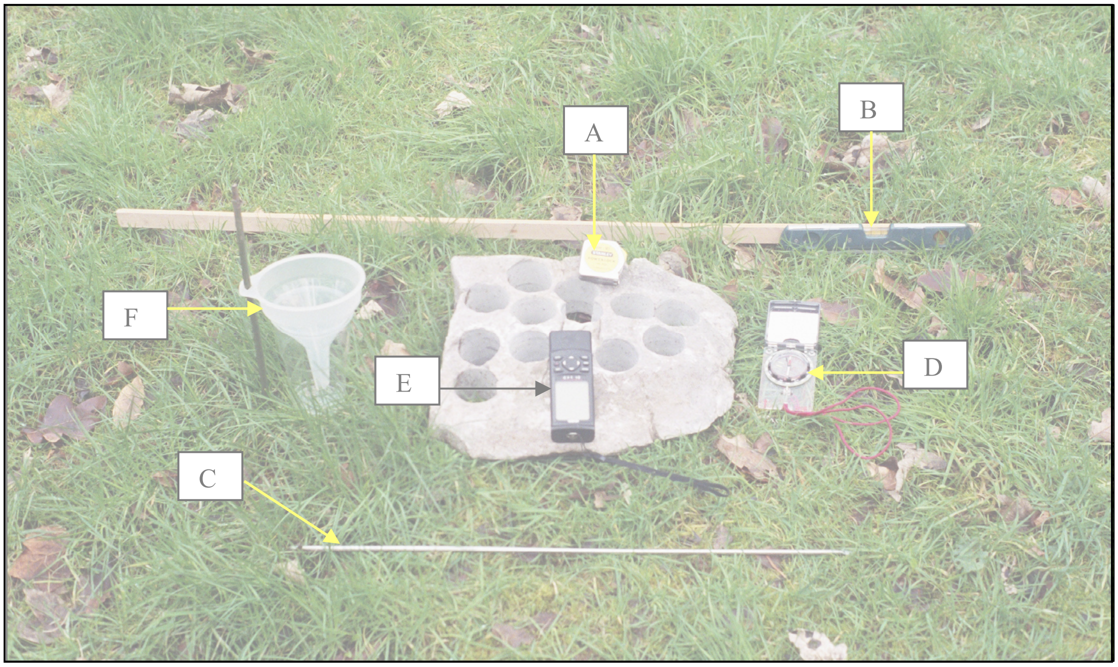


Plate* Error! No text of specified style in document..*1: Field equipment used during surveys and the chunk of Cove Limestone following the removal of cores for cutting into tablets

The equipment consists of a tape (A), rule with attached spirit-level (B) and metal rod (C) to measure pedestal height, a compass (D), a hand-held GPS console (E) and a home-made rain gauge (F).

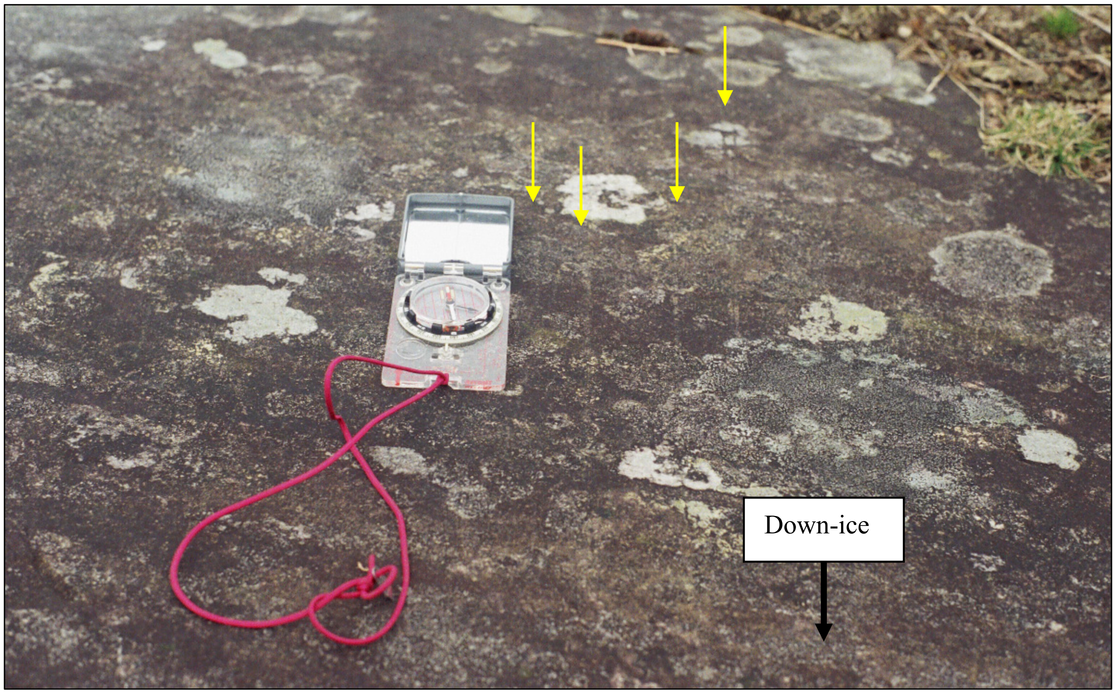


Plate* Error! No text of specified style in document.*.2: Striae at Location 4 above the northern backwall of the 'amphitheatre' in Crummackdale

Although definition is poor due to post-deglaciation weathering and lichen growth, four striae (yellow arrows) can be made out to the right of the compass. For purposes of scale, the compass case is approximately 18x6.5cm in size.

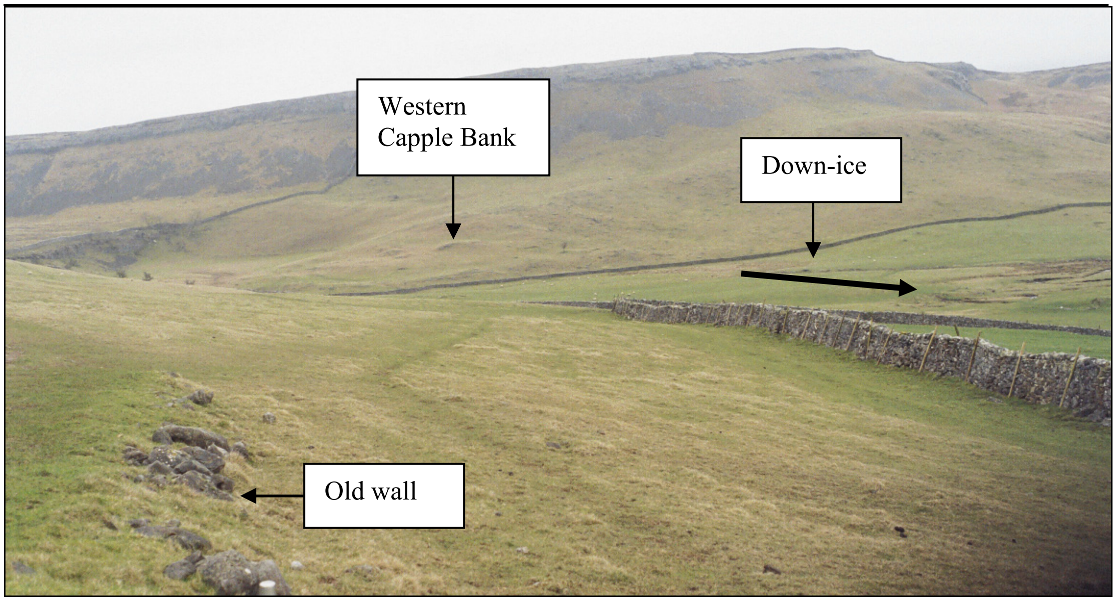


Plate 5.3: Crummackdale between Capple Bank and Crummack)

Even allowing for the fact that the distance from foreground to background is about 1km, it is clear that very few plucked outcrops are present on the western margins of Capple Bank and that erratics are scarce.

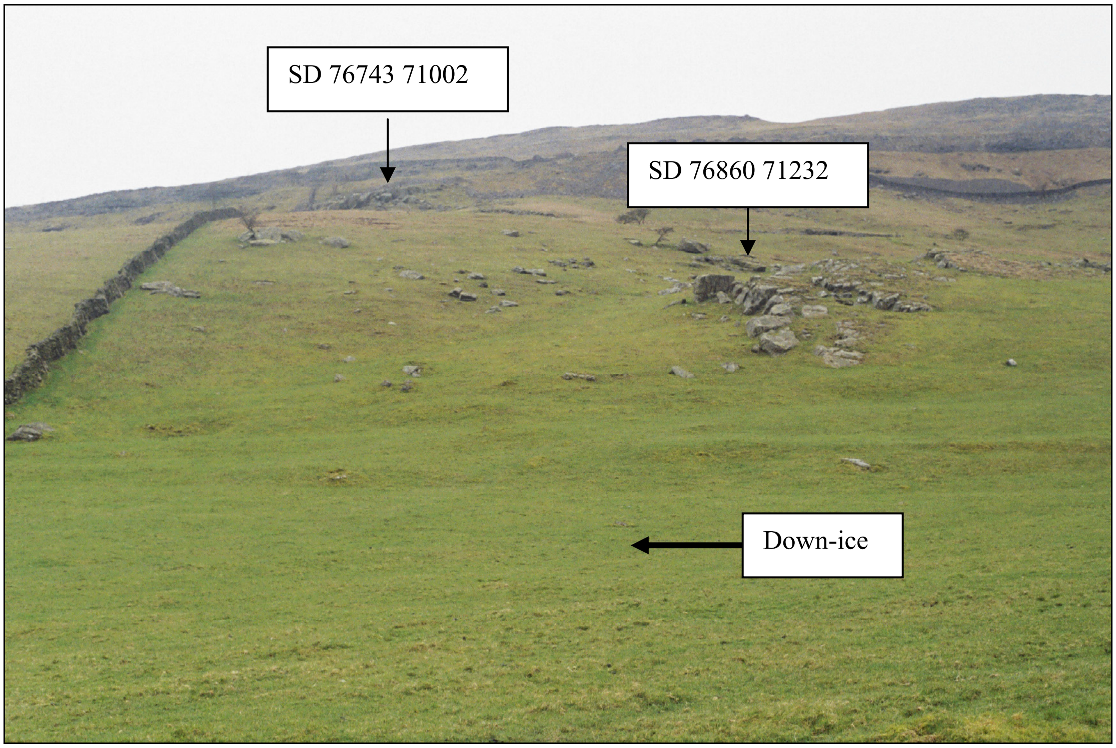


Plate 5.4: Part of Crummackdale between Crummack and the Old Limekiln

Relatively few erratics occur between Crummack and the Old Limekiln except at three relative 'hotspots' of plucking, such as at SD 76860 71232 and in the core of the eroded anticline close to the Carboniferous-Lower Palaeozoic unconformity at SD 76743 71002. Nonetheless, as so few clasts trail down-ice from the three sites it is not considered that any has contributed many erratics to the overall total at Norber.

Plate* Error! No text of specified style in document..*3: The northern backwall of the 'amphitheatre' in Crummackdale

The backwall is 3-4m high, and is tall enough to have calved even the largest of erratics at Norber. The site is that photographed by Dunham et al. (1953) at SD 769707 as Norber erratic provenance, and it would also seem that it forms the up-ice end of the erratic train that envelops Norber, as illustrated by Waltham et al. (1997).

Plate 5.6: The eastern sidewall of the 'amphitheatre' in Crummackdale

The cliffs of the eastern sidewall of the 'amphitheatre' are also over 2m tall. Fewer erratics emanate from them than from the northern backwall, which means it is not considered that as many erratics at Norber are derived from them.

Plate *Error! No text of specified style in document.**.4: Looking south towards Norber from the northern backwall of the 'amphitheatre' in Crummackdale***

A huge number of erratics trail towards Norber, which is in blind ground beyond Norber Brow, from the northern backwall of the 'amphitheatre'

Plate** Error! No text of specified style in document.**.5: Site of erratic provenance in Crummackdale as proposed by Arthurton et al. (1988)

No plucked cliffs and few erratics occur at the site proposed by Arthurton et al. (1988) as erratic provenance (foreground). In contrast, a plethora of erratics emanates from the northern backwall of the 'amphitheatre', which is up-ice of Arthurton et al.'s (1988) site.

Location no. and GR	**Approximate altitude(m)**	**Geological Formation**	**Number of stria(e)**	**Circular mean (° azimuth)**	**Geographical location**
1: SD 76861 71230	321	Austwick	12	024-204°	West Crummackdale
2: SD 76864 71039	314	Austwick	1	014-194°	West Crummackdale
3: SD 76810 70903	316	Austwick	40	009-189°	West Crummackdale
4: SD 76899 70777	281	Austwick	10	026-206°	West Crummackdale
5: SD 77090 70652	242	Austwick	1	032-212°	West Crummackdale
6: SD 77492 70526	242	Austwick	10	023-203°	Central Crummackdale
7: SD 76746 71118	357	Austwick	2	040-220°	West Crummackdale
8: SD 76762 71153	350	Austwick	1	020-200°	West Crummackdale
9: SD 78023 70666	270	Horton	1	028-208°	East Crummackdale
10: SD 78898 69812	274	Horton	9	036-216°	Wharfe
11: SD 76689 69945	300	Malham	1	040-220°	Norber (N11)
12: SD 76684 69869	296	Malham	1	036-216°	Norber (N12)
13: SD 76731 69926	299	Malham	1	040-220°	Norber
Survey area mean	n/a	n/a	90	020-200°	n/a

Table** Error! No text of specified style in document.**.1: Striae-trend results

Specimen no. and GR	**Matrix**	**Mineral 1**	**Mineral 2**	**Other constituents**	**Grain size, shape and sorting**	**Rock name**
Sample 17 SD 77820 72100	18%	Quartz 60%	Muscovite mica 10%	‘Opaques’ and rock fragments 5% each. Biotite mica 1%. Traces of chlorite and plagioclase feldspar.	< 0.75mm Largely angular. Very poorly sorted.	Lithic wacke (arenaceous).
Sample 18 SD 77861 72081	21%	Quartz 60%	Muscovite mica 8%	Biotite mica and ‘opaques’ 5% each. Traces of chlorite and plagioclase feldspar.	< 0.8mm Largely angular. Very poorly sorted.	Feldspathic wacke (arenaceous).

Table 5.2: Summary of constituent contents and grain sizes of rock samples taken from the Austwick Formation at Capple Bank (SD 7872)

Specimen no. and GR	**Matrix**	**Mineral 1**	**Mineral 2**	**Other constituents**	**Grain size, shape and sorting**	**Rock name**
Sample 21 Hunterstye Member SD 77935 71300	90%	Quartz 8%	–	'Opaques' 1%. Traces of biotite and muscovite micas, and plagioclase feldspar.	< 0.04mm (95% silt size or finer). Angular quartz. Moderately sorted and bi-modal.	Feldspathic mudrock (argillaceous).
Sample 22. Capple Bank Member SD 77940 71286	88%	Quartz 10%	Muscovite mica 1%	'Opaques' 1%	<0.0625mm Angular quartz. Moderately sorted.	Mudrock. (argillaceous).

Table 5.3: Summary of constituent contents and grain sizes of rock samples taken from the Crummack Formation in the vicinity of Hunterstye (SD 7871)

Specimen no. and GR	**Matrix**	**Mineral 1**	**Mineral 2**	**Other constituents**	**Grain size, shape and sorting**	**Rock name**
Sample 19 SD 77769 71813	83%	Maximum of 30% quartz in graded bedding unit base.	–	'Opaques' 1%. Trace of rock fragments and muscovite mica.	< 0.5mm Largely angular. Graded.	Graded wacke.
Sample 20 SD 77661 71887	99% (?)	(Too fine and/or too altered to identify).	–	Trace of rock fragments and muscovite mica.	< 0.8mm (99% silt size or finer). Rock fragments sub-rounded. Graded.	Graded mudrock.

Table 5.4: Summary of constituent contents and grain sizes of rock samples taken from the Sowerthwaite Formation at Austwick Beck Head (SD 7770)

Specimen no. and GR	**Matrix**	**Mineral 1**	**Mineral 2**	**Other constituents**	**Grain size, shape and sorting**	**Rock name**
Sample 9 SD 76860 71232	39%	Quartz 50%	Muscovite mica 5%	'Opaques' 2%. Chlorite, biotite and rock fragments 1% each. Trace of plagioclase feldspar.	< 0.4mm Largely angular. Very poorly sorted.	Lithic wacke (arenaceous).
Sample 10 SD 76902 70788	32%	Quartz 55%	Muscovite mica 5%	'Opaques' 5%. Chlorite and rock fragments 1% each. Traces of plagioclase feldspar and biotite mica.	< 0.7mm Largely angular. Poorly sorted.	Lithic wacke (arenaceous).
Sample 11 SD 77091 70650	33%	Quartz 50%	Muscovite mica 5%	Rock fragments and 'opaques' 5% each. 1% biotite mica and plagioclase feldspar.	< 2.0mm Largely angular. Very poorly sorted.	Lithic wacke (arenaceous).
Sample 12 SD 76743 71002	46%	Quartz 40%	Muscovite mica 10%	'Opaques' 3%. Traces of plagioclase feldspar and biotite mica.	< 1.0mm Largely angular. Poorly sorted.	Feldspathic wacke (arenaceous).
Sample 13 SD 77100 70451	36%	Quartz 40%	Muscovite mica 15%	'Opaques' 7%. 1% biotite mica. Traces of chlorite and rock fragment.	< 1.0mm Largely angular. Poorly sorted.	Lithic wacke (arenaceous).
Sample 14 SD 76973 71018	30%	Quartz 60%	Muscovite mica 3%	'Opaques' 5%. Biotite mica 1%. Traces of plagioclase feldspar and chlorite.	< 0.3mm Angular to Sub-rounded. Very poorly sorted.	Feldspathic wacke (arenaceous).
Sample 15 SD 76813 70543	56%	Quartz 40%	Muscovite mica 3%	Traces of 'opaques' and biotite mica.	< 0.2mm Largely angular. (95% silt size or finer). Moderately sorted.	Wacke (argillaceous).
Sample 16 SD 76821 70707	45%	Quartz 30%	Muscovite mica 20%	'Opaques' 5%	< 0.5mm Largely angular. (95% silt size or finer). Moderately sorted.	Wacke (argillaceous).

Table 5.5: Summary of constituent contents and grain sizes of rock samples taken from the Austwick Formation between Crummack (SD 7771) and Norber Brow (SD 7769)

Specimen no. and grid reference	Matrix	Mineral 1	Mineral 2	Other constituents	Grain size, shape and sorting	Rock name
Sample 1 SD 76746 70010	37%	Quartz 55%	Muscovite mica 5%	'Opaques' 2%. Traces of biotite mica, chlorite and plagioclase feldspar.	< 1.0mm Largely angular. Poorly sorted.	Feldspathic wacke (arenaceous).
Sample 2 SD 76655 70228	38%	Quartz 50%	Muscovite mica 10%	'Opaques' 1%. Traces of biotite mica, chlorite and plagioclase feldspar.	< 0.5mm Largely angular. Poorly sorted.	Feldspathic wacke (arenaceous).
Sample 3 SD 76622 69984	40%	Quartz 50%	Muscovite mica 5%	Rock fragments and 'opaques' 2%. Traces of biotite mica, chlorite and plagioclase feldspar.	< 0.5mm Largely angular. Very poorly sorted.	Lithic wacke (arenaceous).
Sample 4 SD 76339 69691	51%	Quartz 40%	Muscovite mica 5%	Biotite mica and 'opaques' 1% each. Traces of plagioclase feldspar, chlorite, calcite and rock fragments.	< 0.7mm Largely angular. Poorly sorted.	Feldspathic/ lithic wacke (arenaceous).
Sample 5 SD 76549 69775	41%	Quartz 50%	Muscovite mica 3%	Rock fragments and 'opaques' 2% each. Biotite mica 1%. Traces of chlorite and plagioclase feldspar.	< 0.5mm Largely angular. Very poorly sorted.	Lithic wacke (arenaceous).
Sample 6 SD 76460 70139	49%	Quartz 45%	Biotite mica 3%	Muscovite mica and 'opaques' 1% each. Traces of plagioclase feldspar.	< 0.4mm Largely angular. Very poorly sorted.	Feldspathic wacke (arenaceous).
Sample 7 SD 76121 70023	29%	Quartz 55%	Muscovite mica 5%	'Opaques' 10% Biotite mica 1%.	< 0.3mm Largely angular. (90% siltstone size or finer). Moderately well-sorted.	Wacke (argillaceous).
Sample 8 SD 76684 69869	62%	Muscovite mica 20%	Quartz 15%	Rock fragments and 'opaques' 1% each. Traces of chlorite, biotite mica and augite.	< 0.5mm Largely angular. (90% siltstone size or finer). Poorly sorted.	Lithic wacke (argillaceous).

Table 5.6: Summary of constituent contents and grain sizes of rock samples taken from the Norber Erratics

CHAPTER 6: THE NORBER PEDESTAL ROCKS – LITERATURE REVIEW

6.1: Introduction

A number of the Norber erratics (*sensu lato*) rest on limestone pedestals, the two features together forming a pedestal rock, as outlined in Section 1.6. It is believed that the pedestals at Norber have formed due to the erratics protecting the limestone beneath them from erosion. Thus, without the erratics there would be no pedestals. Although it is of no consequence to pedestal formation where the provenance of the Norber erratics (*sensu lato*) is located, the erratics nevertheless provide the link between the foregoing and following chapters. A total of thirty-two pedestal rocks were observed at Norber. All are perched pedestal rocks and all caprocks are comprised of erratics, thirty of Silurian grit and two of Carboniferous limestone. As it is known that the rocks that cap the pedestals are erratics this aspect of pedestal rock formation is not pursued further, and the work undertaken in Chapters 6-12 focuses instead on the formation of the pedestals. For a full list of Norber pedestal rocks refer to Appendix 5 N.

6.2: The Norber pedestal rocks

The Norber pedestal rocks were probably first chronicled by Phillips (cited in Hughes, 1886: 530) who in 1855 wrote that geologists "…will be rewarded for enquiring into the remarkable distribution…of blocks…which have been drifted so as to rest on the limestone hills…above the village of Austwick ...the blocks being very often perched." Phillips (cited in Hughes, 1886) did not, however, offer any explanation for the fact that the blocks were perched. Not so Hughes (1886: 531-2), who attributed the formation of the pedestal rocks to the great Silurian boulders "…intercepting rainfall with the result that the original face of the limestone has been preserved under them, while all around it has been eaten away by the rain-water, and so the boulder stands on a small pedestal of irregular shape, according as the surface has been more or less protected from the splash and wind-blown rain." The observation by Hughes (1886) that the erratics have protected the limestone beneath them from dissolution by intercepting rainfall is the first allusion to the 'Umbrella Theory'. In the article of 1886 Hughes elaborated further on the possible mode of formation for the perched blocks at Norber (and also at Cunswick Tarn and on Farleton Fell in Cumbria), suggesting (p. 534) the boulder "…does not merely protect the underlying rock from the mechanical action of the rain, but also by keeping it dry not only prevents it being broken up by frost but also interferes with the growth of vegetation." Furthermore, Hughes (1886: 534) stated that even pure water "…will dissolve two grains per gallon of carbonate of lime…the conditions are entirely altered as soon as specks of vegetation fix themselves upon the rock…not only is there a much larger quantity of carbonic acid derived from the decomposing plants ...but the growing masses…hold the water like a sponge, fretting the rock away."

Although the pedestals at Norber have been touched on in many articles since Hughes wrote about them in 1886, none has dealt with their formation in such detail apart from Goldie (2005). Rather, they have been referred to in passing within the general context of the origin of karst topography or of the creation of the landscape of northern England. Thus Kendall and Wroot (1924) mention that some of the erratics stand on pedestals eighteen inches (46cm) above the general level of the limestone, this height being a measure of the solution of the general surface of the limestone since the Ice Age. This observation has been reiterated, with minor variations, many times since and Dunham *et al.* (1953) wrote that many of the erratics are found on pedestals, and they suggested that at least two feet (61cm) of limestone had been removed since the retreat of the ice. According to Jones (1965) it is not usually possible to view a pedestal surface under the erratics, but sometimes one may be exposed where small stones are lodged between the surface and the blocks, and such pedestals have tight fitting joints and may have preserved glacial striae on their surfaces. Jones (1965) also observed that many pedestal surfaces are protected from direct rain in wet weather, but that many have drip marks and little channels on them caused by solution from acidulated water dripping off the boulders. Raistrick and Illingworth (1965) found that nearly all the large boulders were standing on pedestals about 10 inches (25cm) in height, noting that the boulders act as an umbrella preserving striae on the limestone surface under their shelter and that pedestal height is a measure of limestone removed since the Ice Age by the solvent action of rain. Sweeting (1966) observed that the surface of pedestals under the Norber boulders is 30-50cm above the surrounding pavements and considered that for some of the pedestals this indicates the amount of lowering by solution of the whole surface beyond. Sweeting (1966) also observed that where pedestals have developed under erratics on sloping ground they are often of greater height on their downslope side and perhaps level with the general surface on their upslope side, a circumstance which may mean that soil-creep in response to gravity is partly accountable for their formation. Penny (1974) suggested a similar average pedestal height of 40-45cm, and like King (1976) mentioned that solution has played a part in their formation, the latter adding that pedestals occur on the more susceptible beds of the limestone pavement. In contrast Wood (1985) asserted that the erosion of the limestone by wind, as well as the weather, is believed to explain their development. Talbot and Whiteman (1991) offered a somewhat different view of formation explaining (p. 151) the fact that many of the erratics are perched on plinths, some a foot high, is that the surrounding softer limestone – unprotected by the umbrella effect of the harder boulders – "...has been dissolved away by 10000 years of rainfall." This view is echoed by Goudie and Gardner (1992: 31) who wrote that the erratics "…have protected the underlying pavement from rainfall, rather like an umbrella, so that they are now perched on pedestals of protected rock up to 30cm high." Bell (1996) also attributed pedestal formation to the dissolution of the limestone since he stated (p. 47) that for 12000 years "…the sandy greywacke boulders have acted as umbrellas. Slightly acidic water has dissolved the surrounding limestone pavement leaving each greywacke boulder perched on a remnant block some thirty centimetres high." Ward (1996) proposed a somewhat similar origin.

The only authors to have noted the relative slenderness of some pedestals vis-à-vis their cap-rocks are Waltham *et al.* (1997), and they broadened pedestal formation by marrying surface lowering to dripwater dissolution. They explained (p. 52) that the erratic boulders now stand on pedestals of limestone which have been "… protected from corrosion by direct rainfall while the surrounding limestone surface has been lowered by subaerial and subsoil solution…[and that]…the protected pedestals are mostly 400-500mm high." They added that the narrowness of the pedestals and their incision by solution grooves may be accounted for by dripwater "…flowing down the underside of the boulders." Smith (2001), on the other hand, mentioned merely that the pedestals had formed since the ice melted due to the surrounding pavement being eroded, except for the areas sheltered from the weather by the boulders. Waltham (2005: 145) noted that although protection of the plinths from post-glacial rainfall by the erratic blocks makes an attractive story "…only a few of the many erratics do stand on plinths, and these may be largely ascribed to bench edges where erratics happened to be dropped on them." This viewpoint was greatly expanded by Goldie (2004; 2005), who wrote (2005: 437) that limestone character and disposition in relation to topographic slope is "…crucial to pedestal interpretation. Limestone bedding inclines at between +2 to -2°, which is a gentler angle than the topographic slope (4 to 8°) [towards the east]; the limestone is well bedded and well fractured. The resulting surface thus consists of many small limestone steps". Goldie (2004; 2005) consequently interprets pedestal formation in a new light, and proposed (2005: 439) that the stepped structure must have provided "…an uneven surface of steps and plinths for boulder deposition", that "…mechanical weathering results in step retreat", and that (2004: poster) most so-called pedestals are "…thus steps." Norber is also mentioned on several web sites, for example Cragface (2006). Here pedestal formation is attributed to the erosion of the limestone surface "…by the wind and rain, the area beneath each of the Norber erratics has remained protected by the rocks themselves leaving each of the erratics sitting on a little platform raising them 20-60cm above the level of the surrounding landscape."

6.3: Pedestal rocks with pedestals composed of Carboniferous limestone at other sites in England, Ireland and Wales

The earliest account of pedestal rocks other than those at Norber is probably by Hughes (1886), who noted the occurrence of perched rocks at Cunswick Tarn and at Farleton Knot in Cumbria. The pedestal rocks at Cunswick Tarn are similar in make-up to those at Norber, as the pedestals are comparable in height and in form, and as the caprock is composed of Silurian greywacke; pedestal surroundings are also similar. It is thus of relevance to Norber that Hughes (1886: 529) wrote that the time taken to reduce the surrounding limestone by the height of the pedestal "…is obviously not due to the rain only, but also and chiefly to the action of the damp soil and vegetation, which has covered it all, up to the very base of the pedestal on which the boulder rests." In contrast, the pedestal rocks on Farleton Fell are dissimilar to those at Norber in a number of respects. Thus all caprocks are composed of Carboniferous limestone while (p. 529) pedestals are "…not often more than three to seven inches high. Some, however, are as much as a foot high, but only in those cases where the growth of vegetation along the master-joints had obviously helped the work. In many cases the boulders seem to have protected a somewhat larger surface of the limestone than that immediately below them; but the part of the limestone so preserved was always on the side from the southwest wind. It seemed also that the boulders and pedestals were breaking down over the whole hill, and here and there one could see a round bump, from three to five inches high, rising above the general level of the limestone and marking the place where a boulder had formerly been perched. Often the boulder was seen close by, whether pushed off by a tourist or rolled from a pedestal which had perished too far on one side, we could not tell." As with Norber no subsequent descriptions of pedestal rocks match those of Hughes (1886). Thus Jones (1965) merely mentioned that drip marks on pedestals under erratics on Scales Moor are due to acidulation of rainwater crossing the lichen-covered caprock. Sweeting (1966: 201), though, produced more detail declaring that some of the best localities for perched blocks "…are those on Harry Hallam's Moss and on Scar Close on the north-west side of the Ingleborough massif." Sweeting (1966) added that the clint surface has "…been lowered by about 50cm since their formation" and that although many caprocks may be true erratics many are "…pseudo-erratics i.e. residuals left by stripping of the bed by solution." The only reference to mushroom pedestal rocks is by Goldie (1994: 3) who wrote that on Great Asby Scar in Cumbria there are "…quite massive, cushion-shaped clints on top of well fractured undercut pedestals resulting in mushroom-shaped features." Goldie (1994: 3) also mentioned that remnants of an upper bed of limestone "…stand perched on sloping pedestals of the underlying limestone" that are "…about 10cm in height and spread beyond the base of the overlying block for about 10cm in width." There is a photograph of a pedestal rock (known as the Cuckoo Rocking Chair) teetering above Hutton Roof village, also in Cumbria, by Milligan (2003: 28).

The only reference to pedestal rocks in Wales is by Thomas (1970), who wrote (p. 101) that the protective umbrella effect of the many erratic blocks at Twyn Du, limited as they are in size,"…has been negligible" and that the height of seven pedestals is "… 0.2 to 0.4m." Moving across the Celtic Sea to the Republic of Ireland, Williams (1966: 170) asserted that pedestal heights in the Clare-Galway district "…vary from nothing to eighteen inches, but average about six inches." This assertion is followed up with an observation of two pedestals at over 1000 feet OD in County Leitrim which "…have a mean height of roughly twenty inches" and that this suggests "…greater superficial denudation at higher levels where precipitation is more abundant." Williams (1968: 27) also wrote that evidence from the height of pedestals beneath erratics in the Fergus area indicates that the solution lowering of the limestone surface "…does not seem to have exceeded a mean of about 15cm since the last glaciation (about 14-15000 years ago)." Drew (2001: 14), in common with many of the preceding authors in England, asserted that pedestals at Fanore (M139081) in County Clare have formed due to the underlying bedrock being "…protected from solutional erosion for the past 12000 years…by glacially transported boulders" and that typical pedestal heights "…range from 400-600mm suggesting an average rate of lowering of the limestone surface of c.0.04mm per year." Simms (2001: 14-15) observed that the caprocks on the Burren are "…usually of limestone but sometimes of Galway Granite or other rock types." A similar conclusion for pedestal formation as Drew (2001) was proposed, except that development was qualified by stating that "…rainfall has slowly lowered the limestone surface by dissolution…since the ice sheets disappeared… about 14000 years ago", adding that pedestal heights are sometimes "…several tens of centimetres." Dunne and Feehan (2001) conducted a wide survey of wave stones, which they regard as a type of mushroom rock, in lowland karst regions in Eire. All the stones are situated less than 70m above OD, and the authors described them (p. 33) as "…limestone boulders, erratics or bedrock found in certain bog and wetland sites that are notched and undercut in such a fashion as to suggest prolonged exposure to standing water at some time in the past." In a more comprehensive overview of the stones Dunne and Feehan (2003: 15) explained that erratics may end up standing partly submerged in the shallow water of a lake margin and that long-continued wave action "…corrodes the limestone below the water more rapidly than above the water." Their account of the formation of the mushroom and wave stones is thus completely at odds with all the preceding authors since a non-terrestrial origin is advocated. Dunne and Feehan (2001; 2003) do add, though, that to attribute the formation of all the mushroom stones they surveyed to water erosion alone is unsound, and that the notching (2003: 25) may have come about as a result of "… burial for a long time in acid soil or peat."

6.4: Pedestal rocks with pedestals composed of rock other than Carboniferous limestone

The most widespread and abundant occurrence of pedestal rocks is in arid or semi-arid regions where a lack of vegetation and regolith led early twentieth century geomorphologists to attribute their origin to sand blasting. Thus, Blackwelder (1909: 443) noted that in most parts of the dry west USA the wind "…has been an agent of great importance, and mushroom monuments and other wind carved forms are widely distributed." Hume (1914: 424) wrote that though the main features of a desert land depend on the geological structure and in part on past climatic conditions, there are characteristics which are typical of all desert regions. These typical features "…include…the formation of mushroom shaped pillars undercut by the sand." During succeeding years a reinterpretation of features previously attributed to processes peculiar to the desert environment was undertaken. Accordingly, Peel (1966) noted that the intriguing 'mushroom' rocks in southern Libya would seem best explained by moisture-assisted weathering near ground level, perhaps aided by salt-crystallization, rather than by invoking sand-blast. He observed that the pedestals had formed in an area of unidirectional sand-driving but were symmetrically cut all round, with the necks rough and weathered, and revealing none of the polish and pitting of sand-blast.

Pedestal rocks are also found in river channels and Martel (1910) declared that they form due to a combination of abrasion and chemical weathering acting together to reduce the base of boulders and individual rock outcrops that protrude above the level of the river. Bryan (1925) came to a similar conclusion in a study of four boulders in four streams, finding that different combinations of scour, chemical weathering and abrasion allied with exfoliation, freeze-thaw and granular disintigration are responsible for the production of the shafts, with scour being the most important of these processes. Features morphologically akin to pedestal rocks may form along coasts (Twidale and Campbell, 1992) when undercutting by marine agencies of weathering and erosion causes stacks to display a base that is narrower than the cap. Dunne and Feehan (2003) have likewise noted that mushroom-shaped rocks can develop at the edge of the sea, especially in areas where coral limestone is undergoing erosion. Induced tensile fracture is thought to play a part in the formation of localised pedestal rocks by Ollier (1978), who pointed out that when an upper rock or boulder rests on a lower rock it will subject the latter to unconfined or uniaxial compressive stress if the lower rock is not bounded on all sides. Ollier (1978) suggested that the mechanism of induced fracture, which can result from this applied stress, may provide a satisfactory explanation for the many examples of sharply angular supporting rocks found beneath perched boulders.

In areas where weathering is responsible for rock disintegration, opinion has long backed the preferential weathering of exposed blocks at and near the ground surface and it was suggested as long ago as the nineteenth century by Merrill (cited in Twidale and Campbell 1992: 6) that the lower parts of exposed blocks "…are continually moist." Bryan (1923), however, argued that rain which runs off the edges of the caprock and down the sidewalls below can lead to the development of certain pedestal rocks by a combination of interlinking processes. An alternative conclusion was reached by Leonard (1927: 473) who found that the differential expansion and contraction of the different mineral constituents (in granite) as caused by diurnal temperature changes "… must be the principal factor operative in the disintigration of pedestal rocks in the Texas Canyon of south east Arizona." Petty (1932) thought that chemical processes were of overriding importance, however, and suggested that humic acids produced by decaying vegetable matter, together with the capillary rise of water from below, would lead to the greatest rates of weathering (of granite) taking place near the soil surface. Crickmay (1935) advocated that although rain may drench the entire exposed block (of granite), evaporation is relatively more rapid on the upper surface of the cap with the result that hydration with consequent disintegration is largely restricted to the overhanging, shaded portion of the pedestal. Twidale and Campbell (1992: 1) took this a stage further by stating that the field evidence suggests that most pedestal rocks are "…two-stage forms. Preferential weathering by soil moisture produces the shaft and takes place beneath the land surface, while the cap retains its integrity, in some instances by virtue of its massive structure, but in others by being exposed, relatively dry and protected by lichens, mosses and chemical crusts which have, in places, added to its resistance to weathering and erosion. The exposure of the stem is due to the removal by erosion of the regolith, commonly by wash and streams, but in some instances by the action of wind or waves or soil creep." This removal may result from either natural or anthropogenic phenomena.

6.5: Conclusion

The origin of the cap-rocks (*sensu lato*) at Norber is not in dispute since it was established in Chapters 3 that they are all glacial clasts that were deposited during the demise of Devensian ice, in ca.14500BP. In sharp contrast the formation of the underlying Carboniferous limestone pedestals is not at all clear, as they may have formed due to the lowering of the inter-caprock limestone surface in a plethora of environments if all possibilities are considered. At Norber, dissolution of the limestone by rainwater operating in either a subaerial or a sub-regolith environment would appear to be the key factor, but to this must be added the prospect that limestone fabric, soil-creep, step retreat and wind may have played a part. Elsewhere in England and also in the Republic of Ireland it seems that dissolution acting in a subaerial environment has performed the major role in pedestal formation, although dissolution in a sub-regolith setting cannot entirely be discounted. In addition, it has been proposed that certain pedestal rocks in the Republic of Ireland have formed due to dissolution in a lacustrine environment. More options unfold when environments from abroad are considered, as differential expansion and contraction, hydration, induced tensile fracture, marine waves, rivers and salt-crystallization have also played a role.

CHAPTER 7: PEDESTAL FORMATION AT NORBER – EROSION ENVIRONMENTS

7.1: Foreword

It has been proposed, for instance by Pigott (1965), Trudgill (1983a) and Waltham *et al.* (1997), that the immediate post-ablation Carboniferous limestone panorama in the Ingleborough area consisted primarily of a glaciokarst 'staircase' landscape of scars and pavements, the latter peppered with erratics and partially overlain by till. This setting would seem to be appropriate to Norber as it has been shown that the erratics and till are Devensian in age (Section 3.4.1). Moreover, the occurrence of striae on the upper surface of three pedestals confirms that the limestone surface on which the erratics rest was not inherited from a time prior to glaciation. The very existence of the pedestals (and survival of the striae) beneath the erratics indicates that the latter have protected the post-glaciation limestone surface beneath them while the surrounding surface has been eroded. In other words, the pedestals are residuals remaining after the removal of the inter-erratic limestone surface. Consequently, the main aim of the work undertaken in Chapter 7 is to resolve which of the erosion environments outlined in the conclusion of Chapter 6 is lowering the inter-pedestal limestone surface. The environments are presented in alphabetical order, so as not to presume that one is more important than another is. In addition glacial erosion is also considered. Strictly speaking, examining the role played by glacial erosion in pedestal formation does not fall within the definition of a pedestal rock as outlined in Section 1.6, since glacial erosion pre-dates surface lowering. Nevertheless, its inclusion is justified on the grounds that erratics deposited above bench edges have protected the glacial scar beneath them from erosion following ablation of the Devensian ice.

At this point, it is worth recalling the definition of a pedestal rock, as formulated in Section 1.6:

'A pedestal rock is comprised of an overlying caprock consisting of any type of rock supported by a pedestal composed of Carboniferous limestone that has formed since Devensian ice melted. The caprock and pedestal may be separated by a structural break (a perched pedestal rock) or the two can be structurally contiguous (a mushroom pedestal rock). The girth of the pedestal can be narrower or broader than that of the caprock and the caprock might or might not have protected its pedestal from weathering/erosion. The pedestal rock can have formed in a wide diversity of weathering and/or erosional environments.'

All the cap-rocks at Norber are erratics (*sensu lato*) that were deposited during the demise of Devensian ice in ca.14500BP (Section 3.4.1). Consequently, it follows that all the pedestal rocks at Norber are perched pedestal rocks and that no further investigation into cap-rock origin is required.

7.2: The Norber pedestal rocks: locations and features

Prior to the commencement of investigations to determine the formation of the pedestals at Norber a survey was undertaken to pinpoint all pedestal rocks at the site and to record their salient features. Pedestal rocks were located by conducting a systematic survey along nine transect lines about one hundred metres apart on bearings of 020/200° and 200/020° azimuths that are roughly parallel with the eastern dry-stone boundary wall of Norber. The start and end of each transect was recorded using a hand-held Garmin GPS 12 Personal Navigator (Plate 5.1). Refer to Appendix 3TL for the start and end grid reference points. Each pedestal rock was numbered (e.g. N1, N2 and so forth). The site of each (to two grid letters and ten grid numbers) and the altitude of its upper surface (to within 10m) were established using either a Magellan Promark X Global Position System (GPS), as outlined in Section 4.3.3, or the Garmin GPS 12. The caprock geology (e.g. Silurian grit or Carboniferous limestone) was recorded and caprock size (maximum length, width and height) was measured. Pedestal sidewall dip (i.e. vertical or sloping) was recorded, and pedestal height and discontinuity spacing were measured (refer to Section 9.3 for the methods employed). The nature of the immediate inter-pedestal surroundings was recorded (e.g. note was made of geomorphological features, such as glacial scars, and the presence/absence of bare rock/regolith). The solid geology was determined from British Geological Survey 1:50000 Series, England and Wales Sheet 60 (Solid Edition): Settle (1989). It transpired subsequent to the survey that due to the sheer number of erratics present that some pedestal rocks had inevitably been missed. These were added to the initial list upon detection, but as they were discovered at various stages of the research, not every one has been included in all investigations. Refer to Appendix 5N for a full list of the location and features of all pedestal rocks that had been identified at Norber by the completion of the thesis.

7.3: Aeolian erosion

7.3.1: Introduction

The formation of pedestal rocks by aeolian processes is normally associated with arid or semi-arid areas (e.g. Blackwelder, 1909; Hume, 1914). Wood (1985) and Cragface (2006) have asserted, however, that wind is believed to partly explain the development of the limestone pedestals at Norber, although no evidence is provided to support this view. Wind is also a popular explanation for pedestal-rock formation at Norber with the general public. It is generally accepted (e.g. Cooke *et al.*, 1993) that wind erodes in two main ways: by deflation, whereby incoherent sediment is entrained: and by abrasion, in which consolidated, cohesive materials are worn down. The only reference to the entrainment of Carboniferous limestone particles is by Moses and Smith (1993), who showed that wind power acting alone can remove fragments previously loosened by lichen in kamenitzas. The latter, however, do not occur at Norber. Accordingly, it would appear that wind is only capable of eroding the well-lithified strata that forms the pedestals if it is able to entrain and transport particles to use as a tool to effect abrasion. The efficiency of abrasion is, however, subject to a number of constraints. For example, Cooke *et al.* (1993) note that a vital control is a supply of loose grains and that abrasion is accomplished predominantly by sand-sized particles. Wolfe and Nickling (1993) note also that vegetation reduces or prevents aeolian sediment loss by covering a proportion of the surface and by trapping particles in transport. Further, Twidale and Campbell (1992) state that only in regions of very high wind velocity (such as Antarctica) can the formation of pedestal rocks be attributed to sand-blasting. Abrasion also produces diagnostic geomorphic features such as polishing and, if one wind direction predominates over all others, pedestals with a degree of asymmetry (Peel, 1966). Accordingly, if abrasion is contributing to pedestal formation at Norber it is necessary not only to consider the constraints, as outlined, but also to examine pedestals for the occurrence of direct evidence of sandblasting.

7.3.2: Aim and objectives

The aim of the work undertaken in Section 7.3 is to establish whether or not abrasion of pedestals is occurring. The objectives are to record areas of particle supply, to measure particle size, the height of vegetation (and other obstacles to wind flow), and the undercut of pedestals to their windward and leeward, and to record sand-blasted features.

7.3.3: Method

Ten pedestals were sampled, N5, N11, N12, N14, N15, N17, N19, N21, N25 and N27. The pedestals were not sampled at random but were chosen because no others had a relatively uninterrupted wind fetch to the south-west of at least 50m. The bearing was chosen because it is the direction of the mean prevailing and strongest winds (Briffa and Atkinson, 1997), and the distance because it is well beyond that at which turbulence created by intervening solid objects (i.e. erratics) might affect fetch (Ahrens, 2003). The height of vegetation and other obstacles to wind movement was measured at six sampling points that were 0, 10, 20, 30, 40 and 50m from the base of each pedestal along a 50m transect line with a strike of 225º azimuth. The presence/absence of bare ground and sand-blasted features was documented also. Five surface soil samples were collected (from molehills), and sieved and examined in the laboratory. Pedestal undercut to the windward and leeward was measured. In addition, thin sections of the Kilnsey and Cove limestones were examined for material that could effect abrasion of the limestone. Refer to Appendix 3TS.3 for full thin-section descriptions of the two limestones.

7.3.4: Results

Fifty-three of the sixty sampled points consist of vegetation with a mean height of 23.1cm, five of limestone clasts with a mean particle height of 12.2cm and one of an erratic with a particle height of 37cm giving an overall mean height of 18.5cm. A gryke 30cm in depth was also sampled. Sand-blasted features were not present on any pedestals or any caprocks. No bare soil was encountered along any transects, although scraps of sheep-poached ground at the leeward-base of some pedestal rocks together with an approximate 100m linear east-west train of several tens of molehills, each about 36cm in diameter and 12cm in height, were observed. The areal extent of non-vegetated soil/ground was not measured, but it is estimated that it comprises less than one percent of the land surface. (The amount of vegetation cover at Norber can be clearly ascertained by examining Plates F1 and 1.1). The mean grain-size of surface soil is 4.6% granules (range 0.1-11.3%), 31.1% sand (range 19.3-42.5%) and 64.3% silt/clay (range 54.8-78.1%) as shown in Fig. 7.1. Mean pedestal undercut is about 26cm to the windward and about 23cm to the leeward (Table 7.1). Refer to Appendix 3A for full vegetation height, pedestal undercut and soil sieving results. On the basis of thin section analysis approximately 15% (range 10-20%) of the constituents of the Kilnsey Limestone consist of sand-sized material (largely Lower Palaeozoic greywacke extraclasts but also allogenic quartz) that is capable of abrading calcite. No material that is capable of abrading calcite was found in the Cove and Gordale Limestones.

7.3.5: Analysis

Although thin-section findings show that sand-sized particles occur within the Kilnsey Limestone, they can only become available to effect abrasion if released from a bare limestone surface. The Kilnsey Limestone only crops out as a relatively narrow strip along the south-eastern and eastern margins of Norber where it is largely mantled in vegetation-covered regolith. It also occurs mostly to the leeward of the main parts of Norber from which it is separated by a line of overlying Cove Limestone scars several metres in height. The limestone is thus not only of limited areal extent, but as it does not form any pavements a subaerial supply of grains is restricted to dissolution of intermittent scars that are generally less than 0.5m in height. Furthermore, if any sand-sized particles were to become entrained subsequent to subaerial dissolution they are likely either to be transported away from Norber by the prevailing wind or to be prevented from travelling northwards and westwards to pedestals higher in the succession by intervening cliffs. Sieving results show that an alternative supply of sand-sized particles suitable for abrasion exists within the surface soil at Norber, although the amount of vegetation cover means that bare soil is at a premium, and is restricted to relatively insignificant areas of sheep/cattle poaching and/or molehills. Poached surfaces, though, tend to be hard when dry and poorly-drained when wet due to hoof-compaction. This further diminishes supply since soil crusts may inhibit or even prevent entrainment of grains (Pye, 1994), while as a crude estimate soil must be dry to 4% of water content (15% of pore space) before entrainment can begin (Livingstone and Warren, 1996). Besides, poaching is confined to the sheltered leeward side of the larger erratics, which is normally an environment of deposition rather than of deflation. Ground disturbed by moles is a more likely source of grains since molehills occur in open situations and are composed of loose soil, the surface layers of which readily dry out in sunny/windy weather. Yet molehills are few in number and restricted in locality, and more to the point, perhaps, is the fact that the soil does not readily break down into individual components when dry. Instead it tends to form aggregates several millimetres across, presumably due to clay particles adhering to each other. Sand grains often form part of the aggregates, but as it is assumed that the latter are too heavy to be transported by the wind it follows that such grains will remain *in situ* rather than become available for sandblasting.

Some grains from whatever source will inevitably become wind-borne if conditions are suitable, and they may then move in three distinct ways, which, in increasing order of wind velocity, are creep, saltation and suspension (Livingstone and Warren, 1996). The swathe of plants and other obstacles at Norber clearly rule out the prospect of creep and saltation occurring (at least for more than the fetch of a molehill). It would also appear unlikely that sand grains could travel in suspension, since Bresollier and Thomas (1977) found that no movement of arenaceous grains was occurring (on dunes in France) in an environment with similar constraints, apart from a surplus of particles, to those at Norber (Table 7.2). The height of pedestal rocks at Norber is greater than that of maximum aeolian abrasion, which is between 0.1 and 0.4m above ground level (Cooke *et al.*, 1993), thus the absence of wind polishing confirms that grain transport is not taking place. Consequently, the findings that mean pedestal undercut of the ten pedestals is some 3cm greater to the windward than to the leeward cannot be attributed to aeolian erosion.

7.3.6: Conclusion

Wind is unable to effect abrasion at Norber due to the lack of a readily available supply of sand-sized particles, and because vegetation density and height restricts entrainment and prevents transport. It is also considered improbable that the mean annual wind speed, which registers only as a light breeze on the Beaufort Scale (Table 7.2), is of sufficient high velocity to cut pedestals by abrasion. Therefore, aeolian erosion has played no part in pedestal formation at Norber.

7.4: Fluvial erosion

Martel (1910) and Bryan (1925) have shown that pedestal rocks can form in river channels largely as a result of abrasion, although weathering processes may also play a part. The drainage at Norber is, however, entirely subterranean because the limestone is permeable and because the surface of the land lies above the water table. There is also no field evidence to suggest that post-Devensian-ablation watercourses have existed at Norber, while features indicative of river attack, such as arcuate indents, are not found on any of the pedestals. A short gully occurs between Robin Proctor's and Nappa Scars, but as it contains till it must pre-date ablation. In any case, the widespread distribution of the pedestal rocks militates against an origin in river channels. Moreover, fluvial abrasion is indicative of a relatively high energy erosional environment in which coarse material is rounded and fine material is removed. Clearly, neither attrition nor winnowing has occurred at Norber following erratic deposition, as the unconsolidated deposits found at the base of pedestals contain angular rather than rounded clasts while some 64% of particles consist of silt/clay (Fig. 7.1). Therefore, fluvial erosional processes have played no part in the formation of pedestal rocks at Norber.

7.5: Glacial erosion

Waltham (2005) has written that some pedestals at Norber may be bench edges (= plucked scars?) where erratics happened to be dropped on them and Goldie (2005) has illustrated likewise. It is thought that erratics N1, N3, N19, N25 and N26 are examples of clasts deposited on bench edges. This is because laterally tracing the downslope sidewalls of the pedestals reveals that they were once part of more extensive scars that have been separated into remnants by the lowering of sections of rockhead. Consequently, it follows that the downslope sidewall is a pre-erratic-deposition scar that has been protected by the erratic whereas the lateral and upslope sidewalls are features that have formed due to post-deposition erosion of rockhead. 'Bench edge' pedestal sidewalls tend to have a greater downslope than an upslope height (with N26 the former is 50cm and the latter 20cm, for example), so it is feasible that 'bench edge' pedestals and Sweeting's (1966) 'soil creep' pedestals (Section 7.10) are one and the same.

7.6: Karstic erosion (sub-regolith)

7.6.1: Carbonate dissolution processes

It is acknowledged (e.g. Monroe, 1966; Jakucs, 1977; Trudgill, 1985) that limestone (or rather its main constituent calcite (calcium carbonate)) is soluble in water that contains dissolved acids, the most important of which is carbonic acid from dissolved carbon dioxide. An important source of carbonic acid is rainfall that has absorbed carbon dioxide from the atmosphere, but a more significant supply is soil water that has absorbed carbon dioxide from plant root respiration (e.g. Adams and Swinnerton, 1937 (cited in Ingle Smith, 1965); Zámbó, 1992). In addition, bacterial decay of organic matter also produces acids that can effect dissolution (e.g. Hughes, 1886; Jennings, 1985), while Goldie (2005: 439) has written (with reference to Norber) that increased acidification from sheep urine and faeces "…may enhance solution".

7.6.2: Pre-experimentation survey

The first account of dissolution re pedestal formation at Norber is that of Hughes (1886) who observed that cap-rocks intercepted rainfall thereby preserving the original surface of the limestone under them. In addition Hughes (1886) reasoned that the surrounding surface was reduced in height chiefly by the action of acidulated water held in the soil and vegetation since they covered the limestone up to the base of the pedestals. This view is supported by Kendall and Wroot (1924), Dunham *et al.* (1953), Sweeting (1966) and Bell (1996), for instance, and to some extent by Goldie (2005), who wrote that solution from surrounding soil and vegetation is a possibility. Not everyone is of the same opinion, though, as Raistrick and Illingworth (1965), Wood (1985) and Goudie and Gardner (1992), for example, envisage lowering of the inter-cap-rock surface by rainfall i.e. in a subaerial rather than in a sub-regolith environment. There is no doubting that dissolution is occurring at Norber as Pentecost (1992) measured a calcite saturation ratio of 0.5-2 in the spring-water at Norber Syke head, which according to Carter and Dwerryhouse (1904) drains the site (plus much of Long Scar). Also, tufa is being deposited at the point of spring issue. Nonetheless, although it is plain that pedestal formation is largely attributed to the lowering of the inter-cap-rock surface in a karstic environment, no experimentation of any kind has been undertaken to endorse this assertion. Consequently, it was considered necessary before trialling commenced to visually survey the ground at Norber in order to reveal the proportion of vegetation-covered regolith to bare rock. The outcome revealed that bare rock is of limited extent and that it is contiguous with only part of one pedestal (N32), the remaining surface being comprised of vegetation-covered regolith. The survey also revealed that although regolith is rarely exposed, mole hill, poaching and auguring evidence show that it principally comprises brown earths at the surface with weathered till below, although 'soils' comprising little more than turf lying directly on rockhead also occur. Brown earths are regarded as being moderately to weakly acidic, and Whittow (1984), for example, has written that they have a pH from 5 to 7. Therefore, as brown earths abut all but part of one pedestal it follows that the potential exists at Norber for the dissolution of calcite in acid soil water to take place at the regolith-limestone interface.

7.6.3: Measuring dissolution at the regolith-limestone interface

A number of methods can be used to measure dissolution at the regolith-limestone interface (Trudgill, 1983b). Of these the emplacement of pre-weighed limestone tablets at the interface measures both the potential of soil water to dissolve limestone and the potential rate of surface retreat, the latter being particularly relevant to Chapter 14. The key principle is that pre-weighed tablets are buried (usually for at least a year) at the interface in order to expose them to the dissolution processes operating there. After retrieval any subsequent weight loss encountered is attributed to dissolution, which can be used to determine the potential loss of *in situ* rock thickness (Trudgill, 1975) as follows: $(w/d)/a$

(Where w=weight loss (g), d=specific density (2.64) of Cove Limestone (g/cm^3) and a=tablet surface area (cm^2))

7.6.4: Aim and objectives

The aim of the work undertaken in Section 7.6 is to establish if sub-regolith dissolution of the inter-pedestal limestone surface is occurring, and the objectives are to measure limestone tablet weight loss and regolith acidity/alkalinity, and to record morphological features produced by sub-regolith dissolution.

7.6.5: Method

It was planned to bury sixty tablets beneath the regolith at Norber, thirty at rockhead at separate inter-pedestal locations and thirty against individual pedestal sidewalls (with the c-axis of each tablet placed normal to the interface) for the duration of the 2004-2005 water year. A trial dig revealed, however, that emplacing tablets at rockhead was not feasible because:

1. Excavation proved time-consuming due to the abundance and often large size of clasts present (as seen in Plate 1.1, for example), which meant that the deadline for tablet emplacement would not nearly have been met

2. Digging around large clasts led to ever-widening excavations that were destructive of pasture

3. Attempts to reach rockhead became ever-more invasive of the regolith, and Goudie (1990) has pointed out that disturbance of pore size and ped arrangement may influence results

4. Fears for the well-being of my fifty-eight year-old back

As a result, plans to bury tablets at rockhead were abandoned. In contrast, the trial run showed that the burial of tablets against sidewalls was feasible, as emplacement merely involved pulling back the turf/soil that abutted the sidewalls and lowering the tablets to below root level (i.e. beneath the main zone of soil carbon dioxide production). Accordingly, a lump of limestone was removed from the Cove Limestone at Norber and twelve cores 1.75cm in diameter were drilled from it with a combined length of about 80cm (Plate 5.1). The cores were cut into sixty tablets that were prepared according to procedure outlined in Trudgill (1975). Prior to burial, all tablets were tied into wide-mesh nylon bags and labelled (Plate 7.1). Post-burial preparation of the tablets was also that of Trudgill (1975). Thirty tablets were then emplaced adjacent to pedestal sidewalls at Norber; thirty were also buried in woods on Oxenber (Section 12.6.4). Refer to Appendix 4.1 for a full account of the procedures used re the tablet survey.

The easiest and most reliable method of determining soil pH is to measure the soil hydrogen ion concentration of samples in the laboratory, and this procedure was carried out using a Jenway 3010 pH meter to two decimal places. The tenet behind measuring soil pH is that where limestone is surrounded by acid soils, an increase in alkalinity (or pH grade) at the soil/regolith-limestone interface is attributed to dissolution. Thirty-nine soil samples were collected over two days as follows:

1. Thirteen using a trowel from adjacent to the thirteen tablets that remained *in situ* at the end of the 2004-2005 water year upon their retrieval

2. Thirteen using an auger from immediately below root level and thirteen from maximum penetration depth 1m to the west of the thirteen tablets/pedestal sidewalls. This meant that samples were not collected in a caprock rain shadow and that calcite contamination from pedestal sidewalls by soil drainage would be unlikely as the ground generally slopes to the east

Pentecost (1992) has written that samples for pH analysis should not be collected until after 5 days following a period of rainfall. As far as is known, no rain fell at Norber during the five days prior to the first day of tablet retrieval or during the intervening night prior to the second day. Apart from burying tablets and collecting soil samples, consideration was given to landforms that are indicative of dissolution at the soil/regolith-limestone interface, and a record was made of them. Refer to Appendix 4.2 for a full account of the procedures used re the pH survey.

7.6.6: Results

Table 7.3 shows that only thirteen tablets still remained emplaced against the sidewalls of pedestals at the end of the 2004-2005 water year, and that eleven were missing, five were not *in situ* and one was in two fragments. Refer to Appendix 3T, Tables 3T.1 and 3T.2 for full tablet results. The thirteen retrieved tablets all suffered weight loss, and the mean equivalent thickness loss was 0.004mm (range 0.0001-0.019mm) for the year. This extrapolates into a mean depth equivalent of 4cm over the past 10000 years (for an explanation why sub-regolith dissolution may have occurred only over this time-span, refer to Section 11.2.1). The mean pH of soil samples from immediately below the root zone is 5.9 (range pH 5.1-6.6) and at maximum augur depth is 6.8 (range 4.7-7.9) 1m to the west of pedestals (Table 7.4), and is 7.4 (range 6.5-8.1) adjacent to tablets i.e. at pedestal sidewalls (Table 7.5). Refer to Appendix 3pH, Tables 3pH.1 and 3pH.2 for full results. Four sub-superficial dissolution features were encountered, and they are:

1. Open joints partly or entirely infilled with regolith exposed by 'rambler erosion' at rockhead (Plate 7.2)

2. Relatively small pipe-like solution hollows up to about 30cm in depth (including vegetation/regolith) adjacent to pedestals (Plate 7.3) and in areas of pavement (Plate 7.4)

3. Sub-superficial undercuts in pedestal sidewalls (Plate 7.3), limestone residuals and scar faces

4. Rundkarren on exposed bedrock surfaces (Plate 7.4)

In addition, features that were thought to be rundkarren were noted under thin turf/soil.

7.6.7: Limitations

Trudgill (1975) has written that it is important for all tablets to have the same surface area so that results from each tablet are comparable and that at least thirty tablets ought to be employed at an experimental site for standardisation purposes. Neither constraint was met. Thus, although all tablets were of similar diameter they were of dissimilar thickness, which according to the cutters (Kirkstall Laboratories) was caused by "technical difficulties with the rock". In addition, seventeen tablets could not be included in the results, largely because they were lost, the majority presumably because of 'rodent vandalism'. Nonetheless, as the main objective of burying the tablets was to reveal only the dissolution potential at the regolith-pedestal sidewall interface this was not considered to be an undue hindrance. A far graver drawback was not being able to discern whether maximum augur penetration reached rockhead or an intervening clast, but short of hiring a mini JCB to dig sample pits this deficiency appears insoluble. In addition, the 'dirty' nature of rockhead under shallow turf/soil and in areas of poaching, which is the removal of vegetation/soil by livestock-trampling, meant that it was difficult to determine for sure whether certain small-scale rounded features were or were not rundkarren.

7.6.8: Analysis

No consideration was given to the role of sheep urine and faeces in pedestal formation (re Goldie, 2005), as animal husbandry is a relatively recent phenomenon in terms of the post-ablation history of the site and animal head per hectare is low. Besides, sheep urine is normally alkaline (Rush and Groteleuschen, 1996) while Barrow (1975: 66) has described the pH of faeces (of Merinos in Australia) as being "…high". Hence sheep excreta may, in fact, buffer limestone from dissolution, although decay may release (humic?) compounds that will promote acidity. Undue consideration was not given to the role played by subaerial dissolution in pedestal formation either, as only one small bare area of rockhead is contiguous with only one pedestal, N32 (Plate 7.4).

The results, as illustrated in Fig. 7.2, show that water in the regolith has the potential to dissolve rockhead at Norber. Thus, the mean sub-root superficial pH at 1m distance from pedestals is 5.9 (i). In a study of limestone weathering and erosion at Malham, Trudgill (1985a) found a similar surface pH range to that at Norber. Trudgill (1985a) also found that pH increased to >7 above rockhead due to the dissolution by downward percolating water of calcite from intra-regolith Carboniferous limestone clasts and/or from rockhead, and that the pH above rockhead ranged from 7.6 to 8.1. At first sight, then, the mean maximum augur penetration depth pH of 6.8 (ii) would appear to denote that dissolution of rockhead is not occurring at Norber. What is not known for sure, though, is whether the auger actually reached rockhead or if penetration terminated against one of the many 'acid' clasts present in the regolith. The relatively low pH values near pedestals N3 (pH 5.89) and N 26 (pH 4.66) probably indicate that the augur terminated above clasts composed of Silurian grit. In contrast, the relatively high values near pedestals N14 and N25 (pH 7.81 in both cases) probably indicate that it terminated against 'basic' Carboniferous limestone, but whether it did so at rockhead or at a supra-rockhead clast is unknown. Consequently, the vertical pH gradient at Norber shows only that dissolution of rockhead might be rather than actually is occurring. Rundkarren (iii) prove otherwise, though, all authors (e.g. Jennings, 1985; Trudgill, 1985) concurring that they form in a sub-soil environment. Thus, their presence under the regolith indicates that dissolution of rockhead is currently taking place, while their presence on exposed pavement surfaces indicates that sub-regolith dissolution has occurred in the relatively recent past (rundkarren are quite well-preserved in the vicinity of N32 (Plate 7.4)). Solution hollows (iv), which are especially well developed in the vicinity of N32 (Plate 7.4), and open joints (iv) (Plate 7.2) are likewise indicative of dissolution at rockhead. Some authors (especially Rose and Vincent (1985a) re Morecambe Bay grykes), though, have suggested that open joints may pre-date glaciation.

Nonetheless, Hughes (1886) and Jones (1965) have observed that joints protected beneath erratics at Norber are unopened whereas those away from such protection have been widened (an observation corroborated in the field with the odd exception), which indicates that joint-opening post-dates glaciation. The potential for soil water to dissolve limestone at the regolith-pedestal sidewall interface (at least below root level) is revealed by the weight loss of all thirteen tablets (vi). Moreover, the mean regolith pH horizontal gradient increase from 5.7 at 1m to the west of pedestals (i) to 7.4 abutting sidewalls (v) demonstrates that dissolution of sidewalls is occurring. This is confirmed by the presence of sub-regolith undercuts (vii) in pedestal sidewalls, as seen in Plate 7.2, which according to Jennings (1985) result from particularly active solution in the soil against projecting rock.

Any one or more of several factors can explain the range of soil pH values and tablet equivalent depth losses. These are differences in interception rates caused by cap-rock size/shape/overhang variables (Twidale, 1962), in regolith make-up (Bullock, 1971) and water pathways (Crowther, 1983), and in infiltration rates and acidity (Trudgill, 1985a). Crowther (1983), and Ford and Williams (1989) have indicated that solution tablet data must be interpreted cautiously when determining specific rates of surface lowering, while Trudgill (1983a) has warned that the validity of extrapolating through time is unknown. Nonetheless, Trudgill (1975) has written that tablets have been used effectively to compare the relative importance of limestone solution. As such, it is likely that post-ablation vertical dissolution rates are greater than lateral dissolution rates. This is because solution hollow depth, which ranges from 10 to 30cm from apex to base, is greater than the potential retreat of pedestal sidewalls as indicated by tablet depth equivalent, which has a mean of 4.0cm. This is not surprising since gravity and ped arrangement draw soil moisture downwards.

7.6.9: Conclusion

Sub-regolith pH gradients, tablet weight losses and karstic landforms together indicate that dissolution in a sub-regolith karstic erosion environment is occurring at Norber, while the presence of relatively fresh karstic landforms on exposed pavement indicates that it has occurred in the recent past. Therefore, as regolith covers (or lately covered) rockhead up to the base of all pedestals it follows that karstic erosion operating in a sub-regolith environment is (or was) causing both inter-cap-rock surface lowering and pedestal sidewall retreat.

7.7: Lacustrine erosion

Dunne and Feehan (2003) have advocated that certain types of mushroom rocks described in the Republic of Ireland show signs of erosion by wave action or dissolution suggestive of prolonged exposure to standing water in lake margins. A lake cannot have flooded Norber since there are no down-valley natural dams or constrictions behind which water could have been ponded, either in the immediate vicinity or in the Wenning or Lune valleys. Therefore, the pedestal rocks at Norber cannot have formed as a result of lacustrine processes of erosion.

7.8: Marine erosion

Twidale and Campbell (1992), and Dunne and Feehan (2003) have noted that mushroom-shaped rocks may develop along coasts that are undergoing marine erosion. There is no field evidence that Norber has been covered by the sea after erratic deposition given that typical marine deposits, such as rounded beach material admixed with marine bioclast remains, are totally absent. In fact, the Pennines were last covered by seas that withdrew in the Cretaceous about 65Ma ago (Anderton *et al.* 1979). Therefore, the possibility that marine processes of erosion have been involved in any aspect of the formation of the Norber pedestals can be discounted.

7.9: Poaching erosion

Poaching is the removal of vegeation and soil due to trampling of the ground by livestock, and at Norber it occurs to the lee of some of the larger pedestal rocks due to sheep (*Ovis aries*) and cattle (*Bos taurus*) using them for shelter. Poaching is considered to have a conflicting role re erosion since the wearing away of rockhead by trampling may cause an increase in surface lowering, whereas the removal of regolith may cause a decrease as bare rock is less susceptible to subaerial dissolution than sub-superficial dissolution (Trudgill, 1983a). Either way, poaching erosion is not thought to be significant in the greater scheme of things, as it comprises less than 1% of Norber.

7.10: Soil-creep

Sweeting observed (1966: 203) that many pedestals "…are raised above the surrounding limestone on the downslope side only. On the upslope side they are at the same level as the limestone, a fact which suggests soil-creep as a contributory agent in the development of the pedestals." Goudie (1990) has pointed out that creep can occur on almost any slope, and as the mean incline at Norber is approximately 4-6° it follows that this is sufficient for soil-creep to occur. Proof that it is taking place is revealed by the accumulation of regolith upslope of erratics/pedestals and the eastern boundary wall, the ground alongside the latter being as much as 17cm higher on the upslope than the downslope side. In fact, pedestals are just as likely to have greater upslope heights as downslope heights, as of twenty-one pedestals measured on level ground, ten had greater downslope height, nine had greater upslope height and two were of equal height (Table 7.6). The reason why the downslope height appears greater is because of a build-up of regolith behind the upslope height due to creep. This is exemplified by N5 and N9, which respectively appear to have pedestals with upslope and downslope heights of 0 and 16cm, and of 0 and 34cm. If their heights are measured through the surrounding regolith (refer to Fig. 9.1 for the method used) then respective upslope and downslope heights are instead 33 and 35cm (N5), and 47 and 43cm (N9). In contrast, glacial-scar pedestals (Section 7.5) do have greater downslope than upslope heights. Thus N25 and N26, for example, have upslope and downslope heights of 35 and 42cm (N25), and 20 and 50cm (N26).

It is challenging to understand why Sweeting (1966) used the term 'soil-creep' in connection with pedestal development given that the pedestals are composed of *in situ* well-indurated limestone with generally tight discontinuities rather than loose, superficial material. Sweeting (1966) did not expand on this observation, yet it would seem it was implied that loss of rock from the lee of pedestal sidewalls must have been taking place in order to explain their greater down-slope development. Clowes and Comfort (1982) have contended that creep can 'pluck' fragments from bedrock, but as down-slope pedestal sidewalls are to the lee of creep movement it ensues that deposition is more likely to take place here than erosion. The formation of shoals downstream of bridge abutments, crag and tail and seif dunes support this supposition while the plucking of roches moutonnées counters it. Clowes and Comfort (1982) also note that well-bedded or cleaved rocks are most susceptible to plucking by creep, but although pedestal bedding may be thin, discontinuity spacing is moderately wide to wide (Appendix 5N). This means the limestone would appear to be too massive to undergo plucking by creep. The term 'soil-creep' is often interchanged synonymously with 'creep' under whose aegis 'rock-creep' is also included. Rock creep can occur within the body of a rock, although it is normally restricted to weak rocks such as evaporites or shale (e.g. Anderson and Richards, 1987; Goudie, 1990) and not Carboniferous limestones. In fact, the presence of limestone scars at Norber (and elsewhere) is testament to its strength. Rock masses can also undergo creep along discontinuities if their angle of friction, which is 35°-45° for hard limestone (Hoek and Bray, 1981; Waltham, 1997), is not exceeded by their angle of rest. This tenet is subject to certain constraints, though, such as the degree of openness of the discontinuities and their amount of fill. Pedestal bedding planes are more-or-less horizontal, and are normally tight and devoid of fill, which means that rock creep is not viable. It is quite feasible, though, for blocks to topple or slide along joints that dip more steeply than the angle of friction, but such failures belong to the realm of rapid mass-movement rather than of creep. If soil-creep were a contributory agent in the development of the pedestals then there should be some form of physical evidence, such as a trail or a concentration of loose limestone clasts below pedestals on their downslope side only, to indicate this. Yet such features are not evident downslope of N1, N3, or N26, which have or appear to have greater downslope than upslope heights. Limestone clasts are found below the downslope sidewall of N25, however, but as they are admixed with clasts of Silurian rock it is more likely that they are part of the original till. Therefore, it is concluded that soil-creep (and rock-creep) is not a contributory agent in the development of the pedestals at Norber.

7.11: Step retreat

7.11.1: Introduction

Goldie (2005) has proposed that the pedestals at Norber are the remains of steps that have been eroded back by mechanical processes. According to Goldie (2005) the prerequisite for step retreat is the placing of erratics on a stepped landscape (Fig. 7.3) composed of 'weak' limestone (i.e. rock that presumably has relatively closely-spaced discontinuities). Although much of rockhead at Norber is masked by regolith, there is no doubting that the erratics were deposited on a stepped landscape because stepping is plainly visible to the north along the strike of Long Scar where regolith is thinner. The expression 'weak' is subjective, but as the limestone is mainly thinly to medium bedded with moderately wide to wide joints (Appendix 5N) its usage is just considered acceptable. Moreover, Wager (1931) has pointed out that joint density at Norber is relatively high, probably due to the site's close proximity to the Craven Fault Zone. Goldie (2005) does not expand on the actual processes involved in step retreat other than citing (p. 438-439) "…frost action, and gravity fall…[and]…human and animal action" under the heading 'Possible processes at work since [erratic] deposition'.

7.11.2: Frost action

Frost action is normally associated with high altitude (alpine) and/or high latitude (periglacial) (e.g. Clowes and Comfort, 1982; Easterbrook, 1993) and/or continental climates (Whittow, 1984), a far cry from Norber which is situated just 300m above OD in middle latitudes with a temperate climate. Thorn (1979), and Fahey and Lefebure (1988) have highlighted that there is a paucity of field information pertaining to areas experiencing frost activity with regards to rock-face retreat, and none is available from Britain. Fahey and Lefebure (1988) have, however, monitored the effects of frost on a section of a dolomite rock face (the Niagara Escarpment, Canada) in the winter of 1983-1984. Although their findings cannot be contrasted directly with Norber, the fact that the rocks at the two sites are limestones that have similar discontinuity spacing and that precipitation is comparable (Table 7.7) means that some idea of the incidence and intensity of frost damage at Norber can be construed. In their survey, Fahey and Lefebure (1988) estimated that the monitored section of escarpment retreated by 0.1mm by ice wedging and the removal of broken material by gravity. Fahey and Lefebure (1988) discovered that Lautridou events (i.e. 9-10 hours of -5°C) might well constitute an effective frost cycle in bedrock disintegration. They added the rider (p. 303), however, that the timing of maximum release corresponds with "…high intensity, long duration cycles, i.e. those in which the freezing phase lasts three to five days with freezing amplitudes of -14°C in the air. Shorter (one to two day) events were less productive." A total of eight Lautrido events may have been responsible for rock damage in the winter of 1983-1984, which was close to the norm weather-wise. Such temperature extremes are wholly atypical of long-term regimes at Malham (Table 7.8). In fact, they are hardly applicable even to the winter of 1962-1963, which was the coldest in England since 1740 (Met Office, undated), as can readily be seen in Table 7.9. The lowest air temperature registered at Malham during the 1962-1963 winter was -9.4°C, and although the number of Lautridou events amounted to nine (Table 7.10), none is judged to be effective frost shattering cycles when the rider is adhered to. Thus, although six Lautrido Events lasted more than two days the mean minimum temperature never dropped below –7.5°C. All things being equal, it follows that rock retreat at Norber during the 1962-1963 winter was very likely to have been less than the 0.1mm that occurred at the Niagara Escarpment in the winter of 1983-1984, and that during an average winter it will be negligible. Furthermore, as the climate in Britain throughout the Flandrian has been similar to that of the recent past (e.g. Briffa and Atkinson, 1997) it follows that frost action has been no more rife for the past 10000 years than of late. This generalisation applies even to the Little Ice Age, which was the coolest period of the last 2000 years (Barber *et al.*, 1999), since the latter cite a mean air-temperature warming in Britain of 0.2 ± 0.06°C per century during the last 350 years. This means that Britain was only slightly colder in the Little Ice Age than at present. It is also likely that frost action was no more rife in the Windermere Interstadial (13000-11000BP), as it was only marginally colder than today (mean annual temperature range of about 17.5°C (17.5 to 0°C) (Briffa and Atkinson, 1997)).

It would be unwise to put an exact figure on the rate of step retreat at Norber based on Fahey and Lefebure's (1988) estimation of 0.1mm at Niagara Escarpment over one winter. Nevertheless, climatic evidence indicates that the incidence and intensity of frost action at Norber has only equalled or exceeded that at the Niagara Escarpment for ca.2500 of the past ca.14500 years at most, i.e. during the Late-glacial (ca.14500-13000BP) and the Loch Lomond Stadial (ca.11000-10000BP) (Section 10.2). Consequently, it would seem probable that no more than about 25cm of retreat due to frost action has occurred since the Devensian ice ablated. If so, and if step-retreat is a reality, a typical isolated erratic (e.g. C and D: Fig. 7.3) would have had to have been neatly deposited on a step-island of similar size to itself. This is because erratics now sit astride pedestals that are centrally positioned beneath them with mean undercuts of about 25cm (Table 7.1). There is no reason to think that ice could be so selective. It is, of course, possible that steps were more extensive than those proposed above and that retreat might have proceeded at a much greater rate than based on Fahey and Lefebure's (1988) estimation. Nonetheless, Goldie (2005) does not explain why retreat should proceed in such a manner as to sweep around the erratics (rather like a marine wave refracting around a small island perhaps?) so as to leave isolated residuals beneath them.

There is ample evidence of frost action in the area, however, since shattered erratics, small patches of scree and putative blockfield (shillow) are found at Norber, while well-developed screes occur in Crummackdale. An examination of pedestal sidewalls and scree-clast upper surfaces at Norber revealed that most are lichen-covered rather than 'fresh', which suggests that few clasts are being produced at present and belies Goldie's (2005) use (p. 437) of phrases in the present tense, such as "…suffers mechanical weathering, including frost action". Furthermore, Plate 4.1 shows that the screes are partly covered in vegetation (mostly grass and herbs but some trees), which is suggestive of senility and stability. The only known examination of scree in the locale is at Victoria Cave near Settle, the clasts of which are composed of Carboniferous limestone, as indeed are those at Norber/Crummackdale. Tiddeman (1876) and Jackson (1938) (cited in Murphy and Lord, 2003) assign the greater part (5.7 of 7.5m) of this scree to a Late-glacial age, which lasted from ca.14500-13000BP (Table 10.1), when the mean annual temperature range was approximately 37°C (7 to -30°C) (Briffa and Atkinson, 1997). Murphy and Lord (2003) are more specific, and narrow down formation to the Killard Point Stadial (of the north Irish Sea Basin), which according to McCabe *et al.* (1998) lasted from 14700 to 13700BP. Screes found elsewhere in northern England are also considered to date largely from this period. Thus Vincent (1985) has noted that after Morecambe Bay became ice-free in ca.14500BP it is thought that extensive talus slopes formed on the flanks of the Carboniferous limestone hills of Arnside Knott and Whitbarrow. The blocky scree slopes found in the summit area of Cross Fell, which Manley (1936: 103) cites as being the most "...chilly part of England", are likewise thought to be relict and associated with the severe climatic conditions of the Late-glacial period (Lowe and Walker, 1997). In addition, the Wasdale screes have been described in Huddart and Glasser (2002: 347) as being

"…probably almost relict landforms that are not in equilibrium with today's processes." Consequently, it is argued that the bulk of both local and regional screes are not newly formed but date from frost action prior to the Windermere Interstadial. This is almost certainly confirmed by the lack of scree of a similar stature to that at Arnside Knott and Whitbarrow on the Burren, which was glaciated during the Killard Point Stadial, and which is of comparable relief and altitude to the Morecambe Bay sites. It is likely that freeze-thaw activity might also have been widespread in the Loch Lomond Stadial when the mean annual temperature range was about 25°C (7 to -18°C) (Dawson, 1992), so it is probable that scree development might have been augmented from ca.11000-10000BP. Nevertheless, it stands to reason that if frost action has been negligible at the above quoted sites for the past 10000 years that step retreat as visualized by Goldie (2005) at Norber is not feasible.

7.11.3: Gravity fall

Without erosion, weathered material (such as the products of freeze-thaw) remains *in situ* (e.g. Simms, 2004). As Goldie (2005) mentions only gravity fall in the context of erosion at Norber any clasts liberated by frost action should be found in close proximity to the pedestals they were ostensibly derived from. Consequently, if step retreat due to frost action is a reality high pedestals (A and B: Fig. 7.3) should have a fan abutting their downslope sidewall. Moreover, isolated pedestals (C and D: Fig. 7.3) should be sheathed in shillow up to the height of their pedestal upper surfaces and cliff-top pedestals (E: Fig. 7.3) should have a scree deposit below them. This is very clearly not the case since the upper parts of sidewalls on horizontal ground (e.g. N5, N6 and N12) are surrounded by empty space and the lower parts by vegetation-covered regolith, in some cases for many tens of metres in all directions. In fact, the only area of *in situ* bare rock that abuts a pedestal (N32) has scarcely a clast on it, as can be seen in Plate 7.3. Moreover, although some bench-edge pedestals (e.g. N24 and N25) do have clasts below them, others have few (e.g. N3 and N26) and some none (e.g. N1 and N18). Goldie (2005) does not address the absence of frost-riven clasts re step retreat.

7.11.4: Human and animal action

Apart from frost action, Goldie (2005) also cites anthropogenic/animal action under the aegis of mechanical erosion, citing the artificial removal of limestone to build walls and sheep helping to knock limestone pieces off pedestals. There is no doubting that man has removed limestone from the ground at Norber since dry-stone walls surround the site (indeed, walls have been built over N18 and N31) and the odd cairn dots it. It is not envisaged that limestone has been robbed from the sidewalls of many pedestals, though, as all are surrounded by vegetation-covered regolith (excepting part of N32). Besides, Raistrick (1970) has noted that material used in wall construction is normally gathered from close-by, and most pedestals (including N32) are not located near walls or cairns. The greasy patina/strands of wool coating the lower sides of the larger boulders confirm that sheep use them for shelter, but grease/wool is rarely found on the pedestals themselves, partly because prone-sheep height is normally greater than pedestal height and partly because the pedestals are overhung. Consequently, erosion of pedestals by sheep is considered to be negligible at best, especially as grazing is a relatively recent phenomenon in terms of post-erratic-deposition history.

7.11.5: Further aspects

Goldie (2005) does not specify whether the steps on which the erratics were deposited were till-free or till-covered, though no till is present in Fig. 7.3. If the former, it is not explained why regolith now mantles rockhead up to the base of pedestals at present. Moreover, if the latter it is not explained how step retreat proceeded under such a mantle, bearing in mind that a regolith cover will insulate the rock beneath it from frost action in the present clime. Furthermore, from ca.10000 to 3000BP Norber was covered by the Wildwood (Section 10.2), which according to Pigott and Pigott (1959) largely consisted (in Craven) of an oak/elm climax. It goes without saying that temperate forest and frost shattering of bedrock make for incompatible bedfellows. The presence of many intact caprocks also militates against on-going frost action, especially as N26 and N31, which are composed of Carboniferous limestones, appear to have been weathered by subaerial dissolution only, as can be seen in Plate 7.5. As a final point, Fahey and Lefebure (1988) discovered that maximum release of rock following freezing closely corresponded with maximum groundwater seepage, yet there is no evidence of such seepage at Norber, since runnels emanating from discontinuities simply do not exist. In fact, the very openness of discontinuities in scar faces, the lack of surface water, and the relative short lag-time (observed, not measured) between rainfall and spring-flow at Norber Syke all intimate that insufficient moisture may be present in the body of the limestone to effect frost damage.

7.11.6: Conclusion

There is no climatic or field evidence to show that frost action has been intense or rife enough to cause other than very limited retreat of the limestone steps at Norber. This is above-all confirmed by the almost complete absence of clasts abutting pedestal sidewalls despite the fact that no natural erosion process other than gravity fall is cited by Goldie

(2005) for their removal. Nor is there any proof that anthropogenic/animal erosion has caused retreat of steps. Therefore, pedestal formation due to step retreat via mechanical processes as envisaged by Goldie (2005) is not considered viable.

7.12: Overall conclusion

Erosion regimes operating in marine and lacustrine environments have played no part in the lowering of the inter-pedestal limestone surface at Norber, as there is no evidence of flooding by water following the demise of Devensian ice. Nor have fluvial processes played a part, as drainage is entirely subterranean, while aeolian erosion is discounted because the amount of vegetation cover is too great to allow movement of the few particles that are capable of effecting erosion. Although it can be stated with confidence that none of these regimes has contributed whatsoever to pedestal formation at Norber, it would be imprudent to suggest that neither soil creep nor step retreat has done likewise, since either process could have released clasts that abut pedestal sidewalls. Nevertheless, few clasts can have been liberated by either process because the general lie and spacing of discontinuities as well as the inherent strength of the limestone is antipathetic to creep, and because mechanical processes have barely operated at Norber for ca.10000 of the past ca.14500 years. The role played by poaching erosion is likewise negligible due to its limited aerial extent and to its lack of longevity, but glacial erosion is of greater importance since it has directly led to the formation of some downslope sidewalls. In contrast to the above, there is overwhelming field and experimental evidence of both potential and actual dissolution of the inter-pedestal limestone bed-rock surface and of pedestal sidewalls to show that sub-regolith karstic erosion is widespread. Therefore, it is proposed that of the erosion environments outlined in Section 6.6, sub-regolith karstic erosion has played by far the greatest role in pedestal formation at Norber, abetted to a very limited degree by soil creep, step retreat and poaching, and with a pre-ablation input from glaciation.

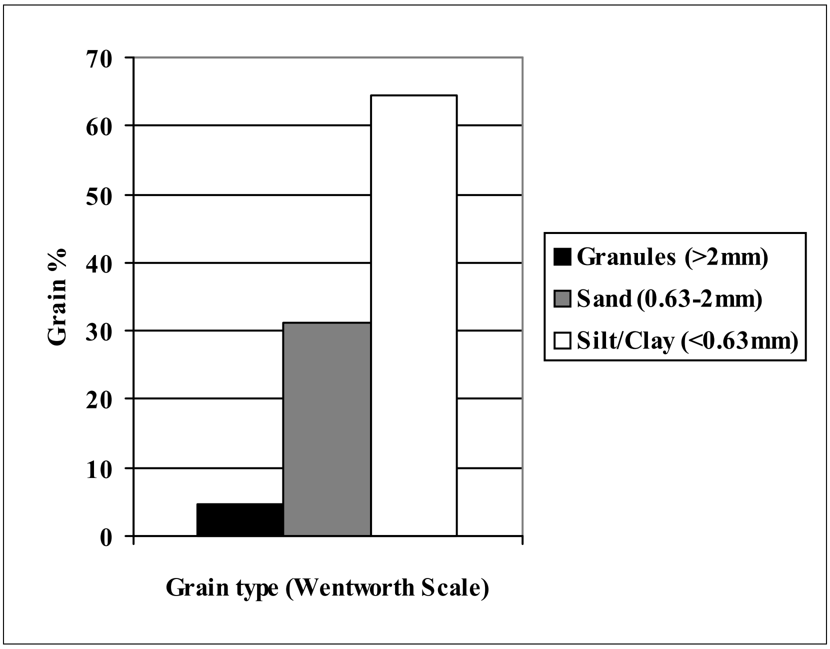
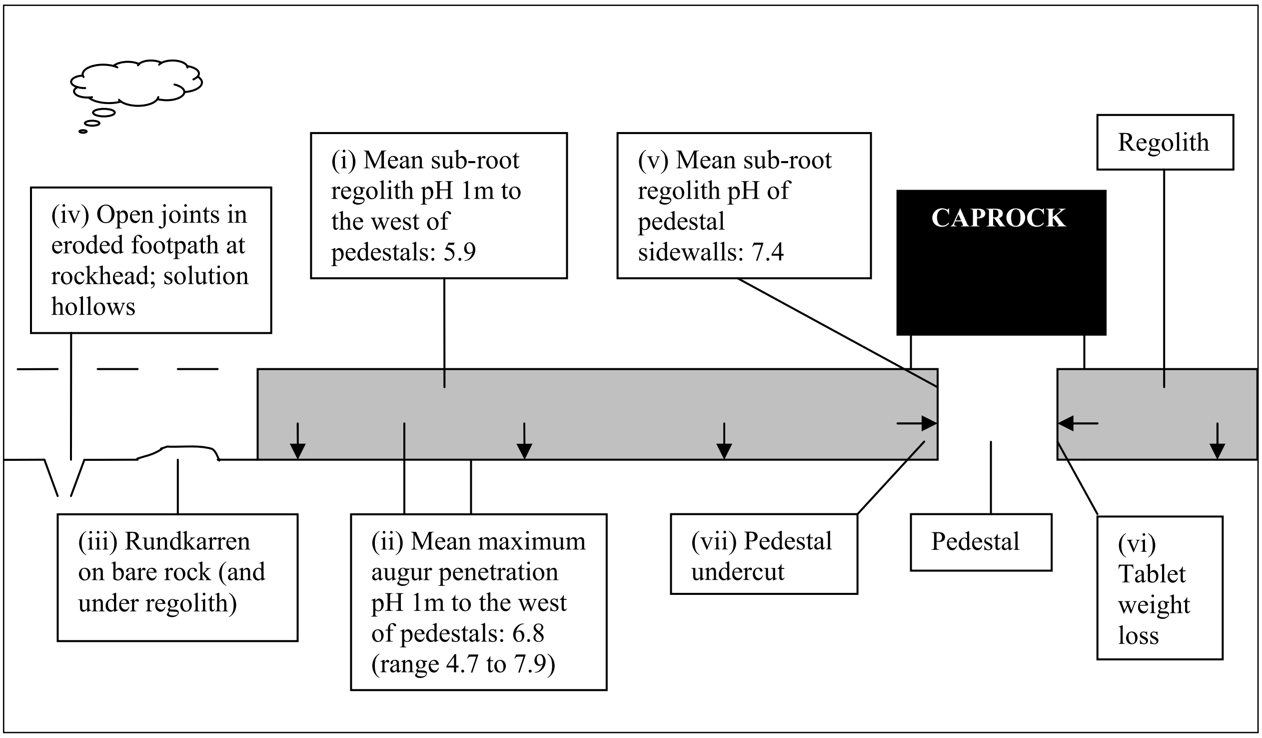
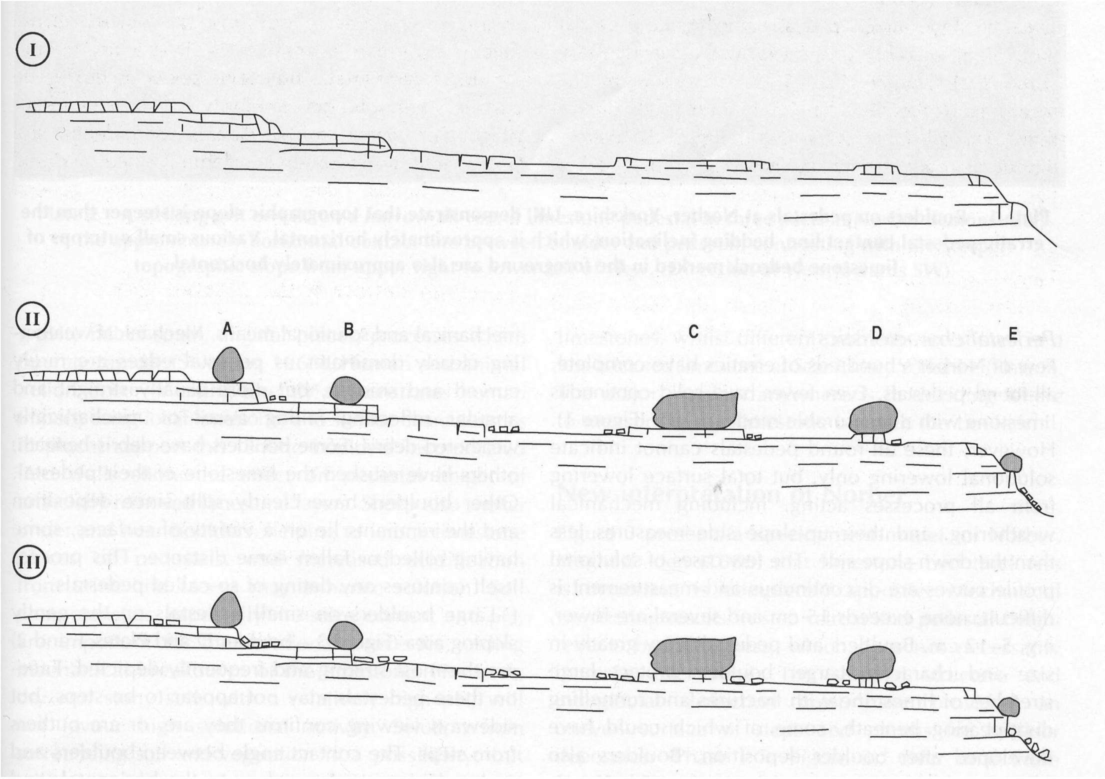


Fig.** Error! No text of specified style in document.**.1: Mean surface soil grain types (from five molehills) at Norber



KEY: → Lateral dissolution of pedestal sidewall ↓ Vertical dissolution of rockhead

Fig.** Error! No text of specified style in document.**.2: Soil pH, morphological features and tablet weight loss as evidence of dissolution at sub-regolith-limestone interfaces at Norber



KEY:
White = limestone. Shaded = Silurian grit erratics.
I = pre-deposition boulder-free stepped surface.
I I = early stage after boulder deposition on that stepped surface.
I I I = later stage similar to the present, with steps and pedestals having eroded back since I I.
From left to right boulders A and B demonstrate high pedestals involving two limestone layers; the third, large, erratic, C, is on a wide pedestal reflecting boulder size; the fourth boulder, D, is a classic isolated example on a narrow pedestal; the fifth erratic, E, on cliffs low down Norber Brow emphasizes the slope effect.

Fig.** Error! No text of specified style in document.**.3: Pedestal formation through step retreat at Norber (Goldie 2005, Fig. 3)

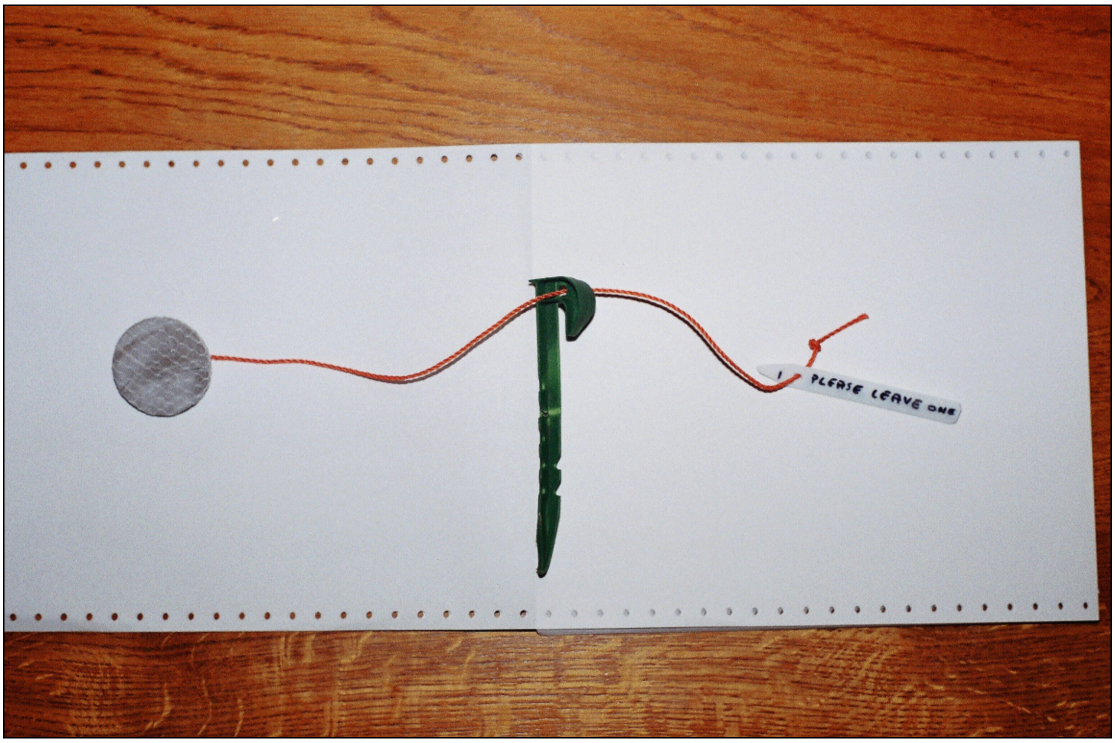


Plate** Error! No text of specified style in document.**.1: A limestone tablet prior to its emplacement

The tablet is encased in fine, open-mesh nylon to allow easy ingress of regolith-water, while the peg facilitates secure fixing and the plastic label straightforward re-locating.

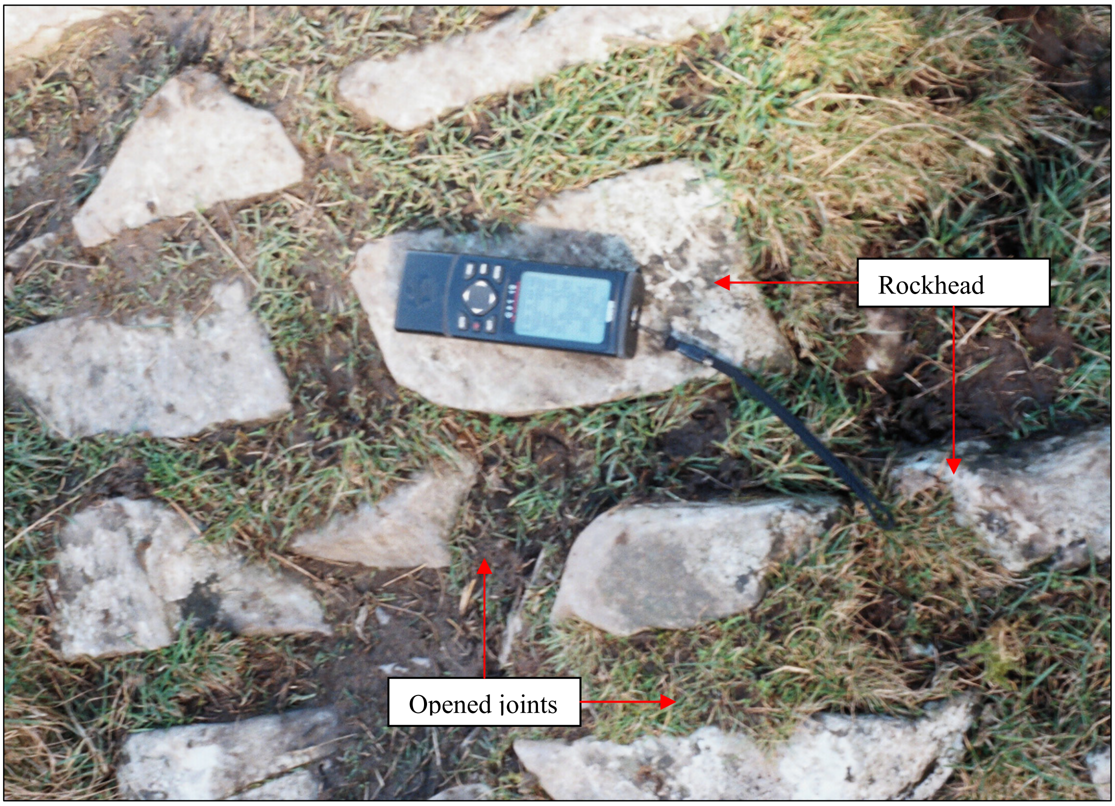


Plate** Error! No text of specified style in document.**.2: Opened joints at SD 76617 69755 at Norber

The infilled inter-limestone gaps are joints that have been opened by dissolution at the regolith/rock-head interface; they have been revealed by 'rambler erosion'. It is possible that the opened joints may pre-date erratic deposition, but as joints in pedestal crowns tend to close beneath erratics at Norber (this is especially apparent beneath N9) it is assumed that joint-opening post-dates erratic deposition. The blocks are in situ. For purposes of scale, the GPS console is approximately 15x5cm.

Plate *Error! No text of specified style in document.**.3: Part of the eastern sidewall of N11 at Norber***

Evidence of sub-vegetation-covered regolith lateral and vertical dissolution is respectively revealed by horizontal undercuts (hidden from view), which are 2-3cm deep (red arrows), and by perpendicular pipe-shaped solution hollows (yellow lines), which are up to 30cm deep.

Plate** Error! No text of specified style in document.**.4: In situ bare rock in the environs of N32 at Norber

The occurrence of rundkarren (black arrows) shows that the present bare limestone surface was once covered in regolith, the rundkarren and small-scale solution hollows (red arrow) providing ample evidence of sub-vegetation-covered regolith dissolution (Section 7.6). The regolith-less limestone surface is the only area of in situ bare rock that abuts a pedestal at Norber. The difficulties of determining pedestal height are clearly revealed by the two yellow arrows, as although sidewall height is about 21cm at A, as revealed by the tape plus extension, it almost doubles to about 40cm immediately to the left at B (Section 9.4).

Plate *Error! No text of specified style in document.***.5: Pedestal rock N31 at Norber***

The caprock of N31 is one of only two Norber erratics (sensu lato) that are composed of Carboniferous limestones (the other is N26). The generally rounded corners of the upper portions of the caprock militate against on-going frost action, as envisaged by Goldie (2005), since their shape is more indicative of subaerial dissolution. Note that the pedestal, which may be unique to Norber in that it is composed of limestone clasts, is largely covered by vegetation.

Pedestal rock	**Windward distance (cm)**	**Leeward distance (cm)**
N5	+64	+43
N11	+17	+52
N12	-17	+21
N14	+32	+23
N15	+23	+24
N17	0	+41
N19	+23	+9
N21	+51	+25
N25	+6	0
N27	+61	-7
Mean	+26	+23

Table** Error! No text of specified style in document.**.1: Pedestal undercut (+ve) and extension (-ve) in relation to the windward (south-west) and leeward (north-east) quadrants at Norber

Location	Sand availability	Sand size (Wentworth Scale)	Vegetation cover (%)	Mean vegetation height (cms)	Mean wind Speed (m/sec)
French dunes	Plentiful	Fine to medium	100	20	3.04 (trialling)
Norber	Limited	Fine to coarse	>99	18.5	4.8-5.1 (annual)*

*In the western Pennines for 1961-1990 (Barrow *et al.*, 1993).

Table** Error! No text of specified style in document.**.2: Comparison of entrainment constraints for French Dunes (after Bresollier and Thomas, 1977) and for Norber

Caprock/ Tablet No.	**Depth equivalent (mm/yr)**	**Root zone pH**	**Max. auger depth pH**	**Adjacent to tablets pH**
N3	0.00096	6.6	5.9	7.7
N4	0.0014	5.8	7.9	6.5
N5	0.0027	5.8	7.0	7.2
N10	0.004	5.6	7.2	7.6
N12	0.006	6.3	6.4	7.4
N14	0.0019	6.1	7.8	7.6
N19	0.0001	5.9	7.2	7.2
N24	0.019	6.3	7.8	6.8
N25	0.007	6.0	7.2	7.1
N26	0.00033	5.9	4.7	8.0
N28	0.0072	5.3	6.0	7.0
N29	0.0006	5.1	6.8	7.9
N30	0.0014	5.8	6.6	8.1
Mean	0.004	5.9	6.8	7.4

Table** Error! No text of specified style in document.**.3: Tablet depth equivalent (of surface erosion rates) result, and pH values of regolith samples 1m to the west of pedestals and regolith samples from adjacent to limestone tablets at the regolith-pedestal sidewall interface at Norber

Pedestal number	**Upslope pedestal height (cm)**	**Downslope pedestal height (cm)**
N2[1]	33	35
N5	35	34
N6	50	37
N7	50	52
N9	47	43
N10	53	69
N12	48	62
N13	43	46
N14	65	58
N15	68	64
N16	40	40
N17	51	36
N18	62	62
N19	49	45
N20	39	61
N21	48	30
N23	20	36
N24[1]	29	79
N28	51	27
N29	52	53
N30	21	40

[1] Kilnsey Limestone. All others Cove Limestone.

Table** Error! No text of specified style in document.**.4: Pedestal height at Norber

Site features	**Norber-Malham, Yorkshire**	**Niagara Escarpment, Canada**[1]
Rock type	Carboniferous limestone	Dolomite (Mg-rich limestone)
Bedding	Thinly to medium bedded	Thinly bedded
Joints	Moderately wide to wide	Moderately wide
Precipitation (mm)	362.1 (snow depth unknown) (1962-63)	373.5 (excluding 399.2 snow) (1983-84)
Porosity	5-8% (Sweeting and Sweeting, 1970)	Porous

[1]Fahey and Lefebure (1988)

Table** Error! No text of specified style in document.**.5: Site features – Norber and Niagara Escarpment

Air temperatures (°C)	Malham, Yorkshire 1961-1990 [1]	Wiarton, Canada 1951-1980 [2]
December means	Max. 4.6, min. -0.1, range 4.7	-3.7
January means	Max. 3.6, min. -0.9, range 4.5	-7.1
February means	Max. 3.4, min. -1.1, range 4.5	-7.5
March means	Max. 5.7, min. 0.0, range 5.7	-2.8
Winter means	Max. 4.3, min. -0.5, range 4.8	-5.3

[1] Met Office [2] Fahey and Lefebure (1988)

Table** Error! No text of specified style in document.**.6: Mean winter air temperature range – Malham (Norber) and Wiarton (Niagara Escarpment)

Mean air temperature (°C)	**Malham, Yorkshire 1962-1963 [1]**	**Niagara Escarpment, Canada 1983-1984 [2]**
December	0.6	-6.3
January	-2.5	-9.8
February	-2.8	-2.2
March	3.2	-5.9

[1] Raw figures obtained from Malham Tarn Field Centre [2] Fahey and Lefebure (1988)

Table** Error! No text of specified style in document.*.*7: Mean winter air temperature – Malham and Niagara Escarpment***

Lautrido event dates[1]	**Duration (days)**	**Mean minimum temperature(°C)**
December 5	1	-6.1
December 23-26	4	-6.6
December 29	1	-7.0
January 12-15	4	-6.3
January 17-18	2	-6.4
January 21-25	5	-7.5
February 2-7	6	-7.0
February 17-20	4	-5.5
February 24-March 2	7	-7.3

[1] Raw figures obtained from Malham Tarn Field Centre

Table** Error! No text of specified style in document.**.8: Lautrido events in the winter of 1962-1963 at Malham

CHAPTER 8: PEDESTAL FORMATION AT NORBER – MODIFICATION ENVIRONMENTS

8.1: Introduction

It was concluded in Chapter 7 that erosion operating almost exclusively in a karstic sub-regolith environment is responsible for the lowering of the inter-pedestal Carboniferous limestone surface at Norber. Erosion leads to the exposure of virgin surfaces, however, and as such the possibility must be considered that pedestals may be subject to post-formation modification either in new erosion environments or in weathering environments. Consequently, attempts at clarifying pedestal formation at Norber continue, in Chapter 8, with investigations that are restricted solely to processes operating in a variety of pedestal-modification environments, either outlined in Section 6.5 or in Section 7.1. The environments are presented in alphabetical order, so as not to presume that one is more important than another is.

8.2: Biogenic weathering and erosion

Micro-organisms, such as bacteria and lichen, have long been known to effect the weathering of rocks (Danin *et al.*, 1982). For example, they are said to be partly responsible for damaging the surfaces of buildings by causing disintegration of the micro-crystals that cement the building stone together (Brimblecombe, cited in Arthur, 2004). Little research has been undertaken on the status of weathering by micro-organisms of Carboniferous limestone surfaces, however, and Gilbert (2000) has written that it must be regarded as a neglected habitat as far as lichens are concerned. Furthermore, some of the work that has been published is contradictory in opinion. Thus, Sweeting (1972) and Jennings (1985) have written that lichen may inhibit the effect of weathering and erosion of limestone, while Jones (1965) (on clint at Runscar Great Scar), and Ford and Williams (1989) have shown that smooth limestone surfaces become irregular and pitted under a cover of micro-organisms. It also appears that lichen growth may lead to both Carboniferous limestone surface accretion and to surface destruction. Hence Trudgill (1983b) has argued that calcium carbonate precipitation may occur on the surface of some lichens, the accretion also leading to an increase in surface hardness, while penetration may bring about surface disintegration by loosening crystals, thus increasing the surface area open to water contact after death. Viles (1987) has pointed out that it is difficult to monitor the progress of lichen weathering and that data did not indicate whether saxicolous lichens (i.e. those which grow upon rock substrates) had an overall erosive or protective effect on Carboniferous limestone surfaces (in the Mendips). Nevertheless, Moses and Smith (1993) have shown that the thallus of the lichen *Collema auriforma* can pluck Carboniferous limestone fragments that are 10-50μm along their long axis from the substrate surface of kamenitzas, and that upon drying out the resultant fragments may be removed by the wind. In addition, Danin (1983) concluded after measuring pitting on walls composed of massive limestone that cyanobacteria (i.e. blue-green algae) were responsible for weathering rates (in Israel) of 1mm in 200 years.

All pedestal surfaces at Norber are covered to a greater or lesser degree by micro-organisms. The life-form and species present, and their degree of cover appear to be related to a complex inter-association of environmental and physical factors. These include aspect, shading from nearby erratics, the extent of caprock overhang, pedestal sidewall height and upper surface area, and the tightness of pedestal upper and caprock basal surfaces. Nevertheless, a few broad patterns of micro-organism type and distribution appear to be discernible. Some pedestal crowns consist of a distal zone coated in crustose lichen (species unknown) and a proximal zone covered in thin films of green algae (cyanobacteria?), although where contact between caprock and pedestal is tight an innermost zone where micro-organisms appear to be absent may also occur. In contrast, pedestal sidewalls normally consist of a mosaic of crustose lichen (species also unknown) and bare rock, typically with a greater degree of cover to the lee than to the windward. The lichen on pedestal crowns and windward sidewalls appear to consist mostly of the same species since the majority of growths are pale grey in colour, but a greater number of species are found on windward sidewalls since a variety of colour-splashes occur here, including grey, apple-green, orange and sooty-brown.

There is no physical evidence to show that biogenic weathering of pedestal crowns is taking place at Norber as kamenitzas are absent while striae that were eroded in the Devensian prior to ca.14500BP are still discernible beneath green algae. In addition, touch reveals that the algal-free zone passes into the algal zone and the algal zone passes into the lichen zone with no apparent change in level or texture. It is not possible to determine whether or not micro-organisms are modifying pedestal sidewalls since only crustose lichens are present, and Danin *et al.* (1982) have written that crustose lichens erode to produce smooth rock faces. Nonetheless, as caprock overhang to the windward and leeward is all but identical (Table 7.1) but lichen cover greater on leeward sidewalls, it would appear that biogenic weathering of sidewalls is playing little or no part in pedestal development. Therefore, the effect of micro organisms on pedestal formation at Norber is considered to be rather limited at best.

8.3: Freeze-thaw weathering

There are no grounds to suppose that freeze-thaw is playing anything other than a very limited role in pedestal modification at Norber (refer to Section 7.11.2). Hughes (1886) thought that frost shattering of pedestals was unlikely also, since the caprocks kept the underlying limestone dry.

8.4: Hydration weathering

Crickmay (1935) suggested that hydration, whereby minerals absorb water into their crystal lattice which establishes tensile stress in addition to chemical alteration, may lead to disintegration of the overhanging, shaded portion of pedestals in granite in the Appalachians. Hydration, though, is largely confined to mafic silicates, clay particles and minerals such as gypsum or limonite, and not to calcite. Thin section findings do show, however, that the Cove Limestone at Norber contains traces of limonite and that the Kilnsey Limestone contains a mean of 20% extraclasts, which include mafic silicates, as well as grains of biotite mica (Appendix 3TS.3). Nevertheless, there is no evidence in the form of staining by iron to suggest that hydration is taking place. There is also no evidence that aspect has played any part in pedestal formation since mean caprock overhang to the sunlit west-south-west and shaded east-north-east is all but identical (Table 7.1). Therefore, it is extremely unlikely that hydration has contributed to the modification of pedestals at Norber.

8.5: Induced fracture weathering

8.5.1: Introduction

There is no indication in the literature that stress produced by the burden of the greywacke caprock might have affected pedestal formation at Norber apart from that of Goldie (2005: 438), who wrote that some boulders "...have crushed the limestone of their pedestals". Goldie (2005) does not elaborate further. Nevertheless, Ollier (1978) has argued that a group of minor (granite) landforms (in Australia), including pedestals bounded by or split by straight fresh cracks that were not joints of any kind, have been fashioned by stress due to the lowering of corestones onto angular weathered jointed blocks or bedrock. Ollier (1978) wrote (p. 251) that there are "…many examples of sharply angular supporting rocks beneath perched boulders where the process of induced fracture seems to provide a satisfactory explanation…" for their formation. It may thus be of relevance that Jones (1965) has noted that where the surface of a pedestal is exposed under a boulder its margins are sharp edged.

8.5.2: Aim and objectives

The aim of the work undertaken in Section 8.5 is to establish if induced fracture weathering of pedestals is occurring at Norber, and the objectives are to evaluate the unconfined compressive strength of the limestone of pedestals and the stress exerted upon them by their caprocks.

8.5.3: Method

8.5.3.1: Determining unconfined compressive strength (UCS)

Unconfined compressive strength (in MPa) was evaluated by recording rebound numbers on pedestal sidewalls using a Schmidt Hammer. This is a non-invasive hand-held portable instrument originally designed for *in situ* non-destructive concrete testing that has found application in rock mechanics as a simple test of strength or durability. It is used by lightly pressing an impact plunger against the surface to be tested. This causes a spring-loaded mass to be released that strikes the plunger and rebounds to give the rebound number (R), which can be converted to (cube) unconfined compressive strength. A Type N hammer (manufactured by A. Eisenhut, Basle, Switzerland), which is intended for testing concrete in ordinary building and bridge constructions, was used as this is recommended as being best suited for the testing in hand. Five tests were carried out on each of twenty-four pedestals. Refer to Appendix 3IF, Table 3IF.1 for full R number results and Appendix 4.3 for a full account of the procedures employed.

8.5.3.2: Determining stress

The stress imposed upon a pedestal by the overlying caprock is determined using the formula:

$S = L/A$

(Where S = Stress (MPa), L = Applied load (MN) and A = Area of contact (m^2))

The applied load of a caprock is determined using the formula:

$L = V \times BD \times g$

(Where: V = Volume (m^3), BD = Bulk Density (t/m^3) and g = gravitational acceleration (9.81))

Caprock volume and area of contact were resolved by direct measurement in the field.

8.5.3.3: Determining bulk density

Small samples of rock were removed from ten pedestals and from ten erratics, and the bulk density (in t/m^3) of each was calculated using a chemical balance in the laboratory following procedures outlined by Read (1962). The following formula was used:

$BD = Wa/(Wa – Ww)$

(Where Wa = Weight in air and Ww = Weight in water)

The limestone samples were collected from widely scattered pedestals at different altitudes so that results were not restricted to a single or to a limited number of horizons, while greywacke samples were taken from scattered caprocks in order to represent a broad lithological spectrum.

8.5.4: Limitations

It was not possible to comply with all the recommendations outlined in the Schmidt Hammer Manual when recording rebound numbers on pedestal sidewalls. Thus, for environmental reasons uneven surfaces were not ground down, nor was weathered material removed and nor were surfaces cleaned of vegetation. Accordingly, 'off shots' could not always be eliminated and replaced by a further impact test, which means that the unconfined compressive strength of the limestone is apt to be under-estimated in most cases since a firm surface is required to obtain the most accurate results. Uniaxial compression tests in the laboratory would give more accurate results but removal of cores or chunks of rock from pedestals is considered to be unnecessarily invasive. The Schmidt Hammer is designed for testing vertical surfaces but corrections can be made to rebound numbers if surfaces incline away from the upright. Although some of the tested pedestal sidewalls are not vertical it was not considered necessary to make any adjustments to results since their incline from 90° is only slight.

Measuring the dimensions of caprocks proved problematical since they consist of jagged blocks of irregular shape. As a result, it was felt that an element of subjective uniformity had to be introduced into gauging their proportions and if, for example, two opposing sides of a block were seen to be of different but relatively equal dimensions then volume was derived from only the larger. This approach was adopted since there was no wish to skew results in favour of a rejection of induced fracture, a response that could readily be drawn from the lack of calved blocks present beneath sidewalls and crushed pedestal crowns. In instances of even greater relative inequality volume was derived by visually compartmentalising the caprocks into blocks that were measured as separate entities and then summed, the same element of uniformity as previously used being applied where necessary. As a result, the methodology used is likely to lead to an over-estimation of applied stress values.

In all, just three pedestal rocks (N5, N19 and N21 in the Cove Limestone) from twenty-four lent themselves to the investigation. Eleven caprocks were excluded because they consisted of several separated blocks or their shape was too asymmetrical to deduce even their approximate volume or they did not rest entirely on their underlying pedestal or they were propped up by an adjacent erratic or they were incorporated into dry-stone walling. A further ten pedestal rocks were excluded since measuring the areas of contact between caprock and pedestal was not attainable. This was because the gap between the two was sometimes so tight or because one or both surfaces were so undulating that it was not possible to reach some/all areas of contact in order for measuring to take place. In addition, the presence of erratics/raised ground in close proximity to several caprocks meant that some areas of contact were likewise inaccessible. Moreover, actually measuring those few contact areas that could be reached was not without difficulty, since all are irregular in shape while evaluation took place lying underneath caprocks in confined and cramped spaces, a restriction which does not readily lend itself to accuracy. As a result, both unconfined compressive strength and stress values should be regarded as being indicative rather than precise. Furthermore, using just three pedestal rocks to determine whether or not induced fracture has played a role in pedestal modification at Norber is inadequate science. Consequently, all twenty-four pedestals were tested for their compressive strength, and seven caprock and seven pedestal samples that had been used for thin sectioning were measured for specific density to discover if the three caprocks were typical re these criteria.

8.5.5: Results

8.5.5.1: Unconfined compressive strength and bulk density of the Carboniferous limestone

Table 8.1 shows that the unconfined compressive strength of the Cove Limestone ranges from 31.5MPa to 71.4MPa with a mean of 59.2MPa, and reveals that that none of N5, N19 and N21 is atypical within this range. All values are at the lower end of those outlined by Waltham (1999) who envisaged a range of 50 to 150MPa and a mean of 100MPa for the Carboniferous limestone in general. The relatively low overall values of unconfined compressive strength can be explained not only by the shortcomings outlined in Section 8.2.4 but also by the comparative closeness of discontinuities at Norber (refer to Section 7.11.1). Hence, information in the Schmidt Hammer Manual indicates that the increased elasticity of slabs less than 10cm thick can lead to low test values. Table 8.2 shows that the bulk density of the Cove Limestone samples lies within a narrow range of between 2.60 and 2.71t/m^3 with a mean of 2.65t/m^3, and reveals that none of N5, N19 and N21 is out of the ordinary within this range. The mean result is very similar to Waltham's (1999) dry density value of 2.6t/m^3 for the Carboniferous limestone.

8.5.5.2: Stress

The bulk density of the greywacke caprock samples ranges from 2.43 to 2.74t/m^3 with a mean of 2.56t/m^3 (Table 8.3). None of N5, N19 and N21 is awry within the range, and the mean result is very similar to Waltham's (1999) dry density value of 2.6t/m^3 for greywacke. The approximate volume of the three caprocks ranges some three-fold from 1.64 to 5.10m^3, the applied load some three-fold from 0.04 to 0.13MN and the area of contact some three-fold from 0.015 to 0.046m^2 (Table 8.4). The stress imposed on the underlying limestone by the caprocks is similar in all three cases, though, as it lies within a relatively narrow range of 2.67 to 2.93MPa, with a mean of 2.81MPa.

8.5.6: Analysis

Although definitions of the expressions "sharply angular" (Ollier, 1978) and "sharp edged" (Jones, 1965) are somewhat subjective, most pedestals include lengths of acutely angled junctions either between their crowns and sidewalls, and/or between adjacent sidewalls. Nevertheless, this does not confirm induced fracture as the few sidewalls (whether with sharp junctions or otherwise) that can be traced down to ground level appear mostly to be discontinuity-related. Moreover, few other phenomena proposed by Ollier (1978) as being indicative of induced fracture are present. Thus, pedestal sidewalls are generally not bounded by straight cracks but are instead stepped, fluted or have dissolution runnels on their surfaces. Moreover, the exposed surfaces of sidewalls and of limestone clasts found at the foot of some pedestals are not fresh since they are almost entirely covered in lichen. Indeed, the only clear evidence of undoubted induced fracture at Norber is an arcuate, clean crack occurring in a small clast with a surface area of approximately 0.021m^2 wedged between the caprock and pedestal of N12.

The stress generated by the greywacke caprocks at Norber is not nearly as great as that created by the granite caprocks of comparable volume as deduced by Ollier (1978) in Australia despite the fact that the two rocks have almost identical bulk densities. The different shapes of the two types of caprock offer a ready explanation. The granite caprocks have weathered roughly spherical with an even surface due to their inherent massive nature, whereas the greywacke caprocks are roughly cuboidal with uneven surfaces due to the configuration and density of discontinuities. As a result, the area of contact between the granite caprock and the underlying bedrock is single and of a relatively small dimension, which leads to stress concentration. In contrast, the planar form of the caprock under-surfaces at Norber allied to their uneven nature means that the area of contact is both multiple (N5 has four areas of contact, and N19 and N21 three each) and greater, which leads to stress dilution. As a result, the mean stress imposed by the caprocks (2.81MPa) upon the Cove limestone at Norber is greatly exceeded by the limestone's mean unconfined compressive strength (59.2MPa). Consequently, as neither the caprocks nor the limestone comprising the pedestals of N5, N19 and N21 are atypical of their neighbours or of greywacke and Carboniferous limestone in general re their physical characteristics, none of the caprocks at Norber is able to induce fracture of the underlying Cove Limestone. Nor are any of the caprocks able to induce fracture of the underlying Kilnsey Limestone, even though it has a slightly lower mean unconfined compressive strength of 52.8MPa. Moreover, as the bulk densities of greywacke and Carboniferous limestone are very similar (their respective means are 2.56 t/m³ and 2.65 t/m³) it follows that caprock N27, which is composed of Carboniferous limestone, would also be unable to induce fracture of its underlying pedestal.

As an aside, it is possible to gain a fairly precise idea of the required increase in volume needed for caprocks N5, N19 and N21 to induce fracture of the underlying limestone, assuming that their areas of contact remained unchanged. Thus:

Vr = (UCS/S) x V

(Where Vr = required volume; UCS = unconfined compressive strength; S =stress; V = volume of caprock)

The figures in column six of table 8.5 show that the caprocks would respectively require an increase in volume of approximately x24, x22 and x19 in order to induce fracture. This would require caprock 5, for example, to be transformed into a 'colossus' of over 118m³, which is some x15 greater than the bulkiest erratic found at Norber (Section 3.1).

Although there are mechanisms which may diminish rock strength, such as static fatigue, or which may accommodate stress, such as plastic deformation, the discrepancy between strength and stress is so great at Norber that it was not felt necessary to pursue these avenues of rock mechanics further. The unconfined compressive strength of the limestone at Norber means, however, that it is a 'hard' rock (Hoek and Bray, 1981; Clayton *et al.*, 1995), and Bell (2000) has stated that most strong rocks exhibit little time-dependent strain or creep. The fact that the Carboniferous Limestone forms upstanding cliffs (the prime example in Craven is Malham Cove, which is a precipice of Devensian age (Murphy, 2005) that is 80m high and 200m in lateral extent) is additional proof that it does not readily undergo strain or body creep.

8.5.7: Conclusion

Induced fracture of the limestone at Norber is feasible only if the stress imposed upon it by the overlying caprock surpasses its unconfined compressive strength. But even after considering the lack of precision of some of the methodology used, it can readily be seen that the mean unconfined compressive strength of the limestone is some x20 greater than the mean stress imposed upon it by the caprock above. Therefore, induced fracture weathering of the limestone by the caprocks at Norber, whether composed of greywacke or Carboniferous limestone, is not feasible.

8.6: Insolation weathering

The most frequently expounded mechanism for rock breakdown in the early days of research in desert regions was insolation, whereby rocks expand and contract as diurnal temperatures rise and fall thus inducing disintegrative stress (Goudie, 1997). Consequently, Leonard (1927) proposed that differential mineral expansion and contraction must be the principal factor operative in the crumbling of pedestal rocks in the Texas Canyon of south east Arizona. Goudie (1997) has pointed out, though, that later work tends to be rather equivocal or inconsistent about the power of insolation. Hence, Griggs (1936), for example, was unable to detect any significant deterioration in rock structure after he had experimentally heated and cooled a granite cube through a temperature range of 30-40ºC for the equivalent of 245 years. The improbability of insolation causing disintegrative stress at Norber would seem to be borne out by field evidence. Thus, pedestals fashioned from the Kilnsey Limestone, which contain a mean of 20% extraclasts (themselves composed of different minerals) as well as traces of quartz and mica, are no more crumbly than those composed of the Cove Limestone, which consist almost entirely of calcite (Appendix 3TS.3). Moreover, even if rock disintegration through insolation was an accepted fact, it is very doubtful that the temperature range at Norber would be extreme enough for crumbling to occur. This is because the mean diurnal temperature range at Malham was approximately 6.0ºC (mean minimum-maximum range of 3.76-9.75ºC) for the years 1961-2003 (author analysis). This is a much smaller span than found in the tropical deserts where diurnal ranges can exceed 50ºC (Thomas, 1997); it is also well below that of Griggs' (1936) experimentation. In addition, the mean diurnal sunshine rate at Malham for the years 1983-2003 was a mere 3.2 hours (author analysis), a figure that is normally exceeded in hot desert regions due to the lack of cloud cover. Furthermore, individual sidewalls may receive little or no insolation due to their aspect and shading by overlying caprocks. Therefore, it is argued that differential mineral expansion and contraction weathering has not contributed to pedestal development at Norber.

8.7: Karstic erosion (subaerial)

8.7.1: Introduction

Bryan (1923) has argued that the development of certain pedestal rocks (largely in conglomerate on shale in arid south-west areas of the U.S.A.) is dependent on rain running off caprock edges to form an outer 'drip curtain' and running down pedestal sidewalls as an inner 'water film'. Bryan (1923) contends that these two processes are responsible for opening up joints (and also for bringing soluble salts to the surface thus causing the rock to crumble (Section 8.8)) and for converting the sidewalls into shafts. The formation of the pedestal rock is enhanced further not only by splashing from the 'drip curtain' lowering the ground surface below, but also by run-off from the 'inner film' washing away any disintegrated material from the shaft. Although the climate, rock types and processes that have led to pedestal formation in the arid south-west USA may not all be directly applicable to the Ingleborough area, there is evidence that subaerial moisture has contributed to pedestal formation at Norber. Thus, Jones (1965: 430) has written that many pedestal surfaces "… bear signs of special solution. Their positions show them to be caused by water dripping from the boulders. Where the drips fall, the limestone dissolves to leave a characteristic mark with little channels leading away". Jones (1965) added that during the short time it takes rain to trickle over a boulder "…it is acidulated…", increasing in acidity from pH 7.0 on the boulder exterior to a mean of pH 6.3 above drip marks, seemingly due to the presence of epi- and endo-lithic lichens growing on the caprock surface. Waltham *et al.* (1997) also contend that subaerial karstic erosion has played a role in pedestal formation, and propose (p. 52) that drip-water "…flowing down the undersides of the boulders is responsible for the narrowness of pedestals [relative to their overlying caprocks] and their incision by solution grooves."

8.7.2: Aim and objectives

It is clear from the above that Waltham *et al.* (1997) envisage that subaerial water has played a greater role in pedestal formation at Norber than Jones (1965) and that there is disagreement as to how water is transferred from caprock to pedestal. Accordingly, the aim of the work undertaken in Section 8.7 is to determine the role played by subaerial karstic erosion in pedestal modification at Norber. The objectives are to record aspects of pedestal-rock morphology, to monitor water moving through the pedestal-rock system and to measure the potential of water to dissolve limestone.

8.7.3: Method

Thirty pedestals were examined for the presence of decantation runnels (cf. Jones' (1965) drip-water channels and Waltham *et al.*'s (1997) solution grooves). Ten of the pedestals (N5, N11, N12, N14, N15, N17, N19, N21, N25 and N27) were sampled for a rainwater/drip water study, and pedestal subaerial windward and leeward undercut relative to the outer edge of the overlying caprock was measured. The pedestals were not sampled at random but were chosen because no others had a relatively uninterrupted wind fetch to the south-west (the direction of the prevailing wind) of at least 50m. Also, each had an exposed pedestal height greater than 19cm (the minimum required to place a rain gauge beneath the caprock). The pedestal rocks were visited in turn prior to a period of precipitation when the following procedures were undertaken:

1. Five rain gauges were staked beneath the caprock wherever it was possible to do so (against sidewalls or under the caprock lip or in-between, which meant that placement was random), in order to catch drip-water/rainwater. In addition, a standard control was staked to the windward of each caprock to catch rainwater. The sub-pedestal gauges were not of customary design (Plate 5.1), but Linacre (1992) found that the amount of water caught in simpler gauges is within a few percent of that in standard types. Measurement was made of overhang fetch (i.e. the distance from funnel mid-top to distal caprock lip).

2. A length of pre-weighed fabric (towelling) was fastened to a pedestal sidewall(s) to absorb moisture.

3. The pedestal and equipment were fenced off from human/sheep interference by erecting a 2m-high nylon-net barrier (Plate 8.1). Net with a narrow gauge (1mm) and a wide mesh (150mm) was used to minimise interception.

4. Subsequent to precipitation the volume of water in all gauges was recorded, and the percentage within each sub-pedestal gauge was calculated re the standard control. The fabric was re-weighed and its percentage water content was also calculated.

5. Eleven pre-weighed limestone tablets were attached to the sidewalls of N1, N5 (4 tablets), N6, N21, N24 (3 tablets) and N27 for the duration of the 2004-2005 water year (Plate 8.2), ten on non-decantation runnel

sidewalls and one directly on decantation runnels (N25). The tablets were discards, and were employed to determine only the dissolution potential. The tablets were prepared as in Section 7.6.5.

Apart from tablet emplacement, the survey was undertaken in September and October 2003 between the 'summer rambling season' and a pre-known sheep-grazing period to best avoid human/animal disturbance. Following its completion, coefficients of assorted pairs of variables were correlated using Spearman's rank (r_s) test as follows:

$r_s = 1\text{-}6d^2/n^3\text{-}n$

(Where d = difference in rank of each pair of values and n = number of pairs)

Spearman's rank correlation coefficient is used quite frequently in geographical analysis (e.g. Walford, 1995). This method was chosen because it is quick and easy to calculate, and because of a lack of author expertise in statistical analysis.

8.7.4: Limitations

It was intended to collect rain/dripwater from only single periods of frontal precipitation that lasted several hours rather than from several showery periods, since it was reasoned that between-shower evaporation of water in the more exposed gauges might occur. The survey coincided with one of the driest late summer/early autumn rainfall periods on record (Dorling, 2003), however, which meant that showers had to be incorporated. Allaby (2002) has indicated that the distance between rain gauges and obstructions, i.e. caprocks in this case, should be at least equal to the height of the obstruction in order to evade its sheltering effect. It was never possible to comply with this ruling due to the small area enclosed by the nylon-net barrier. Consequently, the contents of the controls and the more exposed gauges may not be a true reflection of actual rainwater/dripwater. It was also intended to place sub-caprock gauges at the eight points of the compass, but staking difficulties prevented this. Instead, five gauges were used as this is the minimum required for a Spearman's rank correlation coefficient test. Only four gauges could be staked under N25, which meant that r_s could not be calculated. It was planned to record the pH of all sampled water in the field, but this proved possible only for N5 due to the failure of two portable pH meters. Just three tablets remained *in situ* at the end of the 2004-2005 water year, which means that discussion relating to them is drawn from a far smaller sample than was intended. The use of fabric is a somewhat crude way of discovering if water is flowing down sidewalls. Hence, it may, for instance, absorb moisture directly from the air or dry out in the wind; it was also not possible to sheath a complete pedestal while aspect varied from site to site. In addition, the failure to prevent destruction by wind of a control (fabric wrapped around a limestone residual under an umbrella) employed to measure absorption of water vapour was considered to be of importance. Nonetheless, fabric use was considered the only option until the idea of using tablets was conceived (covering sidewalls with water-soluble paint and attaching blotting paper to them were also deliberated). In the end, though, tablet loss justified fabric employment.

8.7.5: Results

Seven of the thirty pedestals were found to have decantation runnels etched into them. The runnels are restricted to a narrow zone where the sidewall more-or-less directly underlies either a caprock outer edge (N7, N10, N14, N15 and N25) or a wide intra-caprock crack (N1 and N27). The runnels are generally several centimetres in length, and a few millimetres wide and deep, as seen in Plate 8.3. No runnels occur on N26 despite the fact that water was seen dripping onto its pedestal. Table 7.1 shows that not all caprocks are undercut by their pedestals (e.g. parts of N12, N17, N25 and N27), that maximum pedestal undercut is 64cm (N5) and that mean windward and leeward undercuts are respectively 26 and 23cm. Table 8.6 reveals that the percentage of water in the gauges relative to the control ranged from 0 to +323%, the latter 'excess' caused by the channelling of run-off on caprock surfaces prior to it shedding into some of the gauges as dripwater. Table 8.6 (N5 only) also reveals that precipitation is less acid (pH 5.61) than decanted water (pH 5.00-5.56), as noted by Jones (1965). (Refer also to Section 12.6.3). The percentage by weight of moisture absorbed by fabric ranged from 1.8 to 62.4 (Table 8.7). The percentage was determined as follows:

ww-dw/ww

(Where ww=wet weight and wd= dry weight)

Of the three tablets still in place on sidewalls at the end of the 2004-2005 water year, the two on non-decantation runnel sidewalls (N1 and N21) respectively suffered weight losses of 0.02% and 0.04% while that overlying decantation runnels (N25) suffered a loss of 0.39%. Weight loss was determined as follows:

prbw-pobw/prbw

(Where prbw=pre-burial weight and pobw=post-burial weight)

Refer to Appendix 3M Tables 3M.1-11 for full moisture/precipitation results and 3M.12 for decantation runnel data, and Appendix 3T Table 3T.3 for tablet data.

8.7.6: Analysis

The mean dripwater pH of 5.3 and the greater percentage weight loss of the tablet overlying decantation runnels show that the potential exists for dripwater erosion to modify pedestals. Moreover, as the decantation runnels are fresh-looking (Plate 8.3) and as water was observed trickling down them there is no doubt that dripwater erosion is occurring, even if it is relatively uncommon and essentially restricted to sidewalls that directly underlie caprock outer edges. The weight losses of tablets emplaced on N1 and N21, which were positioned respectively about 45 and 80cm beyond their caprock outer edges, show that a second potential for subaerial karstic erosion of pedestal sidewalls also exists since neither tablet was placed above runnels. The only reference in the literature to non-decantation-runnel modification of pedestals is by Waltham *et al.* (1997), who explain that pedestal narrowness may be accounted for by dripwater flowing down the underside of the caprocks. There are three reasons why this explanation cannot hold true. Firstly, all caprock under-surfaces are riddled with irregularities (Plate 8.4), and Porter and Rose (2000) have pointed out that irregularities (on any material) impede water movement and encourage it to accumulate at barriers where the increase in weight results in a drip being formed (Fig. 8.1). The Swedish-Finnish Timber Council (1992) has shown that a gap of only 6mm is normally adequate to prevent the further inward movement of water by surface tension along the underside of exterior windowsills. (A slightly larger gap is required in Britain since water is usually ‘dirty’.) This is because the ‘height’ of a globule of clean water standing on a non-porous surface is approximately 5mm. The Council also states that a downstand weather bar will likewise perform the same function. The glut of caprock under-surface irregularities means that the inward movement of rainwater is severely restricted (observation shows that dripping usually occurs within a few centimetres from caprock outer edges). Hence, as mean caprock overhang is in excess of 23cm (Table 7.1) it follows that drip-water cannot account for pedestal narrowness. In any case, caprock outer surfaces would have been enveloped in vegetation (most likely Sphagnum moss) from ca.10000 to 3000BP, since they were overhung by trees (Section 11.2.2), as envisaged in Plate 8.5, the moss acting as ‘drip-points’ thus preventing the movement of water along caprock undersides. Secondly, Waltham *et al.* (1997) do not stipulate how the flowing water is transferred from caprock to pedestal sidewall. It cannot drip onto the sidewalls of narrow pedestals, since decantation runnels are restricted to sidewalls that directly underlie caprock outer edges and to below intra-caprock cracks. Nor can it flow down the few points of contact between caprock and pedestal (just three in the case of N21) and move across pedestal crowns prior to reaching the sidewalls, as there is no sign of water-flow erosion on the crowns. Thirdly, undercuts 7cm in fetch occur below N26, yet despite the fact that water was seen dripping onto its pedestal no decantation runnels were present. This is because its caprock is composed of Carboniferous limestone, and water trickling over its surface becomes alkalised due to it dissolving calcium carbonate, which means that it loses much of its aggressiveness (Section 12.6.3). Hence the moisture responsible for the weight loss of tablets on N1 and N21 must be derived from a source other than that envisaged by Waltham *et al.* (1997). Observations during rainfall revealed that the sole alternative is air-borne moisture in the form of direct precipitation and/or wind-blown droplets (and/or undoubtedly water vapour too), and it is proposed that this moisture is responsible for the weight loss of the tablets on N1 and N21.

It stands to reason, all things being equal, that the effects of air-borne moisture on pedestal modification ought to be inversely proportional to overhang fetch due to the increasing ‘umbrella’ effect of the caprocks, although this will apply more to wind-blown rain than fog or dew. If the two variables (i) distance of gauges to erratic outer edge and (ii) amount of water in gauges (as a % of precipitation) are correlated for the sampled pedestal rocks using Spearman’s rank then negative r_s values result (Table 8.8). This indicates that as distance of gauges to caprock outer edge increases the amount of water in gauges decreases. In other words, increasing overhang fetch causes a progressive decrease in the amount of airborne moisture penetrating under caprocks, which in turn must lead to a parallel decrease in pedestal modification by that moisture. As the critical values of the coefficient corresponding to $n = 5$ and with a significance level of 0.05 (two-tailed) is ± 1.0, however, the correlations are not statistically significant. The general lack of correlation can be accounted for by any one or a combination of several factors such as variations in caprock shape (Fig. 8.2), the location of intra-caprock discontinuities (Fig. 8.3), pedestal height (Fig. 8.4), the position of caprock under-surface irregularities and wind capriciousness.

Although it has been highlighted that the fabric-moisture results should be treated with a fair degree of caution, plotting fabric moisture against distance of fabric to distal caprock edge reveals that the maximum distance wind-blown droplets penetrate under caprocks at Norber is about 45cm (Fig. 8.5). If so, subaerial dissolution beyond about 45cm must be effected by water vapour only. Hence, as air-borne water normally has a mean pH of <7, as it is reaching (in one form or another) all sidewalls and as tablets N1 and N21 suffered weight loss, it is proposed that sub-aerial karstic erosion has the potential to modify pedestals. It must be understood, though, that the potential declines with increasing overhang fetch. It is also proposed that the very presence of decantation runnels on pedestal sidewalls indicates that the dripwater erosion rate exceeds the potential air-borne water dissolution rate.

8.7.7: Conclusion

Once a pedestal has been exposed it can be modified by acid rainwater flowing/dripping off its caprock. This occurs only in a narrow environment where pedestal sidewalls more-or-less directly underlie caprock edges or open caprock fractures, however, as under-surface irregularities prevent the movement of water inwards to more proximal zones. Accordingly, as most pedestals are overhung by intact caprocks, drip-water flowing down the undersides of the boulders is not responsible for the narrowness of pedestals as proposed by Waltham *et al.* (1997). In contrast, the potential exists for air-borne moisture to modify all pedestals. Yet even if this is an actuality it too prevails more at distal than at proximal caprock under-surface zones. It also operates at a much slower rate than erosion caused by water decanting off caprocks. Therefore, the role played by sub-aerial karstic erosion in pedestal modification is mostly restricted to specific areas of pedestal sidewalls that more-or-less directly underlie caprock distal edges.

8.8: Salt crystallisation weathering

Peel (1966) argued that salt crystallisation might aid pedestal disintegration in southern Libya. The process operates predominantly in semi-arid areas where relatively low precipitation and high evapo-transpiration rates act to draw up ground water and concentrate dissolved salts in sub-surface pore spaces hence rendering the rock liable to granulation. Loose grains of limestone are not, however, present on upper pedestal surfaces at Norber while pedestal sidewalls are well-indurated rather than friable (and covered for the most part in lichen). Moreover, the mean annual precipitation rate at Malham Tarn Field Centre was 1501mm for the years 1961-2001 (author analysis) while potential evaporation is about 500mm (Bullock, 1971), the excess of precipitation over evaporation encouraging a downward movement of ground water and dissolved minerals. The downward movement of salts is confirmed by the presence of bleached horizons, some with iron pans below, in exposed podsols developed in regolith on the Carboniferous limestone at many sites in the Ingleborough area, such as near Gaping Ghyll and on Sulber. Therefore, the likelihood that salt crystallisation has contributed to the formation of the pedestals at Norber can be discounted.

8.9: Sidewall-failure weathering

Intact-rock failure occurs where discontinuities dip more steeply than the angle of friction, which for Carboniferous limestone is 35° (e.g. Waltham, 1997). The bedding at Norber is more-or-less horizontal and most joints are more-or-less vertical, which means that in theory sidewall failure is not viable. Nonetheless, there is evidence of its occurrence at Norber as witnessed by, for example, the block in front of N10 (Plate 1.4) and the clasts below the pedestal of N27 (Plate 8.1). Examination of pedestals reveals that dissolution causes widening of joints (e.g. N9) and bedding (e.g. N5), and undercutting of sub-regolith sidewalls (e.g. N11), this providing an environment of block instability that can lead to failure. If the size of some of the failed blocks is considered (the block by N10 is about 0.03m^3), failure need occur only sporadically for it to be an effective agent of pedestal narrowing, especially as it has had millennia in which to operate. The actual incidence of sidewall failure is, however, hard to gauge. This is partly because it is often impossible to distinguish between toppled blocks and erratics, partly because blocks will become incorporated into the regolith, which renders them 'invisible', and partly because creep may remove blocks from below sidewalls. Therefore, although sidewall failure has undoubtedly contributed to pedestal modification via narrowing its actual importance remains somewhat conjectural.

8.10: Overall conclusion

Evidence from the literature on pedestal formation abroad suggests that a variety of weathering processes, i.e. insolation, salt crystallization and hydration, may be involved in subaerial pedestal evolution. Each process was examined in the context of Norber, but no evidence was found to indicate that they have any bearing on pedestal modification. In addition, weathering processes that have been proposed or are suspected of playing a role in pedestal modification at Norber itself were examined. The outcomes indicate that induced fracture has not contributed to pedestal formation since the stress imposed upon the limestone by the overlying caprock does not surpass its unconfined compressive strength. The part played by biogenic weathering remains somewhat unresolved largely because there is little hard evidence, especially knowledge of its effect on dissolution rates, on which to base any conclusions. Nonetheless, it is suspected from field evidence that weathering of pedestals by biogenic forces is negligible. The relative roles played by sidewall failure and sub-aerial karstic erosion in pedestal modification are difficult to judge. On the one hand some sub-aerial karstic erosion probably occurs during every period of rainfall even if it is mostly restricted to cutting decantation runnels on parts of some pedestal sidewalls, while on the other hand failure occurs sporadically but involves relatively large volumes of rock. Therefore, as biogenic weathering is barely modifying pedestals, the largest contribution to pedestal modification is sidewall failure and sub-aerial karstic erosion, both processes causing pedestal narrowing.

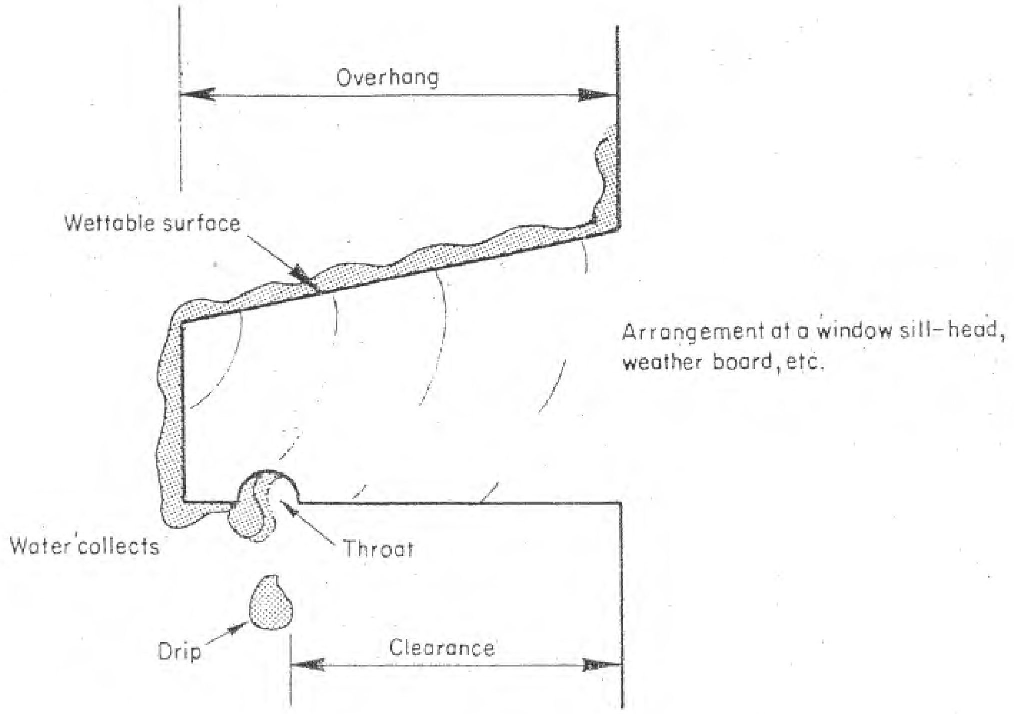


Fig. *Error! No text of specified style in document.****.1: Encouraging water to drip on the underside of a window-sill head or weather board (Porter and Rose, 2000, Fig. 13.4)***

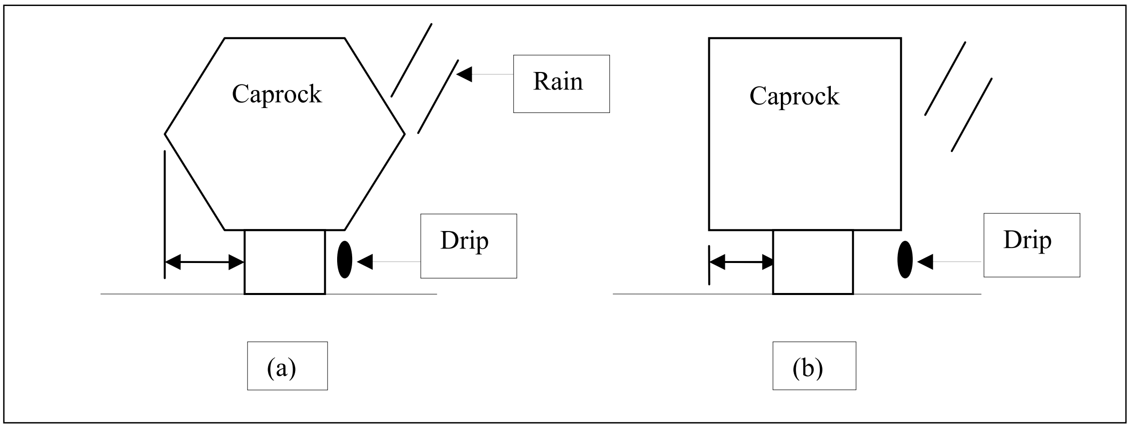


Fig. *Error! No text of specified style in document.**.2: Caprock shape: Caprock fetch ( ) is greater in (a) than (b), but differences in caprock shape mean that dripwater is liable to drop at a greater distance from the pedestal of (b) than (a)***

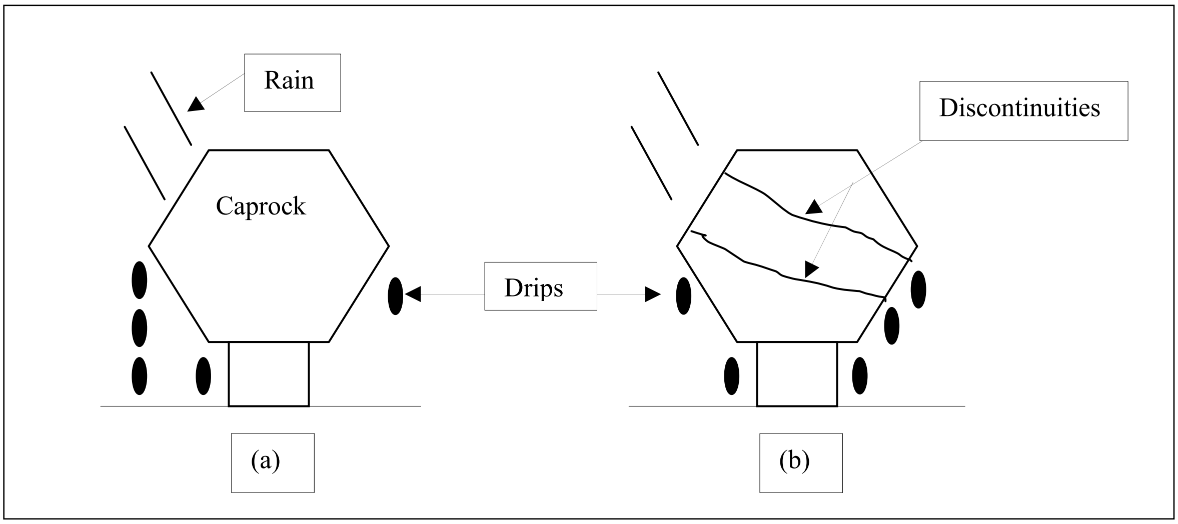


Fig. *Error! No text of specified style in document.**.3: Discontinuities: The absence (a) and presence (b) of discontinuities may lead to differences in the distribution of dripwater from caprocks***

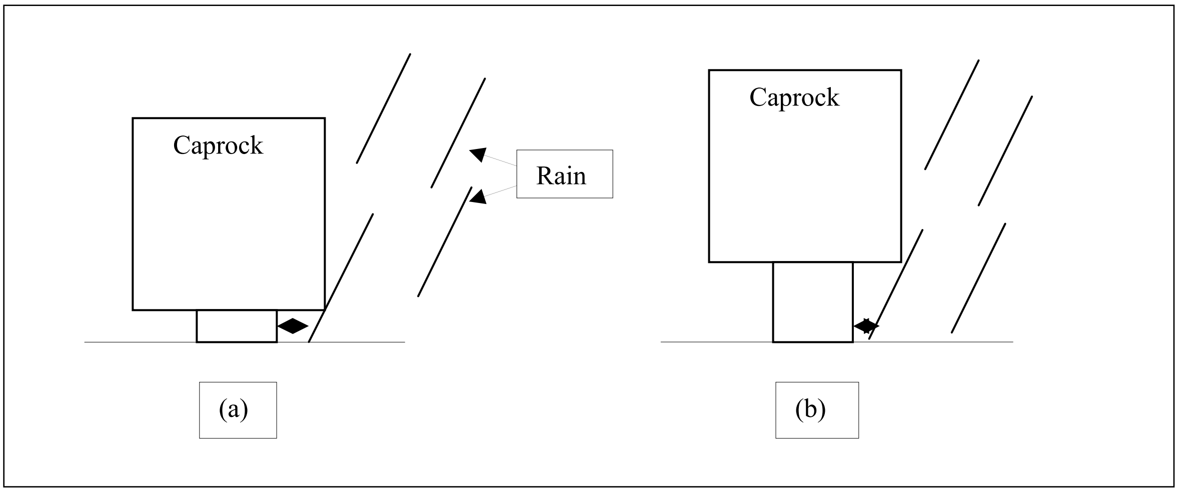


Fig. *Error! No text of specified style in document.**.4: Exposed pedestal height: Although caprock fetch is equal, differences in pedestal height mean that rainwater is liable to fall at a greater distance ( ) from the pedestal of (a) than (b)***

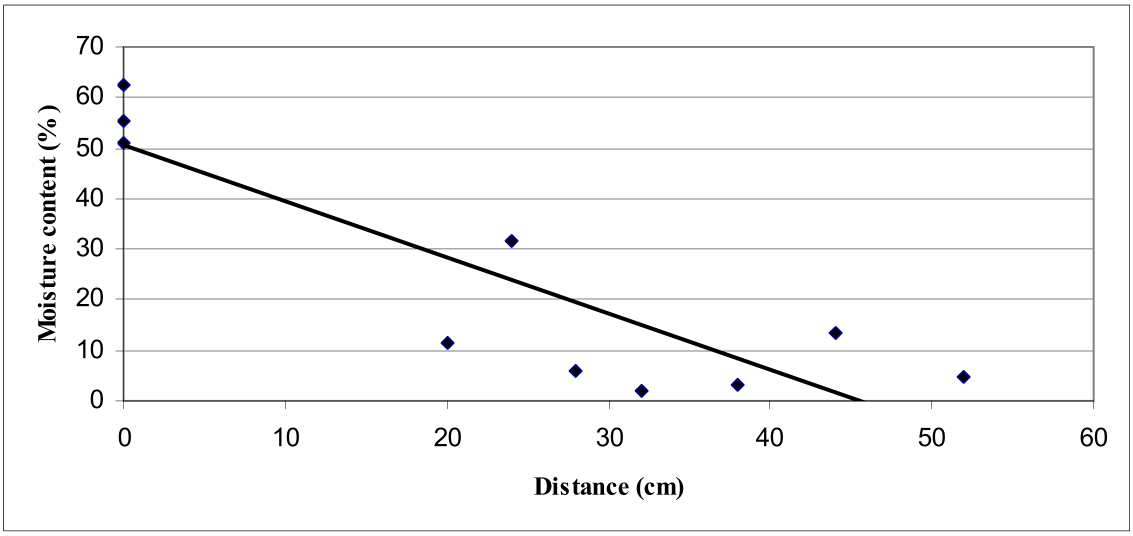


Fig.** Error! No text of specified style in document..**5: Scatter graph of fabric distance from distal caprock edge (cm) against fabric moisture content (%) at Norber

Plate 8.1: Pedestal rock N27 during subaerial-dissolution trialling

The thin-gauge net was erected to protect a standard rain gauge (yellow arrow), five non-standard water-collection gauges, two of which can be seen in the foreground (red arrows), and a length of water-retaining fabric (black arrow) from sheep/human interference during trialling. The photograph was taken after a period of rainfall during which part of the fabric was moved by winds. Note the limestone clasts at the foot of the pedestal, which may well be the products of sidewall failure (Section 8.9).

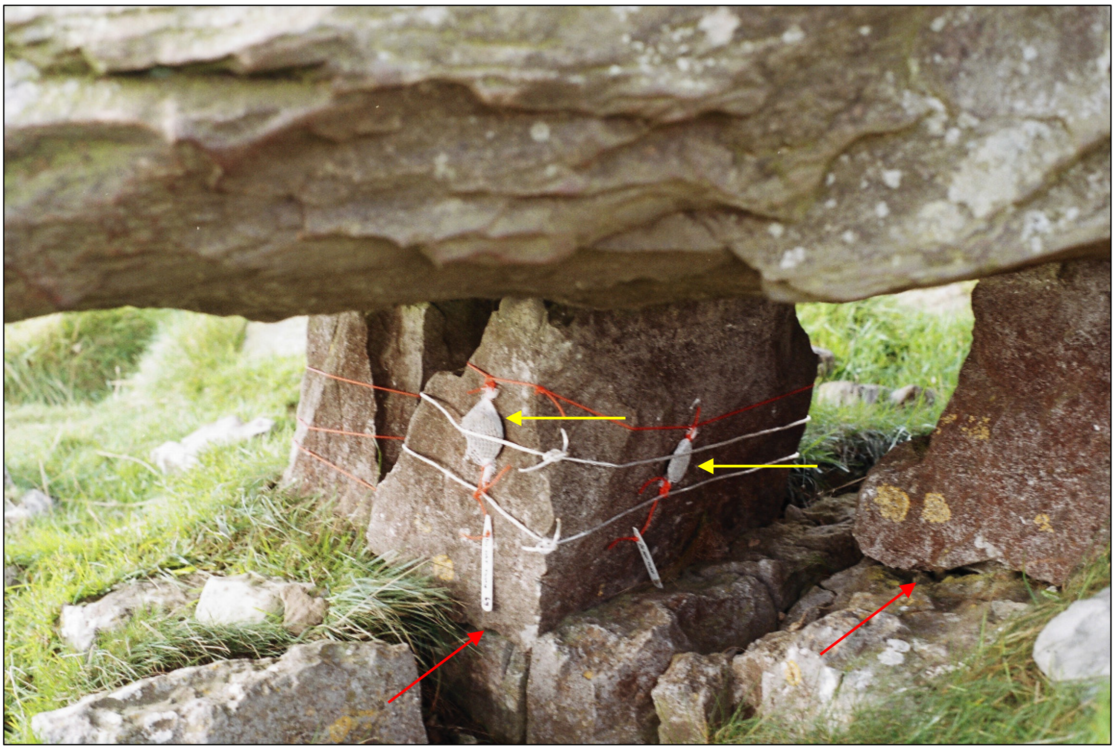


Plate** Error! No text of specified style in document.**.1: Limestone tablets attached to a pedestal sidewall of N5 at Norber

Although four tablets, two of which can be seen above (yellow arrows), were securely tied to the sidewalls of N5, none survived the 2004-2005 water year in situ. Note that the pedestal sidewall/rock head junction appears to be formed of a bedding plane (red arrows) (Section 9.5).

Plate** Error! No text of specified style in document.**.2: Decantation runnels on the pedestal sidewall of N25 at Norber

Seven pedestals at Norber were found to have decantation runnels (red arrows) etched into them, mostly where a pedestal sidewall more-or-less directly underlies a cap-rock outer edge as above. The runnels are formed due to dissolution by acid rainwater that has been channelled on cap-rock surfaces and then decanted onto the sidewall as dripwater. The pedestal is about 42cm high.

Plate** Error! No text of specified style in document.**.3: The underside of cap rock N5 at Norber showing under-surface irregularities

The underside of cap rock N5 is typical of others at Norber, and is riddled with grooves, ledges and projections that encourage dripping. Consequently, it is considered implausible that water could flow along its underside and drip onto the pedestal sidewalls as envisaged by Waltham et al. (1997). The pedestal is about 35cm high and the fetch from erratic edge to pedestal sidewall is about 64cm.

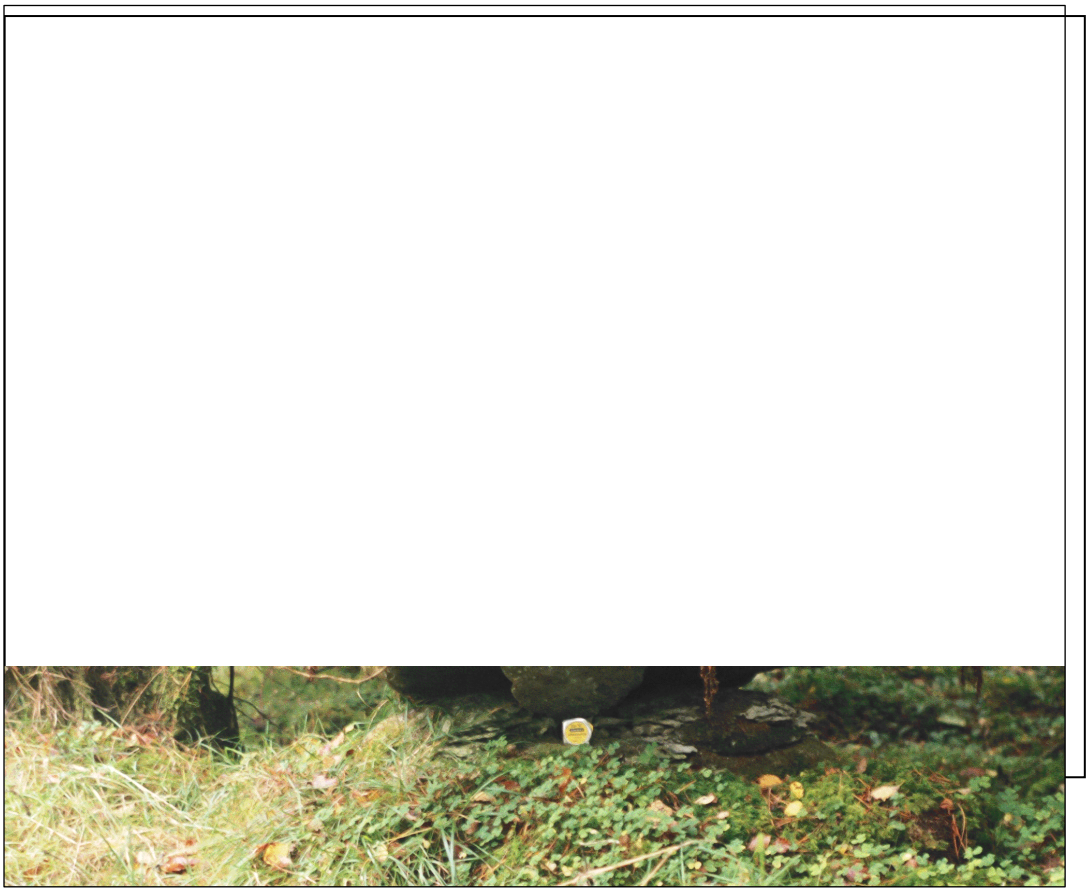


Plate** Error! No text of specified style in document.**.4: How Norber may have looked from ca.10000-3000BP

Norber was overcanopied by the Wildwood from ca.10000-3000BP when it is likely it would have appeared similar to the scene above (Section 11.2.2). Note that the upper and lateral surfaces of the cap rock are covered in Sphagnum moss and vegetation, which would have acted as drip points (yellow arrows) to the downward movement of water, and that the pedestal sidewalls are all but encased in vegetation/organic soils. (In actuality, the plate is of CB3 on the Cavan Burren in the Republic of Ireland (Section 12.8).)

Pedestal rock	**UCS (MPa)**	**Pedestal rock**	**UCS (MPa)**	**Pedestal rock**	**UCS (MPa)**
N1[1]	43.9	N10[2]	71.4	N18[2]	53.1
N2[1]	47.3	N11[2]	60.3	N19[2]	65.7
N3[1]	52.9	N12[2]	51.1	N20[2]	47.3
N4[2]	58.4	N13[2]	31.5	N21[2]	51.5
N5[2]	69.8	N14[2]	57.5	N23[2]	58.7
N6[2]	63.6	N15[2]	66.4	N24[1]	66.9
N7[2]	70.2	N16[2]	50.3	N25[2]	66.0
N9[2]	71.4	N17[2]	64.0	N26[2]	65.2

[1] Kilnsey Limestone; [2] Cove Limestone

Table** Error! No text of specified style in document.**.1: Mean unconfined compressive strength of pedestals at Norber

Pedestal rock	**Bulk density (t/m^3)**
N1[1]	2.67
N3[1]	2.68
N5[2]	2.64
N7[2]	2.60
N13[2]	2.63
N19[2]	2.64
N21[2]	2.61
N23[2]	2.71
N25[2]	2.67
N26[2]	2.61
Mean	2.65

[1] Kilnsey Limestone; [2] Cove Limestone

Table** Error! No text of specified style in document.**.2: Bulk density of Carboniferous limestone pedestal samples at Norber

Pedestal rock	**Bulk density (t/m³)**
N5	2.57
N12	2.74
N16	2.56
N18	2.43
N19	2.46
N21	2.69
N27	2.58
N/A*	2.49
N/A*	2.56
N/A*	2.50
Mean	2.56

*Sample removed from erratic without a pedestal.

Table *Error! No text of specified style in document.***.3: Bulk density of Silurian greywacke caprock samples at Norber***

Pedestal rock	**Approximate volume (m^3)**	**Bulk density (t/m^3)**	**Applied load (MN)**	**Area of contact (m^2)**	**Stress (MPa)**
N5	4.97	2.57	0.13	0.046	2.83
N19	5.10	2.46	0.12	0.041	2.93
N21	1.64	2.69	0.04	0.015	2.67

Table** Error! No text of specified style in document.**.4: The stress imposed by caprocks N5, N19 and N20 on their underlying pedestals and the criteria used in its calculation at Norber

Caprock	**UCS (MPa)**	**Stress (MPa)**	**V (m^3)**	**Vr (m^3)**	**Vr/V**
N5	69.82	2.83	4.97	118.40	23.82
N19	65.70	2.93	5.10	114.36	22.42
N21	51.50	2.67	1.64	31.63	19.30

Table** Error! No text of specified style in document.**.5: Required volumes needed for caprocks N5, N19 and N21 to induce fracture of Cove Limestone bedrock at Norber

Gauges	Water (ml)	% re pptn.	Distance from caprock lip (cm)	pH
N5: 1 Control	100 (Pptn.)	100	In open – 16	5.61
2	27	27	Lip – 0	5.26
3	0	0	Under – 22	–
4	75	75	Lip – 0	5.56
5	0	0	Under – 24	–
6	91	91	Lip – 0	5.00
N11: 1 Control	186 (Pptn.)	100	In open – 68	
2	94	51	Lip – 0	
3	+600*	+323	Lip – 0	
4	4	2	Under – 6	
5	+600*	+323	Lip – 0	
6	0	0	Under – 44	
N12: 1 Control	81(Pptn.)	100	In open – 14	
2	178	220	Under – 7	
3	3	4	Under – 30	
4	29	36	Under – 23	
5	24	30	Under – 47	
6	15	19	Under – 26	
N14: 1 Control	102 (Pptn.)	100	In open – 31	
2	292	286	Lip – 0	
3	3	3	Under – 19	
4	0	0	Under – 17	
5	74	73	Under – 10	
6	3	3	Under – 27	
N15: 1 Control	379 (Pptn.)	100	In open – 34	
2	197	52	Under – 15	
3	+600*	+158	Lip – 0	
4	211	57	Under – 12	
5	+600*	+158	Lip – 0	
6	0	0	Under – 47	
N17: 1 Control	76 (Pptn.)	100	In open – 43	
2	166	218	Lip – 0	
3	76	100	Under – 6	
4	22	29	Under – 32	
5	4	5	Under – 42	
6	2	3	Under – 6	
N19: 1 Control	146 (Pptn.)	100	In open – 41	
2	23	16	Lip – 0	
3	222	152	Lip – 0	
4	0	0	Under – 52	
5	0	0	Under – 27	
6	184	126	Lip – 0	
N21: 1 Control	68 (Pptn.)	100	In open – 50	
2	0	0	Under – 10	
3	6	9	Under – 36	
4	52	76	Under – 31	
5	0	0	Under – 69	
6	78	115	Under – 51	
N27: 1 Control	134 (Pptn.)	100	In open – 75	
2	0	0	Under – 19	
3	0	0	Under – 27	
4	196	146	Lip – 0	
5	34	25	Under – 20	
6	69	51	Under – 20	

*Gauge full to the brim and overflowing.

Table** Error! No text of specified style in document.**.6: Water content and location of gauges for N5, N11, N12, N14, N15, N17, N19, N21 and N27 at Norber

Pedestal rock	% moisture	Distance to caprock edge (cm)
N5	1.8	32
N11	13.6	44
N12	62.4	0
N14	55.3	0
N15	3.1	38
N17	31.6	24
N19	4.7	52
N21	5.9	28
N25*	51.1	0
N27	11.5	20

*Covering erosion decantation runnels as seen in Plate 8.3

Table** Error! No text of specified style in document.**.7: Fabric moisture percent and distance of fabric to caprock edge at Norber

Pedestal rock	**r_s coefficient**
N5	-0.36
N11	-0.38
N12	-0.70
N14	-0.63
N15	-0.78
N17	-0.51
N19	-0.36
N21	-0.90
N25	Void*
N27	-0.45

* Only four sub-caprock rain gauges were emplaced

Table 8.8: r_s analysis of gauge distance to caprock outer edge (cm) and water in gauges (as a % of precipitation) at Norber

CHAPTER 9: PEDESTAL FORMATION AT NORBER – LIMESTONE FABRIC AND COMPOSITION

9.1: Introduction

Hughes (1886) contended that structure played a role in pedestal formation at Norber, noting (p. 535) that pedestals "…almost exactly represent the thickness of beds." Goldie (2005: 439) echoes this contention by asserting that pedestal height "…reflects bed thickness" and that "…composition of more than one bed explains pedestals of 80cm, while most 30-50cm cases relate to single bed thickness." Goldie (2005) also asserts (p. 439) that steps and plinths have reduced in extent "…along horizontal weaknesses", which seems to imply that pedestal bases coincide with a bedding plane. King (1976) also thought that structure played a part in pedestal formation observing that the pedestals have developed on the more susceptible beds of the limestone pavement, presumably equating susceptibility with greater discontinuity density. Goldie (2005) broadens the notion that discontinuity density may affect pedestal formation by proposing that weathering of weak and strong limestone results respectively in relatively high and low pedestal height. Goldie writes (p. 433) that the limestone at Norber is "…relatively weak" and "…well fractured" and accordingly places the site in the high pedestal category. Nothing has been penned on how limestone composition may affect pedestal formation at Norber, but Sweeting and Sweeting (1970) have written (p. 203) that an examination of bare rock (in north-west Yorkshire and the Burren) suggests that biomicrites "…weather more rapidly and are differentially more soluble than the sparry limestones". They also found (in north-west Yorkshire) (p. 204) that the presence of quartz "…normally tends to make the beds more resistant to weathering and solution." Matsukura *et al.* (2007: 1113) also argue that height differences of pedestals on Kikai-jima, Japan were due probably to the difference in the rate of surface lowering (of reefoid limestone) caused by geomorphological settings of each site "…including inhomogeneous lithology of limestone." Consequently, it would appear that fabric has played a role in pedestal formation at Norber and that limestone composition may perhaps have done likewise.

9.2: Aim and objectives

The aim of the work undertaken in Chapter 9 is to establish if limestone fabric and composition have influenced pedestal formation at Norber. The objectives are to measure pedestal height and discontinuity spacing, to note the nature of pedestal base/bedrock junctions and to examine thin sections of the limestones that compose the pedestals.

9.3: Method

Pedestal height was determined in a similar way as Goldie (2005: 434) using a rule with attached spirit level (horizontal component) and a metal rod (vertical component) (Plate 5.1). Vertical height was determined by measuring from the pedestal upper surface down to rockhead through any regolith that might be present, as it has been established (Section 7.6) that the inter-pedestal surface has been lowered beneath the regolith that abuts pedestal sidewalls. Pedestal height may thus be comprised of two components, i.e. exposed (E) and/or unexposed (U), as can be seen in Fig. 9.1. For continuity's sake pedestal height was measured at pedestal-width mid-point where feasible. The junction between pedestal base and rockhead was noted if it was exposed. Discontinuity spacing was surveyed and classified according to Bell (1993). Refer to Appendix 3D Tables 3D.1 and 3D.2 for full discontinuity results. Discovering if limestone fabric has influenced pedestal formation was determined largely by using Spearman's rank correlation analysis, as outlined in Section 8.7.3. In this case, the correlations between exposed pedestal height and bed thickness, and between exposed pedestal height and block surface area were calculated. A piece of loose rock was removed from two Kilnsey Limestone pedestals and from eight Cove Limestone pedestals (the numbers roughly representing the proportion of pedestals in each limestone type), and they were examined and described in thin section as in Section 5.3.4. Refer to Appendix 3TS.3 for full thin-section descriptions of the limestones. Spearman's rank correlation analysis was used to determine the relationship between pedestal height and the ratio of sparite cement to micrite matrix.

9.4: Limitations

The discontinuity spacing survey had to be restricted to measuring downslope sidewall only, since upslope and lateral sidewalls were sometimes inaccessible. This meant that although bedding-plane- and joint-spacing distances normal to the pedestal face were measured, joints parallel with the pedestal face were not. Moreover, bedding was measured on only exposed and not on unexposed surfaces, which means that bed-spacing and block surface-area results are not representative of the downslope sidewall as a whole. Bell (1993) has recommended that in order to ensure surveys are representative of the outcrop in question, measurements should be taken over distances of about 30m and a minimum of at least two hundred readings per locality are required. The relatively small size of the pedestals meant it was totally unfeasible to comply with either recommendation. Moreover, it proved possible to measure only approximate pedestal height, as there were difficulties with:

1. Gaining access to pedestal sidewalls where they are overhung by their cap rock

2. Deciding where to measure height from, since pedestals very rarely have a flat upper surface

3. Deciding where to measure height to when the pedestal was surrounded by rockhead or when rockhead occurred nearby since its surface is not flat

4. Knowing whether the measuring rod had reached rockhead or an intervening clast or had plunged down an open joint when pedestals are surrounded by regolith

The first difficulty could not be surmounted, which means that sampling error might have occurred. The remaining difficulties were partially overcome by sight-estimating mean pedestal crown and surrounding bare rock levels, and by hammering the metal measuring rod into the ground until it was believed from hammer on rod 'ring' differences that rockhead had been reached. The difficulties of determining pedestal height are amply revealed in Plate 7.4. Consequently, discontinuity-spacing and pedestal-height results leave something to be desired. Furthermore, it was possible to view clearly the sidewall-bedrock junction of only part of three pedestals, as vegetation/regolith obscured all others.

9.5: Results

Thirty pedestals were examined for the purpose of discontinuity analysis. One (N4) is excluded from the results because it was not possible to measure its downslope (i.e. south-eastern) sidewall height, four (N1, N3, N25 and N26) because they occur on bench edges and two (N8 and N22) because their caprocks had partly foundered. Table 7.6 reveals that pedestal downslope heights range from about 18cm (N11) to 79cm (N24), a four-fold difference. These results are similar to original observations on pedestal heights as reported in the literature (Goldie, 2005), which ranged from about 30 to 80cm. Table 7.6 also reveals that the upslope and downslope height of individual pedestals ranges greatly. For example, N17 has respective upslope and downslope heights of about 51 and 36cm, and N24 of about 29 and 79cm. Table 9.1 shows that the number of beds recorded on exposed downslope sidewalls ranges from 1-5. The spacing of discontinuities on exposed downslope sidewalls also varies greatly, as mean bed spacing ranges from 9cm (N9 and N20) to 56cm (N12), mean joint spacing from 10cm (N13 and N17) to 59cm (N18) and mean block surface area from 100cm² (N13) to 1904cm² (N12). The three pedestal sidewall-rockhead junctions that are exposed consisted of a bedding plane (N5 and N13) and of inter-bedding plane rock (N32) (Plate 7.4). Ten pedestals were sampled for the purpose of thin-section analysis. Table 9.2 shows that the limestones that comprise the pedestals are broadly similar and that most are either bio-pelsparites (Folk, 1959) or pellet packstones (Dunham, 1962), both classifications cited in Tucker (2001); most are also medium grained and contain more pellets than shell debris. Otherwise, differences consist of variations in the relative abundance of allochems, sparite cement and micrite matrix, while Kilnsey Limestone pedestals contain a mean of 20% extraclasts and traces of allogenic quartz. Table 9.3 illustrates that the ratios of sparite cement to micrite matrix range from 1:3 to 7:1.

9.6: Analysis

It is difficult to comprehend how Hughes (1886) and Goldie (2005) concluded that pedestal height is related to the thickness of beds because vegetation/regolith covers the limestone up to the base of all but three pedestals. It was noted in Section 9.5 that the upslope and downslope height of individual pedestals may differ greatly. For example, it can be seen in Table 7.6 that the respective upslope and downslope height of N6 and N12, both of which occur on level ground, are about 50 and 37cm, and about 48 and 62cm. The upslope-to-downslope width of pedestals N6 and N12 is respectively about 2.5m and 2m, which means that as pedestal widths are relatively narrow the thickness of beds within them will remain more-or-less constant. Moreover, the downslope sidewall of N32 suddenly almost doubles in height from 21 to 40cm (Plate 9.2). As a result, Hughes' (1886) and Goldie's (2005) proposal that pedestal height reflects bed thickness is rebutted on the grounds of differences in upslope and downslope pedestal heights of individual pedestals, and changes in their lateral sidewall height. The rebuttal is confirmed using Spearman's rank correlation analysis. Thus, calculation of the correlation between exposed pedestal height and bed thickness gives a coefficient of +0.20 (n=23). It is generally accepted that weak rock, i.e. rock with a relatively high density of discontinuities, is more susceptible to weathering and failure than strong rock, i.e. rock with a relatively low density of discontinuities (e.g. Hoek and Bray, 1981). Hence Goldie's (2005) suggestion that weathering of weak and strong limestone results respectively in relatively high and low pedestals is somewhat perplexing. Barton (1978) has written that block size provides an important indication of rock mass strength. Hence, if discontinuity densities have influenced pedestal development, as suggested by Goldie (2005), lower pedestal height should be mirrored by greater block size. It was not possible to calculate mean individual block size for pedestals, since discontinuity spacing of lateral sidewalls could not be measured. The mean downslope surface area of blocks could be calculated, though, and Spearman's rank correlation between block surface area and exposed pedestal height is +0.37 (n=23). This means that there is, in fact, a positive correlation between the two variables, which is contrary to Goldie's (2005) suggestion, since the correlation is statistically significant at the 90% level. Consequently, Goldie's (2005) suggestion is rejected. King's (1976) observation that the pedestals have developed on the more susceptible beds is also rejected, since pedestals occur in limestone with a block surface area ranging from 100 (N13) to 1904cm² (N12), a nineteen-fold difference. It is not possible to uphold or rebut Goldie's (2005) assertion that steps and plinths have reduced in extent along horizontal weaknesses of beds since just three sidewall-rockhead junctions were exposed.

Sweeting and Sweeting (1970) have written that biomicrites weather more rapidly and are differentially more soluble than sparry limestones. This indicates that pedestal height might be proportional to the ratios of sparite cement and micrite matrix. Pedestals N1 and N3 are excluded from the results since they contain extraclasts and allogenic quartz, and N25 and N26 because they occur on bench edges. Thus, just six pedestals were considered. If biomicrites do weather more rapidly and are differentially more soluble than sparry limestones, it follows that N21 ought to be taller than N5 since their respective ratios of sparite cement to micrite matrix are 7:1 and 1:3. This is the case, as N21 has a mean height of about 39cm and N5 of about 35cm (Table 9.3). Nevertheless, the hypothesis that the ratios of sparite cement and micrite matrix may have a bearing on pedestal height is considered untenable. Thus, although the respective ratios of N7 and N23 are 2:1 and 6:1, N7 is the tallest (about 51cm high) and N23 the smallest (about 28cm high) of the six pedestals. The untenability of the hypothesis is confirmed using Spearman's rank correlation analysis that gives a correlation coefficient of -0.26 (n=6) between the two variables, which is not statistically significant. The sample size of the Kilnsey Limestone pedestals (just two) is too small to reveal whether the presence of quartz/extraclasts has affected pedestal formation or not.

9.7: Conclusion

There is no indication that limestone fabric and composition have influenced pedestal formation at Norber. This is because any link between formation and bedding (Hughes, 1886, King, 1976 and Goldie, 2005) is discounted on field evidence, and because rock strength (Goldie, 2005) and the ratio of sparite cement to micrite matrix (Sweeting and Sweeting, 1970) are discounted on statistical evidence.

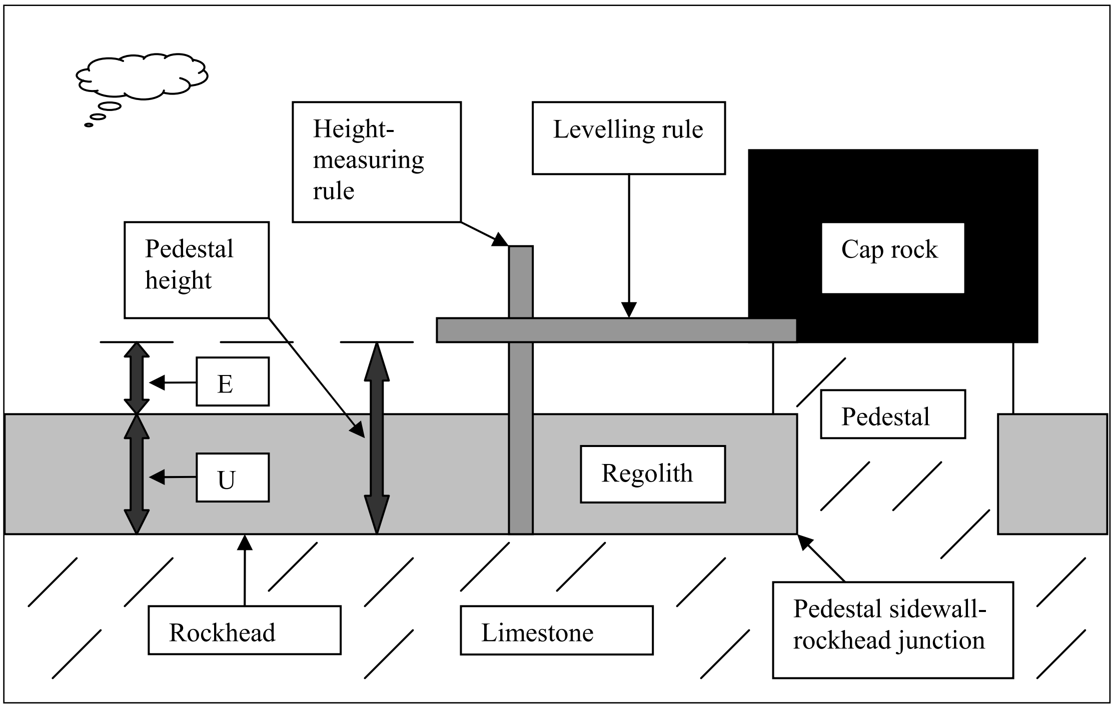


Fig. *Error! No text of specified style in document.***.1: Method for determining pedestal height**

Note that pedestal height consists of two components, E (exposed) and U (unexposed).

Pedestal number	**Downslope pedestal height (cm)**	**Number of downslope beds**	**Mean downslope bed spacing (bs) (cm)**	**Mean downslope joint spacing (js) (cm)**	**Mean downslope block surface area (bs x js) (cm²)**
N2[1]	35	2	18	26	468
N5	34	2	17	24	408
N6	37	3	12	16	192
N7	52	3	17	15	255
N9	34	4	9	16	144
N10	69	2	35	13	455
N11	18	1	18	27	486
N12	56	1	56	34	1904
N13	39	3	10	10	100
N14	41	2	21	21	441
N15	64	3	18	31	558
N16	40	3	13	15	195
N17	36	1	36	10	360
N18	51	4	13	59	637
N19	20	2	10	37	370
N20	43	5	9	49	441
N21	30	1	30	15	450
N23	36	3	12	18	216
N24	58	4	15	29	435
N27	46	1	46	15	690
N28	27	1	27	15	405
N29	30	2	15	12	180
N30	40	1	40	18	720

[1] Kilnsey Limestone. All others are Cove Limestone

Table** Error! No text of specified style in document.**.1: Exposed pedestal height, and exposed mean bedding/joint spacing and mean block surface area of downslope sidewalls at Norber

Pedestal number	**Grain size (Wentworth Scale)**	**Allochems (%)**	**Sparite cement (%)**	**Micrite matrix (%)**	**Classification (Folk, 1959)**	**Classification (Dunham, 1962)**
N1[1]	Medium	70	20	Trace	lithic bio-pelsparite*[1]	lithic pellet packstone
N3[1]	Medium	50	20	Trace	lithic bio-pelsparite*[2]	lithic pellet packstone
N5	Medium	80	5	15	bio-pelmicrite	pellet packstone
N7	Medium	70	20	10	bio-pelsparite	pellet packstone
N13	Medium	80	15	5	bio-pelsparite	pellet packstone
N19	Medium	85	12	3	bio-pelsparite	pellet packstone
N21	Coarse	60	35	5	bio-pelsparite	bioclastic rudstone
N23	Medium	65	30	5	bio-pelsparite	pellet packstone
N25	Medium	75	20	5	bio-pelsparite	pellet packstone
N26	Medium	80	15	5	bio-pelsparite	pellet packstone

[1] Kilnsey Limestone. All others are Cove Limestone

*[1] contains 10% extraclasts

*[2] contains 30% extraclasts

Table *Error! No text of specified style in document.***.2: Summary of grain size and mineralogy of Norber pedestals, and their classification***

Pedestal number	**Mean pedestal height (cm)**	**Ratio of sparite cement and micrite matrix**
N5	35	1:3
N7	51	2:1
N13	45	3:1
N19	47	4:1
N21	39	7:1
N23	28	6:1

All Cove Limestone

Table** Error! No text of specified style in document.**.3: Pedestal height and the ratio of sparite cement to micrite matrix at Norber

CHAPTER 12: PEDESTAL FORMATION AT NORBER – POST-DEVENSIAN-DEGLACIATION PERIGLACIAL TUNDRA AND TEMPERATE ARBOREAL ENVIRONMENTS

10.1: Introduction

There is ample literature evidence to show that changes have occurred in the climate, soils and vegetation of Britain since Devensian deglaciation (e.g. Roberts, 1989; Allen 1997), all of which might be expected to have influenced pedestal evolution at Norber. Accordingly, if pedestal formation is to be completely understood, it is important to know what past environments have occurred at Norber subsequent to erratic deposition in ca.14500BP. It has been pointed out by Pigott and Pigott (1959) that a comparison of post-deglaciation pollen diagrams from many sites scattered over the British Isles reveals a very great deal of similarity in the main pattern of change in frequency of the various pollen types. Other countrywide patterns occur, for example, in periglacial features (Briffa and Atkinson (1997) and in Coleoptera assemblages (Lowe and Walker, 1997). Consequently, it would seem that evidence relating to post-ablation environmental changes drawn from elsewhere in the British Isles can be applied to Norber. This is especially so with those changes that are known to have occurred at nearby localities such as Malham Tarn/Tarn Moss (Pigott and Pigott, 1959), lowland Lonsdale (Oldfield, 1960), Scar Close (Gosden, 1968), Thieves Moss (Smith, 1986) and Craven (Gascoyne *et al.*, 1983; Bartley *et al.*, 1990).

10.2: Literature review of climate, soil and vegetation changes since ca.14500BP with emphasis on localities in close proximity to Norber

The expansion of Devensian ice began at ca.28000BP and at its maximum extent at ca.18000BP (e.g. Gascoyne *et al.*, 1983) an ice sheet covered the Craven area reaching as far south as the Wash, the southern Pennines and South Wales (Fig. 3.2). By ca.14500BP the ice was in retreat or had vanished altogether in western England and Wales (Atkinson *et al.*, 1987) leaving behind areas of bare, scraped rock and a variety of diverse deposits. Little is known of the years during the period of glacial wasting, but vegetation was so sparse in the Lake District prior to ca.14500BP to have left no organic record in coarsely laminated clays deposited from seasonal melt of a remnant ice cap (Pennington, 1977). Pollen analysis from many post-ca.14500BP sites dotted over the British Isles is indicative of treeless tundra vegetation that had colonised the immature soils of the newly deglaciated land (Ingrouille, 1995). It is envisaged that the climate was probably similar to that found in north-west Siberia at present (Atkinson *et al.*, 1987), and that the mean monthly warmest temperature was 7°C and the coldest was -30°C (Briffa and Atkinson, 1997).

There is evidence of amelioration from ca.13500BP late in the Devensian, but the first clear proof for sustained and widespread warming occurred at ca.13000BP (Lowe and Walker, 1997). The climatic improvement beckoned in the Windermere Interstadial, and by ca.12500BP respective mean summer and winter temperatures were approximately 17.5°C and 0°C (Briffa and Atkinson, 1997), a few degrees colder than at present. Precipitation was probably less than that of today (Lowe and Walker, 1997). The earliest vegetation was one of tundra *Dryas* heath and the initial soils were probably nutrient-rich until leaching made them more acidic (Ingrouille, 1995). The *Dryas* heath was replaced by a flora dominated by Arctic alpines, sedges, shrubby willow and dwarf birch, and then by one of open woodland. Prior to ca.12000BP there is little evidence of woody plants at Malham Tarn/Tarn Moss, but after this date pollen grains of *Betula* (birch) and later *Pinus sylvestris* (Scots pine) appear (Pigott and Pigott, 1959). Similar changes took place at Thieves Moss and in lowland Lonsdale. Winter temperatures were too cold to allow a continuous tree cover, however, and the vegetation has been called 'park-tundra' emphasizing its open aspect (Ingrouille, 1995).

Temperatures gradually declined throughout the Windermere Interstadial and by ca.11000BP they had deteriorated sufficiently for periglacial conditions (the Loch Lomond Stadial) to reappear in the Craven area. The mean July and January temperatures dropped respectively to 7°C and -18°C (Dawson, 1992) similar to present day Alaska and Spitzbergen; it was also drier than at present (Briffa and Atkinson, 1997). The waning temperatures led to a regression in the vegetation, and the shrubs and woodland of the Windermere Interstadial were replaced by low-growing tundra communities similar to those of 2000 years beforehand.

An abrupt climatic improvement occurred at ca.10300BP and by ca.10000BP temperatures had attained levels typical of today (Briffa and Atkinson, 1997). The warming, which ushered the Flandrian in, went hand-in-hand with much expansion of trees. By ca.7000BP, at the time of the so-called climatic optimum, *Quercus* (oak), *Ulmus* (elm) and other broad-leaved trees had spread into the area; similar vegetational changes likewise occurred in lowland Lonsdale. In fact, by this time a woodland cover (the Wildwood) was established over most of upland Britain, and as the tree-line was about 700-800m in England and Wales throughout the period (Atherden, 1992) Norber (approximate altitude 300m) lay below it at all times. There is evidence of increasing wetness of climate during the establishment of the climax community and Ingrouille (1995) states that precipitation in upland Britain was 120% and in lowland Britain 110% of the present average. The early soils of the Flandrian forests were base rich and shallow, and were low in organic content (Berglund, 1986), but it is likely that calcareous brown earths with a mul humus had developed on most limestone areas by ca.5000BP.

At ca.5000BP retrogressive changes in the vegetation of Britain occurred that led to a reduction in tree cover and an increase in heaths, blanket mires and grasslands, and the tree line dropped to its present level of about 530m (Ingrouille, 1995). This transformation was brought about by a natural progressive leaching of the soil and an associated change from a mor to a mul humus, which may have been exacerbated by an increase in precipitation between ca.4000-2500BP (Berglund, 1986). Thus peat began to accumulate at Scar Close at the expense of open alder and hazel due to increased cloudiness and decreased evaporation (Gosden, 1968). Furthermore, Neolithic man was settling the country at ca.5000BP and was making forest clearances; this continued unabated throughout the Bronze and Iron Ages (Hockey, 1969). At Malham Tarn/Tarn Moss, as also in lowland Lonsdale, the clearances are marked initially by a decline in elm and later by an increase in herb pollen (Pigott and Pigott, 1959), as 'poeticised' in 'The Elm Decline' by Norman Nicholson (cited in Halliday, 1997):

"Seven
thousand years ago
trees grew
high as the tarn.

Then
round the year Three
Thousand BC,
the proportion of the elm pollen
preserved in the peat
declined from twenty
percent to four.

Stone axes,
chipped clean from the crag face,
ripped the hide off the fells.
Spade and plough
scriated the bared flesh
skewered down to the bone."

Different areas of Craven appear to have been cleared of trees at different times, as Bartley *et al.* (1990) have shown that limestone grassland was not established at Eshton until ca.3100BP while the clay-rich soils of White Moss were not cleared until ca.1400BP. Pigott and Pigott (1959) suggest that the present treeless condition of the limestone pavements at Malham Tarn/Tarn Moss followed clearance in the Iron Age at ca.3000BP. Nevertheless, there is circumstantial evidence that areas of Craven were still wooded at the time the Britons were settling the area in ca.2600BP. Hence, the place name Craven is possibly derived from the Welsh 'craf' meaning garlic (Ekwall, 1960; Smith, 1986), and garlic is a plant of damp woods (Clapham *et al.*, 1981). There is indication of an increase in pasture between ca.650-450BP, while large areas of Craven were put under grass in the late eighteenth century (Bartley *et al.*, 1990). The net effect of the forest clearances was an acceleration of soil degradation; thus mor humus accumulated and soils became podsolized or even eroded (Berglund, 1986). There is much evidence to show that rainfall acidity has increased over the past 200 or so years, the increase being started by the industrial revolution (Elsworth, 1984). Thus, Alcamo *et al.* (1990) state that (in the last 20-50 years) the chemistry of (forest) soils over large areas of Europe has changed significantly, including a five-to-ten-fold increase in acidity. A generalised summary of the above past environments can be found in Table 10.1.

10.3: Field evidence for past environments

10.3.1: Introduction

Evidence from the literature review shows that the time-span between Devensian deglaciation and the creation of the present-day man-made landscape consisting largely of grasslands in south Craven can be grouped into two past environmental periods, an earlier periglacial tundra period and a later temperate arboreal period. Both are vastly different from the present day environment. Accordingly, it is important to confirm in the field that the periglacial tundra and the temperate arboreal periods once existed at Norber, because doing so will have a bearing on dissolution rates, step retreat (Goldie, 2005) and the authenticity of the umbrella theory.

10.3.2: Aim and objectives

The aim of the work undertaken in Chapter 10 is to establish whether there is evidence of post-Devensian-deglaciation periglacial tundra and temperate arboreal environments at Norber. The objectives are to record periglacial tundra landforms and vegetation at Norber and in Crummackdale, and to undertake a vegetation survey at Norber.

10.3.3: Method

The landform survey involved recording cold-climate features at Norber and in Crummackdale. The vegetation survey was based on the floristic approach of Kent and Coker (1995), and was carried out along two transect lines, one each on regolith and limestone pavement. This enabled the maximum variation in vegetation to be covered over the shortest distance within a comparatively limited time-span. A 1x1m quadrat was used to resolve the number of species present and the distance between each count was twenty metres in most cases. All species were identified in the field, flowering plants using Clapham *et al.* (1981) and ferns using Phillips (1980). The survey was carried out in late spring as this allowed maximum identification of different species since dead heads, open flowers and closed buds were present on flowering plants, and leaves were unfurled on woody plants and ferns. In addition, the presence of vegetation which was thought relevant to the survey but which did not occur on transect lines was also noted. Refer to Appendix 3V.1 for a full list of species recorded in quadrats.

10.3.4: Limitations

The floristic survey concentrated on the identification of ferns, herbs and woody plants due to author knowledge in this field of botany, although sedges and grasses were named where possible. No attempt was made to name mosses, liverworts and lichen, however, as it was not felt that this could be undertaken with confidence. Consequently, only some of the vascular flora and no lower plants were identified. The objective of the survey is, though, relatively unsophisticated and it is not felt that the shortcomings detracted from the results obtained.

10.3.5: Results

A record of frost action landforms and an account of their formation are given in Section 7.11. Further to cold-climate results, the author has previously seen periglacial tundra vegetation, such as purple saxifrage (*Saxifraga oppositifolium*), lady's mantles (*Alchemilla* spp.) and clubmosses (*Lycopodium* spp.) on Ingleborough and Pen-y-ghent. Today, these plants grow only in the Arctic and above the tree line on some/all of the main European mountains ranges (Raven and Walters, 1956).

Seventeen species were identified in the plant community growing on the Malham Formation limestone pavement. Nine are suggestive of an under-canopy arboreal environment since habitat descriptions in Clapham *et al.* (1981) are couched in such terms as (p. 28) "Chiefly in deciduous woodland …" or (p. 190) "In woods…":

Dryopteris filix-mas (male fern)
Asplenium scolopendrium (hart's tongue fern)
Anemone nemorosa (wood anemone)
Geranium robertianum (herb robert)
Oxalis acetosella (wood sorrel)
Fragaria vesca (wild strawberry)
Sanicula europea (sanicle)
Mercuralis perennis (dog's mercury)
Primula vulgaris (primrose)

Three further species, *Hedera helix* (ivy), *Crataegus monogyna* (hawthorn) and *Fraxinus excelsior* (ash) either form or are part of the structure of hedgerows/scrubland/woods. In addition, *Asplenium trichomanes* (maidenhair spleenwort), *Asplenium ruta-muraria* (wall-rue spleenwort) and *Mycelis muralis* (wall lettuce), which are indicative of a rupestral environment, *Urtica dioica* (stinging nettle), which is mainly ruderal, and *Thymus praecox* (wild thyme), which grows in turf, were found.

Eighteen species were identified in the plant community growing on the regolith. Fifteen plants are indicative of an open, pastoral environment as descriptions of the habitat of individual species in Clapham *et al.* (1981) is peppered with such phrases as (p. 31) "Common in meadows and pastures…" or (p. 455) "Widespread in grassy places…".

Ranunculus acris (meadow buttercup)
Polygala vulgaris (common milkwort)
Cerastium fontanum (common mouse-ear chickweed)
Cerastium semidecandrum (little mouse-ear chickweed)
Minuarita verna (vernal sandwort)
Lotus corniculatus (bird's-foot trefoil)
Potentilla erecta (common tormentil)
Vaccinium myrtillus (bilberry)
Thymus praecox (wild thyme)
Plantago lanceolata (ribwort plantain)
Galium sterneri (Sterner's bedstraw)
Hieracium sp. (hawkweed)
Carex flacca (glaucous sedge)
Festuca ovina (sheep's fescue)
Briza media (common quaking grass)

Two further species, *Veronica chamaedrys* (germander speedwell) and *Urtica dioica* (stinging nettle) have a more catholic taste in habitat, since each can also occur in an arboreal as well as in a pastoral environment, while one further species, *Crataegus monogyna* (common hawthorn), is a plant of hedgerows and scrubland.

It was also noted that ash is established on a dozen or so erratics, *Sambucus nigra* (elderberry) grows amongst scree at Norber, mature hawthorn, elderberry, ash and *Ulmus procera* (English elm) flourish at Nappa Scars, semi-natural woodland occurs at Oxenber and native plantations thrive on Thwaite Top. All species are typical of a temperate environment.

10.3.6: Analysis

Most plant geographers, including Darwin (1859), have argued that the discontinuous nature of the European cold-climate flora is generally interpreted as a relict distribution of plants formerly much more widespread than today. There is no uncertainty that a tundra flora was once more prevalent in Britain, as many tundra plant remains have been found in deposits that occur to the south of the maximum extent of the Devensian ice sheets. These include sites at Barnwell in Cambridgeshire (Chandler, 1921), the Lea Valley in Essex (Reid, 1949) and Upton Warren in Worcestershire (Coope *et al.*, 1961), the former yielding amongst many other species purple saxifrage. Raven and Walters (1956: 79) explain the present scattered distribution of the cold-climate flora in Britain by writing that a great migration "… must have taken place since the retreat of the ice. In the course of this migration with climatic improvement, many species and colonies have become extinct over quite large areas, but have generally found odd 'refuges' on mountains where soil and climate conditions are most suitable for them", which explains the presence of the tundra vegetation on Ingleborough and Pen-y-ghent.

Silvertown (1982: 651) has written that it is difficult to imagine "…how pavements, which are now isolated in a sea of sheep hostile to woodland plants, could have been colonized by these plants after grazing began." In fact, Silvertown (1983) believes that the under-canopy flora evident in the grykes of open pavements may be a relict of a former arboreal setting. Ingrouille (1995) has pointed out, though, that grykes provide similar conditions of shade and humidity to an arboreal environment. Thus the presence of woodland plants whose spores/seeds/fruits could have arrived on the wind (male fern, hart's tongue fern and ash) or via bird droppings (wild strawberry, hawthorn and ivy) or on animal coats (sanicle) do not necessarily indicate a former arboreal setting. Moreover, no flowers or seed/fruit heads were present on the hawthorn, ash and ivy due to nibbling, which suggests that they may never have fruited and that all three are immigrants. The seeds of the five remaining under-canopy species, i.e. wood anemone, herb robert, wood sorrel, dog's mercury and primrose, are not spread by the wind or by animals, however, and discard much less freely. Consequently, as their nearest known extant site is Oxenber (an area of semi-natural woodland) some 2km distant across livestock-browsed meadows (Plate 1.1), it is proposed that these five species are a relict arboreal flora. This origin is further substantiated by the observation that the lower parts of the five species (and of all the under-canopy ferns and herbs) in the grykes were un-nibbled. This means that flowering is possible, that progeny is being produced (spore sacs/seed heads were present) and that the flora is being maintained. The occurrence of plants characteristic of exposed rock and walls admixed with the sub-canopy vegetation is typical of that found on limestone pavements in the area (Ward and Evans, 1976; Ratcliffe, 1977). Clearly, if the pavement was once clothed in woodland, as the presence of the five herbs suggests, the rupestral flora must have migrated onto the pavement after the trees had been removed, and it is significant to note that the spores/seeds of the three colonizers are all wind-dispersed. Stinging nettles may or may not be relict, whereas the thyme must have colonized the clints from the nearby grassland.

The regolith at Norber mostly consists of brown earths developed on weathered till (Section 7.6.2) that is relatively fertile, since none of the identified species are indicative of waterlogging or of high acidity. It is also relatively thick in places, as the presence of molehills shows it is at least 15-18cm deep over fairly wide areas, since moles (*Talpa europaea*) require an underground nest chamber of this diameter for breeding purposes (Harrison Matthews, 1952). The natural climax vegetation of brown earths is a thick cover of deciduous forest (e.g. Whittow, 1984), and the presence of nearby woodland shows that the pasture at Norber, which appears to be no different from that in the vicinity, could well support such a cover. Thus the lack of woodland species and presence of pastureland species on the regolith can be explained by the grazing action of domesticated sheep (*Ovis aries*) and cattle (*Bos taurus*). Moreover, the single hawthorn (which had recently germinated since cotyledons were present) in the pasture shows that regeneration would inevitably occur if grazing ceased.

10.3.7: Conclusion

The presence of scree at many localities in the immediate area, and the relict cold-climate flora on Ingleborough and Pen-y-ghent confirms that a periglacial tundra environment preceded the present grassland setting at Norber. The literature evidence suggests that this environment was extant between ca.14500 and 10000BP. The relict pavement under-canopy flora at Norber and the presence of relict woodland in Craven show that a temperate arboreal environment also preceded the present grassland setting, the literature evidence suggesting that this environment lasted from ca.10000 to 3000BP. Pigott and Pigott (1959) have pointed out that to judge from fragments of ancient woodland which survive today on pavements (e.g. at Colt Park) a closed tree canopy can be produced even if the trees are restricted only to grykes. Thus, as rundkarren occur on clints at Norber (which indicates that the regolith were once more extensive than it is today) and as the pavement is well-jointed, often broken and generally has well-developed grykes, it is likely that the arboreal environment consisted of a closed canopy. Moreover, there would appear to be no pedalogical constraints to a closed canopy having developed on the regolith at Norber. Hence, dense woodland occurs on regolith at Oxenber, while mature trees readily grow near Norber in far more inimical conditions, such as from cracks in the limestone on Nappa Scars (Plate 10.1), and on scree in Upper Wharfedale and in Littondale, for example. Woodland also occurs at higher altitudes than Norber at Colt Park and at Scar Close. Therefore, it is proposed that both a periglacial and an arboreal environment preceded the present-day grassland setting at Norber, and that the woodland formed a closed-canopy forest.

Plate** Error! No text of specified style in document.**.1: Trees at Nappa Scars

The mature trees at Nappa Scars, which are a few hundred metres to the south of Norber, are growing on/from limestone cliffs that are largely devoid of soil. Consequently, it is impossible to envisage that Norber, which is largely mantled in regolith up to 1m thick, was not totally over-canopied by the Wildwood prior to forest clearance.

Dates (BP)	**Temp. (°C)**	**Relative precipitation**	**Soil**	**Vegetation and Pollen Zone**	**Geological-Climatic unit**
14500-13000	7° to -30°	Drier	Immature developing on drift	Tundra: treeless with low growing vegetation: I	Devensian Stadial
13000-11000	17.5° to 0°	Drier	Nutrient rich with leaching later	Park-tundra: birch/pine meadows: II	Windermere Interstadial
11000-10000	7° to -18°	Drier	Nutrient rich	Tundra: treeless with low growing vegetation: III	Loch Lomond Stadial
10000-5000	Degree or two warmer than today	20% wetter	Brown earths with mul humus	Arboreal: Scots pine, oak and elm: IV to VIIa	Flandrian
5000-3000	Similar to today	Increased wetness	Leaching with mor humus	Arboreal: alder, and oak: VIIb	
3000-present	Similar to today	Similar to today	Leaching with soil erosion	Pastoral: limestone grassland: VIII	

Table *Error! No text of specified style in document.**.1: Generalised summary of post-ca.14500BP climate, soils and vegetation in south Craven***

CHAPTER 11: THE FORMATION OF THE LIMESTONE PEDESTALS AT NORBER

11.1: Introduction

It has been shown in Chapters 7-9 that although a variety of processes operating in the present temperate grassland environment has contributed to pedestal formation at Norber, that in essence sub-regolith dissolution has played the primary role with sidewall failure and sub-aerial dissolution playing a secondary role. In the following account these three processes are fused with additional processes (and phenomena) from the tundra/periglacial and arboreal environments outlined in Chapter 10 to reveal pedestal formation at Norber through time. In addition the effects of glacial erosion, which occurred prior to pedestal formation, is also considered, as is future pedestal development.

Preciously few observations have been undertaken in high-latitude Arctic environments either to establish rates of limestone dissolution or to explore pedestal formation. Thus, of the two studies that are most applicable, i.e. Smith (1972) and Lauritzen (2005), neither is especially relevant to Norber, since the limestones at their sites are, or at least appear to be, largely subaerial. Nothing has been written exclusively on Carboniferous limestone dissolution rates in an arboreal environment, the closest example being that of Pentecost (1992), who conducted a survey in the southern Yorkshire Dales that included woodland but which did not differentiate between it and contrasting environments. Consequently, the following account of pedestal formation at Norber can draw on little literature information re dissolution in these two environments. For simplicity's sake minor processes, such as soil creep erosion and biogenic weathering, are not included in the ensuing account, while for clarity's sake vegetation is omitted from diagrams. No attempt has been made to put figures on limestone dissolution rates; rather, they are relative to those of today. Accounts of two other features at Norber, i.e. erratics without pedestals (Section 11.3) and pedestals without caprocks (Section 11.4), and reference to the umbrella theory (Section 11.5) are also included.

11.2: Limestone pedestal formation

11.2.1: The periglacial/tundra environment of ca.14500 to 10000BP

As indicated in section 7.1, the immediate post-Devensian-deglaciation periglacial/tundra panorama at Norber in ca.14500BP consisted primarily of a glaciokarst 'staircase' landscape of limestone scars and benches, the latter peppered with erratics and mostly overlain by till. The erratics were not only to be found spread across the broad expanse of the benches but also teetering above their edges, as noted by Goldie (2005) and Waltham (2005). Today, every erratic at Norber that can be seen to have a pedestal beneath it rests either directly on *in situ* limestone or at most is separated from it by till a few centimetres thick or by glacial clasts up to 12cm in size. In addition, every pedestal is surrounded by vegetation-covered regolith. Consequently, those erratics that have since become caprocks would originally have been deposited more-or-less directly on rockhead and the lower part of their sidewalls would have been abutted by regolith (Fig. 11.1).

Periglacial/tundra areas typically receive about 300mm of precipitation per annum today (Lockwood, 1974), which when combined with the presence of tundra vegetation implies that the potential for groundwater to effect dissolution by absorbing carbon dioxide from the regolith was present at Norber from ca.14500BP onwards. Yet Gascoyne *et al.* (1983) found that speleothem growth in the caves of Craven (including Ingleborough and Gaping Gill close to Norber) did not begin before ca.13000BP because the ground/bedrock water was frozen. This means that water was neither available to dissolve limestone nor to drain into the caves below. As such, pedestal formation would have been unable to commence prior to this date. The incidence of treeless tundra vegetation in the area (Pigott and Pigott, 1959), however niggard, signifies that an active layer must have been present, though, if only for the few months of the short tundra summer. Consequently, it is conceivable that dissolution of rockhead by active-layer water might have occurred prior to ca.13000BP, the dissolved calcium carbonate being carried away in surface/ground water. There is no evidence at all of overland drainage at Norber, however, (Section 7.4) and nor is there any account in the literature of local active-layer landforms, such as solifluction lobes or cryoturbation, despite the numerous quarry sections available for inspection. Therefore, it is believed that the active layer must have been of little or no consequence, especially as Norber largely faces east, which means it would have received only early-morning insolation. Accordingly, it is proposed that pedestal formation commenced but little until ca.13000BP when thawing of the permafrost occurred. The thawing allowed aggressive till-water to corrode rockhead, the latter not including the limestone surface beneath erratics where they rested directly on it, and this marks the beginning of the lowering of the inter-erratic limestone surface and pedestal formation. The dissolution produced vertical-walled pedestals, since the rate increased from 'insignificant' under the erratics to 'significant' beyond their distal margins. At this juncture in time the erratics 'morph' into caprocks since pedestals have formed beneath them and the inter-erratic limestone surface consequently 'morphs' into the inter-pedestal limestone surface. As soon as incipient sidewalls had formed they would have become subjected to concomitant lateral sub-regolith dissolution, which leads to pedestal narrowing relative to the overlying caprock via undercutting (Fig. 11.2). It would seem that dissolution of rockhead probably progressed at a relatively slow pace from ca.13000 to 10000BP, as Gascoyne *et al.* (1983) found that although there is evidence of speleothem growth during this period abundant growth (which is comparable to that of today) did not begin until ca.10000-9500BP. Apart from the relatively low precipitation and temperatures from ca.13000 to 10000BP, Gascoyne *et al.* (1983) also ascribe the lack of speleothem growth to a lack of carbon dioxide generation due to the sparse vegetation cover. The latter point is supported by Ford (1971) and Lauritzen (1981), who have shown elevated carbon dioxide and calcium concentrations below the tree line in Alpine areas. It is also supported by respective figures of the mean depth-equivalent surface lowering rates for Norber and woods on Oxenber using limestone tablets, which are 4.03 (Section 7.6.6) and 6.90mm ka (Section 12.6.3). It must be pointed out, though, that the tablets at Norber were emplaced normal to the limestone surface while those on Oxenber were emplaced parallel with it, which may have affected tablet dissolution rate-loss. Nevertheless, it is proposed that significant pedestal development did not occur from ca.14500-10000BP due to a combination of frozen ground, low rainfall and sparse vegetation. It is also likely that the occurrence of nutrient-rich soils (Ingrouille, 1995) may simultaneously have acted against pedestal formation by buffering rockhead and sidewalls alike from dissolution.

11.2.2: The temperate arboreal environment of ca.10000 to 3000BP

At first sight it would seem that dissolution of rockhead would have proceeded at a greater pace from ca.10000 to 5000BP when compared to today, since upland Britain was up to 20% wetter (Ingrouille, 1995). Interception and evapotranspiration rates are greater over forest than over grassland (e.g. Ward and Robinson, 2000), however. Indeed, O'Loughlin (1988) cites interception rates 20% higher for closed-canopy woodland than for lightly-grazed grassland while Calder (1979) quotes evapotranspiration losses (within the Severn catchment) for a fully forested area as exceeding those of grassland by a factor of two. As a result, it is likely the greater wetness from ca.10000 to 5000BP would have been more than offset by the greater interception and evapotranspiration rates. Berglund (1986) has highlighted that a natural progressive leaching of the soil and an associated change from a mor to a mul humus occurred during the Flandrian, which signifies that dissolution probably rose from ca.10000 to 5000BP due to the attendant increase in soil acidity. At the same time pedestal development may have been augmented by the probing action of tree roots, as many authors (e.g. Curtis *et al.*, 1976) have highlighted that tree roots can cause mechanical disintegration of rock. This is backed up by evidence from the Cavan Burren (Section 12.8) and Underlaid Wood (Section 12.20), which are the only pedestal sites with a continuous over-canopy, where tree roots have penetrated rockhead and pedestals alike. Tree root weathering cannot lower rockhead, though, but it will increase the surface area liable to dissolution. If the physical break-up of rockhead by tree roots has indeed assisted pedestal formation, it is the only process that has contributed to formation at Norber that is not extant today. Curtis *et al.* (1976) have also highlighted that trees can offset the effects of leaching by 'pulling up' calcium and other nutrients from their root zone. The nutrients are then deposited back on the soil in leaf litter. Grasses and other lower plants also do this, but to a lesser extent, because their rooting depth is much shallower and they cannot bring nutrients up from any great depth. As a result, the leaf litter in the Flandrian forests may have buffered both rockhead and sidewalls from dissolution. On balance, then, it would seem that pedestal development probably proceeded at an ever-increasing rate during ca.10000-5000BP, but that overall rates were perhaps similar to those of today.

At some stage in the proceedings (probably when the Wildwood was still standing if only because it constitutes roughly seven tenths of the period of pedestal formation) the upper parts of pedestal sidewalls would have become exposed (Fig. 11.3). This is caused by a reduction in height of the land surface, which is a consequence of dissolution of rockhead, since it follows that as rockhead is lowered the land surface must be lowered with it. There are several factors that may have played a role in determining the relative timing of sidewall exposure. These include variations in dissolution rates, in regolith thickness and in the amount of insoluble residue released from the limestone on its dissolution. Thus, it is possible that Cove Limestone sidewalls became exposed prior to Kilnsey Limestone sidewalls, since the former Limestone contains practically no insoluble residue and the latter Limestone up to 30% (Section 9.5). The factors also include regolith make-up, as the greater the number of limestone clasts in the regolith the greater the amount of regolith volume-loss due to their dissolution. Loss of regolith down grykes (e.g. Drew, 2001; Milligan, 2003) may also have abetted exposure, but this process is not thought to be overly important at Norber as an examination of scars revealed that grykes are not especially well developed.

Subsequent to their exposure the sidewalls would have suffered both lateral subaerial and lateral sub-regolith dissolution, the latter occurring at a greater rate than the former. This leads to below-ground pedestal undercutting, which in turn leads to above-ground failure of sidewall blocks about discontinuities due to the loss of below-ground support, both processes causing further pedestal narrowing. Moreover, as failure occurs about vertical joints, undercutting augments the vertical nature of the sidewalls. With increasing sidewall dissolution/failure the pedestal eventually ceases to wholly support its caprock, which founders due to imbalance (as has happened with N8). Once this has occurred there is nothing to prevent rainwater from reaching former pedestal crowns, which are then subject to dissolution on all sides, as seen in Fig. 11.4 and in Plate 11.1. The causes of differences in pedestal undercut rates are reasoned to be the same as the causes for differences in tablet weight loss, i.e. variations in cap-rock decantation/interception rates, and in the make-up, water pathways, infiltration rates and acidity of the regolith (Section 7.6.8).

11.2.3: The temperate limestone grassland environment from ca. 3000BP to the present

It is possible that dissolution reached a peak from ca.4000 to 3000BP because this period coincides with increased precipitation (Berglund, 1986), although mounting forest removal may have acted as a counter-weight. After deforestation, any organic soil would have wasted away with little trace (e.g. Pigott and Pigott, 1959), thereby leading to an increase in exposed pedestal height and to subaerial dissolution of pedestal sidewalls as today. Since 2500BP precipitation has fallen back to the present level, which implies dissolution rates similar to that of nowadays. The one exception to the latter generalisation is over the past 200 or so years, as the amount of atmospheric carbon dioxide has increased by some 100ppm since pre-industrial-revolution days to over 380ppm (McKie, 2006) largely due to the burning of fossil fuels. This has increased rainwater acidity, which in turn must have led to acceleration in dissolution rates. Acid rain is traditionally defined as rain with a pH below 5.6, which is the natural pH limit maintained by solution of atmospheric carbon dioxide (Elsworth, 1984; McIlveen, 1992). There is no disputing acid rain is affecting Norber, as witnessed by precipitation with a mean pH of 4.9 recorded at the site. It is likely that rainfall may well decrease in the future, as Lamb (1995) has suggested that global warming infers a poleward shift of cyclonic activity. If so, future dissolution rates may well depend on whether governments have the political will to halt the spewing of greenhouse gases into the atmosphere.

The eventual destiny of the pedestals is total removal, but new pedestals will not form beneath the former caprocks since they will no longer rest on rockhead but on regolith, which means they will be unable to protect the underlying limestone surface from erosion by water percolating under them through the regolith (Fig. 11.5). The pedestals at Norber are consequently ephemeral karstic features.

The above sequence of events applies not only to sidewall formation on level ground, but also to the formation of lateral and upslope sidewalls where the downslope sidewall is comprised of a pre-existing glacially-eroded scar (Fig. 11.6). It does not, however, apply to the formation of N31, which although largely obscured by vegetation appears to be composed of limestone clasts (Plate 7.5). As this is the only pedestal of its kind at Norber, and as two similar pedestals occur at other sites (one each at Dowkabottom and Scar Close), an account of its possible formation is found in Section 12.10.

11.2.4: Conclusion

It is argued that little pedestal formation occurred for the ensuing ca.1500 years after erratic deposition at Norber in ca.14500BP, since permafrost conditions prevailed. It is also argued that sub-regolith dissolution of the inter-erratic limestone surface initiated pedestal formation in ca.13000BP, that dissolution in this setting has continued until the present day, and that it operates at a greater speed than subaerial dissolution and sidewall failure. Indeed, the latter two processes are consequential to sub-regolith dissolution. Therefore, the pedestals at Norber have formed mostly as the result of dissolution in a sub-regolith environment, and since rates from ca.13000-10000BP are considered to be less, perhaps considerably so, than those from 10000BP to the present, it follows that the pedestals are essentially Flandrian in age.

11.3: Erratics without pedestals

Norber is littered with erratics of all sizes throughout the Wentworth Scale, yet relatively few have or appear to have pedestals beneath them. Five possible explanations for this phenomenon are suggested:

1. It is envisaged that a pedestal will not form if an erratic is separated from rockhead by a critical thickness of regolith composed of clasts enclosed within matrix, since water will be able percolate under the erratic through interstitial voids thereby dissolving rockhead. Many of the pedestals at Norber are separated from their caprocks by a centimetre or so of regolith (e.g. N6), so it may be that pedestals will not form if sub-erratic regolith exceeds this amount. Other pedestals are separated from their caprocks by regolith composed of only clasts, and here the maximum distance between cap-rock base and pedestal crown is about 12cm (N2); at Winskill (Section 12.21) it is about 16cm. Consequently, it may be that a pedestal will not form if rockhead and erratic are separated by only clasts that are greater than about 16cm in size.

2. A pedestal will not form even when an erratic rests directly on rockhead if the erratic is unable to shield the underlying limestone from dissolution. Lauritzen (2005) has proposed that its ability to do so is governed primarily by its shortest horizontal axis although shape must also play a part, since a spherical erratic will allow greater access of water to rockhead than a cubic/rectangular erratic. At Norber the shortest horizontal axis of any caprock is approximately 50cm (N22 and N25). The pedestals that underlie the two caprocks have suffered undercutting, however, which means that 0.5m is more an indication of the shortest horizontal axis required for a pedestal to have survived erosion subsequent to erratic deposition rather than the minimum required for pedestal formation. Accordingly, the shortest horizontal axis below which an erratic fails to shield the underlying limestone from dissolution remains unknown other than it not greater than approximately 0.5m.

3. Not all erratics at Norber have remained *in situ* since deposition. A few caprocks have foundered due to imbalance caused by pedestal undercutting. In the case of N8 and N22 the caprocks remain propped against their pedestals, but there are a few instances where caprocks have tumbled downslope for a few metres onto regolith, as can be seen in Plate 11.1. Other erratics have shed lumps of rock due to their weathering and these have likewise come to rest on regolith. Since such non-*in situ* ‘erratics’ are not resting on rockhead a pedestal cannot form beneath them.

4. Some pedestals may have been erased from the landscape altogether leaving former caprocks ‘high and dry’. It might be thought that relatively small caprocks are more prone to losing their pedestals than relatively large ones bearing in mind that pedestal undercut may reach 84cm (N4). Yet N8 has foundered due to undercutting despite having a shortest horizontal axis of 1.6m, which is greater than nearly all other caprocks at Norber.

5. A pedestal that has formed in a sub-regolith environment will remain unexposed if the amount of rockhead lowering does not exceed the thickness of the regolith that surround it and if the regolith is not otherwise eroded, as in Fig. 11.2. It is not known how many pedestals remain wrapped in regolith, but those that are may become exposed in the future as ‘new’ pedestals.

11.4: ‘Pedestals’ without caprocks

In addition to pedestals where caprocks have completely tumbled off, a number of limestone residuals that are similar in shape to pedestals but which lack caprocks occur at Norber (Plate 11.1). It is suggested that these residuals have formed in much the same way as pedestals, apart from the lack of caprock protection, because they are comprised of vertical sidewalls that are sometimes undercut and are surrounded by regolith up to several tens of centimetres thick. The residuals are thought to be the remains of clints and scars that have either lost or never had a covering of regolith, and they owe their formation largely to differential karstic erosion, as rates of sub-regolith dissolution exceed those of sub-aerial dissolution both vertically and laterally.

11.5: The umbrella theory at Norber

It was outlined in the Foreward and was proposed by a string of authors in Section 6.2 from Hughes (1886) through to Waltham *et al.* (1997) that the caprocks at Norber have protected the limestone surface underlying them from dissolution by direct rainfall, i.e. by way of the Umbrella Theory. It was proposed in Section 11.2.1 that “...pedestal formation commenced but little until ca.13000BP, which is some 1500 years after erratic deposition, when thawing of the permafrost occurred. The thawing allowed aggressive till-water to corrode rockhead, the latter not including the limestone surface beneath erratics where they rested directly on that surface. This marks the beginning of the lowering of the inter-erratic limestone surface.” Consequently, pedestal formation began because the ‘erratics-cum-caprocks’ protected the limestone surface beneath them from dissolution by till/regolith-water. In fact, the caprocks continued to protect the limestone surface beneath them in this manner until the till/regolith surface was lower than that of the pedestal crown surface, i.e. when pedestal sidewalls became exposed. Moreover, from ca.10000-3000BP the caprocks prevented a rain of arboreal litter from reaching pedestal crowns, which means they protected the crowns not from rainwater/dripwater dissolution but from sub-arboreal organic-soil dissolution. Consequently, it is only since the clearance of the Wildwood, i.e. for the last 3000 years, when caprocks became subaerial, that they have protected pedestal crowns from dissolution by rainwater. Therefore, the hypothesis that the caprocks have protected the limestone that underlies them from dissolution by direct rainfall, i.e. by way of the Umbrella Theory, is safely rejected at Norber.

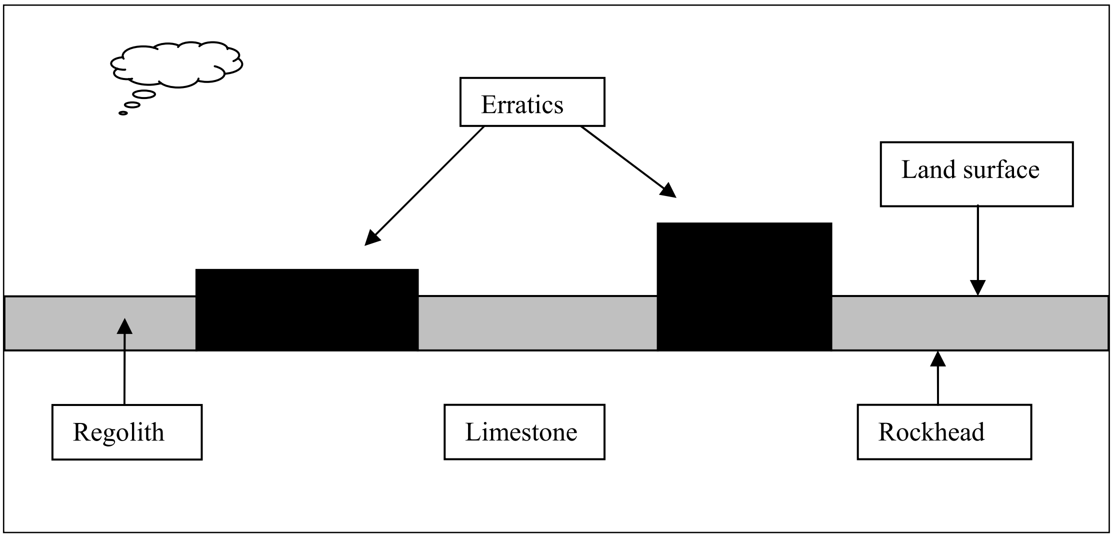


Fig. Error! No text of specified style in document..1: Erratics immediately after deposition at Norber

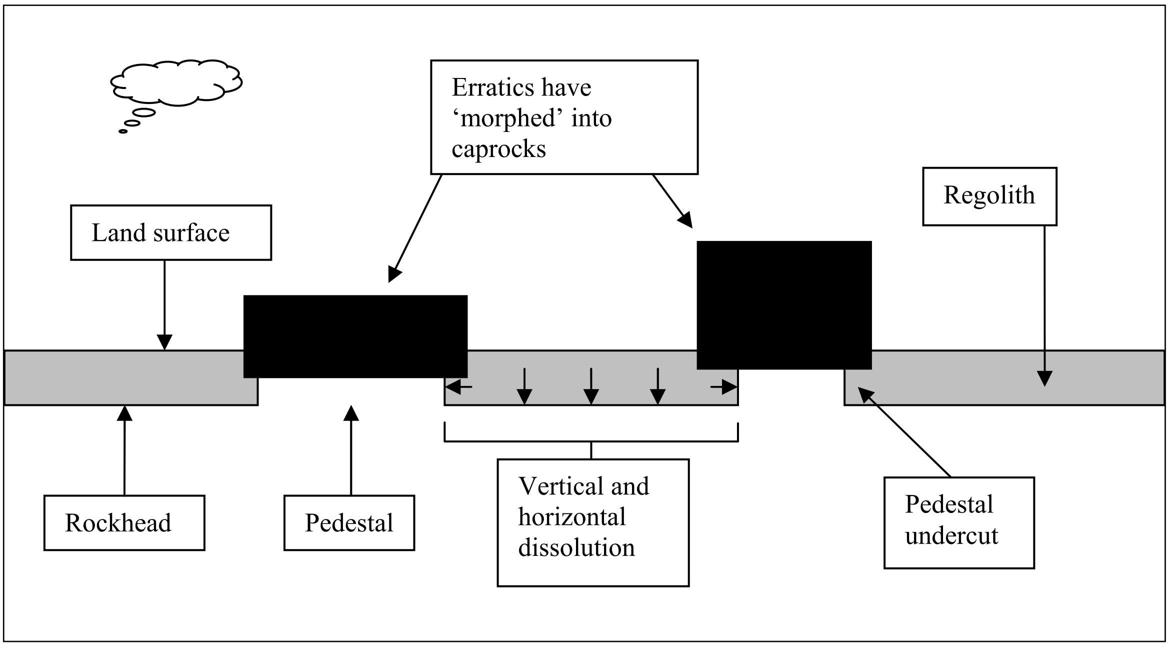


Fig. *Error! No text of specified style in document.***.2: The formation of pedestals and pedestal undercuts at Norber***

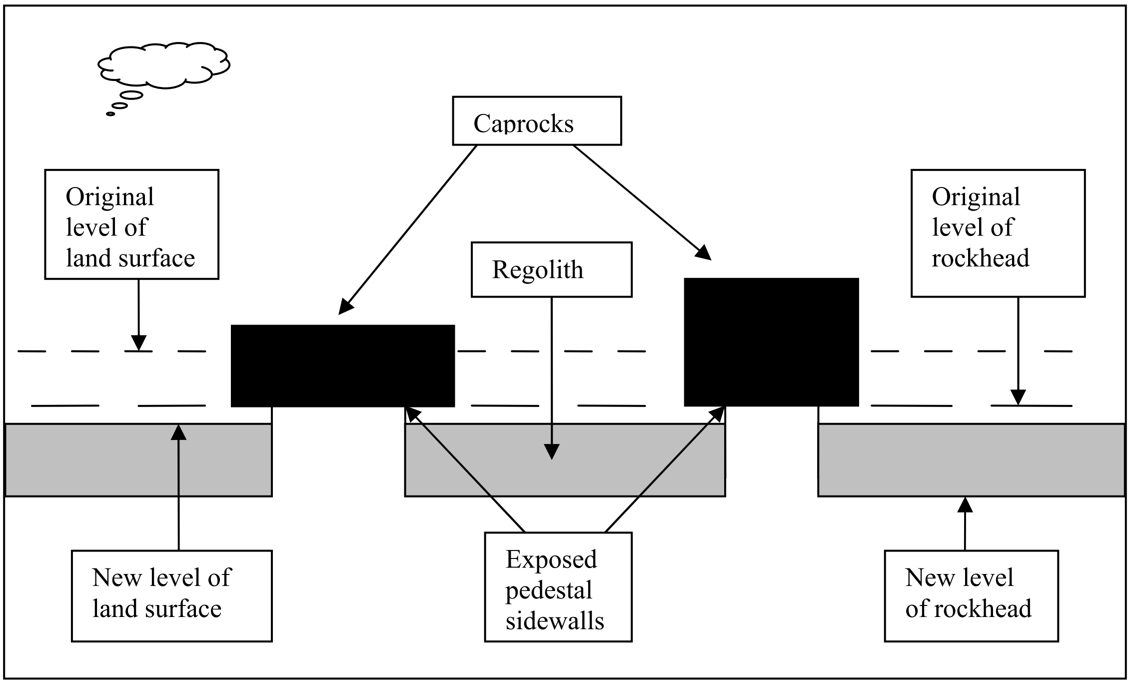


Fig. Error! No text of specified style in document..3: The exposing of pedestal sidewalls at Norber

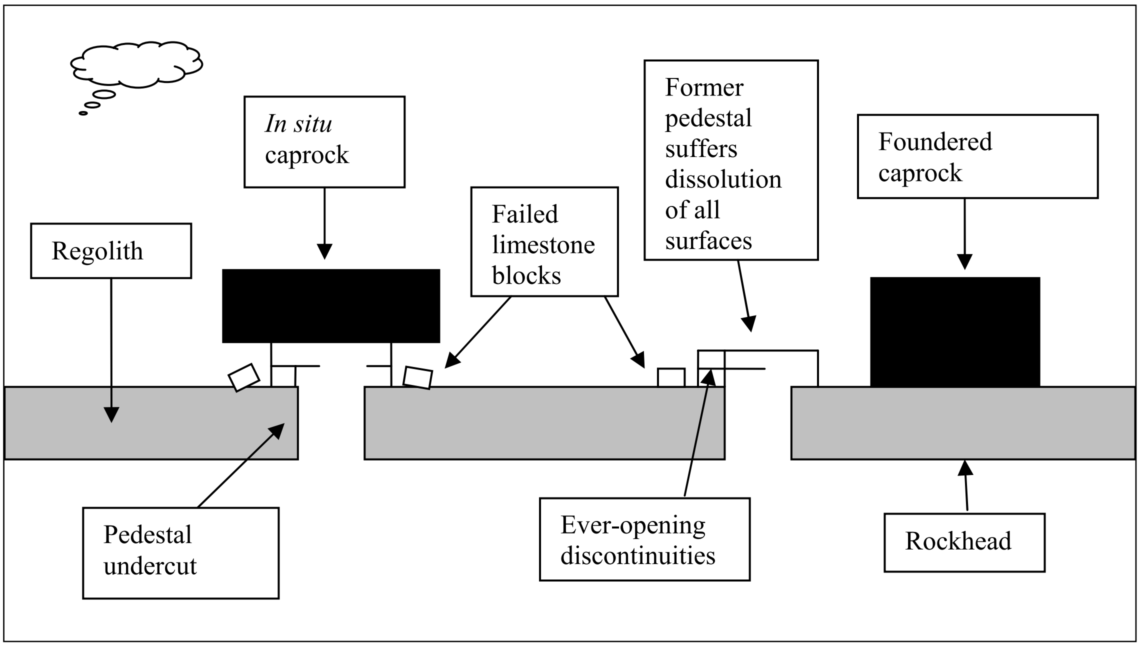


Fig. *Error! No text of specified style in document.***.4: *The narrowing of pedestals due to sidewall undercutting and failure, and caprock foundering at Norber***

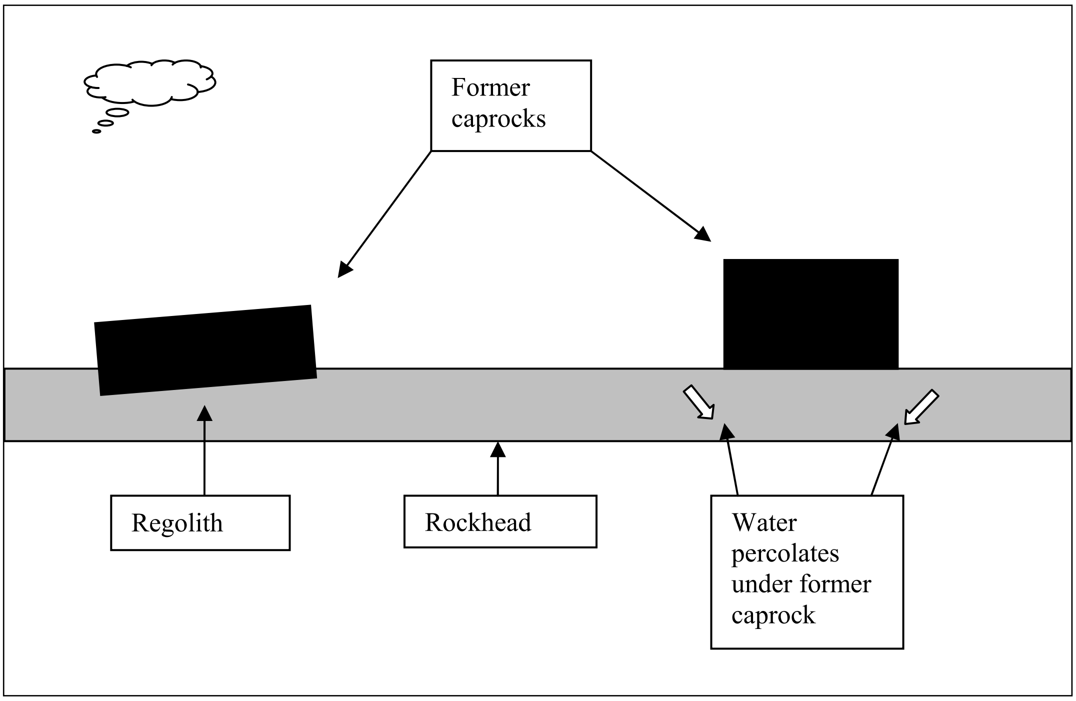


Fig. *Error! No text of specified style in document.***.5: Post-pedestal removal at Norber***

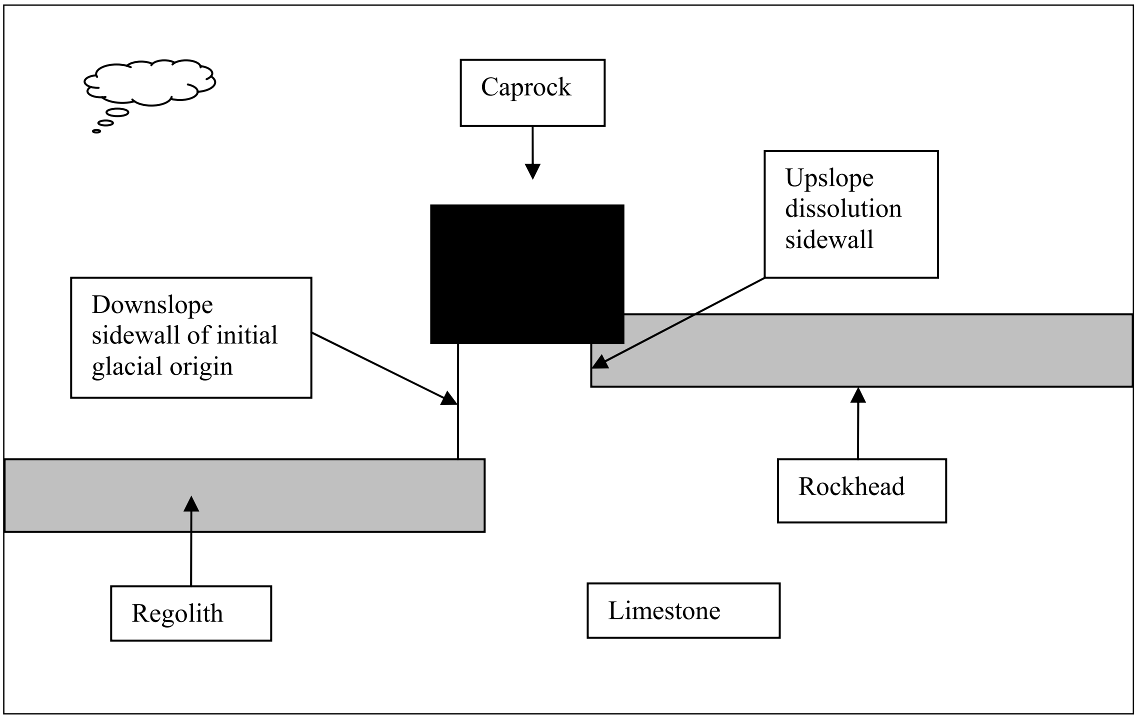


Fig. *Error! No text of specified style in document.* ***.6: Pedestal rock with glacial and dissolution sidewalls at Norber***

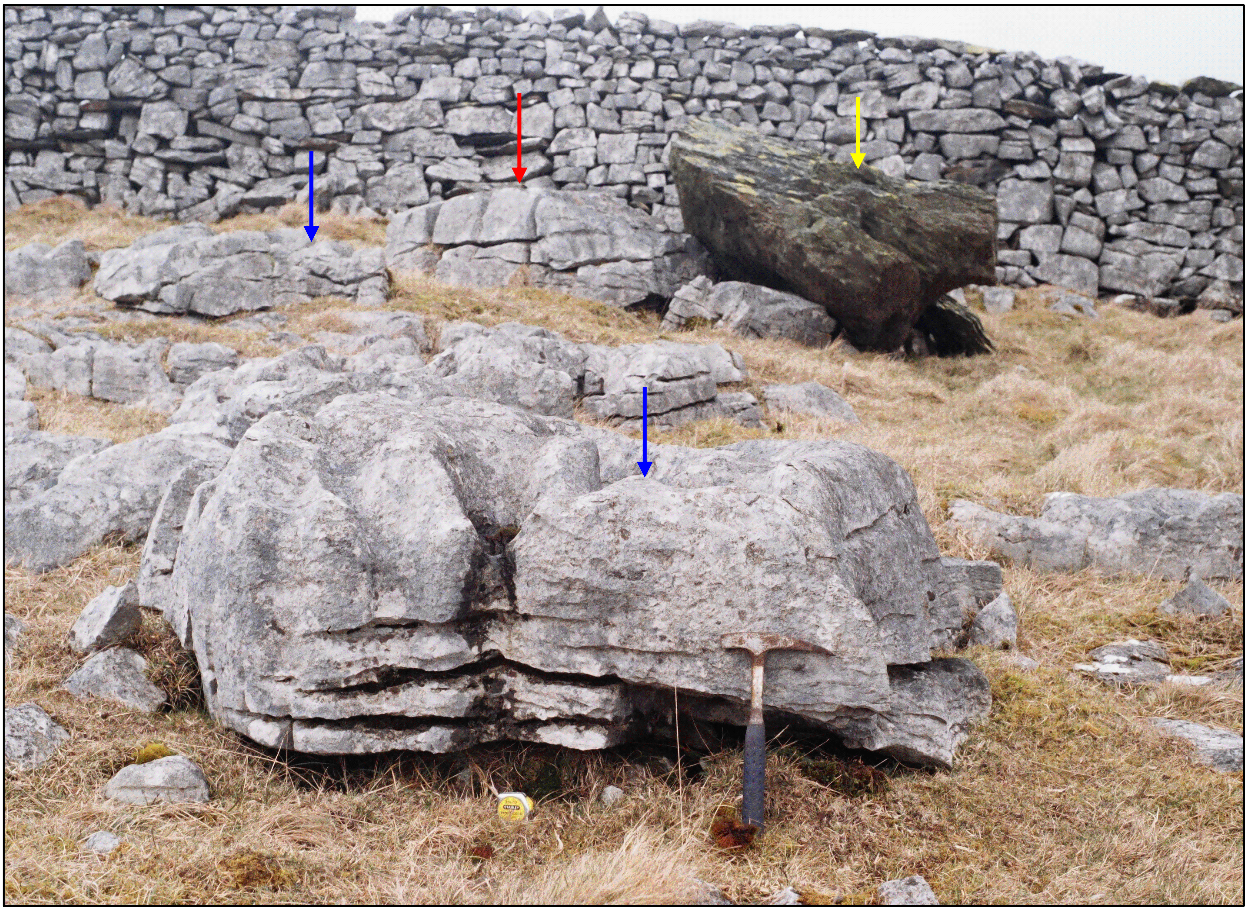


Plate 11.1: Limestone residuals and toppled caprock at Norber

Residual 'pedestals' without caprocks at Norber (blue arrows) are little different in size or shape from 'true' pedestals found beneath caprocks, apart from the fact that their crowns have rundkarren etched into them. Note the undercutting of their bases, and the failed blocks to the left and beneath the 'pedestal' in the foreground, features that are also common of 'true' pedestals. It is possible that the erratic in the background (yellow arrow) once formed the cap of the residual to its left (red arrow). The hammer is 33cm long.

CHAPTER 12: THE FORMATION OF POST-DEVENSIAN-DEGLACIATION PERCHED PEDESTAL ROCKS WITH CARBONIFEROUS LIMESTONE PEDESTALS AT SITES IN ENGLAND, IRELAND AND WALES OTHER THAN NORBER

12.1: Introduction

Evidence from literature (e.g. Hughes, 1886; Goldie, 2005) shows that post-Devensian-deglaciation perched pedestal rocks with Carboniferous limestone pedestals occur at sites other than Norber in England, Ireland and Wales, and that none occur in Scotland. Sites were identified through literature, word of mouth and prior knowledge, by scrutinizing postcards and Ordnance Survey maps, and by quartering Carboniferous limestone outcrops on mountain bike.

12.2: Aims and objectives, and methodology

The aims of the work undertaken in Chapter 12 are to resolve the formation of post-Devensian-deglaciation perched pedestal rocks with Carboniferous limestone pedestals at sites other than Norber in England, Ireland and Wales, and place the pedestals at Norber within a regional context. The objectives are to investigate pedestal-rock-forming processes at the sites and to use the work undertaken in Chapters 7-11 to fulfil the aims. The pedestal rocks and their surroundings were surveyed as outlined in Section 7.2 in addition to any experimentation carried out in subsequent sections.

12.3: The perched pedestal rock sites

Perched pedestal rocks were encountered at the following sites:

1. Cunswick Tarn (SD 4893), Cumbria, England
2. Farleton Knot (Farleton Fell/Newbiggin Crags/Holmepark Fell) (SD 5480), Cumbria, England
3. Great Asby Scar (NY 6510), Cumbria, England
4. Hutton Roof Crags (SD 5577), Cumbria, England
5. Underlaid Wood (SD 4878), Cumbria, England
6. Gait Barrows (SD 4877), Lancashire, England
7. Dowkabottom (SD 9568), North Yorkshire, England
8. Gearstones (SD 7779) near Ribblehead, North Yorkshire, England
9. Runscar Great Scar (SD 7679), North Yorkshire, England
10. Scales Moor (SD 7177), North Yorkshire, England
11. Scar Close (SD 7577), North Yorkshire, England
12. Winskill Stones (SD 8366) near Langcliffe, North Yorkshire, England
13. Marlbank (H 1034), Co. Fermanagh, Northern Ireland
14. The Burren (Lat. 52º 58' to 53º 10'N, Long. 08º 58' to 09º 25'W), Co. Clare, Republic of Ireland
15. Cavan Burren (H 0735), Co. Cavan, Republic of Ireland
16. Twyn Du (SN 8316), Powys, Wales
17. Y Gogarth (The Great Orme) (SH 7682), Gwynedd, Wales

No perched pedestal rocks were encountered at the sites below where Devensian erratics occur on Carboniferous limestones:

1. Gaythorne Plain (NY 6411), Cumbria, England
2. Whitbarrow Scars (SD 4386), Cumbria, England
3. Hyning Wood (SD 5073), Lancashire, England
4. The Yorkshire Dales, North Yorkshire, England, apart from the sites above

No perched pedestal rocks were encountered at the sites below where Carboniferous limestones crop out:

1. The Clouds (NY 0074), Cumbria, England
2. Scout Scar (SD 4891), Cumbria, England
3. The Yorkshire Dales, North Yorkshire, England, apart from the sites above
4. Eglwyseg (SH 2346), Clwyd, Wales

A full account of site location to four figures and perched pedestal rock location to ten figures, and caprock, pedestal, rock mass and site descriptions, soil pH results and the solid geology is found in Appendix 5 by site initials (e.g. Appendix 5B=The Burren, Appendix 5CB=Cavan Burren etc.). Site location maps are found in Appendix 6.

12.4: Layout

Unravelling perched pedestal rock formation commences with a discussion of past environmental and vegetation changes, the origin of caprocks and the formation of pedestals with similar/different morphologies to/from those at Norber (Section 12.5). This is followed by an examination of the seventeen sites where perched pedestal rocks occur. Although the sites are grouped by county and country in Section 12.3 they are not examined in this order in succeeding sections, as adopting this approach does not account best for pedestal formation. Consequently, unravelling the formation of the perched pedestal rocks begins with Scales Moor, North Yorkshire, England (Section 12.6), since a greater range of pedestal rocks and surroundings occur at the site than at any other; ease of access by public transport and mountain bike also carried much weight. Scales Moor is followed by the Burren, Co. Clare, Republic of Ireland (Section 12.7), since more pedestals, and more Carboniferous limestone formations and members occur at this site than at any succeeding site. Thereafter, sites are presented in alphabetical order (Sections 12.8-12.22), as it is not considered that any one site is more important than another. A further consideration against adopting a county/country approach is the fact that the six sites in Cumbria and Lancashire have not been mapped by the Geological Survey since 1892. Thus, bedrock at the sites is designated only as 'Carboniferous Limestone (undifferentiated)', which means it cannot be correlated or compared and contrasted with the limestones occurring at any of the remaining eleven sites. An account of the genetic origin of pavements and pedestal formation (Section 12.23), and an overall conclusion to Chapters 7-12 (Section 12.24) are also presented.

12.5: Discussion

It was established in Section 10.1 that sites in England and Wales have undergone more-or-less similar patterns of past environmental change following Devensian deglaciation in ca.14500BP, (e.g. Pigott and Pigott, 1959; Briffa and Atkinson, 1997; Lowe and Walker, 1997). Environmental changes parallel with those in England and Wales have likewise affected Ireland (e.g. O'Connell, 1994; Bradshaw, 2001) apart from its later deglaciation, which occurred at the end of the Killard Point Stadial in ca.13700BP (McCabe *et al.*, 1998). It is accepted, however, that local variations in the date of Devensian deglaciation have occurred. For instance, it is likely that deglaciation of the Cavan Burren occurred at a later date than the Burren, since the former is found about 180km farther to the north-east and is 150-200m higher than the latter. Nevertheless, unless evidence is presented to the contrary, the dates of Devensian deglaciation are ca.14500BP in England and Wales, and ca.13700BP in Ireland.

It is apparent from literature descriptions/illustrations that pedestal morphology and inter-pedestal surroundings may be similar to Norber (e.g. Cunswick Tarn, Cumbria (Hughes, 1886)) or dissimilar (e.g. Gait Barrows, Cumbria (Goldie, 2004)). It is argued that pedestals with a similar morphology have formed in a similar manner irrespective of site providing their inter-pedestal surroundings are also analogous, unless evidence is presented to the contrary. Thus, Hughes (1886) recognised that the vertical-walled pedestals at Norber and Cunswick Tarn had formed in the same manner, since they are abutted by vegetation-covered regolith. In contrast, although pedestals FK1-2 and FK8-11 at Farleton Knott are likewise vertical-walled, the fact that they are surrounded by clitter, rubbly bedding and upturned clint rather than regolith reveals that they have formed in a different anthropogenic environment.

It was observed during the site surveys that all caprocks are glacial erratics. Consequently, their origin within the context of perched pedestal rock formation is not considered further. It was also observed that arboreal vegetation in grykes and rundkarren on clint were widespread, which reveals that a former cover of woodland and/or regolith was likewise once widespread. This finding is of importance since the presence of woodland implies vegetation rooted in soils, and Trudgill (1972; 1983a) and Smart *et al.* (1983) have shown that dissolution rates are influenced by the type of regolith (e.g. till or soil) and environment (e.g. subaerial or sub-regolith). The existence of a past vegetation cover is upheld, for example, by Ivimey-Cook and Proctor (1966), and Bradshaw (2001) re the Burren, Lewis (1990) re the Morecambe Bay pavements, Goudie and Gardner (1992) re Hutton Roof, Goldie (1995) re Scales Moor and Fareleton Knott, and Goldie (1996) re Great Asby Scar. Inference of a former regolith cover is provided by field systems in totally barren areas on the Burren (Drew, 1983), while Smith (1986) stated that the remains of ancient field banks in Craven, such as above Malham Cove, must indicate that sufficient soil was once adequate for farming purposes. The existence of a past vegetation cover is also upheld by the presence of woodland plants growing in the grykes at all exposed sites, e.g. herb robert (*Geranium robertianum*) and primrose (*Primula vulgaris*) on the Burren (Appendix 3V.2), and lily of the valley (*Convallaria majalis*) at Scar Close (Appendix 5SC). Elsewhere, Goldie (1995) has noted rundkarren, which form beneath a soil cover, on Scales Moor. The soils probably comprised organic and mineral types. Thus, Pigott and Pigott (1959) have written that predominantly organic soils can be produced on bare pavement under a closed tree canopy re Colt Park Wood, while Drew (1983) found mineral soils under walls, in Megalithic tombs and in grykes on the Burren. It is likely that the organic soils were lost following deforestation by simply wasting away (Pigott and Pigott, 1959), as has happened in New Zealand (Trudgill, 1983a). There is, however, some controversy over the former extent and whereabouts of mineral soils in areas where they once supposedly occurred. Curtis *et al.* (1976) have written that grykes may act as a depository for mineral soils and Drew (2001) has written that mineral soils on the Burren have been washed down into caves or grykes. Moreover, Trudgill (1983a) has proposed that mineral soils are able to disappear from the surface without erosional loss, transport and deposition by simply being lowered *in situ* by subsidence into eroding fissures and joints as sub-soil rock dissolution occurs. Trudgill (1983a) has also pointed out, however, that mineral soil is not so readily lost. If so, this may explain the lack of post-glacial mineral material in Malham Tarn (Pigott and Pigott, 1959) and the absence of silts or clays anywhere in the lower parts of the drainage system on the Burren (Farrington, 1965), both of which are obvious sediment traps. Consequently, as organic soil is almost certainly easier to erode than mineral soil and as it cannot be proved that rundkarren-covered bare pavement was once mantled in mineral soil, it is reasoned that the former superficial cover on rundkarren-covered pavement comprised organic soils. Unless, that is, there is evidence to the contrary, such as residual patches of till on otherwise bare pavement.

12.6: Scales Moor (SD 7177: Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997))

12.6.1: The Site

Scales Moor is a linear shoulder of fell in Asbian Gordale Limestone occurring between the Lower Palaeozoic inlier of Chapel-le-Dale to the south-east and the Brigantian limestones of Whernside to the north-west (Fig. A6.5). The site is some 4km² in area and is comprised of peat, till that contains many clasts of Carboniferous sandstones and limestones reaching 6m³ in bulk, and pavement formed of limestones that are generally medium bedded with very wide joints that dip gently to the north-east. Pavement form is variable, as it may consist of broad clints that are dissected by newly-formed grykes (Plate 12.1) or clints a metre or so across divided by well-developed grykes (Plate 12.2) or clint residuals surrounded by wide areas of vegetation-covered regolith (Plate 12.3). Rundkarren may or may not be present. The degree of weathering/erosion of the pavement surface is also variable, as it may be smooth and even or smooth with fresh-looking rundkarren or rough with kamenitzas and eroded rundkarren. Several tens of relatively large Carboniferous limestone erratics up to 6m³ in bulk dot the site, and those that could be seen to rest directly on clints either comprise the caps of pedestal rocks (SM1-6 and SM8-11) or formerly did so prior to toppling off their pedestals. Most caprocks have rounded upper surfaces that may be cockly, while pedestals are bounded by sidewalls that slope (Plate 12.4) or that are vertical (Plate 12.5) or that are a combination of the two (Plate 12.3). Pedestal crowns are flattish, and possible striae with a strike of 082/262º, which is essentially parallel with the strike of Chapel-le-Dale, occur on SM9; there is no evidence that dissolution of crowns has occurred. Sloping sidewalls may merge gradually with the surrounding limestone surface, as seen in Plate 12.4, or they may terminate at the vertical sidewalls of widened grykes or solution areas, as seen in Plate 12.3; rundkarren are sometimes present on sloping sidewalls. Vertical sidewalls are always abutted by regolith, which may be comprised of till or peat or organic soil (Plate 12.3), but sloping sidewalls are entirely subaerial or at most are partly covered in a thin, surface mat of moss with perhaps a few grasses or herbs (Plate 12.4). The height of sloping sidewalls ranges from about 13 to 26cm, while that of vertical sidewalls ranges from about 32 to 99cm of which the greater portion is exposed. The mean height of the three pedestals bounded by only vertical sidewalls is about 44cm while that of the four pedestals bounded by only sloping sidewalls is about 20cm. The angle of sloping sidewall dip varies from approximately 8 to 24º, the lower the angle the more the sidewall tends to extend beyond the distal margin of its caprock. Carboniferous sandstone erratics, which are mostly sub-rounded and which rarely reach 1m³ in bulk, are far more numerous than Carboniferous limestone erratics, but of those that occur on the pavement none has a pedestal beneath it, although SM7 partly rests on one. Instead, all occur above/in grykes (Plates 12.1 and 12.2) (including SM7) or in small solution hollows, which are often ‘lined’ with decantation runnels, that may either fit the basal portion of the erratic like a glove or that may be reminiscent of river-bed potholes. The site was quartered on foot with the aid of binoculars, and twenty pedestal rocks were surveyed. Refer to Appendix 5SM for the locations, form, geology and surroundings of the sampled pedestal rocks.

12.6.2: The formation of vertical pedestal sidewalls

It was pointed out in Section 12.6.1 that all vertical pedestal sidewalls at Scales Moor are abutted by regolith. This situation occurs even where sloping sidewalls are found above vertical sidewalls, as can be observed in Plate 12.3. As none of the vertical sidewalls appear to be comprised of bench edges, it is judged they have formed in an analogous setting to the vertical sidewalls that occur on level ground at Norber. In other words, they have been fashioned largely due to the dissolution of the inter-pedestal limestone surface in a sub-vegetation-covered regolith environment. Unlike Norber, though, dissolution may have occurred beneath peat and/or organic soil and/or brown earths on weathered till rather than just beneath brown earths on weathered till.

12.6.3: The formation of sloping pedestal sidewalls

There are no instances of pedestals bounded by sloping sidewalls at Norber, as only vertical sidewalls occur at the site. It was recorded in Sections 11.2.1 and 11.2.2 that the formation of vertical sidewalls is caused by a quantum leap in the rate of dissolution from ‘insignificant’ under caprocks to ‘significant’ beyond their distal margins and that the vertical nature of sidewalls is enhanced by sidewall failure. This causes two approximate 90º sharp breaks of slope to form, the one between pedestal crown and pedestal sidewall head, and the other between pedestal sidewall toe and the inter-pedestal surface, as is evident in Plate 7.4. Consequently, as sloping sidewalls at Scales Moor dip at angles of about 8 to 24º and as the two corresponding breaks in slope are relatively slight, it is envisaged that sloping-sidewall pedestals have formed in a different environment from vertical-sidewall pedestals. The differences in the two pedestal forms can readily be observed by comparing SM6 in Plate 12.4 with SM5 in Plate 12.5.

It was noted in Section 12.6.1 that where regolith is lacking at Scales Moor, grykes or solution hollows underlie Carboniferous sandstone erratics and pedestals bounded by sloping sidewalls underlie Carboniferous limestone erratics. This is such a non-random pattern that it cannot be coincidental, which means that the two sub-erratic landforms must be a function of difference(s) between the two erratic groups, of which bulk and rock type offer the greatest disparity. Thus, sandstone erratics are, on the whole, a good deal smaller than limestone erratics, which may mean that the latter are better-able to protect the limestone surface beneath them (Section 11.4, #2). Yet pedestals occur beneath relatively large and small limestone erratics alike, even where the latter are not much bigger than the bulkiest of sandstone erratics, as can be seen in Plate 12.6. Accordingly, erratic size is not considered to control the two different sub-erratic landforms. It is well known that rainwater is naturally acidic and has the potential to dissolve calcite (Section 7.6.1). This means that as Carboniferous sandstone erratics are, to all intents and purposes, composed of insoluble quartz, any rainwater that has trickled over them will still be acidic prior to it decanting. In contrast, as Carboniferous limestone erratics are, to all intents and purposes, composed of soluble calcite, any rainwater that has trickled over them will become alkalised prior to it decanting. Consequently, it was hypothesized that differences in the acidity/alkalinity of decanted water might explain the unlike sub-erratic landforms, and this hypothesis was tested by analysing the pH of rainwater, and decanted water collected from ‘acid’ sandstone and ‘basic’ limestone erratics. The samples were gathered by placing up to four home-made rain gauges (F in Plate. 5.1) in the open to collect precipitation, the actual number being determined by rainfall intensity, and single rain gauges below caprock drips to collect decanting water. In the latter case, the gauge funnels were emplaced as far as possible under the caprock so as to allow decanting water to drip into them but to minimise rainwater falling into them. The samples were analysed the following day in the laboratory using a Jenway 3010 pH meter. Attempts at determining pH were not, in the end, carried out at Scales Moor due to difficulties with fitting rain gauges between erratic base and limestone surface, fixing gauges securely to the ground and monitoring gauges to prevent ‘interference’ by sheep. The degree of exposure to strong winds at the site was also a consideration, as winds were observed blowing rainwater into the gauges and blowing decanting water away from them. Instead, sampling was undertaken at Norber where most of the above drawbacks were overcome. Nonetheless, it was only possible to sample water decanting off one Carboniferous limestone erratic (N26), as there are no others large enough for sampling apart from N31, which has had a wall built over it. As an alternative, two gravity-fallen limestone boulders were utilised. Decanted water was collected off three different-length trickle fetches, i.e. about 1m on N26, and about 2m and 3m on the two limestone boulders. Different trickle lengths were employed because it was thought that a greater calcite uptake might ensue from a greater trickle fetch, which might in turn affect the rate of surface dissolution. It was not possible to collect water decanting off Carboniferous sandstone erratics at Norber due to their sub-boulder size. Instead, erratics comprised of Silurian grit provided a handy, if greater-sized, substitute. It was not felt that this compromised the results in any way, since both Carboniferous sandstone and Silurian grit erratics are siliclastic. Moreover, the Carboniferous sandstone erratics on Scales Moor are uncannily similar in size and in distribution to Silurian grit erratics in Underlaid Wood, as is evident by comparing Plates 12.2 and 12.7. Refer to Appendix 3pH Table 3.4 for a full list of results.

The figures in Table 12.1 reveal that the pH range for precipitation is 4.8 to 7.2. 'Normal' rainwater has a pH of 5.6 (Elsworth, 1984), which means that the higher figure is well above average. Nevertheless, the results are comparable with figures analysed by Sweeting (1966) for falling rain in north-west England, which ranged from 4.7 to 7.1. The results also reveal that the four mean pH results for water that has decanted from grit caprocks (sampling events 1, 3-5) are lower than those of their precipitation standards, which are respectively 5.3 and 5.6, 6.2 and 7.2, 5.3 and 6.3, and 5.0 and 5.9. In other words, the water has become acidulated. This is in line with results obtained by Jones (1965) (Section 8.7.1), who measured a decrease in pH from 7.0 (precipitation) to 6.3 (trickle water) on Silurian grit erratics at Norber due to the water trickling over lichen. In contrast, the five mean pH results for water that has decanted from Carboniferous Limestone boulders/caprock (sampling events 2-6) are higher than those of their precipitation standards, which are respectively 6.9 and 4.8, 7.9 and 7.2, 7.4 and 6.3, 7.5 and 5.9, and 5.9 and 5.6. In other words, water which has trickled over the limestone boulders/caprock has become alkalised compared to the precipitation standard. There are no figures in the literature with which to compare the latter results. As a result, gryke/dissolution-hollow formation beneath the Carboniferous sandstone erratics at Scales Moor is explained by decanted acidulated water dissolving the limestone surface at a greater rate than that of the relatively less acid rainwater. (This hypothesis is expanded in Sections 12.6.6 and 12.6.8.) In contrast, pedestal formation about Carboniferous limestone erratics is explained by the decanted alkalised water dissolving the limestone surface at a lesser rate than that of the relatively more acid rainwater. Consequently, the sloping nature of sidewalls results from mounting neutralisation of the decanted alkalised water by acid rainwater with increasing distance from sidewall head to sidewall toe, and beyond the sidewall toe the inter-pedestal limestone surface is lowered only by rainwater. There is no questioning that dissolution of the inter-pedestal-toe limestone surface is occurring, since water decanting off clints (mean pH 6.5) is alkalised compared to the precipitation standard (pH 5.6) (Table 12.1, Sampling event 7). In other words, the decanted alkalised water buffers the limestone surface between sidewall head and sidewall toe from the greater dissolutional effects of the more acid rainwater, just as rainwater that has percolated through basic till buffers rockhead from dissolution (Williams, 1966; Drew, 2001). Consequently, water that has decanted from a limestone erratic onto bare rock at Scales Moor causes a circum-erratic 'dissolution shadow' to form, within which the sloping sidewall is fashioned. This is not to say that the decanted water does not contribute to dissolution of the limestone surface within the shadow, since water with a pH of up to 8.0 can continue to dissolve limestone. Rather, the combined dissolution rate of decanted alkalised water and rainwater found between sidewall head and toe is less than that of rainwater alone. Accordingly, it follows that Carboniferous limestone caprocks are able to 'shield' the exposed limestone surface beyond their distal edges as far as their pedestal sidewall toes. A summary of the formation of sloping sidewalls is illustrated in Fig. 12.1; falling rain and vegetation are omitted for clarity.

It was noted in Section 12.6.2 that pedestals bounded by only vertical sidewalls are also present at Scales Moor despite the fact that their caprocks, like those of pedestals bounded by sloping sidewalls, are composed of Carboniferous limestones. The reason for this is that the vertical-sidewall pedestals are abutted by regolith containing acid soil water. The sub-root pH of the regolith abutting the vertical sidewalls of SM2 and SM9 was respectively 6.1 and 4.2, and it is argued that the acid soil water neutralises the alkalinity of the decanted water prior to it reaching rockhead. This prevents the formation of a dissolution shadow, which means that a quantum leap occurs in the rate of dissolution at the pedestal-crown/sidewall-head junction. Consequently, dissolution of the inter-pedestal limestone surface proceeds as at Norber.

It was planned to conduct more expansive surveys of decanted water subsequent to the findings in sample events 1 and 2 that water trickling over grit and limestone erratics became respectively acidulated and alkalised. Consequently, in sampling event 3 five rather than two decanted samples were collected from Carboniferous limestone boulders/caprock, two from N26 and three from gravity-fallen boulders, while three samples were collected from Silurian erratics, N5, N6 and N27. The sample trickle length was also recorded as was the conductivity of the decanted water. It was hypothesised that greater trickle fetch on Carboniferous limestone boulders might result in greater calcite uptake, which in turn might lead to greater dissolution-shadow areal extent. The survey could not be repeated, however, as rainfall was so light that four gauges were required to gather adequate precipitation for analysis in sampling events 4 and 5. The results of sampling event 3, which are shown in Table 12.2, reveal that no relationship is discernible between trickle fetch and pH re the Carboniferous limestone boulders. Thus, the pH values from trickle lengths of 1, 1, 1.5, 2 and 3m were respectively 8.0, 8.1, 7.7, 7.8 and 7.7. Jones (1965) attributed acidulation of rainwater on Silurian caprocks to the presence of epi- and endo-lithic lichens growing on the caprock surface (Section 8.7.1), but whether this plant-form has any bearing on the results is unknown. Nor is there any relationship between trickle fetch and conductivity, as the results vary wildly, even on the same sample caprock in the case of N26, since conductivity levels of 79 and 184 were each obtained from trickle lengths of 1m. The conductivity results do show, though, that there is a greater uptake of salts (presumably calcite) on the limestone boulders/caprock than on the grit caprocks, since their respective mean decanted water conductivity levels are 109 and 49.

12.6.4: Sloping sidewall development through time since post-Devensian deglaciation

Although it has been shown in Section 12.6.3 that water decanting from limestone caprocks onto bare rock at Scales Moor leads to the creation of circum-erratic 'dissolution shadows' within which sloping sidewalls are fashioned, it would seem improbable that a subaerial setting has always existed in the past. In Section 11.2.1 evidence was presented suggesting that there was little speleothem growth in Craven from ca.14500-10000BP due mainly to frozen ground. This does not necessarily mean, however, that no dissolution of the bare limestone surface at Scales Moor occurred during this period. Thus, although much of the 300mm of precipitation typically received per annum in contemporary periglacial/tundra areas falls as snow, some/all melting does occur during the short summer season (e.g. Lockwood, 1974), which means that water is available to effect dissolution. In fact, Lauritzen (2005) has recorded pedestals on subaerial limestone surfaces in Spitzbergen and in Arctic Norway, which indicates that pedestal inception at Scales Moor almost certainly occurred between ca.14500 and 10000BP. Whether or not the rate of formation increased in the Flandrian is uncertain. This is because although the Flandrian in Craven is associated with relatively high dissolution rates and speleothem growth caused by increases in rainfall, temperatures and vegetation cover (Section 11.2), it is unclear when or even if vegetation actually colonised all bare limestone surfaces at Scales Moor. There is no doubting that vegetation and soil were formerly more widespread on parts of the pavement than today, as the presence of arboreal plants in grykes and rundkarren on clints reveals. Nonetheless, the period of time between deglaciation, and colonization by trees and the formation of an organic soil cover on relatively undissected bare pavement may have been considerable, unless, that is, gryke inception occurred soon after ice-wasting. (Refer to Sections 12.6.6 and 12.6.8 for an account of gryke development.) This is because exposed clints provide an inhospitable environment for plant growth, especially for trees, whereas grykes afford shelter, dampness and a toe-hold for roots. Indeed, it is possible that some of the clints may never have been covered in soil, as Trudgill (1983a) has argued that tabular clint, of which the pavement in Plate 12.1 is an example, is indicative of formation in a subaerial environment. Moreover, it is thought unlikely that gryke formation occurred simultaneously, since some grykes appear more 'mature' than others (compare Plates 12.1 and 12.2, for instance). Consequently, it is hypothesised that vegetation would initially have been absent from the larger expanses of bare, relatively undissected pavement at Scales Moor and that its expansion onto them would have occurred at different times at different places. As such, subaerial dissolution would have continued into the Flandrian for indeterminate periods of time during which the already-formed sloping sidewalls would have developed further.

At some stage, though, it is surmised that organic arboreal soils would have covered at least some of the newly-formed sloping pedestal sidewalls, even if the soils themselves are no longer extant. This begs the question as to why no vertical-sidewall pedestals occur on the bare pavement, since it might be expected that soil water would be sufficiently acidic to transform the sloping sidewalls into vertical sidewalls. The make-up of the Flandrian arboreal soil and forest-floor vegetation at Scales Moor is unknown, but at the two sites where sloping sidewalls occur in arboreal settings it is comprised of little more than litter (Gait Barrows: Section 12.12) and organic mat/*Sphagnum* (Underlaid Wood: Section 12.20). Thus, the pavement cover at Scales Moor may have been rather similar in appearance to that in Plate 12.8, which is of Underlaid Wood. If the pavement was covered in organic mat, it is possible that sloping-sidewall development continued uninterrupted, since Smart *et al.* (1983) found that the mean calcium concentrations of authigenic diffuse percolation waters draining thin organic-mat and bare-pavement (on the Burren) were very similar. No comparable research has been undertaken for water draining from *Sphagnum* and litter. Consequently, an attempt was made to collect water draining from the surface of a sub-arboreal limestone boulder that was covered in *Sphagnum* (in Chapel-le-Dale) for pH analysis, but insufficient sample volume could be gathered. The pH of water dripping from the moss itself was no different from that of contemporaneous rainwater (both pH 5.6), which might mean that dissolution under *Sphagnum* is comparable to that under open skies. It must be acknowledged, though, that only a single sample was analysed and that the sampled water had not drained through to the base of the moss where decaying/decayed matter is apt to be present. Such matter is a source of organic acids, which means it is likely that water dripping from the boulder surface would have a higher pH than that of the contemporaneous rainwater due to the dissolution of limestone at the boulder surface. Nonetheless, as vertical sidewalls are absent beneath Carboniferous limestone caprocks resting on bare pavement it is concluded that the development of pedestals bounded by sloping sidewalls would have continued in an arboreal environment from ca.10000-3000BP. This is accounted for by buffering within dissolution shadows 'overpowering' any arboreal soil acidity, a situation that would arise only if the soils were thin and/or basic/neutral, and/or if vegetation was meagre, as is the case at Underlaid Wood and at Gait Barrows. After deforestation in ca.3000BP the organic soils would have wasted away, as has happened in more recent times following clearance in New Zealand (Trudgill, 1983a). Thereafter, the inter-pedestal surface would have undergone dissolution in a subaerial environment.

Some of the Carboniferous limestone caprock crowns at Scales Moor are partly covered in soil/vegetation, as is evident in Plate 12.3, while others elsewhere, such as at Gearstones and Great Asby Scar, have rundkarren etched into them. Consequently, it was hypothesised that water decanting off soil/vegetation-covered caprocks would be more alkaline than water decanting off soil/vegetation-free caprocks, and if so this would increase the buffering effectiveness of decanted water within a dissolution shadow. With this in mind, the pH of water that had decanted off three caprocks partly covered in soil/vegetation at Gearstones was measured. This site was chosen for sampling instead of Scales Moor for reasons outlined in Section 12.6.3, but also because the vegetation cover on the caprocks at Gearstones is relatively entire and luxuriant (as is evident in Plate 12.28). It was intended to sample decanted water from soil/vegetation-free limestone boulders at Norber during the same period of precipitation for comparison, but the period of rainfall was too short to set up rain gauges at both sites, as inter-site transport was by mountain bike. The results (Table 12.3) reveal that the thirteen decanted samples from soil/vegetation-free boulders/caprocks at Norber (sampling events 2-5) had become alkalised to a greater degree than the three decanted samples from soil/vegetation-covered caprocks at Gearstones (sampling event 6).

Thus, pH increased from a mean of 6.0 (precipitation) to 7.5 (decanted) at Norber but increased from a mean of 5.6 (precipitation) to 5.9 (decanted) at Gearstones. Consequently, the effectiveness of dissolution shadows about caprocks that are soil/vegetation-free is greater than about caprocks that are soil/vegetation-covered. This suggests that the areal extent of dissolution shadows may have been less from ca.10000-3000BP than from ca.3000BP to the present because caprock crowns would have more likely been covered in litter/soil/vegetation prior to forest clearance than after. The current and past presence/absence of soil/vegetation on caprock crowns may explain, at least in part, why some sloping pedestal sidewalls dip at greater angles than others do. Thus, where the inter-pedestal surface has been lowered by the same amount, sidewall dip will be greater within a dissolution shadow of relatively small areal extent than within a dissolution shadow of relatively large areal extent.

Little research has been undertaken on cold-climate dissolution rates, but Smith (1972) has cited rates of 2mm/ka on Somerset Island, and Lauritzen (2005) rates of 6.5mm/ka on Spitzbergen and 20-33mm ka in Arctic Norway. Studies have also been undertaken of temperate climate subaerial dissolution rates, and Trudgill (1983a), for instance, found that mean rates for lichen-coated Carboniferous limestone pavement at Malham were between 3.7 and 13.5mm ka. In contrast, no research has been undertaken of dissolution rates of the Carboniferous limestone in an arboreal setting (Section 11.1). With this in mind, twenty-nine limestone tablets were emplaced between arboreal soil/vegetation and rockhead (Malham Formation: Cove Limestone) in woodland on Oxenber, near Norber, for the duration of the 2004-2005 water year following procedures outlined in Section 7.6. The soil/vegetation varied from some 2cm of *Sphagnum* to some 5cm of litter to some 8cm of loam, all beneath ash, birch, hawthorn and hazel shrubs/trees, which were growing on till-free organic soils. This site was chosen because the limestone is largely till-free and because the woodland is semi-natural, an environment that is perhaps closely akin to that at Scales Moor from ca.10000-3000BP. Twelve tablets were recovered. The pH of soil samples adjacent to the tablets ranged from 6.4 to 7.5 (mean 7.1) (Table 12.4), which reveals that the potential exists for soil water to effect dissolution of the limestone surface. This is confirmed by the fact that all tablets suffered weight loss, and it was calculated, through extrapolation, that the potential lowering rate was approximately 2.4-10.9mm/ka (Table 12.4). Refer to Appendix 3pH Table 3pH.3, and Appendix 3T Tables 3T.4 and 3T.5 for full results

It has been hypothesised that the originally-bare pavement at Scales Moor may have undergone subaerial dissolution under tundra conditions from ca.14500-10000BP, sub-soil dissolution in a temperate arboreal setting from ca.10000-3000BP and subaerial dissolution under temperate conditions from ca.3000BP to the present. If the surface lowering rates are extrapolated for their respective time-periods they translate into a putative combined lowering of between 3.6 and 26.6cm since Devensian deglaciation in ca.14500BP (Table 12.5). At Scales Moor the height range of sloping sidewalls is about 10 to 23cm and their mean height is about 16cm, figures that fall within the range of the extrapolated results. The combined extrapolated figures thus support the proposed model for the formation of sloping sidewalls. This is so even allowing for the constraints outlined in Section 7.6, and for the facts that the figures were not obtained at Scales Moor and that the period of sub-arboreal dissolution at Scales Moor is uncertain. It is suggested that differences in pedestal height and in sloping sidewall dip have resulted from past and present variations in, for example, caprock decantation rates and decanted water acidity, arboreal interception rates, vegetation type, and soil water infiltration rates, pathways and acidity.

12.6.5: The formation of pedestals bounded by sloping and vertical sidewalls

Some of the pedestals beneath Carboniferous limestone caprocks at Scales Moor are bounded by sloping and vertical sidewalls, the former often being terminated by the vertical walls of a gryke or solution area (Plate 12.3). It is suggested that gryke formation post-dates sloping-sidewall formation since sidewall slope sometimes continues across grykes (e.g. SM4 and Plate 12.8). Such a situation could not have arisen if the grykes pre-dated sidewall formation since decanted alkalised water would have drained into them. In addition, grykes were observed to close under caprocks (e.g. SM1), which means that the cap has stilted gryke growth by protecting the underlying limestone from dissolution. The formation of solution areas, both large- and small-scale, may have occurred simultaneously with sloping sidewall fashioning due to dissolution under patches of Devensian till or it may have occurred at a later date under Flandrian peat and/or arboreal soils. There is no doubting that soil water at Scales Moor has the potential to dissolve the inter-pedestal surface since pH measurements indicate that soils in the sub-root zone are acidic, for instance pH 6.1 in the vicinity of SM2 and pH 4.2 in the vicinity of SM9. It is envisaged that subsequent to gryke and solution-area formation sidewall retreat would occur as at Norber (Sections 11.2.2 and 11.2.3). This is thought to be responsible for the abrupt termination of some sloping sidewalls and for the relative narrowness of some pedestals, as seen in Plate 12.3.

12.6.6: The formation of pedestals bounded by vertical sidewalls below Carboniferous sandstone erratics

There is one instance at Scales Moor where a pedestal has developed beneath a caprock composed of Carboniferous sandstone (SM7), although the caprock is no longer *in situ*, as is evident in Plate 12.9. The foundered caprock is surrounded by bare limestone that is generally smooth and lacking in rundkarren, and by patches of organic mat, the latter mostly found in solution hollows. The pedestal is bounded essentially by vertical sidewalls that rise about 15cm above the general level of the limestone surface; they are partly encircled by a moat-like runnel up to about 20cm deep. As there is no evidence that the limestone surrounding SM7 has ever been covered in till, the vertical sidewalls can be explained only by the surrounding limestone surface being lowered in a subaerial/sub-arboreal environment. In other words, they have formed in the same environment as sidewalls that slope The crucial difference between SM7 and pedestals bounded by sloping sidewalls, however, is that the former is capped by an ‘acid’ sandstone caprock and the latter are capped by ‘basic’ limestone caprocks. Accordingly, the caprock of SM7 is unable to ‘shield’ the exposed limestone surface beyond its distal edges, since water dripping off it has not become alkalised. Consequently, there is a quantum leap in the rate of dissolution from ‘insignificant’ under the caprock to ‘significant’ beyond its distal margin at the pedestal-crown and pedestal-sidewall-head junction. This leads to vertical sidewall formation, the moat-like runnel forming due to dissolution by a combination of acidulated decanted water shedding off the caprock outer edges and rainwater. In other words, the runnel represents a circum-caprock ‘dissolution hot-spot’ beyond which the limestone surface is lowered only by rainwater. As such, a ‘dissolution hot-spot’ is the antithesis of a ‘dissolution shadow’. A summary of the formation of the pedestal under SM7 is illustrated in Fig. 12.2; falling rain is omitted for clarity.

As SM7 is the sole one of its kind, since in all other cases grykes or dissolution hollows underlie Carboniferous sandstone erratics (Sections 12.6.1 and 12.6.3), it is worth considering why a pedestal formed below only it. The SM7 caprock is a little larger and is more tabular than most other sandstone erratics at Scales Moor, which may mean it was better able to protect the limestone beneath it. Lauritzen (2005) has proposed that caprocks with concave undersides and distinct drip-edges tend to overlie taller pedestals than caprocks with convex undersides and no drip-edges. Plate 12.9 reveals that the caprock has a concave underside, and although the caprock is now end-on, the presence of the circum-pedestal, moat-like runnel implies that it had distinct drip edges. Consequently, it is hypothesised that a combination of caprock size and shape has protected the limestone beneath, thus leading to pedestal formation.

12.6.7: Pedestal height and bedrock fabric

Goldie (2005) has proposed that weathering of weak and strong limestone results respectively in relatively high and low pedestals (Section 9.1). If so, it might be expected that adjacent pedestals in the same geological horizon would be of comparable height. This is clearly not the case at Scales Moor, as although the pedestals of SM4 and SM5 are less than 40m apart the height of the former is about 15cm whereas that of the latter is about 63cm (Plate 12.5). Moreover, SM10 and SM11 are just a few meters apart, yet the former rests on a pedestal some 16cm high while the latter is lodged in a gryke over 1.5m deep (Plate 12.6). The above examples support findings in Section 9.7 that there is no indication that limestone fabric has played a role in pedestal formation at Norber.

12.6.8: Erratics without pedestals

It was noted in Section 12.6.6 that apart from SM7 Carboniferous sandstone erratics lack pedestals and occur instead above/in grykes or in small solution hollows (Plates 12.1 and 12.2). A similar distribution of ‘acid’ Silurian gritstone erratics is found in Underlaid Wood (Plate 12.7), and Rose and Vincent (1983a) proposed that they were deposited into, or onto, already-opened grykes by meltwaters as the Devensian ice wasted. This proposal implies that the grykes at Scales

Moor pre-date ice wasting, which has repercussions re the timing of the expansion of the Wildwood onto the bare pavement. It goes without saying that meltwater cannot 'choose' which type of erratic it transports, yet similarly-sized limestone and sandstone erratics are found in close proximity at Scales Moor, the former on pedestals and the latter in grykes (Plate 12.6). It is argued that the grykes at Scales Moor do not, in fact, pre-date ice wasting. Consequently, an alternative explanation re the presence of 'acid' erratics in grykes is required, especially as similar distributions of such 'acid' erratics occur at sites other than at Scales Moor and in Underlaid Wood. This is regardless of whether the erratics are comprised of Carboniferous sandstone at Runscar or Shap Granite on the Gaythorne Plain or Devonian conglomerate at Twyn Du. Hence, it is argued that the opposite of Rose and Vincent's (1985a) proposal has occurred, and that the presence of the 'acid' erratics has led to gryke formation. It is envisaged this would occur if decanted acid water dissolved a sub- or circum-erratic hollow in the limestone surface that subsequently became colonised by vegetation, the latter then extending the hollow via sub-vegetation/sub-soil dissolution, as appears to be happening/has happened in Plate 12.1. Therefore, the lack of pedestals under the sandstone erratics at Scales Moor is due to the erratics failing to protect the limestone surface underlying them from dissolution, as proposed in Section 11.4 #2, and not because they have been washed into grykes.

12.6.9: Non-lithological caprock properties

Lauritzen (2005) has proposed that the shortest horizontal axis and shape factor of a caprock, and the rate of condensation erosion beneath the caprock affect pedestal size at Arctic sites in Spitzbergen and Norway. Lauritzen (2005) argues that there is a rough positive correlation between caprock size and pedestal height. That is, the greater the caprock short axis the greater the pedestal height, and caprocks with concave undersides and distinct drip-edges tend to overlie taller pedestals than caprocks with convex undersides and no drip-edges. Lauritzen (2005) also argues that as the caprock acts as a locus of long-lasting, low-levels of moisture and this leads to pedestal crown erosion, as indicated by the presence of botryoidal precipitates on minor protrusions and edges due to seasonal evaporation.

There is clearly no relationship between caprock short axis and pedestal height at Scales Moor, since the height of pedestals bounded by vertical and sloping sidewalls (SM1, SM2, SM3, SM8, SM9 and SM13) may vary greatly. For example, the vertical northern, eastern and southern sidewalls of SM2 are about 48cm high, whereas the sloping western sidewall is about 13cm high. In addition, the shortest horizontal axes of SM4, SM5 and SM10 are respectively about 1.3, 1.0 and 0.7m in length yet the respective heights of their pedestal are about 15, 63 and 16cm. Moreover, the size of limestone caprocks will have decreased through time due to their subaerial dissolution. This will affect the relative short-axis length of small caprocks more than large ones if the amount of loss is the same for all caprocks. The relationship between caprock shape and pedestal height is described by Lauritzen (2005: 4) as being "…very suggestible (or obvious)", yet the pedestal height beneath the flat-bottomed SM1 is about 13cm and that below the round-bottomed SM6 is about 26cm. What is more, the shape of limestone caprocks may have changed through time. No precipitates were noted on pedestal crowns, and as striae may be present on the crown of SM9 this indicates that very little or no crown erosion has taken place at all. Consequently, it is contended that Lauritzen's (2005) proposals are not applicable to pedestals at Scales Moor.

12.6.10: The umbrella theory

Although the umbrella theory does not hold true at Norber since the caprocks have protected the limestone beneath them for the last ca.3000 years only (Section 11.5), this is not the case at Scales Moor for pedestals bounded by sloping sidewalls. This is because the caprocks above the sloping-sidewall pedestals have protected the limestone surface beneath them from karstic solution by rainwater for longer periods. These lasted from pedestal inception in ca.14500BP until the beginning of the Flandrian in ca.10000BP, for an indeterminate period afterwards until the site was overcanopied by the Wildwood and from ca.3000BP to the present following forest clearance. These periods amount to more than half the age of the pedestals.

12.6.11: Conclusion

The essential difference between the pedestals at Norber and Scales Moor is that those at the former site are bounded by vertical sidewalls only whereas those at the latter site are bounded by vertical and/or by sloping sidewalls. Since the vertical sidewall inter-pedestal surroundings are analogous at both sites, i.e. the sidewalls are abutted by vegetation-covered regolith, it is concluded that the vertical sidewalls at Scales Moor have formed in the same manner as those at Norber. The inter-pedestal vertical-sidewall and inter-pedestal sloping-sidewall surroundings at Scales Moor are not, on the other hand, analogous, which means that sloping sidewalls must have formed in a different environment from that in which vertical sidewalls formed. The lack of awareness of when and if vegetation spread onto the present-day bare pavements, and the type and distribution of soils that might have developed under that vegetation make it difficult to assess accurately the past history of pedestals bounded by sloping sidewalls at Scales Moor. Nevertheless, it seems likely that sloping-sidewall formation began in a subaerial circum-erratic dissolution shadow environment between ca.14500 and 10000BP, probably earlier rather than later, and that development in this setting may have continued well into the Flandrian. At some stage during the latter period, forest soils/vegetation may have covered the sidewalls, but the fact that vertical sidewalls did not develop infers that fashioning continued in a circum-erratic dissolution shadow environment. Following forest clearance in ca.3000BP dissolution resumed under open skies, a setting that is still extant today. Therefore, the sloping sidewalls of the pedestals at Scales Moor have formed essentially as the result of dissolution in a subaerial/sub-arboreal environment.

12.7: The Burren (Lat. 52º 58' to 53º 10'N, Long. 08º 58' to 09º 25'W) (Ordnance Survey Ireland Discovery Sheets 51 Clare, Galway 1:50000 (2002) and 52 Clare, Galway 1:50000 (2003))

12.7.1: Introduction

The Burren, which is by far the largest of the sites examined, forms a gently inclined plateau some 360km² in area that extends from sea level to 344m OD. It consists mainly of Carboniferous limestones of Visean age some 500m thick that are divided into a number of formations and members based on lithological characteristics (Table 12.6). The beds have been folded into a series of shallow anticlines and synclines that rarely dip at angles greater than 5º, and they contain two major joint sets that strike approximately north-south and east-west, their relative dominance and spacing varying with locality. The periglacial/tundra Burren panorama immediately following erratic deposition at the end of the Killard Point Stadial in ca.13700BP consisted primarily of a glaciokarst landscape (e.g. Williams, 1966; Smart *et al.*, 1983), which Drew (2001) has likened in appearance to the Yorkshire Dales. Farrington (1965) has written that deposition of drift was irregular and that there were probably drift-free areas, and that deposits are normally very stony and consist almost completely of material derived from limestone apart from finer fractions. Ivimey-Cook and Proctor (1966) have also written that drift is scanty, local and stony, and that in places it consists almost entirely of compacted limestone debris. Today, the limestone landscape consists primarily of diverse amounts of bare rock, clasts and vegetation, the latter mostly characteristic of a past cover of mature grassland or woodland. Refer to Appendix 3V.2 for a list of plant species identified at the site, and Appendix 5B Table 5B.1 for the locations, form, geology and surroundings of the sampled pedestal rocks.

12.7.2: Survey results

Forty-six perched pedestal rocks that occur from 6 to 213m above OD were logged; all caprocks are composed of Carboniferous limestones. The pedestals occur in the Lissylisheen, Ballyelly, Aillwee, Maumcaha, Hawkhill, Fanore and Black Head members, all of which are part of the Slievenaglasha and Burren formations. Neither the Tubber Formation, which comprises a thin, north-coast strip, nor the Fahee North and Balliny members of the Slievenaglasha Formation were visited. The pedestals are either bounded by sloping sidewalls only (Plates 12.10 and 12.11), or by a combination of sloping and vertical sidewalls (Plates 12.12 and 12.13). No pedestals with only vertical sidewalls were encountered. Sloping sidewalls either merge more-or-less imperceptibly with the surrounding limestone surface or terminate at gryke/solution hollow sidewalls, as respectively revealed to the right and foreground of Plate 12.12. Sidewall slope ranges from around 5 to 20º and sidewall height from approximately 2 to 59cm; the mean height of the fifteen pedestals that are bounded by only sloping sidewalls is about 16cm. Vertical sidewalls are comprised of an exposed surface up to about 50cm in height and are abutted by regolith that is up to 20cm thick. Caprocks are more-or-less centrally positioned about pedestals bounded by only sloping sidewalls, but are rarely so about pedestals which are partly bounded by vertical sidewalls. Here, pedestal width is largely determined by the location, spacing and pattern of joints, and is generally greater to the north and south (normal to the more widely-spaced east-west joints) than to the east and to west (normal to the more narrowly-spaced north-south joints). Many pedestal crowns are not exposed, but those that are are generally flat or smooth; no striae were noted. The inter-pedestal surface comprises two end members composed almost entirely of tabular clints (Plate 12.10) or of pasture (Plate 12.13) with all stages in between (e.g. Plates 12.11 and 12.12). Erratics lacking pedestals also occur, especially on bare pavement to the east of Mullagh More in R3495. Erratics were noted under hazel (*Coryllus avellana*) canopy scrub, but it was not possible to determine whether pedestals were present or not due to the presence of ground cover, tree roots and regolith. A few partly-foundered caprocks are present, most commonly occurring to the east or west of their pedestals. Most soils appear to be thin residues a few millimetres thick below organic mat on pavement or organic rendzinas/mineral brown earths in solution hollows; scraps of peat under calcifuge vegetation on clints were also encountered. Clasts on the Burren consist almost entirely of Carboniferous limestones, and only two *in situ* non-Carboniferous limestone clasts, which are composed of sandstone, were found although sandstone boulders were occasionally seen in dry-stone walls. Only two sections of till were encountered, one comprising a fresh 5-6m high exposure of near-vertical cliffs on the north bank of the Caher River (M15003 09108) and the other a weathered 1m high excavation-exposure at An Carn (R2799) that could be viewed close-to only by using binoculars. The Caher exposure consisted primarily of unstratified material composed of some 60% of light grey fine-grained groundmass and of some 40% of dark grey sub-angular to sub-rounded Carboniferous limestone phenoclasts that range up to boulder size, as is evident in Plate 12.14. The An Carn exposure appeared similar, but perhaps with a greater proportion of phenoclasts. In addition the presence of rounded limestone clasts on the Burren plateau infer (patchy?) till was present prior to weathering and soil formation. The area was quartered by mountain bike and on foot, and all pedestal rocks encountered were surveyed.

12.7.3: The formation of the Burren pedestals

As the Burren is so extensive and as circum-pedestal environments are so varied, it was thought good sense to limit accounts of pedestal formation to two end-member sites, i.e. Sheshymore (Plate 12. 10) and Lissylisheen (Plate 12.13), and one in-between, i.e. Gortlecka (Plates 12.11 and 12.12). Sheshymore is characterised by large expanses of flattish pavement with embryonic kamenitzas on some clint surfaces and fresh-looking rundkarren on some clint edges, the pavement being divided by grykes that rarely exceed 30cm in width but that may reach 2, 3 or even 4m in depth (Plates 12.10 and 12.15). Drew (1983) has proposed that until comparatively recently the pavement may have been protected from solutional erosion by a blanket of calcareous till. Evidence cited for this comprises the lack of dissection by karren on clint blocks together with traces of a calcareous mineral soil that can be found at depth in some of the grykes, which suggests it was eroded and washed underground. It is important to establish whether Drew’s (1983) proposals have substance, because if so the Sheshymore pedestals can have formed only after the putative cover was lost, i.e. comparatively recently. There are three major stumbling blocks with Drew’s (1983) proposal. First, the grykes cannot have formed beneath the till since Drew (1983) maintains that the latter was pavement-protective. This means that gryke formation must pre-date till deposition, otherwise no grykes would have been present for the till to be washed into. Yet, if grykes were present at the time of till deposition it is perplexing to comprehend why till erosion commenced only relatively recently. Second, no mineral deposits occur on the clint apart from a smattering of angular limestone clasts up to 2cm in size under the few erratics that dot the site. It is not known if the clasts are of glacial or post-glacial origin, since it is impossible to determine whether the caprocks rest in or on them. Nonetheless, even supposing the clasts are remains of the lost till it is considered they are far too thinly spread to form a protective cover. Third, The Burren till has been described as stony, and this is confirmed by till composition in the Caher Valley (Plate 12.14) and at An Carn, as both contain clasts up to cobble size. Assuming that the putative and extant tills share common characteristics it is difficult to see how such coarse clasts could have been washed several metres by overland flow across flat, horizontal clint often tens of square metres in areal extent into adjacent grykes. This is because Hjulström Curves show that even particles 2cm in size require a velocity of some 10cm/sec to entrain them. Consequently it is argued that a blanket of calcareous till did not cover the pavement at Sheshymore.

Ivimey-Cook and Proctor (1966) have written that the *Corylus* scrub that over-canopies large tracts of the Burren today is largely anthropogenic in origin and in the past much taller trees predominated. Accordingly, it is possible that the pavement surface may have been somewhat akin to that in Underlaid Wood (Plate 12.8), i.e. mostly covered in *Sphagnum*. In fact, it is clear from Plate 12.15 that *Sphagnum* might be more prevalent if an over-canopy was present. If so, it is possible that dissolution of the inter-pedestal clint might have taken place as suggested in Section 12.6.4 re Scales Moor, i.e. largely in a dissolution-shadow subaerial/sub-arboreal environment, which may explain the lack of dissection by karren at the site. Apart from sub-caprock limestone chips and *Sphagnum*, the only other deposit present on the clints is peat with calcifuge vegetation, such as heather (*Erica* sp.), growing on it, as can be seen in the background of Plates 12.10 and 12.15. The peat appears to be retreating, and where it has done so rundkarren occur and/or the pavement surface is uneven. It is clear that dissolution of the limestone surface is occurring under the peat, since two samples analysed four days after collection following procedures outlined in Appendix 4.2 show the pH gradient changes from 5.3 in the root zone to 7.1 immediately above the pavement itself. The limited occurrence of the rundkarren and uneven pavement probably means that the peat was never widespread, but as the immediate surface about B9 is uneven it may well be that that peat has played a role in its development. It was noted in Section 10.2 that at ca.5000BP retrogressive changes in the vegetation of Britain occurred that led to a reduction in tree cover and an increase in heaths, blanket mires and grasslands. Consequently, peat began to accumulate at Scar Close at the expense of open alder and hazel due to increased cloudiness and decreased evaporation (Gosden, 1968). Thus, if peat accumulation occurred concurrently at Sheshymore it follows that the B9 pedestal will have been only modified by its presence. Therefore, the pedestals at Sheshymore formed in the same manner as the pedestals bounded by sloping sidewalls on Scales Moor. This is because the caprocks are composed of Carboniferous limestone, and because pedestal form and surroundings are almost identical at the two sites.

Gortlecka typically comprises a landscape consisting of jumbled limestone clasts, much dissected *in situ* rock and superficial-filled solution areas, the latter ranging in size from less than a metre to hundreds of metres across (Plates 12.11 and 12.12). As at Scales Moor, the sloping sidewalls may merge gradually with the surrounding limestone surface (Plate 12.11) or they may terminate at the vertical sidewalls of widened grykes or solution hollows (Plate 12.12). Since the inter-pedestal surroundings at the two sites are fairly similar (compare Plates 12.4 and 12.12, for instance) it is suggested that the pedestals have formed in the same manner, i.e. within a dissolution shadow but with an input from sidewall retreat caused by widening of grykes or solution areas. It would seem unlikely that till has played any part in the formation of the solution hollows at Gortlecka because Curtis *et al.* (1976) have pointed out that till was deposited on the back of the Burren limestone benches, whereas Gortlecka is situated towards their distal edges.

In contrast to Sheshymore and Gortlecka, pavement is an uncommon feature at Lissylisheen, which instead is characterised by pasture-covered regolith with limestone residuals of various shapes and sizes protruding through it (Plate 12.13). As both pedestal form and inter-pedestal surroundings are generally similar to that in Plate 12.3 at Scales Moor it is contended that the pedestals have formed in the same manner, i.e. within a dissolution shadow with a major input from sidewall retreat caused by widening of solution areas. Similar Burren pedestals can be found by Meggagh East Megalithic Tombs, at Parknabinnia and Doonyvardan and east of Knockanes. There is no questioning that the potential is present for regolith water to effect dissolution since the pH of three sub-root samples at Lissylisheen, Meggagh East and Parknabinnia was respectively 5.9, 7.2 and 6.1. A common feature at these sites is that vertical sidewalls are relatively well-weathered, as exemplified by the vertical sidewall facing the viewer in Plate 12.13, which implies that vertical sidewall retreat has all but ceased. This phenomenon may be explained by the fact that (unlike Norber) water decanting off limestone caprocks is relatively alkaline (Section 12.6.3). It is argued that this causes a decrease in soil-water acidity at the foot of the sidewall thus reducing the potential for soil water to dissolve the limestone. Consequently, retreat falters, which may well explain why fewer caps have toppled from their pedestals on the Burren than at Norber. Little rain fell during either visit to the Burren, which means that this hypothesis was not proved.

The one exception to the rule that the pedestals on the Burren have formed in a similar setting to those at Scales Moor occurs in the Caher Valley. Here, the down-slope sidewall of B44 owes its vertical nature to retreat of a glacially-plucked scar rather than to gryke/solution-area sidewall retreat (Plate 12.16). Its downslope sidewall has thus formed in a similar manner to sidewalls found below bench edges at Norber.

12.7.4: Related topics

The fact that pedestals at Gortlecka, as exemplified by B1 in Plate 12.11, are of relatively low stature when compared to those at Norber is contrary to Goldie's hypothesis (2005) that pedestal height reflects bed thickness, i.e. the greater the bed thickness the lower the pedestal height and vice versa (Section 9.6). Hence, despite the finding that five of six pedestals at Gortlecka and eighteen of thirty at Norber are comprised of thinly-bedded strata (the remainder are more widely-bedded), mean pedestal height is respectively about 20cm and 45cm at the two sites. Moreover, support for the findings in Section 9.6 that limestone composition did not play a role in pedestal formation is provided by the occurrence of pedestals bounded by sloping sidewalls in all Carboniferous Limestone members on the Burren despite their lithological differences. Thus, Table 12.6 column 3 reveals that members may be massive, nodular or dolomitised, and may or may not contain chert. Furthermore, pedestals B41 and B42 confirm the finding that pedestal height is not a reflection of the shortest caprock horizontal axis (Section 12.6.9), as both pedestals are about 24cm in height and yet the short axis of their respective caprocks is about 3m and 0.8m (Plate 12.17).

12.8: Cavan Burren (H 0735: Ordnance Survey of Northern Ireland Sheet 26 Lough Allen 1:50000 (1984))

The Cavan Burren is an upland site occurring about 250m above OD consisting of several square kilometres of fifty-year-old conifer plantations, rough pasture and recently-deforested scrub. Eleven pedestal rocks were noted during a walk in eastern areas of the site. All the caprocks are composed of Carboniferous, pale-grey, medium-grained Glenade Sandstone orthoquartzites and they range in bulk from about 1 to 4m^3. The underlying bedrock is the Knockmore Limestone of the Dartry Limestone Formation that for the most part is thinly- to medium-bedded with wide joints. The pedestals are bounded by vertical sidewalls and by uneven crowns, the latter varying in height by as much as 17cm. The range of inter-pedestal sidewall height is considerable, as it extends from about 8 to 72cm with a mean of about 44cm. The sidewalls of most individual pedestals are likewise of unequal stature. For example, the north and south sidewalls of CB7 (Plate 12.18) have a height difference of about 37cm. Many pedestals show evidence of dissolution by water that has decanted off their overlying caprock, and although this is largely restricted to sidewalls it occasionally occurs on crowns, most often below widened joints in the caprock (Plate 12.19). Two sub-root soil samples were collected, one each from the two different environments comprising the site, i.e. pasture and arboreal. The samples were analysed three days later. The pH values were 5.7 under pasture (CB7) and 6.9 under trees (CB1) indicating that regolith water has the potential to dissolve limestone. Sub-regolith pedestal undercutting, which reaches a maximum indent of 37cm, is fairly common, and a few caprocks have partly foundered. As caprocks are composed of 'acid' grit, sidewalls are vertical and vegetation-covered regolith mantles the limestone up to the base of the pedestals, it is argued that the Cavan Burren pedestals formed in the same manner as the pedestals occurring on level ground at Norber. It is possible also that man has influenced pedestal development, as the heap of limestone clasts on CB7 may have been robbed from around its pedestal (Plate 12.18). Refer to Appendix 5CB for the locations, form, geology and surroundings of the sampled pedestal rocks.

12.9: Cunswick Tarn (SD 4893: Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998))

About ten boulder-sized Silurian grit erratics occur in the field found to the west of Cunswick Tarn and to the south of Ash Spring wood. One of the erratics (CT1) forms the cap of a perched pedestal rock, its pedestal consisting of vertical sidewalls that are overhung by the caprock by as much as 37cm (Plate 12.20). The sidewalls are entirely surrounded by vegetation-covered regolith apart from to the north-east where it has been removed by lamb poaching and rabbit use. This is supported by the occurrence of stinging nettles (*Urtica dioica*) in close proximity to the pedestal (Plate 12.20), as they are indicative of disturbed ground and nutrient enrichment (Chinery, 1977). The regolith loss has revealed that a bedding plane forms rock head. Sidewall dissolution is much in evidence, since vertical concave hollows, discontinuity widening and an undercut some 10cm deep are present. Several blocks that are thought to have calved from the sidewall occur beneath it, and it is envisaged that if undercutting continues a block 35cm thick will fail along the entire north-west face, since the block is separated from the proximal part of the pedestal by an opened joint. The pedestal crown is partly covered by a centimetre or so of regolith, but enough of the surface is exposed to reveal that it comprises a flat, horizontal surface. No striae could be seen, although Hughes (1886), who wrote (p. 528) that they ran from "…north to south", noted them. As such, they reveal that the crown is of Devensian age. Pedestal height rises from 44cm to 55cm down-dip due to a disparity in slope between pedestal crown, which is horizontal, and bedding at pedestal base, which dips at 16º. Relatively fresh rundkarren are present on the pedestal crown at its north-west end, while relatively eroded rundkarren are present on clints just a metre or so distant from the pedestal rock. The site is in undifferentiated Carboniferous limestone that is medium-bedded with wide joints. As the caprock is composed of Silurian grit, sidewalls are vertical and vegetation-covered regolith mantles or mantled the limestone up to the pedestal base it is argued that the pedestal at Cunswick Tarn formed in the same manner as pedestals on level ground at Norber. Of particular interest are the undercut, the widened joints and the calved blocks, all of which confirm that toppling is an integral part of the fashioning of pedestals with vertical sidewalls. In fact, it was suspected that this may have led to caprock foundering, since Goldie (2005) wrote (p. 435) that the erratic at Cunswick "…has fallen off its pedestal." The photograph of CT1 (Plate 12.20) was taken in October 2002, and, in view of Goldie's (2005) assertion, the site was revisited in April 2007 when it was found that CT1 was still *in situ*. Refer to Appendix 5CT for the location, form, geology and surroundings of the sampled pedestal rock.

12.10: Dowkabottom (SD 9568: Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997))

Dowkabottom is a dry valley whose floor is mostly covered in vegetation-covered regolith. A few tens of Carboniferous limestone boulder-sized erratics are present at the site, one of which forms the caprock of a pedestal (Plate 12.21). The pedestal is much divided, and on close inspection appears to be formed of individual clasts rather than of *in situ* bedrock. Two similar pedestals occur elsewhere, N31 at Norber (Plate 7.5) and SC4 at Scar Close (Plate 12.35). All three caprocks consist of Carboniferous limestones. If the pedestals are indeed composed of individual clasts, it is possible that they have undergone comparatively little dissolution compared to those in the surrounding regolith due to alkalised water decanting from the caprocks reducing the acidity of regolith-water that might percolate under the caprocks. In other words, the caprocks cause 'dissolution curtains' to form about them thus buffering the clasts beneath them from dissolution by the relatively more acid regolith-water. A summary of the formation of limestone clast pedestals is illustrated in Fig. 12.3; falling rain, vegetation and rockhead are omitted for clarity. Refer to Appendix 5D for the location, form, geology and surroundings of the sampled pedestal rock.

12.11: Farleton Knot (SD 5480: Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998))

Farleton Knott is an isolated hill some 2.5km² composed of limestone that in places dips at up to 16º. Hundreds of Carboniferous limestone erratics are dotted over the site, many of which have pedestals beneath them. Eleven perched pedestal rocks were sampled, seven bounded by vertical sidewalls, three by sloping sidewalls, and one by a combination of vertical and sloping sidewalls. These were regarded as being more-or-less numerically representative of the pedestal types at the site. The pedestals of FK1-FK3 and FK8-FK11 are bounded essentially by vertical sidewalls, and of these FK2 and FK3 stand out, as they are the only ones abutted by vegetation-covered regolith, which is about 16cm thick. The surroundings of the remaining five pedestals are quite different, since they are encircled by thin deposits of clitter and/or rough, rubbly bedding that lack signs of dissolution and/or upturned clint and/or rotated erratic halves, as seen in Plate 12.22. Pedestal crowns are generally smooth, and striae with a strike of 042/222º were measured on FK1 and FK3. In contrast the pedestals of FK4, FK5 and FK6 are comprised of sloping sidewalls with a mean height of about 9cm that extend beyond their caprocks and merge with adjacent pavement as shown in Plate 12.23. The latter consists for the most part of large clints, which is horizontal about FK4 but which dips at 16º about FK5 and FK6. Rundkarren are not present on any of the sidewalls, occurring only on the pavement beyond FK4; no kamenitzas are present anywhere. Pedestal crowns are generally smooth, but no striae were evident. The pedestal of FK7 consists of both vertical sidewalls some 42cm in height that abut grykes/solution areas containing regolith and sloping sidewalls some 15cm in height that merge with the surrounding pavement, as can readily be made out in Plate 12.24. The site is in undifferentiated Carboniferous limestone that is thinly- to thickly-bedded with wide to very wide joints. Refer to Appendix 5FK for the locations, form, geology and surroundings of the sampled pedestal rocks.

Although the pedestals of FK1 and FK8-11 are similar in form to vertical-walled pedestals on Scales Moor, their inter-pedestal surroundings all indicate that clint removal has taken place. This phenomenon is well documented by Goldie (1995) at the site. Further evidence of removal is provided indirectly by Hughes (1886: 529) who described the pedestals at Farleton Knot as "…not often more than 3 to 7 inches high" although some are "…as much as a foot high." Yet many of the pedestals bounded by vertical sidewalls are higher, sometimes greatly so, and FK1 has an exposed height of 47cm for example. It also occurs in splendid isolation near a public footpath, and with this in mind it seems unlikely that it would have gone unnoticed by such a judicious observer as Hughes (1886). Consequently, it is reasoned that FK1 did not exist in its present form in 1886. As a result, it is argued that the sidewalls of FK1 and FK8-11 are anthropogenic. Further evidence that all is not natural is provided by the presence of dissolution hollows on the underside of 'caprock' FK2, which means it is upside-down (Plate 12.25). In contrast, as the pedestal of FK3 is Carboniferous-limestone capped, is bounded by vertical sidewalls and is abutted by vegetation-covered regolith, it is argued it has formed in the same manner as pedestals of a similar shape and setting at Scales Moor. Furthermore, as the pedestals of FK4-FK6 are Carboniferous-limestone capped, are bounded by sloping sidewalls and are abutted by the open air, it is argued they have also formed in the same manner as pedestals of a similar shape and setting at Scales Moor. It is also contended that FK7, which is Carboniferous-limestone capped and bounded by vertical sidewalls that are abutted by vegetation-covered regolith and sloping sidewalls abutted by the open air, has formed in a similar manner to pedestals of a similar shape and setting on Scales Moor. Evidence that subaerial dissolution has played a role in the formation of the sloping sidewalls at Farleton Knot is provided, again indirectly, by Hughes (1886: 529), who wrote that the boulders seem to have protected "…a somewhat larger surface of the limestone than that immediately below them; but the part of the limestone so preserved was always on the side away from the south-west wind." In other words, the limestone to the north-east was preserved due to the creation of a rain shadow. To what extent rain shadows have complemented dissolution shadows at Farleton Knot and elsewhere is conjectural, but their formation must have contributed something as Ahrens (2003) has pointed out that when wind encounters solid objects eddies occur downwind for about four times the height of the object. Moreover, Allaby (2002) has indicated that the distance between rain gauges and obstructions should be at least equal to the height of the obstruction in order to evade the sheltering effect of the obstruction. Unfortunately, the larger limestone surfaces on the side away from the south-west wind at Farleton Knot have long since been removed, and are now probably adorning rockeries and walls.

12.12: Gait Barrows (SD 4877: Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998)

Gait Barrows is a National Nature Reserve about 2km² comprised of limestone pavements, dense thickets and meadows. For the purposes of the study an additional 3km² of the surrounding area was surveyed from public footpaths. A total of nine Carboniferous limestone erratics were encountered, three of which cap pedestals. Two perched pedestal rocks (GB1 and GB2) occur on limestone pavement within the reserve and one (GB3) just beyond it about a kilometre to the south-east in a field to the west of Yealand Hall Allotment. GB1 and GB2 are comprised of sloping sidewalls that dip at angles of up to 18° and are respectively about 12cm and 15cm in height. The sidewalls extend for about a metre in all directions beyond the extremities of the caprocks and merge almost imperceptibly with the adjacent pavement, as can be observed in Plate 12.26. The pavement is formed of relatively wide clint that is peppered with well-developed kamenitzas, a number of which are more than 10cm deep and almost a metre in diameter; a few mature sinuous rundkarren containing mosses, herbs and grasses are also present. Organic soil is found in some of the kamenitzas and rundkarren, and also under woody vegetation usually in association with litter. Although both pedestals are very similar in form, GB1 is surrounded by bare pavement while GB2 is almost entirely covered in about a centimetre of moss/litter/humus below a near-impenetrable yew (*Taxus baccata*) over-canopy thicket. Apart from the organic soil no other regolith is present on the pavement. In stark contrast, the pedestal of GB3 is bounded by vertical sidewalls some 34cm in height and is overhung by its caprock, as revealed in Plate 12.27. It is also entirely abutted by vegetation-covered regolith (mineral soil on till) that is at least 9cm deep. Gait Barrows is mentioned in Goldie (2004: poster), who writes of GB1 that it is "…a true solution protection pedestal". The site is in undifferentiated Carboniferous limestone that is medium-bedded with moderately wide to extremely wide joints. Refer to Appendix 5GB for the locations, form, geology and surroundings of the sampled pedestal rocks.

There is no evidence to show that the pavement within the vicinity of GB1 has ever been covered in regolith, since rundkarren, other than the few that are sinuous in form, are absent. Moreover, Rose and Vincent (1983b: 495) have shown that the kamenitzas at Gait are at least six thousand years old and suggest that they may have been initiated "…soon after the Devensian Ice wasted". It can be seen in Plate 12.26 that mature trees are growing only from grykes and do not occur on clints. It is contended that gryke-density is sufficient to have allowed a part/complete arboreal over-canopy to have formed and for a moss/litter veneer similar to that covering the pedestal of GB2 to mantle some/all of the clints. Accordingly, it is argued that GB1 and GB2 formed largely in a subaerial/sub-arboreal environment in the same manner as the Carboniferous-limestone-capped sloping-sidewalled pedestals at Scales Moor. In contrast, GB3 has been wholly fashioned in a sub-vegetation-covered-regolith environment in the same manner as the Carboniferous limestone-capped vertical-sidewalled pedestals at Scales Moor.

As noted in Section 9.1, Goldie (2005) has proposed that weathering of weak and strong limestone results respectively in relatively high and low pedestal height. Gait Barrows was placed in the strong limestone category, presumably because the pedestal of GB1 is about 12cm high. Goldie (2005) makes no mention of GB3, but as its pedestal is relatively high (34cm) it follows that the limestone that composes it ought to be weak. The terms 'weak' and 'strong' are, off course, entirely subjective. It could be contended that GB1 is composed of 'stronger' limestone than GB3, since although both pedestals are medium bedded, the jointing of GB1 is extremely wide while that of GB3 is moderately wide. Nonetheless, the limestone that composes the pedestal of GB3 can hardly be described as 'weak'. Apart from their form, the most obvious difference between the GB1 and GB3 pedestals is that they are surrounded by and have formed in different dissolution settings, i.e. respectively subaerial/sub-arboreal and sub-vegetation-covered regolith. Hence, as both Hughes (1886) and Jones (1965), for example, have pointed out that soil and vegetation open up discontinuities, it is suggested that Goldie's (2005) 'weak' and 'strong' limestones are more apparent than real. Furthermore, it would seem that 'weak' limestone passes into 'strong' limestone within a distance of less than a metre. This is because, joints are seen to close under caprocks due to the caprock protecting the limestone from weathering and erosion, a phenomenon recorded by Jones (1965), and by Rose and Vincent (1983a). The narrowing of joints from an inter-pedestal to a sub-pedestal setting can be seen in Plates 12.8 and 12.23. It was noted above that Goldie (2004: poster) has written that GB1 is "…a true solution protection pedestal". It is not made clear exactly what this phrase means, but it implies that 'false solution protection pedestals' must also exist. Could the latter include GB3 and the pedestals at Norber, since they are bounded by vertical rather than by sloping sidewalls? Be that as it may, the point about vertical-walled and sloping-walled pedestals is that both types have been protected from dissolution by their caprocks, whether from subaerial/sub-arboreal dissolution or sub-regolith dissolution.

12.13: Gearstones (SD 7779: Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997))

Gearstones is located in upper Ribblesdale, about 1.5km to the east-north-east of Ribblehead. A few tens of Carboniferous limestone erratics ranging up to 2.5m in size occur at the site, of which eight can be seen to comprise the caps of perched pedestal rocks above the east bank of the ravine cut by Gayle Beck. Pedestal sidewalls are all vertical, those of G1-7 having greater downslope than upslope height, as seen in Plate 12.28, and those of G8 having similar all-round height. The pedestals are overhung by their caprocks to a greater or lesser degree and they are entirely surrounded by vegetation-covered regolith that slopes at up to about 25º towards the gorge. Rundkarren are present in the vicinity of G5 on an exposed limestone bench and on the upper surface of its caprock. Exposed pedestal crowns are ice-smoothed (no striae are present) or presumed ice-plucked; cobble-sized clasts separate some of the caprocks and pedestals. The site is in the Malham Formation, Gordale Limestone that is for the most part thinly- to medium-bedded with wide joints. Refer to Appendix 5G for the locations, form, geology and surroundings of the sampled pedestal rocks.

As G1-7 are situated above ground that slopes at up to 12°, and as the heights of their downslope and upslope sidewalls are so disparate (e.g. those of G1 are respectively 78cm and 41cm), it is argued that their downslope sidewalls have formed due to plucked-scar sidewall retreat, as at Norber. It must be pointed out, though, that there is an almost complete absence of scar faces at the site. Accordingly, it is contended that plucked scars formerly extended to the south-east and to the north-west of the pedestals, and that they have been entirely removed by post-deglaciation dissolution. Three sub-root soil samples were collected, from G1, G6 and G7, and the samples were analysed the next day following procedures outlined in Appendix 4.2. The pH values were respectively 5.8, 4.2 and 5.2, which indicates that regolith water has the potential to dissolve limestone at the site. It is argued that G8 has been fashioned in the same manner as the Carboniferous limestone-capped, vertical-walled, regolith-abutted pedestals on level ground at Scales Moor. Of particular interest at the site is G4, whose caprock leans precariously on a bank of regolith that dips at about 25º towards the gorge (Plate 12.29), and were it not for poaching by sheep to the downside its pedestal would be visually undetectable. The just-uncovered pedestal thus supports the hypothesis made in Section 11.4, #5 that pedestals will remain unexposed if the amount of rockhead lowering does not exceed the thickness of the regolith that surrounds them and if the regolith is not otherwise eroded. Of further interest is the presence of rundkarren on the upper surface of the caprock of G5. It is contended that they formed under a cover of either subaerial vegetation or arboreal litter/soil that has been lost following forest clearance.

12.14: Great Asby Scar (SD 6510: Ordnance Survey Outdoor Leisure 19 Howgill Fells and Upper Eden Valley 1:25000 (1995))

Great Asby Scar is part of an extensive area of east-west-striking limestone pavements that occur between Appleby and the Howgill Fells, many of the pavements having undergone extensive removal (Goldie, 1995). The site has been examined by Goldie (1994; 1996), and at Area 8 (Goldie, 1994; 1996) a few tens of Carboniferous limestone blocks that together extend for a distance of 100m or so rest on pavement close to a north-south striking scar. The pavement in the vicinity of Area 8 is formed of clints that are sometimes more than a metre across; relatively fresh rundkarren are ubiquitous and kamenitzas sporadic. Nine pedestal rocks were located, and their pedestals are all bounded by sloping sidewalls that either merge with the surrounding pavement or pass under organic mat clear of the extremities of their respective caprocks, as can be observed in Plate 12.30. Pedestal height was sometimes extremely difficult to quantify due to the uneven nature of the surrounding limestone surface, but it was estimated that the range is about 7 to 19cm and that the mean is about 11cm. These observations more-or-less match those made by Goldie (1994: 3), who wrote that the remnants stand perched "…on sloping pedestals…about 10cm in height…" that "…spread beyond the base of the overlying block for about 10cm in width." Pedestal crowns are generally flat but one has rundkarren etched into it, as do a few of the caprocks; sidewall slope ranges from about 10 to 24º. The site is in undifferentiated Carboniferous limestone that for the most part is thickly-bedded with wide to very wide joints. Refer to Appendix 5GAS Table 5GAS.1 for the locations, form, geology and surroundings of the sampled pedestal rocks.

Since Goldie (1994: 3; 1996: 130) states that the blocks are respectively remnants of "…an upper bed" and of "…an upper massive bed that forms a scar immediately to the east", it would appear that Goldie (1994; 1996) presumed that the blocks were pseudo-erratics (re Sweeting, 1966). This possibility is almost certainly confirmed by Goldie's (2005) reassessment of the site, as it is stated (p. 435) that no pedestals "…have been found under the erratics at Great Asby." Close inspection revealed, however, that block and pavement discontinuities did not always correspond. In addition, some caprocks were about 10m from the scar edge, which suggests transport, while caprock upper surfaces were generally at least 0.8m below the surface of the pavement they were ostensibly remnants of. Accordingly, the blocks are considered to be glacial erratics rather than pseudo-erratics. Consequently, it is argued that GAS 1-9 have been fashioned in the same manner as the Carboniferous limestone-capped, sloping-walled, open air-abutted pedestals at Scales Moor.

12.15: Hutton Roof Crags (SD 5577: Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern area 1:25000 (1998))

Hutton Roof Crags is described by Lewis (1990), Goudie and Gardner (1992), Goldie (1995), who has noted that the pavement morphology has been much altered by human interference, and Milligan (2003). Only the latter, however, mentions pedestal rocks. Many tens of erratics, composed mostly of Carboniferous limestones, but also of Silurian and Carboniferous grits, occur at the site. Four perched pedestal rocks were recorded, three (HRC1-3) in the field to the north of

Lancelot Clark Storth and one (HRC4), known as the Cuckoo Rocking Chair by Milligan (2003), to the west of the hamlet of Hutton Roof. The field to the north of Lancelot Clark Storth consists partly of bare dissected pavement and solution areas containing thin vegetation-covered organic regolith; eroded rundkarren are present on the clints and on some of the limestone erratics. Evidence of pavement removal, probably up to parts of the bases of the three pedestal rocks, occurs in the form of inverted clint and rough bedding that lacks rundkarren. HRC1, which is composed of Silurian grit, is bounded by vertical sidewalls, while HRC2 and HRC3, which are composed of Carboniferous limestones, are bounded by a combination of vertical and sloping sidewalls, as is evident in Plate 12.31. The mean height of the sloping sidewalls is about 16cm. Exposed pedestal upper surfaces are ice-smoothed (no striae are present) or presumed plucked. There is no evidence of pavement removal in the vicinity of the Cuckoo Rocking Chair, as its pedestal, which is bounded by only vertical sidewalls, is entirely abutted by vegetation-covered regolith. Its upper surface is part abraded (no striae are present) and part plucked; it has a height of 34cm to the south. The site is in the Urswick Limestone (Milligan, 2003) that for the most part is thinly- to medium-bedded with wide to very wide joints. Refer to Appendix 5HRC for the locations, form, geology and surroundings of the sampled pedestal rocks.

It is contended that some of the vertical sidewalls of HRC1 and some/all of the vertical sidewalls of HRC2-3 are anthropogenic, since they adjoin rough, rubbly clints and/or thin deposits of clitter. Nevertheless, two vertical sidewalls of HRC1 do not owe their origin to limestone removal since they adjoin rundkarren-covered clint. Thus, as the caprock is comprised of ‘acid’ Silurian grit and as decantation runnels occur on the limestone surface below the caprock edge it follows that the natural sidewalls have been fashioned in a subaerial environment due to the lowering of the surrounding surface by rainwater, as with SM7 at Scales Moor. In contrast, as the caprocks of HRC2-3 are comprised of Carboniferous limestone and as their natural sidewalls slope, it follows that the latter have been fashioned due to the formation of a dissolution shadow in a subaerial/sub-arboreal environment as at Scales Moor. In further contrast, the pedestal of HRC4 has formed in a similar setting to the Carboniferous limestone-capped, vertical-sidewalled pedestals that are abutted by vegetation-covered regolith at Scales Moor.

12.16: Marlbank (H 1034: Ordnance Survey of Northern Ireland Sheet 26 Lough Allen 1:50000 (1984))

Marlbank, which is a National Nature Reserve, is largely comprised of vegetation-covered regolith with isolated areas of clints. A few tens of Carboniferous, pale-grey, medium-grained Glenade Sandstone orthoquartzite erratics occur at the site, one of which can be seen to form the cap of a partly exposed pedestal (Plate 12.32). The upper surface of the pedestal is undulating (no striae are present) while its sidewalls, which are entirely abutted by vegetation-covered regolith, are vertical; dissolution runnels are present on the crown and sidewalls of the pedestal, especially on the latter. The underlying bedrock is the Knockmore Limestone of the Dartry Limestone Formation that for the most part is thinly-bedded with wide joints. As the caprock is composed of ‘acid’ grit, pedestal sidewalls are vertical and vegetation-covered regolith mantles the limestone up to the base of the pedestal, it follows that the Marlbank pedestal has formed in a similar manner to pedestals on level ground at Norber. There is no doubting that regolith soil water is able to effect dissolution, as the pH of a sub-root sample was 5.7. Refer to Appendix 5M for the location, form, geology and surroundings of the pedestal rock.

12.17: Runscar (SD 7679: Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997))

Runscar is located in upper Ribblesdale, about 1km to the north-east of Ribblehead. The site consists of a dry valley, the floor of which is mostly covered in vegetation-covered regolith. A few tens of Carboniferous limestone erratics occur at the site, and the base of one, which is situated on the side of the dry valley, is exposed and a pedestal occurs beneath it (Plate 12.33). The pedestal is bounded by vertical sidewalls with a greater downslope than upslope height and it appears to have a gently undulating crown. The site is in the Malham Formation, Gordale Limestone that for the most part is medium-bedded with moderately wide joints. A photograph of the pedestal rock is found in Wynne (2006). As the pedestal has a greater downslope than upslope height, is Carboniferous-limestone-capped and is abutted by vegetation-covered regolith, it is argued that it formed in the same manner as the plucked-scar pedestals at Gearstones. Refer to Appendix 5R for the location, form, geology and surroundings of the pedestal rock.

12.18: Scar Close (SD 7577: Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997))

Scar Close consists of bare pavement, vegetation-filled solution hollows, arboreal thickets and peat islands. The pavement is divided by grykes, which may reach 0.5m in width and 1m in depth, into clints up to several metres square in areal extent. Rundkarren are ubiquitous on the clints and kamenitzas are uncommon, the latter rarely being more than 1cm in depth. Three perched pedestal rocks (SC1-3) comprised of Carboniferous limestone caprocks and of pedestals bounded by sloping sidewalls are present on the clints. The pedestals have flattish crowns (no striae are present) and a mean height of about 21cm. The site is comprised of horizontal Danny Bridge Limestone that for the most part is very thickly bedded with extremely wide joints. Refer to Appendix 5SC for the locations, form, geology and surroundings of the sampled pedestal rocks.

A photograph of SC3 occurs in Goldie (2004: poster), who wrote that the lower parts of the pedestals here are explained by "…solution under surrounding damp peaty soil. The boulder can only have protected the higher part; an effect c.12 to 18cm here." A further photograph of SC3 occurs in Goldie (2005: 440) who states that "…two curves [occur] in the limestone beneath the boulder", which presumably refers to the relatively steep and gentle sidewall slopes found to the left of the caprock, as is readily evident in Plate 12.34. If the plate is examined it can be seen that the distal and proximal portions of the sidewall to the left of the caprock dip respectively at about 5 and 50º, whereas the sidewall to the right of the caprock dips at only about 35º. It was noted in Section 12.6.3 that differences in pedestal height and in sloping sidewall dip have probably resulted from past and present variations in, for example, caprock decantation rates and decanted water acidity, arboreal interception rates, vegetation type, and soil water infiltration rates, pathways and acidity. Thus, the different sidewall dips of SC3 can probably be explained by any one or by a combination of these variations within a circum-caprock dissolution shadow. As the caprock of SC3 is more-or-less spherical and only about $1m^3$ in bulk, it is envisaged that the rate and acidity of water decanting from it will be/has been roughly uniform at any one moment in time. In contrast, the degree of cover, and vegetation and soils type are not uniform. After all, the immediate caprock environs presently consist of bare clints and of all manner of vegetation types, ranging from clumps of heather to spreads of moss and from pockets of herb-rich grassland to swathes of rush/sedges, the vegetation underlain by peat and organic mat. As such, it is expected that soil water infiltration rates, pathways and acidity might vary, which means that disparities in dissolution rates about the caprock can be expected. In addition, it is possible that there have been past variations in dissolution rates about the caprock, since the presence of ubiquitous rundkarren on the clint elsewhere at the site indicates that a more complete swathe of vegetation-covered regolith once existed.

It is proposed that sloping sidewalls developed about the caprock of SC3 due to the formation of a dissolution shadow as outlined in Sections 12.6.3 and 12.6.4, but that at some post-formation stage environmental changes led to changes in sidewall form. The steeper pedestal dip to the left of the caprock was probably caused by the superimposition of a new sidewall onto the older one by a retreat of the dissolution shadow cap-wards due to alkalised decanted water being neutralised at a closer distance to the caprock. This probably occurred because the supra-limestone surface environment became more acidic, perhaps for one or more of the reasons outlined in Section 10.2. Thus, the left sidewall is comprised of two "curves". In contrast, it is surmised that no retreat of the dissolution shadow occurred to the right of the caprock, and as a result the right sidewall is comprised of one "curve". An outline of the proposed formation of pedestal SC3 is illustrated in Fig. 12.4; falling rain and vegetation are omitted for clarity. The preceding account shows that different parts of pedestals may have different dissolution histories. As such, Goldie (2004) is probably quite correct in writing that the lower part of SC3 has formed due to solution under surrounding damp peaty soil, the lack of kamenitzas perhaps indicating that that the damp peaty soil was lost somewhat recently. Goldie (2004), however, is not correct in writing that the boulder can only have protected the higher part, the point being that both "curves" have resulted from boulder protection. Otherwise, since the inter-pedestal setting in the immediate vicinity of SC1-SC3 is subaerial and the pedestals are bounded by sloping sidewalls that are Carboniferous-limestone-capped, it is argued the pedestal has formed in the same manner as similar-shaped pedestals at Scales Moor. The pH of two soil samples taken from surface mat in the proximity of SC1 and SC2 was respectively 6.8 and 6.9, which shows that mat water has the potential to effect dissolution of the limestone surface.

A fourth perched pedestal rock (SC4) is present in pasture to the south of the pavement. Its pedestal is composed of individual limestone clasts rather than *in situ* rock and is abutted by vegetation-covered regolith (Plate 12.35). As such, it is considered to have formed in the same manner as the pedestal of D1 at Dowkabottom (Section 12.10). The pedestal rock is mentioned in Nicholson (1990: 102).

12.19: Twyn Du (SN 8316: Ordnance Survey Explorer OL12 Parc Cenedlaethol Bannau Brycheiniog: Ardaloedd gorllewinol a chanalog 1:25000 (2002))

Twyn Du is an interfluve site comprised of several relatively small areas of pavement that are surrounded by vegetation-covered regolith in the upper reaches of Cwm Tawe (the Swansea Valley). The site is described in detail by Thomas (1970). The limestone dips at about 10º to the south and is much disintegrated, since loose material litters the outcrops. Several hundred boulder-sized erratics composed of Devonian grit/conglomerate occur at the site, and Thomas (1970) has sketched (p. 92) two perched pedestal rocks, A and B, the cap of the former having partly toppled off its pedestal, as is evident in Plate 12.36. Pedestal rock A (TD1), whose crown appears to be approximately the same shape as the base of the caprock that partly overlies it, is bounded by vertical sidewalls some 72cm in height that are abutted by vegetation-mat-covered regolith, the latter appearing to be composed largely of limestone clasts. A thorough search on two separate occasions failed to match Thomas' (1970) B pedestal rock with anything similar at the site, although it is thought that TD2 (Plate 12.37) occurs at the same location. In comparison with TD1, TD2 lacks a pedestal entirely and is mostly surrounded by bare rock. A widened gryke and a well-like solution hollow that are both roughly 40cm deep respectively undercut the caprock by some 24 and 12cm to the south and west; decantation runnels are present both on the underlying and on the immediate-surrounding limestone. The site is in the Cil-yr-ychen Limestone that for the most part is medium bedded with moderately wide joints. Refer to Appendix 5TD for the locations, form, geology and surroundings of the sampled pedestal rocks.

It is argued that the pedestal of TD1 has been fashioned in an analogous setting to that of SM7, i.e. due to the caprock protecting the limestone beneath it while the surrounding surface was lowered by dissolution in a subaerial/sub-arboreal environment (Section 12.6.6). Thomas (1970) found seven pedestals at Twyn Du and wrote (p.101) that only one of them "…has remained it its original position, the remainder having foundered because of undercutting by solution along fracture planes…the six blocks are therefore now all tilted in a southerly down-dip direction." Thomas (1970: 101) attributed their foundering as being due to the erratic blocks being of "…insufficient dimensions completely to shield the underlying pedestals from solutional effects, while because of the weakly permeable nature of the sandstone blocks, seepage has been responsible for some measure of lowering." Several of the erratics at Twyn Du, including TD2, are larger than some of the Carboniferous limestone caprocks that overlie pedestals elsewhere, such as those of B42 and SM10 for instance. Nevertheless, most sit in rather than on the limestone, as at Scales Moor and elsewhere (Section 12.6.8). This phenomenon was noted by Thomas (1970), who found that the bases of twenty-five erratics whose larger surfaces had an average area of 0.5m² rested between 8 to 36cm below the average level of the pavement. Consequently, it is contended that the absence of pedestals beneath the caprocks and the presence of solution hollows is due to the formation of dissolution hotspots. It is not known whether seepage through Carboniferous sandstone erratics at Scales Moor and elsewhere, and Silurian grit erratics in Underlaid Wood has contributed to dissolution-hotspot formation, but this cannot be the case re Shap Granite erratics, since they are composed of impermeable rock.

12.20: Underlaid Wood (SD 4878: Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern area 1:25000 (1998))

The site consists of several square kilometres of woodland, pasture and horizontal pavement; regolith is comprised of organic soil and till. The pavement is divided by grykes into clints that are partly bare/partly covered in little more than *Sphagnum*/litter; eroded rundkarren may or may not be present. As the site has been much affected by quarrying, clint removal, and coniferous afforestation and removal, much care was undertaken to ensure that any boulders/erratics encountered were *in situ*. Most of the relatively abundant and small Silurian grit erratics, whose distribution is described by Rose and Vincent (1983a), were considered to be *in situ* (Plate 12.7), but most of the relatively scarce and larger Carboniferous limestone boulders/erratics were not. Nevertheless, one (UW1) forms the cap of a pedestal that is about 8cm in height and that is bounded by sloping sidewalls; a north-south gryke passes under the caprock and closes under it as it does so. Much of the pedestal is covered in *Sphagnum* and the extra-pedestal surroundings in *Sphagnum*/litter, as seen in Plate 12.8. The site is in undifferentiated Carboniferous Limestone that is generally medium-bedded with wide joints. As UW1 is Carboniferous-limestone-capped, open air-abutted and bounded by sloping sidewalls, it is argued it has formed in a subaerial/sub-arboreal environment as have similarly-shaped pedestals at Scales Moor. Refer to Appendix 5UW for the location, form, geology and surroundings of the pedestal rock.

12.21: Winskill Stones (SD 8366) Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western areas 1:25000 (1997))

Winskill Stones consists of a south-west-facing stepped site in Ribblesdale about 10km to the south-east of Norber. A few tens of erratics composed of Silurian grit occur at the site, one of which forms the cap of a perched pedestal rock (W1) (Plate 12.38). The pedestal has vertical sidewalls with a greater downslope (66cm) than upslope (16cm) height, is overhung by its caprock and is entirely surrounded by vegetation-covered regolith apart from a patch of rundkarren-etched bedrock revealed by poaching. The pedestal upper surface is smooth (no striae are present) and cobble-sized clasts up to 15cm in long axis separate it from the caprock. The site is in the Malham Formation, Gordale Limestone that for the most part is thinly bedded with moderately wide joints. The pedestal is part of an intermittent scar that can be traced along the strike of the slope, which means that its down-slope face has formed due to glacial plucking. The pH of a sub-root soil sample taken adjacent to W1 was 6.1, which shows that regolith water has the potential to effect dissolution of the limestone surface. A photograph of W1 is found in Murphy (2005). As the lateral and upslope sidewalls have formed due to sub-regolith dissolution of the inter-pedestal surface, W1 has formed in the same manner as pedestals above bench edges at Norber. Refer to Appendix 5W for the location, form, geology and surroundings of the sampled pedestal rock.

12.22: Y Gogarth (SH 7682: Ordnance Survey Explorer OL17 Yr Wyddfa: Taflen y Gorllewin 1:25000 (2006))

Y Gogarth comprises an undulating headland some 6km² in extent that is encircled by marine cliffs some 200m in height; the limestone has been folded into a gentle syncline. Its ‘open access’ areas are largely comprised of vegetation-covered regolith, but pavement is also present. The limited exposures of limestone that occur near the pedestals are comprised of relatively large clints that have both rundkarren and kamenitzas etched into them. A few hundred Carboniferous limestone erratics dot the site, especially in the east, but the bases of most are not exposed largely because they are swathed in vegetation. Two, though, can be seen to form caprocks above poorly exposed pedestals bounded by vertical sidewalls. This is especially so with YG2, as can be seen in Plate 12.39, which illustrates the point (Section 11.3, #5) that pedestals will remain unexposed if the amount of rockhead lowering does not exceed the thickness of the regolith that surrounds them and if the regolith is not otherwise eroded. The site is comprised of the Great Orme Limestone that for the most part has very wide joints (bedding is barely exposed). The pH of a sub-root soil sample taken adjacent YG1 was 7.6, which shows that regolith water has the potential to effect dissolution of the limestone surface. The site is not described in the literature, but a photograph of YG2 occurs in the frontispiece of Cyngor Cefn Gwlad Cymru (2000). As the pedestals are Carboniferous-limestone-capped, vertical-walled and abutted by vegetation-covered regolith, they have formed in the same manner as similarly-shaped pedestals at Scales Moor. Refer to Appendix 5YG for the locations, form, geology and surroundings of the sampled pedestal rocks.

12.23: Pedestals and polygenetic pavements

Vincent (2004) has proposed that there are genetically four types of pavement in northern England:

1. Glacially eroded joint-dominant pavements
2. Glacially eroded calcrete-dominant pavements without palaeokarst
3. Glacially exhumed calcrete-dominant pavements with palaeokarst
4. Glacially truncated palaeokarst

According to Vincent (2004) many glacially eroded joint-dominant pavements occur on the flanks of Ingleborough whereas good examples of glacially eroded calcrete-dominant pavements without palaeokarst are found at Great Asby Scar and at Gait Barrows. In addition, glacially exhumed calcrete-dominant pavements with palaeokarst can be seen at Scar Close and at several sites around Morecambe Bay, and glacially truncated palaeokarst at Great Asby Scar and in the Ingleborough region. As pedestals are found at all of the above sites it was hypothesised that pavement type might play a role in pedestal formation, although it must be pointed out that Vincent (2004) does not suggest this.

Vincent’s (2004) paper was not read until well after most of the sites listed in Section 12.2 had been surveyed, which meant that the genetic origin of pavements was not taken into account during their surveying. Nevertheless, some observations re pedestal formation and the genetic origin of pavements can be made. It would seem that pedestals SM4 and SM5 are part of the same genetic pavement, since the forty metre stretch of ground that separates them is more-or-less level. Nonetheless, SM4 is bounded by sloping sidewalls about 15cm in height and SM5 by vertical sidewalls about 63cm in height, as is evident in Plate 12.5. It is not known whether the limestone that forms the two pedestals is joint-dominant or calcrete-dominant, the point being that both pedestals have formed on a pavement that is doubtless of only one genetic type. Moreover, erratics SM10 and SM11 are just a few meters apart, yet despite the fact that both occur on pavement of one (unknown) genetic type SM10 rests on a pedestal bounded by sloping sidewalls some 16cm high while SM11 is lodged in a gryke over 1.5m deep (Plate 12.6). Therefore, as dissimilarly-shaped pedestals may occur on pavement of one genetic type and as pedestals may be present or absent on pavement of one genetic type, the hypothesis can be safely rejected.

12.24: Overall conclusion to chapters 7-12

The pedestals studied in Chapters 7-12 are divided into six types, one of which is divided into two sub-types, depending on their environment of formation and on caprock mineralogy:

1. Sub-regolith pedestals, which owe their formation mostly to dissolution of the inter-pedestal limestone surface under regolith (mainly vegetation-covered brown earths developed on till), and partly to sidewall sub-aerial dissolution and sidewall failure, as described at Norber in Section 11.2. Sub-regolith pedestals are bounded by vertical sidewalls caused by a quantum leap occurring in the rate of dissolution at the pedestal crown-pedestal sidewall junction and/or sidewall failure. They are roughly of equal all-round height with a crown that generally mirrors but is commonly smaller in area than the basal surface of the overlying caprock. The caprock may be composed of ‘acid’ (e.g. Silurian grit) or ‘basic’ rock (e.g. Carboniferous limestone). Sub-regolith pedestals occur on the main expanse of limestone benches on level or gently sloping ground, and N5 and GB3 (Plate 12.27) typify them. They are the equivalent of Goldie’s (2005) A, B, C and D pedestals in Fig. 7.3.

2. Glacial scar pedestals, which differ from sub-regolith pedestals in that their downslope sidewall is formed of a scar that has been glacially plucked, as described at Norber in Section 11.2. There may be some input from sub-regolith dissolution and scar failure at the base of the plucked sidewall, and from frost-rivening of its exposed surface, but in essence the downslope sidewall pre-dates erratic deposition. The lateral and upslope sidewalls (if the upslope sidewall is indeed present) owe their formation essentially to dissolution of the inter-pedestal limestone surface in a sub-regolith environment. The caprock may be composed of ‘acid’ (e.g. Silurian grit) or ‘basic’ rock (e.g. Carboniferous limestone). Glacial scar pedestals occur on or above steeply sloping ground, such as on limestone bench edges, and N1 and G1 (Plate 12.28) typify them. They can be recognised by the greater height (sometimes considerably so) of their plucked sidewall in comparison to their lateral and upslope sidewalls, and by the fact that they can usually be linked to a scar that can be traced laterally along the strike of the slope. The pedestal crown generally mirrors but is commonly smaller in area than the basal surface of the overlying caprock. Glacial scar pedestals are thought to be the equivalent of Sweeting’s (1966) soil-creep pedestals (Section 7.10), Goldie’s (2005) E pedestal (Fig. 7.4) and Waltham’s (2005) pedestals below bench-edge erratics (Section 7.5).

3. Subaerial/sub-arboreal pedestals, which owe their formation essentially to dissolution of the inter-pedestal limestone surface under open skies or arboreal organic soils/vegetation, such as litter, organic mat or *Sphagnum*. They are divided into two sub-groups depending on caprock geology:

   (i) Subaerial/sub-arboreal pedestals capped by calcareous rock (Carboniferous limestone), as described at Scales Moor in Sections 12.6.3 and 12.6.4. The pedestals are bounded by sloping sidewalls due to the creation of a ‘dissolution shadow’ about the caprock caused by alkalised water decanting onto the surrounding surface. They are roughly of equal all-round height with a crown that generally mirrors the basal surface of the overlying caprock in aerial extent, but with sidewalls that may extend for up to about a metre beyond the distal edge of the caprock. SM6 (Plate 12.4), B1 (Plate 12.11) and GB1 (Plate 12.26) typify subaerial/sub-arboreal pedestals with calcareous (Carboniferous limestone) caprocks.

   (ii) Subaerial/sub-arboreal pedestals capped by siliclastic rock, as described at Scales Moor in Section 12.6.6. The pedestals are bounded by vertical sidewalls, since a quantum leap occurs in the rate of dissolution at the pedestal crown/pedestal sidewall junction. They are roughly of equal all-round height with a crown that generally mirrors but is commonly smaller in area than the basal surface of the overlying caprock; the sidewalls may show signs of subaerial dissolution, such as runnels or drip marks. SM7 (Plate

12.9) and TD1 (Plate 12.36) typify subaerial/sub-arboreal pedestals with siliclastic caprocks are typified, though in both cases the caprock has foundered, and in the latter the pedestal also.

4. Sub-regolith and subaerial/sub-arboreal pedestals, which owe their formation to a combination of dissolution in environments 1 and 3(i) above, as described at Scales Moor in Section 12.6.5. Thus, the pedestals are bounded by vertical and sloping sidewalls. SM9 (Plate 12.3) and B5 (Plate 12.12) typify sub-regolith and subaerial/sub-arboreal pedestals.

5. Limestone clast pedestals, which owe their formation due to decanted alkalised water from calcareous (Carboniferous limestone) caprocks forming a ‘dissolution curtain’ about them, as described at Dowkabottom in Section 12.10. This reduces the acidity of regolith-water that might percolate under the caprocks, which buffers the clasts beneath them from dissolution. D1 (Plate 12.21) and possibly N31 (Plate 7.5) typify limestone clast pedestals.

6. Anthropogenic pedestals, which owe their formation to the removal of the inter-pedestal limestone surface by man, as described at Farleton Knot in Section 12.11. This produces vertical sidewalls since the limestone has been removed mechanically. In some cases all sidewalls are anthropogenic (e.g. FK1) but in others the sidewalls may be part anthropogenic and part natural (e.g. HRC2). Anthropogenic pedestals may appear little different from sub-regolith, and sub-regolith and subaerial/sub-arboreal pedestals. The key to their identification is the nature of the surrounding limestone surface, as upturned clint, rubbly limestone and clitter-like clasts indicate that clint removal has taken place. FK1 (Plate 12.22) and HRC2 (Plate 12.31) typify anthropogenic pedestals.

More has been probably written about the formation of perched pedestal rocks at Norber than at any other site. Indeed, it is sometimes regarded as the type site against which others are judged, e.g. Goldie (2005). Nevertheless, the pedestals at Norber are mostly atypical of pedestals found at other sites. This is because the surveys revealed that all bar one (N31) of the thirty-two sampled pedestals at Norber are Type 1 and 2 pedestals. Yet of the one hundred and nineteen pedestals sampled at the seventeen other sites, just twenty-seven are Types 1 and 2, the remainder largely being comprised of Types 3 (i) and 4.

None of the pedestals studied in the thesis has formed entirely in a glacial environment, as plucking leads to the formation of downslope sidewalls only, while anthropogenic pedestals are mostly restricted to two sites, Farleton Knot and Hutton Roof Crags. Accordingly, it follows that the vast majority of pedestals are residuals that have formed essentially due to the lowering of the inter-pedestal limestone surface by dissolution. It is clear that caprock composition, i.e. ‘acid’ sandstone or ‘basic’ limestone, does not have any input regarding pedestal formation where the inter-pedestal limestone surface is mantled in relatively acid regolith, as pedestals bounded by vertical sidewalls form regardless of caprock mineralogy. Glacial scar and anthropogenic pedestals also form regardless of caprock mineralogy. It is equally clear that it is only when the inter-pedestal limestone surface is exposed or mantled in sub-arboreal soils/vegetation that caprock mineralogy has a role to play in the nature of sidewall formation. Therefore, pedestal formation is primarily a product of environment and secondarily of caprock mineralogy.

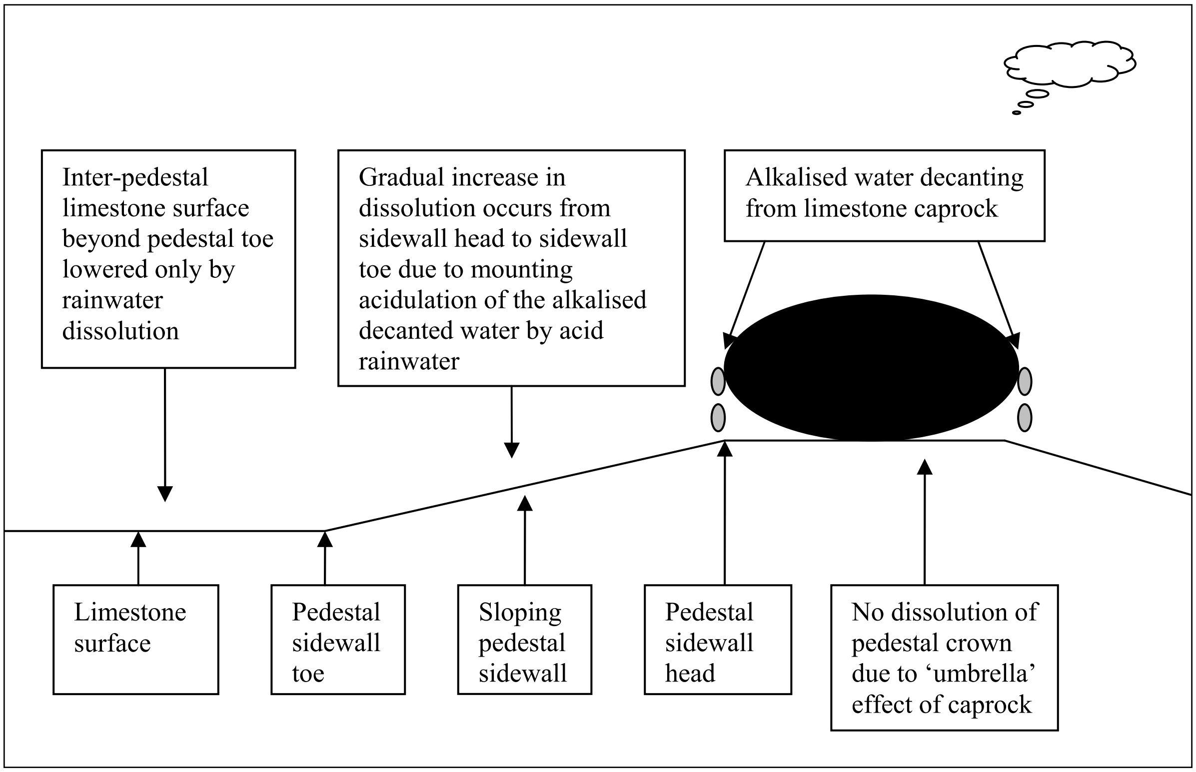


Fig.* Error! No text of specified style in document.*.1: Proposed formation of sloping sidewalls at Scales Moor

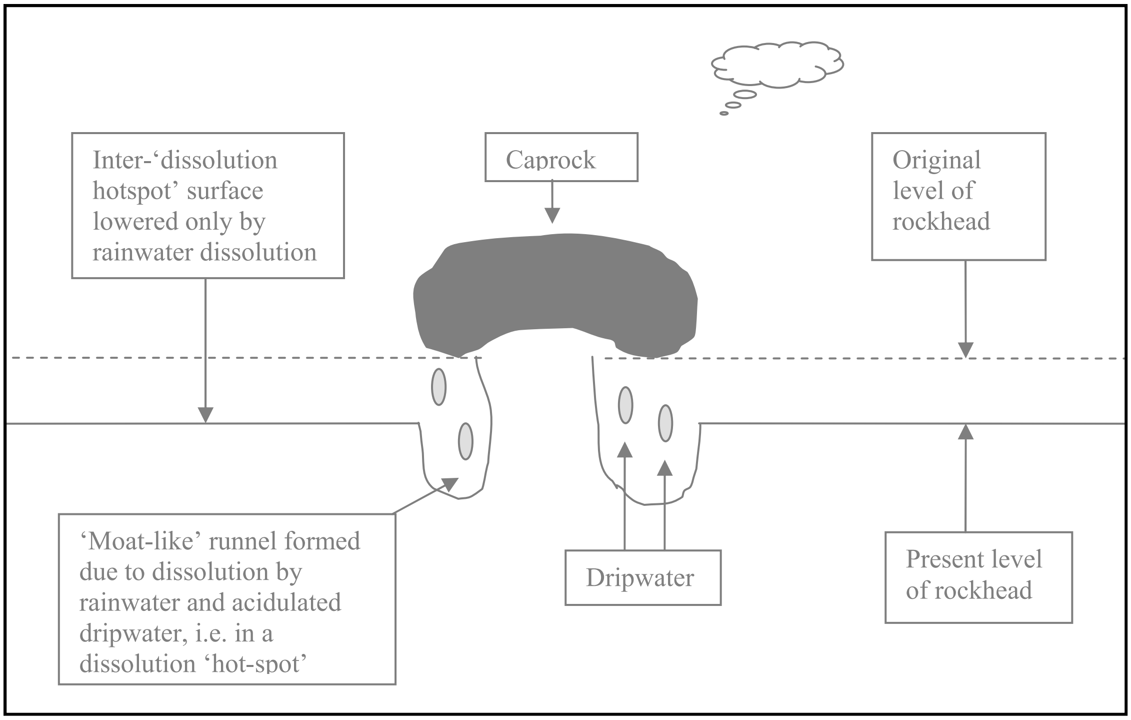


Fig.* Error! No text of specified style in document..*2: Proposed formation of the pedestal and 'moat-like' runnel under SM7 at Scales Moor

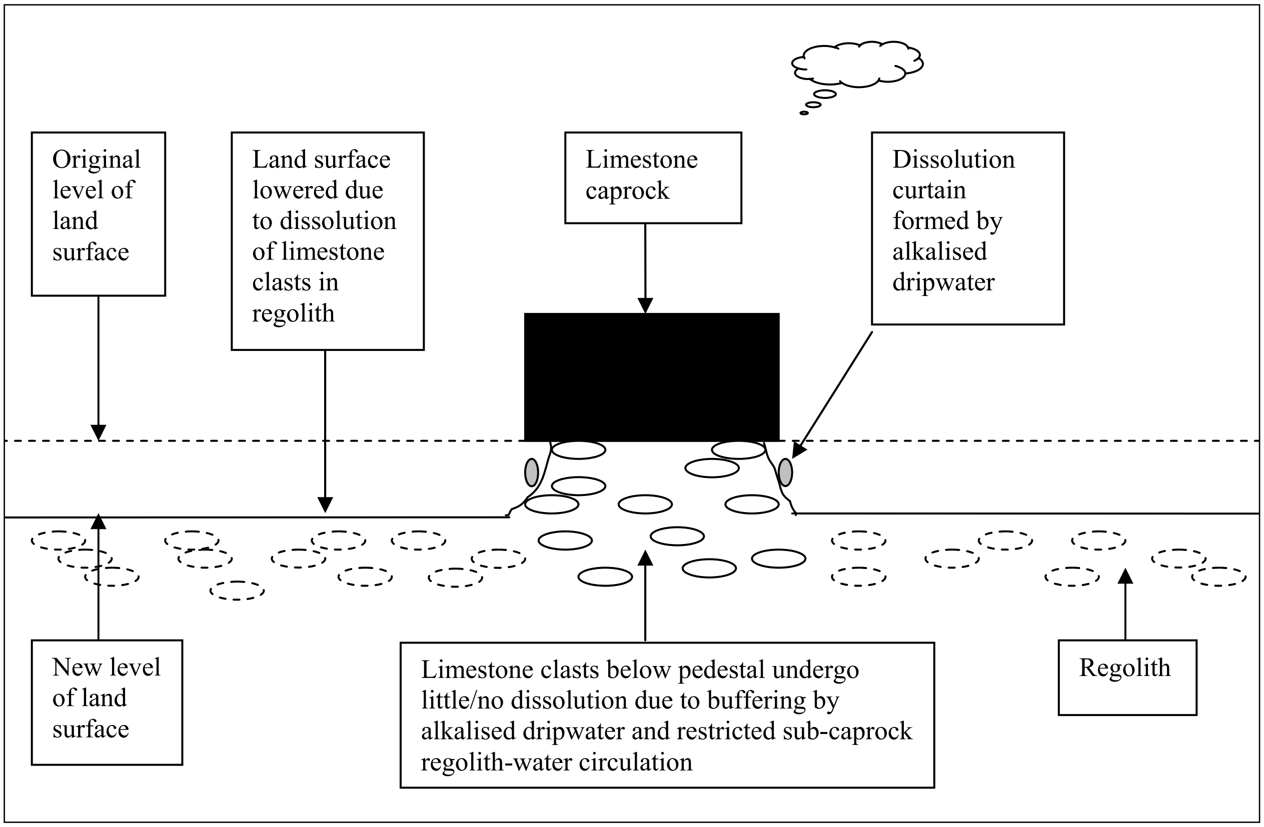


Fig.* Error! No text of specified style in document.*.3: Proposed formation of the limestone clast pedestal at Dowkabottom

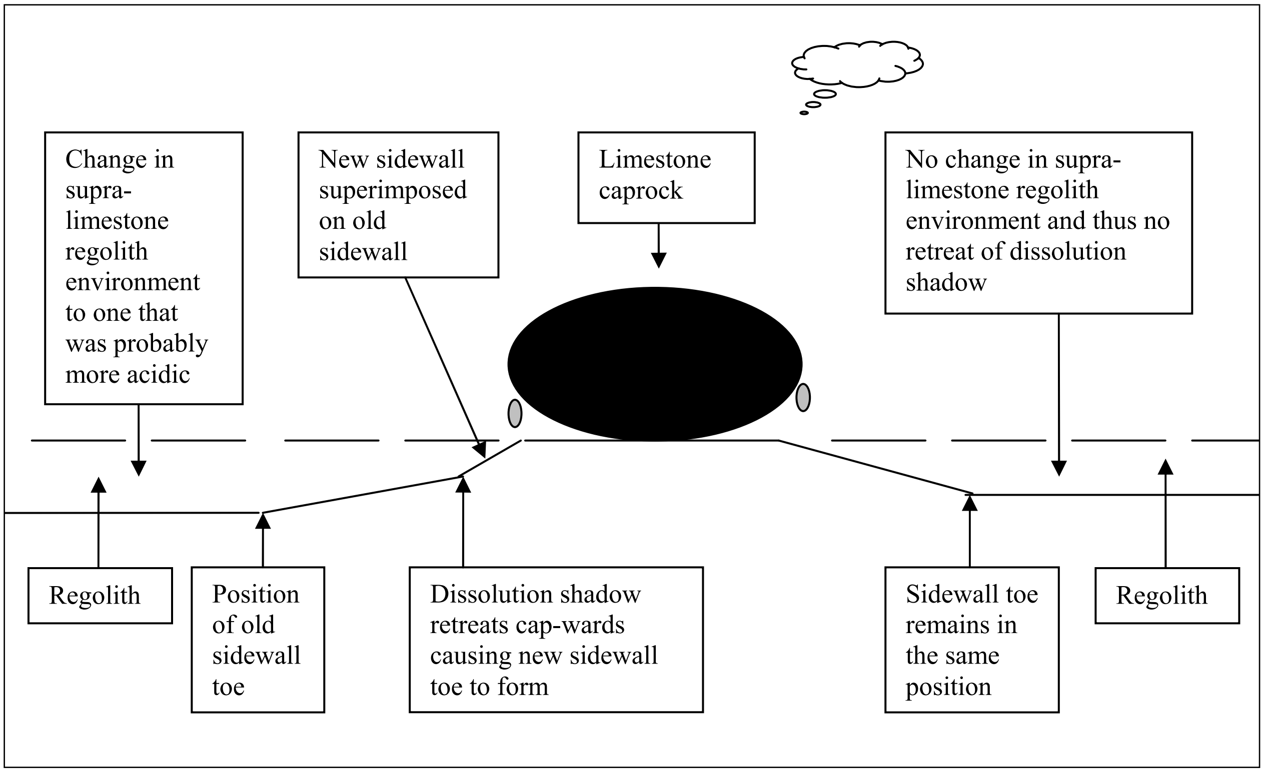


Fig.* Error! No text of specified style in document..*4: Proposed formation of pedestal SC3 at Scar Close prior to regolith loss

Plate** Error! No text of specified style in document.**.1: Pavement in the vicinity of SD 72438 77429 at Scales Moor

Some of the pavement at Scales Moor appears relatively 'fresh', and here it consists of smooth, broad clints that are dissected by few grykes. Note that Carboniferous sandstone erratics (blue arrows) are found only in grykes, and that gryke-widening has occurred in their vicinity. For purposes of scale in this and in succeeding plates the tape-measure case, which is circled, is 5cm across.

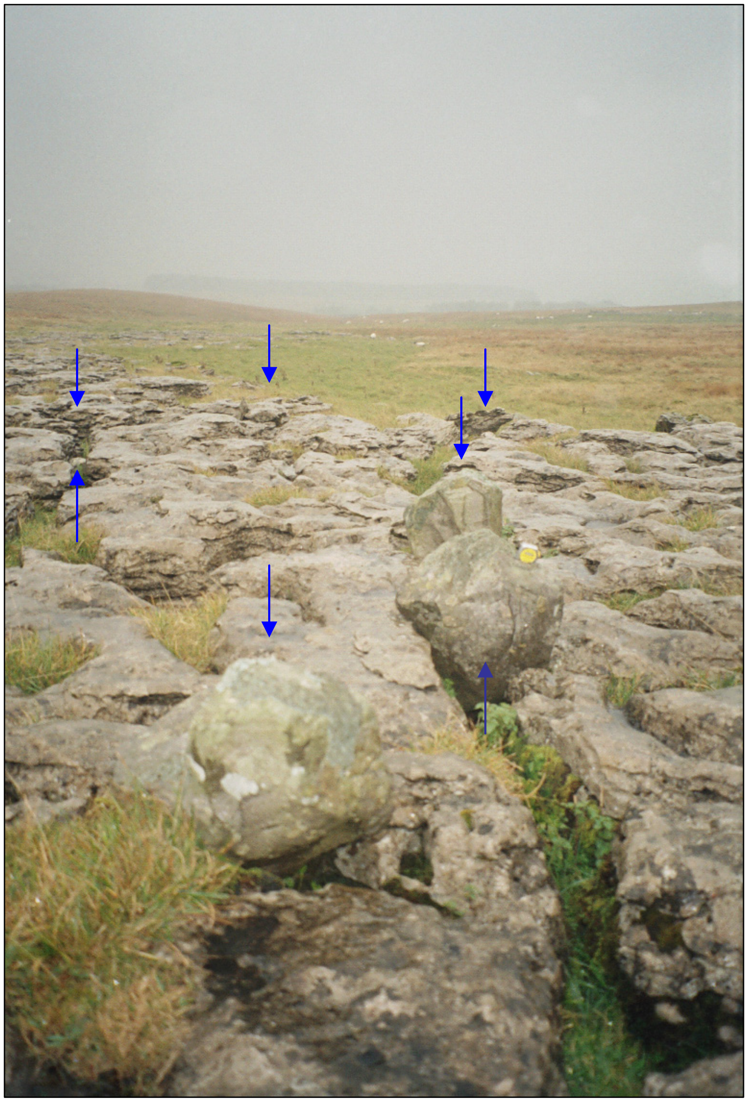


Plate* Error! No text of specified style in document.*.2: Pavement in the vicinity of SD 72717 77385 at Scales Moor

In comparison to Plate 12.1 the pavement here is more dissected, and it consists of rough clints a metre or so across with eroded rundkarren and a smattering of kamenitzas divided by well-developed grykes. Note, once again, the presence of Carboniferous sandstone erratics (blue arrows) only in grykes or in small solution hollows.

Plate* Error! No text of specified style in document..*3: Perched pedestal rock SM9 at Scales Moor

In contrast to Plates 12.1 and 12.2 the clints in the vicinity of SM9 are comprised of little more than residuals surrounded by wide areas of vegetation-covered regolith. The pedestal of SM9 is bounded by a sloping sidewall, which dips at about 10º (blue line) and by vertical sidewalls, which have respectively formed mainly in subaerial/sub-arboreal and in sub-regolith environments. The pedestal crown is flat with putative striae on its surface, which indicates that it is a glacially eroded surface. At present, the immediate surrounding limestone surface is undergoing dissolution beneath damp peaty soils that have a sub-root pH of 4.2, and this probably explains the relatively great height of the pedestal, which is about 99cm (84e, 15u).

Plate *Error! No text of specified style in document.****.4: Perched pedestal rock SM6 at Scales Moor***

SM6 is surrounded mainly by bare, dissected pavement, which is partly rundkarren-covered, that is entirely lacking in regolith apart from thin organic soils below a grass mat. The pedestal of SM6 is bounded by sloping sidewalls (white lines). The height of the pedestal, which is about 21cm, and its conical shape is typical of pedestals that have formed in a largely subaerial/sub-arboreal setting below Carboniferous limestone caprocks.

Plate** Error! No text of specified style in document.**.5: Perched pedestal rocks SM4 (background) and SM5 (foreground) at Scales Moor

SM4 and SM5 are barely 40m apart, yet the pedestal of SM4, which is surrounded by bare limestone, is bounded by sloping sidewalls about 15cm in height, while that of SM5, which is surrounded by vegetation-covered regolith, is bounded by vertical sidewalls about 63cm in height. The pedestal crowns are respectively about 396m and 394m above OD, which indicates that the pedestals have essentially been fashioned from the same limestone horizon.

Plate** Error! No text of specified style in document.**.6: Adjacent erratics SM10 and SM11 at Scales Moor

Although the two erratics SM10 and SM11 are similar in size, a pedestal bounded by sloping sidewalls underlies SM10, which is composed of Carboniferous Limestone, and a gryke underlies SM11, which is composed of Carboniferous sandstone. This shows that erratic composition rather than erratic size is the controlling factor re the formation of the two sub-erratic landforms.

Plate *Error! No text of specified style in document.**.7: Silurian grit erratics in Underlaid Wood***

The Silurian grit erratics (red arrows) in Underlaid Wood are similar in distribution to Carboniferous sandstones erratics at Scales Moor (as seen in Plates 12.1 and 12.2), since nearly all occur in grykes. Note that the covering of Sphagnum moss is present on the pavement only under the trees.

Plate** Error! No text of specified style in document.**.8: How the present bare pavement at Scales Moor might have looked from ca.10000-3000BP

Scales Moor was probably overcanopied by the Wildwood from ca.10000-3000BP when till-free pavement might have appeared similar to the scene above (which is of UW1 in Underlaid Wood (Section 12.20)). Thus, pedestal sloping sidewalls (denoted by the red lines) and pavement alike might have been covered in little more than Sphagnum moss. The grykes, which tend to narrow in the vicinity of the limestone caprock (the gryke under the tape-measure case closes entirely), must post-date sidewall formation, otherwise alkalised water decanting from the caprock would have drained into them, which means that sloping sidewalls would not occur on the gryke far-sides.

Plate** Error! No text of specified style in document.**.9: The pedestal and foundered caprock of SM7 at Scales Moor

The caprock of SM7 is composed of Carboniferous sandstone, and it is the only non-Carboniferous limestone erratic below which a pedestal has developed at Scales Moor. Note that a gryke and a moat-like runnel surround much of the pedestal (white line).

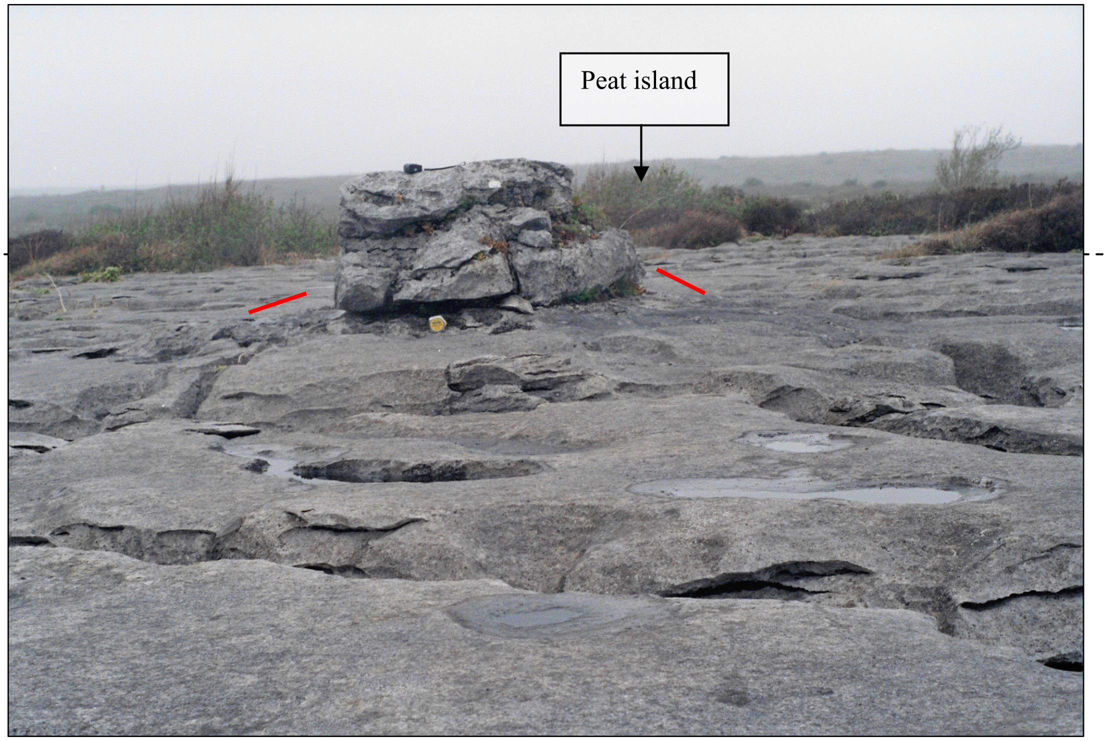


Plate** Error! No text of specified style in document.**.10: Perched pedestal rock B9 at Sheshymore, the Burren

The sloping sidewalls (red lines) of B9 merge more-or-less imperceptibly with the surrounding limestone surface, which consists of uneven, bare clint. Note that peat islands covered in acid vegetation are present on the pavement.

Plate** Error! No text of specified style in document.**.11: Perched pedestal rock B1 at Gortlecka, the Burren

The pedestal of B1 is bounded by sloping sidewalls (marked by the red lines) that more-or-less merge imperceptibly with the surrounding limestone surface.

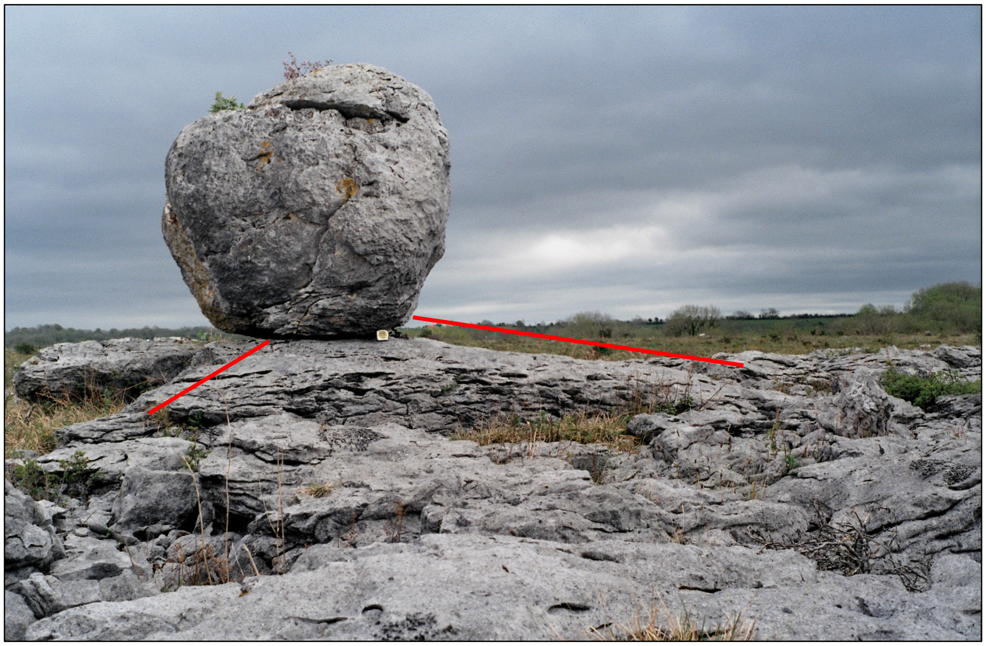


Plate** Error! No text of specified style in document.**.12: Perched pedestal rock B5 at Gortlecka, the Burren

The pedestal of B5 is bounded by a combination of sloping sidewalls (marked by the red lines) that more-or-less merge imperceptibly with the surrounding limestone surface and vertical sidewalls (in blind ground, to the left) that are abutted by vegetation-covered regolith.

Plate *Error! No text of specified style in document.**.13: Perched pedestal rock B18 at Lissylisheen, the Burren***

The inter-pedestal surface in the vicinity of B18 consists almost entirely of limestone residuals surrounded by superficial-deposit-covered pasture. Note that the pedestal of B18 is bounded by a combination of sloping (right and left) and vertical sidewalls (foreground), and that judging by the weathered state of the latter it appears that vertical-sidewall retreat has all but ceased. For purposes of scale the tape-measure case is ringed.

Plate** Error! No text of specified style in document.**.14: Section of till in the Caher Valley, the Burren

The exposure consists of some 60% of light grey-brown fine-grained groundmass and of some 40% of dark grey sub-angular to sub-rounded Carboniferous limestone phenoclasts that range up to cobble size. Note the presence of just one non-Carboniferous limestone clast, which is composed of Carboniferous sandstone (circled).

Plate** Error! No text of specified style in document.**.15: Sphagnum moss growing on pavement under an elderberry canopy at Sheshymore, the Burren

The moss is able to survive because of the relatively damp micro-climate beneath the elderberry (Sambucus nigra). In contrast to the uneven pavement in the vicinity of B9, the pavement here consists of flat, horizontal clint often tens of square metres in areal extent. These are separated by grykes that may reach 4m in depth.

Plate *Error! No text of specified style in document.****.16: Perched pedestal rock B44 in the Caher Valley, the Burren***

The down-slope sidewall of pedestal B44 (yellow arrow) is a glacially-plucked scar. The caprock is about 1.5m tall.

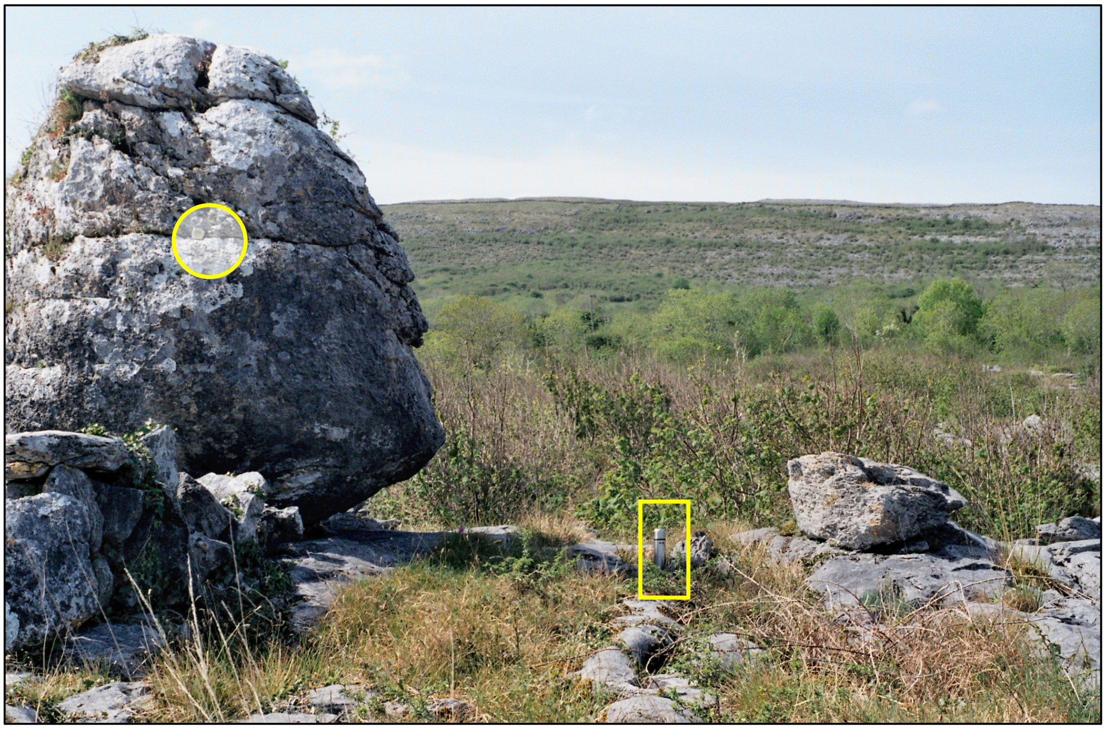


Plate** Error! No text of specified style in document.**.17: Perched pedestal rocks B41 and B42 to the east of Mullagh More, the Burren

The pedestals of B41 (left) and B42 (right) are both about 24cm in height. This shows that neither caprock long axes, which are respectively about 3 and 0.8m, nor trickle-fetch has influenced lowering rates of the inter-pedestal limestone surface. For purposes of scale, the tape-measure case is circled whereas the flask, which is 24cm tall, is' squared'.

Plate** Error! No text of specified style in document.**.18: Perched pedestal rock CB7 at Cavan Burren

The caprock, which is composed of 'acid' sandstone, and the pedestal, which is bounded by vertical sidewalls of near-matching height that are abutted by vegetation-covered regolith, are very similar to those at Norber. It is possible that the pedestal is partly anthropogenic in origin, since the limestone clasts on the caprock crown may have been robbed directly from the pedestal sidewalls.

Plate** Error! No text of specified style in document.**.19: Perched pedestal rock CB1 at Cavan Burren

The decantation runnel has been cut into the pedestal sidewall by water trickling down and decanting from the weather-widened discontinuity in the cap rock. It is argued that the cap rocks at Norber would have been similarly mantled in moss/ferns/herbs throughout the time of the Wildwood.

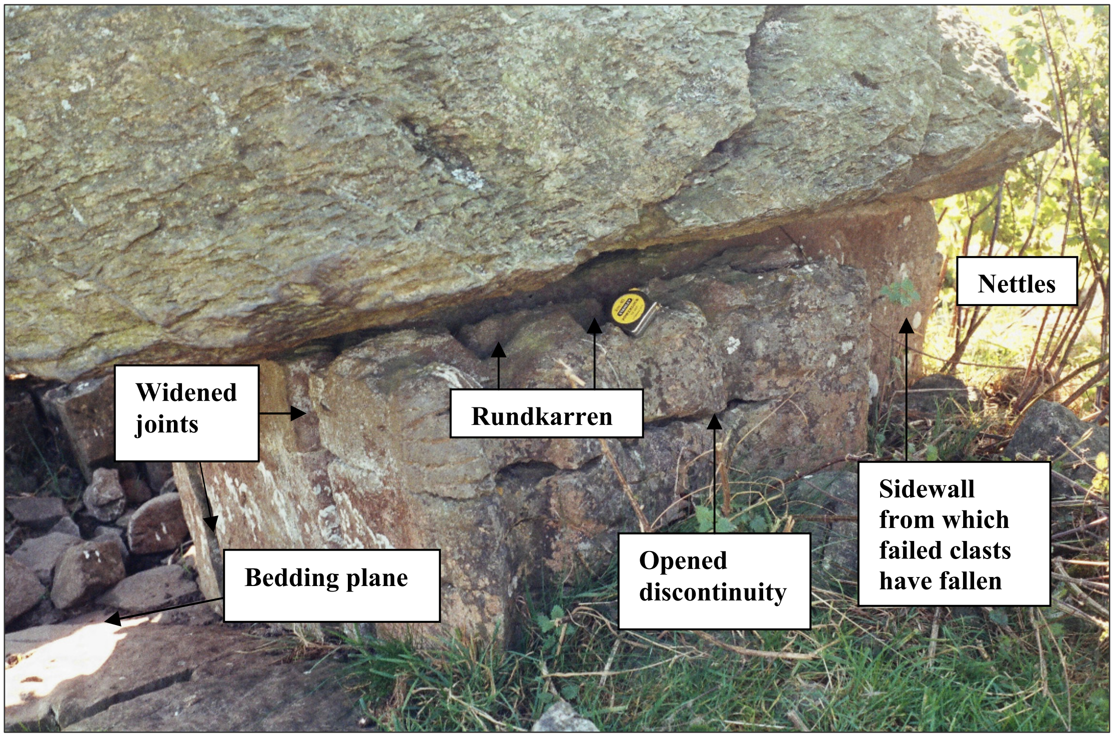


Plate *Error! No text of specified style in document.**.20: Perched pedestal rock CT1 at Cunswick Tarn***

The pedestal of CT1 is identical in form to vertical-walled pedestals at Norber, which is not surprising considering the caprock is composed of Silurian grit and the sidewalls were formerly abutted by vegetation-covered regolith. Some of the regolith is still present, and it is reasoned that it formerly covered part of the pedestal crown, since rundkarren occur on it. The relatively fresh-looking sidewall face above the failed limestone clasts indicates that failure of the far-right portion of the sidewall above them was comparatively recent. The relatively older nature of the remainder of the face is illustrated by the solution groove below the left rundkarren, by the opened horizontal discontinuity and by its overall well-weathered appearance. It is likely that the entire sidewall face will eventually fail at some point in the future along the already-widened joint. The inter-pedestal surface is composed of a bedding plane that dips away from the viewer, though this is not especially evident in the photograph. Thus, as the pedestal crown is horizontal, pedestal height increases from 44 to 55cm down-dip, which illustrates the difficulty of determining pedestal height.

Plate** Error! No text of specified style in document.**.21: Perched pedestal rock D1 at Dowkabottom

The pedestal appears to be formed of individual clasts rather than of in situ bedrock. Otherwise it is similar in form to Carboniferous-limestone-capped, vertical-walled pedestals that are surrounded by vegetation-covered regolith at Scales Moor.

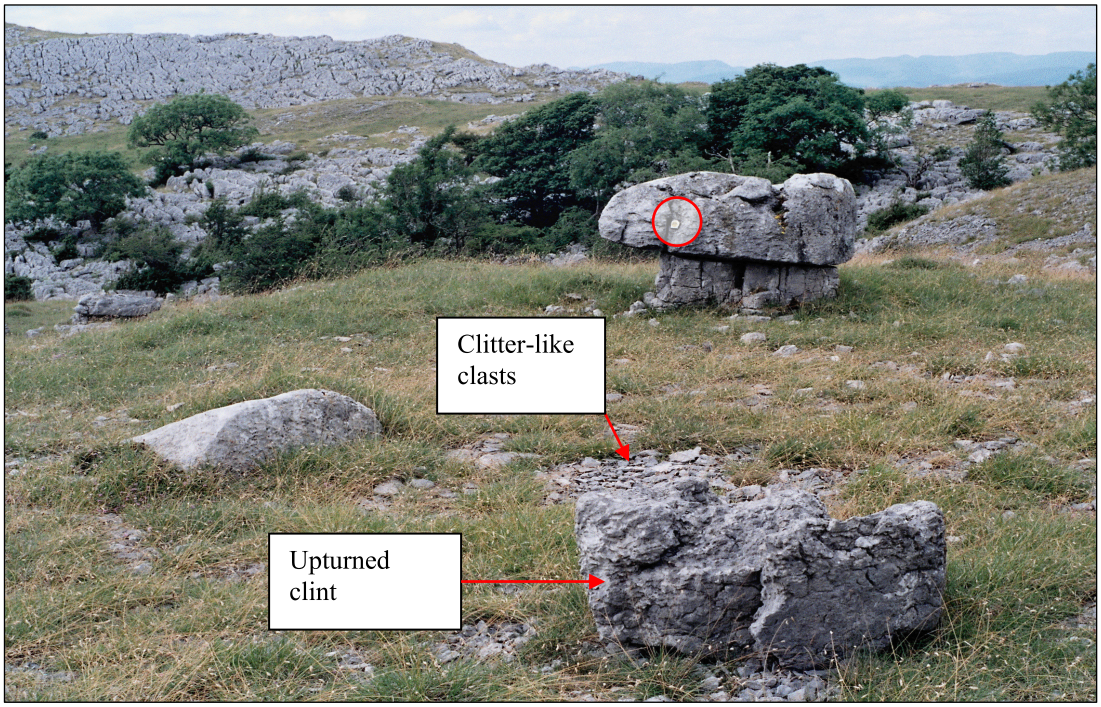


Plate** Error! No text of specified style in document.**.22: Perched pedestal rock FK1 on Farleton Knot

The presence of upturned clint and many relatively small clitter-like limestone clasts, and the absence of vegetation-covered regolith, a scene that typifies much of Farleton Knot, is indicative of pavement removal. Hence, the sidewalls of FK1 are, at least in part, anthropogenic in origin.

Plate** Error! No text of specified style in document.**.23: Perched pedestal rock FK4 on Farleton Knot

The pedestal of FK4 is bounded by sloping sidewalls that are about 13cm high. The narrowing of the two vertical grykes in the vicinity of the caprock (the right joint closes under it) indicates that the joints post-date Devensian deglaciation. The rundkarren on the inter-pedestal surface show that it was once covered in regolith. The caprock is about 1.8m tall.

Plate** Error! No text of specified style in document.**.24: Perched pedestal rock FK7 on Farleton Knot

The pedestal of FK7 is bounded by vertical and sloping sidewalls (one of the latter is marked by the green rod). The pedestal illustrates once again the difficulties of determining pedestal height, since the sloping sidewalls are about 15cm high whereas the vertical sidewalls are about 42cm high

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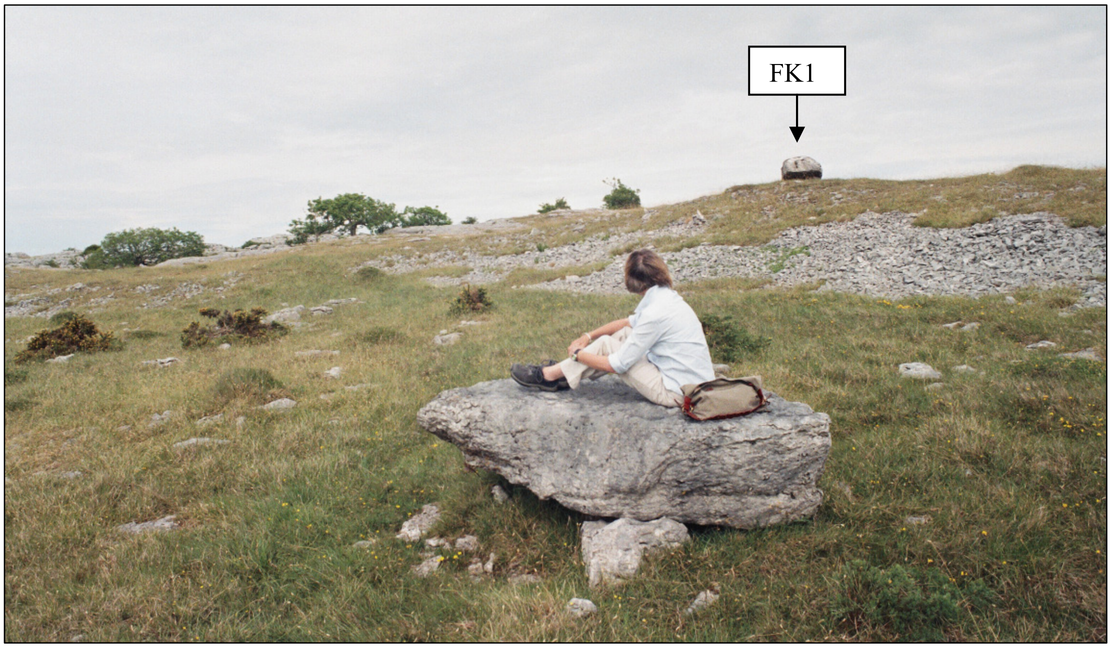

Plate *Error! No text of specified style in document.**.25: Perched pedestal rock FK2 on Farleton Knot***

The caprock of FK2 has dissolution features on its underside, which indicates that it is not only upside down but also of anthropogenic origin. FK1 can be seen in the background.

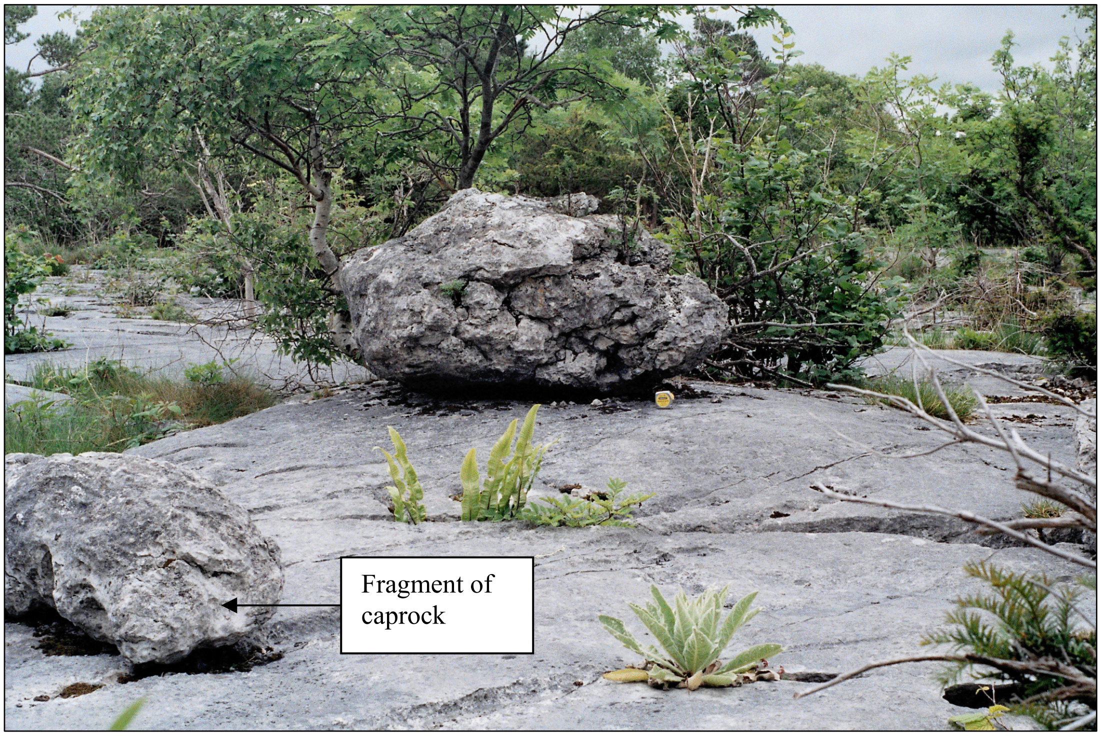

Plate *Error! No text of specified style in document.****.26: Perched pedestal rock GB1 at Gait Barrows***

The pedestal of GB1, which is subaerial, is bounded by sloping sidewalls. The clast in the foreground is not an erratic but a fragment of caprock.

Plate *Error! No text of specified style in document.****.27: Perched pedestal rock GB3 at Gait Barrows***

In contrast to GB1, the pedestal of GB3, which is completely surrounded by vegetation-covered regolith, is bounded by vertical sidewalls.

Plate *Error! No text of specified style in document.***.28: Perched pedestal rocks G1 (foreground) and G2-G3 (background) at Gearstones***

The downslope sidewall heights of G1 (foreground) and G2-3 (background) are much greater than their upslope sidewall heights. Consequently, it is envisaged that a glacial scar formerly linked the two prior to its complete removal by dissolution. The smooth nature of the pedestal crown of G1 almost certainly denotes that it is an ice-eroded surface.

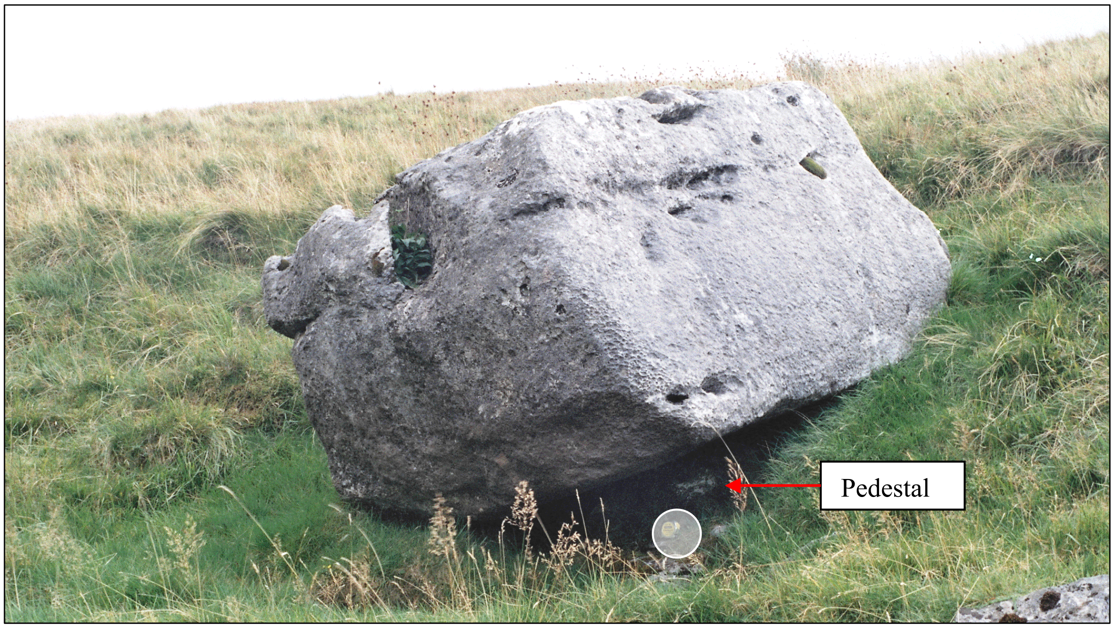

Plate** Error! No text of specified style in document.**.29: Perched pedestal rock G4 at Gearstones

The pedestal of G4 has been revealed by downslope poaching (which is not very evident in the photograph) and would otherwise be 'invisible'. This shows that unexposed pedestals may be present under erratics that are surrounded by vegetation-covered regolith.

Plate** Error! No text of specified style in document.**.30: Perched pedestal rock GAS1 at Great Asby Scar

The presence of rundkarren on the inter-pedestal surface denotes that a former soil/vegetation cover mantled the limestone. It is argued that the cover consisted of organic material since organic soil underlies vegetation and since erratics are thinly spread throughout the site, both on the ground and in dry-stone walls. As the pedestal rocks at Great Asby Scar are almost indistinguishable from many at Scales Moor, such as SM1 and SM2, they have likewise formed in a subaerial/sub-arboreal setting.

Plate** Error! No text of specified style in document.**.31: Perched pedestal rock HRC2, Hutton Roof Crags

The pedestal of HRC2 is bounded by sloping (white lines) and vertical sidewalls. It is likely that the vertical sidewalls are of anthropogenic origin, since there is much evidence of pavement removal both in the immediate environs of the pedestal and over the site as a whole. The hammer is about 32cm in length.

Plate *Error! No text of specified style in document.****.32: Perched pedestal rock M1 at Marlbank***

Plate *Error! No text of specified style in document.****.33: Perched pedestal rock R1 at Runscar***

Plate* Error! No text of specified style in document..*34: Perched pedestal rock SC3 at Scar Close

The white lines show that the distal and proximal portions of the sidewall to the left of the caprock of SC3 dip respectively at about 5 and 50º, whereas the sidewall to the right of the caprock dips at only about 35º. It is possible that the lower part of the pedestal (at least to the left) has formed due to solution under surrounding damp peaty, as proposed by Goldie (2004).

Plate *Error! No text of specified style in document.****.35: Perched pedestal rock SC4 at Scar Close***

Although it cannot be viewed clearly, the pedestal of SC4 is composed of glacial clasts, and has thus formed in a similar manner to D1 at Dowkabottom.

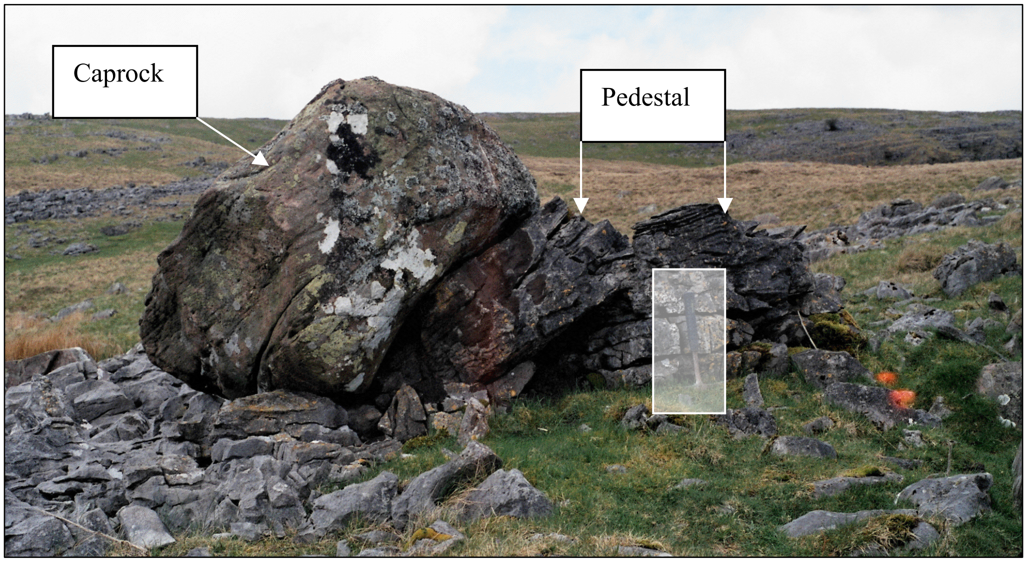

Plate *Error! No text of specified style in document.**.36: The foundered caprock and pedestal of TD1 at Twyn Du***

The toppled caprock of TD1 is composed of 'acid' Devonian conglomeratic sandstone. The pedestal is in two parts, an in situ lower part and a foundered upper part, and if their heights are summed then an overall height of about 68cm ensues. There is no doubting that the caprock formerly protected the limestone beneath it since caprock base and pedestal crown are of similar shape and aerial extent. The hammer, which is boxed, is about 32cm in length.

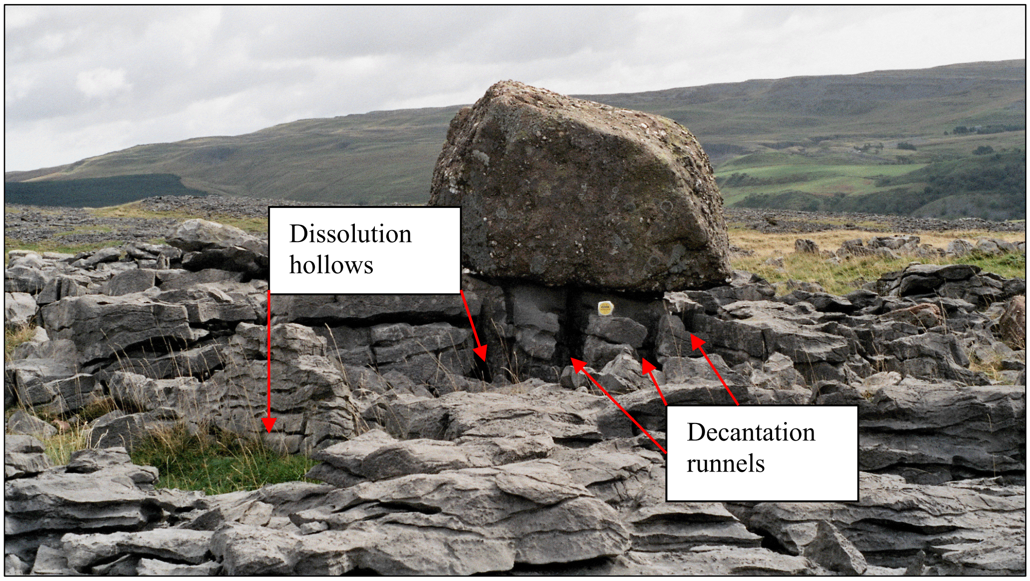

Plate *Error! No text of specified style in document.**.37: TD2 at Twyn Du***

In contrast to TD1, TD2 lacks a pedestal altogether. Instead, much of the immediate surrounding surface consists of dissolution hollows, which have formed due to sub-vegetation-covered-regolith dissolution, and/or runnels, which have formed due to acidulated water decanting from the erratic.

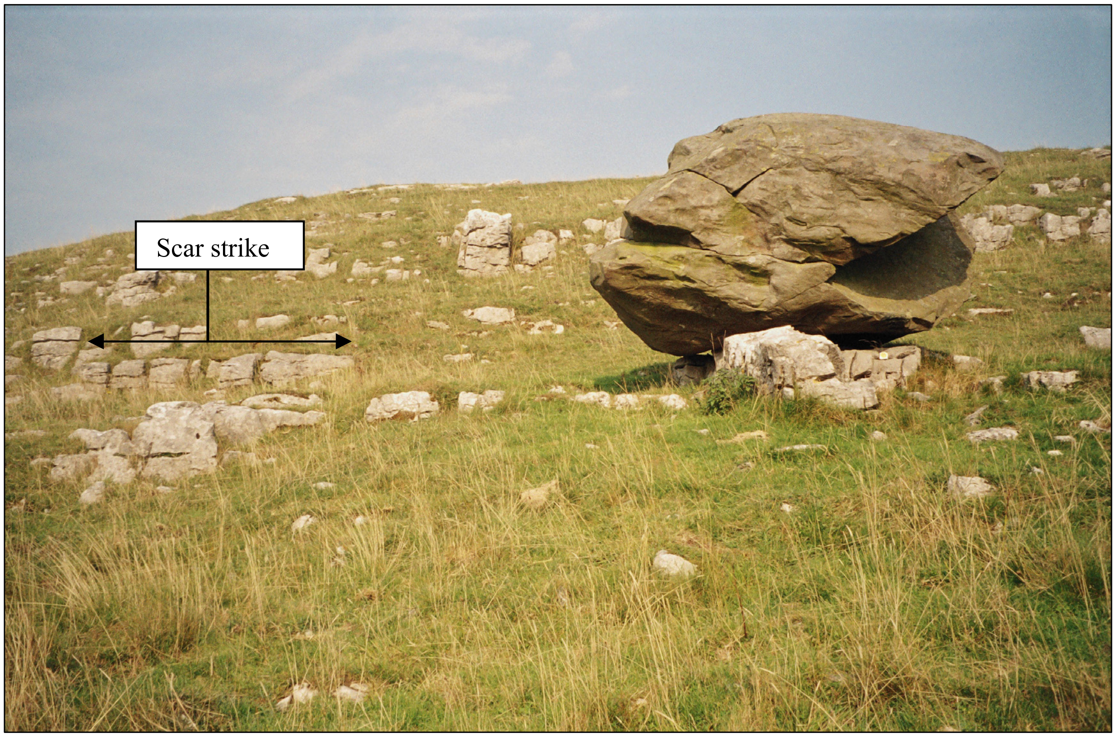

Plate** Error! No text of specified style in document.**.38: Perched pedestal rock W1 at Winskill Stones

The pedestal of W1 has greater downslope (66cm) than upslope (16cm) height, the downslope sidewall having formed due to glacial plucking. The pedestal is part of an intermittent scar that can be traced along the strike of the slope. The caprock is about 1.5m tall.

Plate** Error! No text of specified style in document.**.39: Perched pedestal rock YG2 at Y Gogarth

The caprock of YG2 appears to have slipped downslope, which explains why the pedestal crown beneath the mountain bike is exposed. The presence of a vertical sidewall beneath the ground's surface is indicated by the upright measuring rod, which has penetrated about 15cm of vegetation-covered regolith.

Sampling event and site	**Water type**	**pH**
1 Norber	Precipitation Decanted mean from four Silurian grit caprocks	5.6 5.3
2 Norber	Precipitation Decanted mean from two Carboniferous limestone boulders	4.8 6.9
3 Norber	Precipitation Decanted mean from three Silurian grit caprocks Decanted mean from five Carboniferous limestone boulders/caprock Decanted mean from five Carboniferous limestone clints	7.2 6.2 7.9 7.4
4 Norber	Precipitation Decanted mean from three Silurian grit caprocks Decanted mean from three Carboniferous limestone boulders/caprock	6.3 5.3 7.4
5 Norber	Precipitation Decanted mean from three Silurian grit caprocks Decanted mean from three Carboniferous limestone boulders/caprock	5.9 5.0 7.5
6 Gearstones	Precipitation Decanted mean from three vegetated Carboniferous limestone caprock	5.6 5.9
7 Scales Moor	Precipitation Decanted mean from five Carboniferous limestone clints	5.6 6.5

Table* Error! No text of specified style in document.*.1: The pH of precipitation and decanted water at Norber, Gearstones and Scales Moor

Sample boulders/ caprocks	**Approximate trickle fetch (m)**	**pH**	**Mean pH**	**Conductivity (чS)**	**Mean conductivity (чS)**
N26 (SD 76767 69889)	1	8.0	7.9	79	109
N26 (SD 76767 69889)	1	8.1		184	
Boulder 1 (SD 76941 69730)	3	7.7		83	
Boulder 2 (SD 76943 69697)	2	7.8		93	
Boulder 3 (SD 76948 69720)	1.5	7.7		105	
N5 (SD 76796 70083)	1.2	6.7	6.2	51	49
N6 (SD 76747 70006)	2.0	5.3		66	
N27 (SD 76746 70010)	1.2	6.7		30	
Precipitation	–	7.2	–	46	–

Table* Error! No text of specified style in document.*.2: Trickle fetch, pH and conductivity of decanted water from selected boulders at Norber for sampling event 3

Sampling event and site	**Water type**	**pH**
2 Norber	Precipitation Decanted mean from two Carboniferous limestone boulders	4.8 6.9
3 Norber	Precipitation Decanted mean from five Carboniferous limestone boulders/caprock	7.2 7.9
4 Norber	Precipitation Decanted mean from three Carboniferous limestone boulders/caprock	6.3 7.4
5 Norber	Precipitation Decanted mean from three Carboniferous limestone boulders/ caprock	5.9 7.5
Mean pH for sampling events 2-5	Precipitation Decanted	6.0 7.5
6 Gearstones	Precipitation Decanted mean from three soil/vegetation-covered Carboniferous limestone caprocks	5.6 5.9

Table* Error! No text of specified style in document.*.3: The pH of precipitation and decanted water from Carboniferous limestone caprocks/boulders at Norber and Gearstones

Tablet No.	Soil pH adjacent to tablets	Extrapolated depth equivalent (mm ka)
31	7.5	3.5
32	7.2	8.9
33	7.3	9.2
35	7.3	10.7
36	6.4	5.9
40	7.0	10.9
41	7.1	2.8
42	6.8	8.5
54	7.1	7.6
56	6.6	8.8
57	7.1	2.4
60	7.5	3.9

Table* Error! No text of specified style in document..*4: Soil pH adjacent to tablets and extrapolated depth equivalent results at Oxenber

Source	**Environment**	**Surface lowering rate (mm ka)**	**Time span**	**Extrapolated minimum surface lowering (cm)**	**Extrapolated maximum surface lowering (cm)**
Smith (1972)	Subaerial tundra	2	ca.14500-10000BP	0.9	–
Lauritzen (2005)		33	ca.14500-10000BP	–	14.9
Limestone tablets	Sub-soil temperate arboreal	2.4-10.9	ca.10000-3000BP	1.6	7.6
Trudgill (1983a)	Subaerial temperate	3.7-13.5	ca.3000BP-present	1.1	4.1
			ca.14500BP-present	3.6	26.6

Table* Error! No text of specified style in document..*5: Putative surface lowering rates since Devensian deglaciation

Formation	**Member**	**Lithology**
Slievenaglasha	Lissylisheen	Cyclical crinoidal limestone
	Ballyelly	Nodular and crinoidal limestone with chert
	Fahee North	Fossiliferous limestone with chert
	Balliny	Cyclical crinoidal limestone
Burren	Upper Aillwee	Fossiliferous limestone with *Davidsonia*
	Lower Aillwee	Bedded and massive fossiliferous limestone
	Maumcaha	Massive limestone, sparsely fossiliferous
	Hawkhill	Peloidal limestone with chert
	Fanore	Dolomitised limestone with shale
	Black Head	Limestone and dolomite with corals
Tubber	Finavarra	Bioturbated limestone with dolomite

Table** Error! No text of specified style in document.**.6: The Visean Limestone succession of the Burren (after Geological Survey of Ireland Sheet 14: Galway Bay: 2003)

CHAPTER 13: THE FORMATION OF MUSHROOM PEDESTAL ROCKS

13.1: Introduction

Mushroom pedestal rocks were located through examining literature sources (Section 6.3), and by quartering limestone outcrops on foot/mountain bike. They were encountered at the following sites:

1. The Burren (Lat. 52º 58' to 53º 10'N, Long. 08º 58' to 09º 25'W), Co. Clare, Eire.
2. Great Asby Scar (NY 6510), Cumbria, England.
3. Semer Water (SD 9287), North Yorkshire, England.

Only Goldie (1994; 1996) re Great Asby Scar, and Dunne and Feehan (2003) re the Republic of Ireland refer to mushroom pedestal rocks in the literature. The sites where mushroom pedestal rocks were encountered are presented in alphabetical order, so as not presume that one is more important than another.

13.2: Aim and objectives

The aim of the work undertaken in Chapter 13 is to resolve through time the formation of mushroom pedestal rocks in England and Ireland. The objectives are to investigate pedestal-rock-forming processes and to use the work undertaken in Chapters 7-11 to fulfil the aim. As the caprocks of mushroom pedestal rocks are 'residuals' remaining after preferential weathering/erosion of the limestone below them, caprock origin within the context of the formation of mushroom pedestal rocks is not considered further.

13.3: The Burren (Lat. 52º 58' to 53º 10'N, Long. 08º 58' to 09º 25'W) (Ordnance Survey Ireland Discovery Sheets 51 Clare, Galway 1:50000 (2002) and 52 Clare, Galway 1:50000 (2003))

Ten wave stones (as named by Dunne and Feehan, 2003), which are a type of mushroom rock, were sampled on the Burren, three at Gortlecka a short distance north-east of Lough Gealáin, six close to Rinnemona Lough and one on a hillside at Fahee North. According to Dunne and Feehan (2003:15) wave stones formed in loughs that were more extensive than today when "…long continued wave action corrodes the limestone below the water more rapidly than above the water." The two lacustrine sites are described by Dunne and Feehan (2003), and they include four wave stones listed by them, namely Gortlecka 1 and 2 (Plates 13.1: B54 and 13.2: B53), which are about 2m in height, and Rinnamona 2 (Plate 1.4: B47) and 3, which are about 1m in height. The lacustrine sites were visited twice. In May 2005 the surrounding ground, which consists of soggy peat covered in rank vegetation, was otherwise dry, but in October 2006 it was flooded to a depth of at least 1m. The caprock lips of Gortlecka 1 and 2 are neither horizontal nor straight, as they not only slope at gentle angles but also undulate, while the caprock lip of Gortlecka 2 is absent in a lake-facing direction. Solution embayments occur in the sidewalls of both wavestones, one of which cuts through Gortlecka 1 in the manner of a phreatic tube, as seen in Plate 13.1. The wave stones at Rinnemona are similar in form and in surroundings to those at Gortlecka. The mean pH of the water closest to both sites was alkaline (Table 13.1) apart from Rinnemona Lough in October 2006. A thin coating of greyish pelletal lime-mud (marl) covered submerged aquatic vegetation at both sites and formed ooze on the lough floors. A thin, dry powder of similar colour was present on the pavement immediately surrounding Lough Gealáin between the water's edge and a strand line composed of vegetation remains, which indicates that the powder had been deposited from the lake when water levels were higher. Plate 13.3 shows that the epi-lacustrine limestone pavement consists of relatively large, smooth clints. These become increasingly fretted and dissected landwards, eventually merging with more broken subaerial pavement, such as that surrounding B1 (Plate 12.11). The sub-lacustrine limestone surface was likewise comprised of relatively large, smooth clints. None of the scores of limestone erratics protruding from the lake, or any littering its shore, or any of the cliffs abutting its margins showed any signs of water-worn erosion apart from perhaps a general smoothness of surface. The same sub- and epi-lacustrine landforms were also noted at a number of unnamed turloughs to the south of Lough Gealáin. The wave stone at Fahee North (B56) is not listed by Dunne and Feehan (2003), but is similar in form to Clorhane 1 and Rinnamona 3 stones (Dunne and Feehan, 2003: 17 and 20). The wave stone has five lips one above the other, the lower and deepest 'waist' circumventing it at regolith surface level, as is partly revealed in Plate 13.4. Refer to Appendix 5B Table 5B.2 for the locations, features and surroundings of the sampled pedestal rocks.

Dunne and Feehan (2003) have proposed that wave stones are the products of dissolution in lake water. There are four reasons that militate against this (at least for the sampled wave stones):

1. The waters that feed Lough Gealáin and Rinnemona Lough, and the turloughs are, to all intents and purposes, of subterranean origin. Thus, none of the loughs/turloughs have any inflow streams while only Rinnemona Lough has a permanent exit stream. This means that the alkalinity of the lough/turlough waters is explained not

by dissolution of their basins, but by dissolution of the body of the limestone the waters have passed through beforehand. Consequently, the loughs/turloughs waters will, in fact, buffer the lake basins from dissolution, which explains the absence of wave-stone-like features in epi-lacustrine cliffs and erratics, and the presence of relatively smooth and undissected sub- and epi-lacustrine clints. Moreover, the absence of wave-stone-like features, and the presence of relatively smooth and undissected clints denotes that lacustrine dissolution of the loughs/turlough basins has not prevailed in the past. The view that dissolution of the lake basins is not occurring is supported by observations made by Simms (2002) along the margins of three interconnected lakes in western Ireland, the waters of which are at or near saturation with respect to calcium carbonate. Erosion features include röhrenkarren, solution pits and corrosion notches, none of which occurs at any of the surveyed sites.

2. While water with a pH of <8.0 is capable of dissolving calcium carbonate providing there is carbon dioxide in solution, the fact that marl is present on submerged seasonal vegetation indicates that calcium carbonate precipitation rather than calcium carbonate dissolution is taking place.

3. As lake surfaces are essentially flat sheets of water, it follows that if the pedestals have resulted from dissolution in lake water the caprock lips of individual wave stones should be entire and horizontal. This is clearly not the case. For example, B53 (Gortlecka 2) lacks a caprock lip from its southerly to north-westerly points; the lips of B48, B50, B55 and B56 are also incomplete. Moreover the caprock lip of B53 is undulating in form and generally dips lakewards, as is plainly evident in Plate 13.2. In fact, measurements of the distance from caprock lip to water-level taken at approximate 30cm intervals from the north-westerly to the southerly points of B53 show that heights range from about 31 to 67cm. It follows, also, that if the pedestals have resulted from dissolution in lake water that the caprock lips of wave stones at the same site should be level with each other. Again, this is not the case. Thus, the heights of the caprock lips of B47, B51 and B52 were respectively about 13, 23cm and 59cm above an arbitrarily measured datum, which is more than a four-fold difference. Yet all the wave stones occur within about 250m of each other.

4. The main ‘waist’ of B56 has formed on a relatively steep hillside with open ground on all sides except to the east, i.e. it has formed in a lake-free environment.

In view of the points raised above, it is argued that the sampled wave stones on the Burren have not formed in lakes.

This is supported by observations made of dissolution features on two limestone erratics (known as the Mermaids by Wood (1985)) found in Semer Water, in North Yorkshire (Plate 13.5). The Mermaids lie just offshore in lake water that is weakly acidic (the mean pH of three samples analysed on 13-11-2004 was 6.4 (Appendix 5 SW)), which means that the water has a greater potential to effect dissolution than the waters in the loughs/turloughs on the Burren. Yet the main focus of dissolution in Semer Water has occurred not below mean lake level but above it. Thus, sub-lacustrine dissolution has led only to a smoothing of the Mermaids’ sidewalls. In contrast, supra-lacustrine dissolution has formed wave-cut platforms at mean lake level and lakeward-sloping, swash-backwash karren (which perhaps should be called ‘wellekarren’ (=wave karren)) above them, as is evident in Plate 13.5. In other words, lacustrine dissolution has produced, for want of a better term, an inverted pedestal rock.

So how have the Burren wave stones formed? The presence of solution embayments and ‘phreatic tubes’ in the sidewalls of B47 and B54 (Plates 13.1 and 1.5), for example, and the presence of the hillside-facing ‘waist’ of B56 (Plate 13.1), which occurs at the erratic/upper-regolith-surface junction, are all indicative of dissolution in a sub-regolith environment. The undulating and relatively sharp nature of the caprock lip of B47 likewise points to dissolution in the same environment. Consequently, it is judged that all the pedestals of the sampled wave stones have formed due to dissolution in a sub-regolith environment of some kind, probably under damp, vegetation-covered organic soil in the cases of B47-B55 and under vegetation-covered mineral soil in the case of B56. Indeed, it is more than feasible that dissolution about B47-B55 has occurred in a past peaty environment, as Ivimey-Cook and Proctor (1966) have noted that bogs were once more common in Ireland than they are today. If so, it is likely that exposure of their pedestals has resulted from the loss or shrinkage of peat following forest clearance and/or drainage of the peat. The fact that drainage can result in peat shrinkage/loss is illustrated by the Holme Post, which is a metal post driven into underlying clay at Holme Fem (TL 1987) in England in about 1851 so that its top was flush with the level of the surrounding peat. The post now rises about 4m above the ground due to peat shrinkage and oxidation caused by drainage (Waltham, 2001). Moreover, Dunne and Feehan (2003: 25) recognise that a small number of mushroom stones “…may have formed as a result of burial for a long time in acid soil or peat. The water passing through such soil can react with much more CO2 and is thus capable of dissolving limestone more rapidly than ordinary water can. The sharp-edged cusps which occur at the base of some mushroom stones, at times penetrating right through the rock [as seen in Plate 13.1], are probably the result of erosion under acid mineral soils or organic soils such as peat." It is probable that all thirty-two wave stones illustrated in Dunne and Feehan (2005) have formed in a similar setting to the sampled wave stones. This is because not one of the illustrated wave stones is atypical of the sampled wave stones, and because no features that can be attributed to wave erosion, such as wave-cut platforms or 'wellekarren', are anywhere present. As such, it is proposed that the term 'wave stone' be dropped.

13.4: Great Asby Scar (SD 6510: Ordnance Survey Outdoor Leisure 19 Howgill Fells and Upper Eden Valley 1:25000 (1995))

A mushroom rock field was surveyed at Great Asby Scar, and this is Goldie's (1994; 1996) area 13. The caprocks, which are gryke-bound, cushion-shaped and about 25cm thick, are generally formed of rock that is relatively more massive than that of the pedestals beneath, and the fact that some form natural arches is testimony to its massiveness. In contrast, the pedestals are commonly composed of fractured limestone, as can be seen in Plate 13.6. These observations more-or-less match those made by Goldie (1994: 4), who wrote that there are "…quite massive, cushion-shaped clints on top of well-fractured undercut pedestals." Kamenitzas and well-weathered rundkarren are etched into the surface of many of the caprocks. The pedestal sidewalls are more-or-less vertical except where they fan out immediately below the cap, while the exposed mean height of twenty pedestals chosen at random was about 22cm. The amount of caprock undercut varies considerably from practically nothing to a maximum of about 0.5m, and in some instances undercuting had proceeded to such an extent that pedestals had foundered. Gryke floors are mantled largely in vegetation-covered regolith, which ranges in thickness from <1 to 5cm. The regolith is strewn with and contained angular limestone clasts that reach cobble size. Refer to Appendix 5GAS Table 5GAS.2 for the locations, features and surroundings of the sampled pedestal rocks.

The initial stage of pedestal fashioning probably began with gryke formation, the grykes dividing the pavement into clints of varying sizes. Once gryke depth exceeded the thickness of the massive bed differential horizontal erosion of the limestone would have occurred, the massive limestone undergoing erosion at a lesser rate than the fractured limestone, thus leading to the formation of a caprock and a pedestal. It is likely that the first process to effect horizontal erosion was sub-regolith dissolution, the discontinuities in the fractured limestone providing a greater surface area for dissolution to function. At some stage in the proceedings the base of the caprock and the upper part of the pedestal sidewalls would have become exposed. This would have come about due to sub-regolith dissolution causing the gryke floor to be lowered, since it follows that when this happens any regolith present on gryke-floor surfaces is lowered too. Following exposure, failure of pedestal sidewalls and caprock bases would have occurred, as witnessed by the fact that in one or two instances it was possible to re-fit some of the clasts lying on the gryke floors back into the sidewall or the pedestal base they were derived from. Thus, pedestal height would have increased in two directions due to two different processes, i.e. from below due to dissolution of the gryke floor and from above due to failure of the base of the caprock. Eventually, some pedestals would have become too narrow to support their caprocks, which would founder. Goldie (1996) does not account for pedestal formation at Great Asby Scar, writing (p. 131) only that the clints are markedly undercut "…due to heavily fractured weaker bed[s] underlying clint-bearing limestone".

Although little regolith is now present on the clints, as is evident in Plate 13.6, the occurrence of rundkarren indicates that it was once more prevalent than today. Moreover, the fact that the rundkarren are well-weathered shows that the regolith cover was lost some time ago, perhaps following deforestation. Consequently, it is possible that the main phase of pedestal development took place in an arboreal environment, i.e. from ca.10000-3000BP.

13.5: Semer Water: the Carlow Stone (SD 9287: Ordnance Survey Outdoor Leisure 30 Yorkshire Dales: Northern and Central areas 1:25000 (1984))

The Carlow Stone, as named by Wood (1985), is a relatively large, marooned Carboniferous limestone erratic that is partly entombed in the terminal moraine that dams Semer Water (Plate 13.7). It is situated some 25m inshore of the lake edge and is surrounded by vegetation-covered regolith. Elsewhere, the foreshore consists of a gravel beach and alder (*Alnus* sp.) stands. The vegetation-covered regolith that surrounds the sidewalls of the Carlow Stone is about 1.5m above normal water level, although strandlines indicate that it had been inundated several times in the recent past. Much of the cap has a cockly surface while the pedestal sidewalls, which are rough, small-stepped and vertical, and which drop some 70cm from overhang to ground level, are complete only to the west, north and east. The overhang under-surface is more-or-less horizontal and is about 1m deep to the west and east, and 30cm deep to the north. The southern (i.e. lake-facing) erratic sidewall merely tapers slightly inwards (it cannot be called a pedestal sidewall) and is smooth. The subaerial surfaces of two relatively small limestone erratics that occur at the south-west corner of the Carlow Stone are also smooth, whereas their sub-regolith surfaces are rough. The moraine is underlain by Malham Formation, Gordale Limestone. Refer to Appendix 5SW for the location, features and surroundings of the pedestal rock.

Although strand lines indicate that the base of the Carlow Stone is frequently flooded, the rough and angular nature of its pedestal shows it is not a product of lacustrine dissolution. Besides, only three sidewalls are present, none of which is lake facing, and no lacustrine-dissolution features akin to those on the Mermaids, which are only 25m distant, are present either. Instead, it is argued that the pedestal sidewalls have formed due to dissolution in a sub-vegetation-covered regolith environment, as they are similar in form to sidewalls occurring at Norber. Examination of ground down-ice of the moraine revealed that the latter is several metres thick, which means that the Carlow Stone is enclosed within the body of the moraine rather than resting on the limestone bedrock that underlies it. Thus, the pedestal sidewalls cannot have become exposed due to a reduction in height of the land surface as a consequence of dissolution of rockhead, as has happened at Norber, since any removal of rockhead would have resulted in moraine and the Carlow Stone being lowered concurrently. Consequently, it is arued that sidewall formation and retreat occurred adjacent to a covering of regolith that has since been lost. It is not known what once mantled the beach/car park, but a likely contender is an over-consolidated conglomeratic till that occurs at the western end of the moraine. The till, which is being actively eroded by lake waves, as can be ascertained in Plate 13.8, is about 0.5m thick and contains pebble/cobble phenoclasts that are identical with the beach material. This almost certainly indicates that the till was once more widespread than today. The pre-anthropogenic environment of the site is not known. As the moraine is soggy underfoot, has several strand lines and alder thickets on its surface, and as stands of alder occur along the western fringe of the lake, however, it is likely that it was formerly one of alder carr. Consequently, it is proposed that the conglomeratic till plus a cover of carr vegetation/humus once abutted the western, northern and eastern sidewalls of the Carlow Stone, and that lateral dissolution at the Carlow Stone-till/carr interface is responsible for pedestal formation. This proposal is backed up by the fact that till thickness and pedestal height are similar. It is also proposed that stands of Alder growing in water abutted the southern sidewall of the Carlow Stone, and that water lapping against it led to the rounding of its lake-facing base and of the two adjacent erratic boulders.

13.6: Conclusion

The mushroom-rock pedestals on the Burren, at Great Asby Scar and at Semer Water have all formed in a setting that is analogous to the pedestals of perched pedestal rocks bounded by vertical sidewalls, since it is argued that vegetation-covered regolith abutted or formerly abutted their sidewalls. Of the three sites, the environment at Great Asby Scar has the greatest affinity with that in which the vertical walls of perched pedestal rocks have formed. This is because the pedestals are contiguous with bedrock, which means that bedrock lowering and sidewall failure have played a part in pedestal fashioning. On the contrary, the mushroom rocks on the Burren and the Carlow Stone at Semer Water are not contiguous with bedrock, which means that only lateral dissolution in a sub-regolith environment has played a part in pedestal fashioning. It must be pointed out, though, that as caprock protection has played no part in pedestal formation it follows that the pedestals have formed due to preferential weathering/erosion. Therefore, dissolution in a sub-regolith environment is the main process involved in the formation of the pedestals of mushroom pedestal rocks in England and the Republic of Ireland.

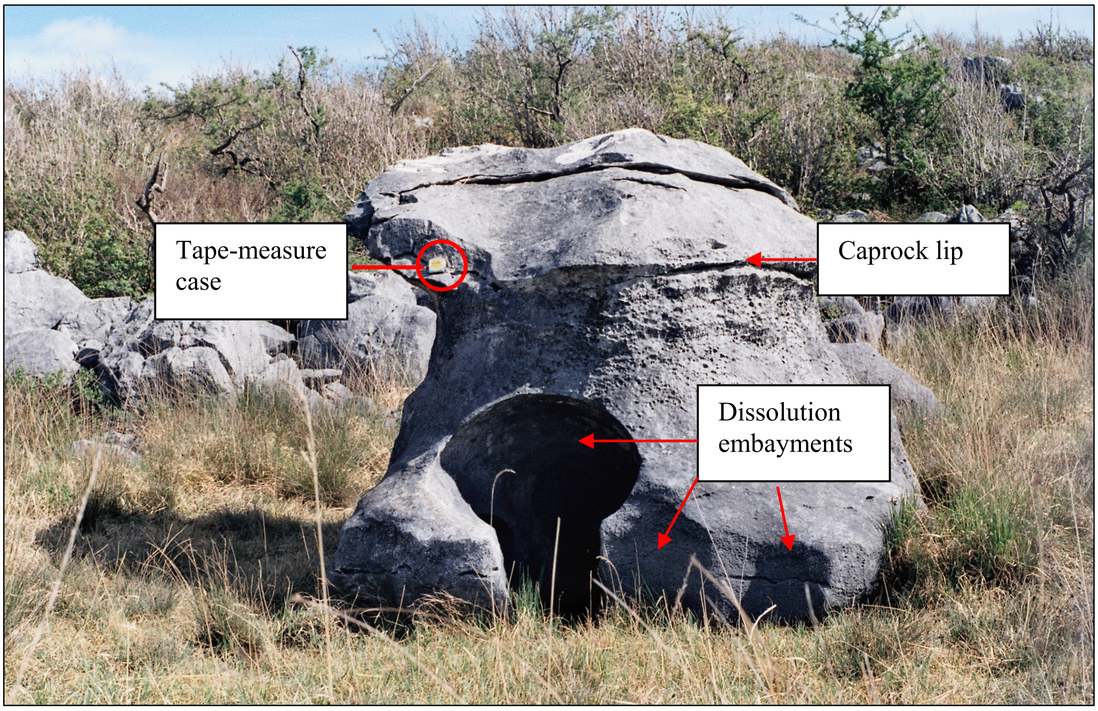

Plate** Error! No text of specified style in document.**.1: Wave stone B54 (known as Gortlecka 1 by Dunne and Feehan (2003)) on the Burren

According to Dunne and Feehan (2003) the caprock lip marks the position of a former lake level, the pedestal having formed due to long-continued wave action corroding the limestone below the water more rapidly than above the water. Three dissolution embayments are present in the sidewall of the wave stone, the left of which has completely pierced it.

Plate** Error! No text of specified style in document.**.2: Wave stone B53 (known as Gortlecka 2 by Dunne and Feehan (2003)) on the Burren

The caprock lip of B53 is sharply-defined, undulating and only partly complete (the part of the lip that is lacking is in blind ground). The wave stone is about 1m high.

Plate *Error! No text of specified style in document.**.3: The epi-lacustrine limestone surface of Lough Gealáin, the Burren***

The epi-lacustrine (and sub-lacustrine) limestone surface of Lough Gealáin consists of relatively large and smooth clint that is a far cry from the more broken subaerial pavement with which it eventually merges (refer to Plate 12.11). The thin, creamy-grey surface deposit on the limestone is dried-out pelletal lime-mud (marl) that was deposited from the lake when water levels were higher.

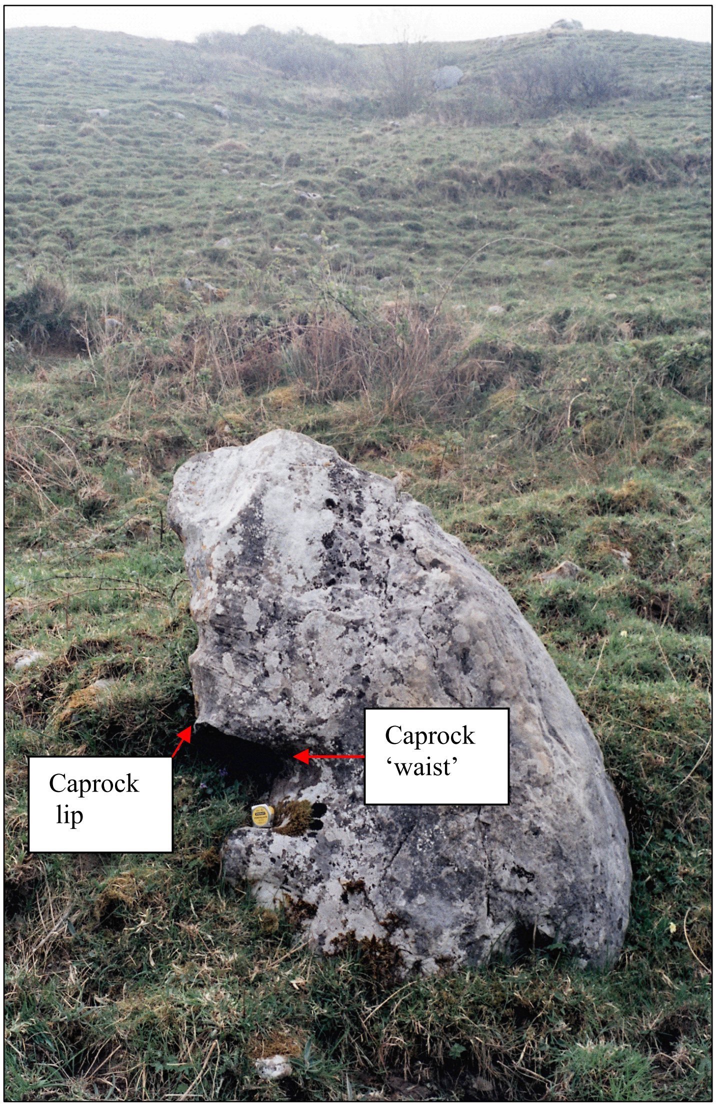

Plate** Error! No text of specified style in document.**.4: B56 near Fahee North, the Burren

Although much of the caprock lip of B56 is hidden, it completely circumvents B56 at the regolith surface-erratic junction. The 'waist' below the lip is deep enough and extensive enough for a human arm to fit comfortably inside it. B56 is little different from some of the wave stones illustrated in Dunne and Feehan (2003) that occur on level ground in pasture or bogs.

Plate** Error! No text of specified style in document.**.5: The Mermaids, Semer Water

The main focus of lacustrine dissolution of the two Mermaids has occurred at or above mean lake level. This has led to the formation of a wave-cut platform and of lakeward-sloping, swash-backwash karren ('wellekarren'). The Mermaids are about 1.2m tall.

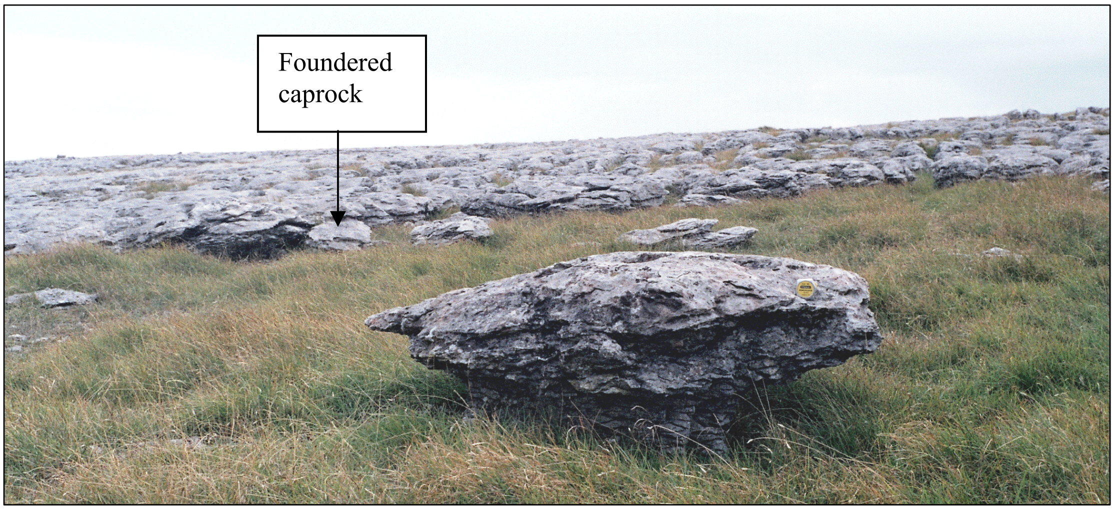

Plate** Error! No text of specified style in document.**.6: Mushroom rocks at Great Asby Scar

Although not readily apparent from the photograph, the caprock is comprised of a relatively massive bed and the pedestal of a relatively fractured bed. Several foundered caprocks are present in the main part of the pavement.

Plate** Error! No text of specified style in document.**.7: The Carlow Stone, Semer Water

Pedestal sidewalls are present on three sides of the Carlow Stone only, to the left, right and road-side. The lake-facing sidewall of the Carlow Stone is water worn, as are the two in situ boulders beneath the caprock overhang to the left. Much of the immediate surroundings are considered to be anthropogenic in origin. The Carlow Stone is about 1.8m tall.

Plate** Error! No text of specified style in document.**.8: Eroding till at the western end of the terminal moraine, Semer Water

Although they are not clearly visible, clasts in the till are identical to those that make up the beach, which probably means that the till was once more extensive than it is at present. The cliffs are about 0.5m tall.

Location	**Sample date**	**pH**
Rinnemona Lough	May 2005	8.2
Rinnemona exit stream	May 2005	8.3
Gortlecka	May 2005	7.8
Lough Gealáin	May 2005	8.2
Rinnemona Lough	October 2006	6.8
Lough Gealáin	October 2006	7.1

Table** Error! No text of specified style in document.**.1: Mean water pH analysis of wave stone sites, the Burren

CHAPTER 14: PEDESTAL HEIGHT, AND THE AMOUNT AND RATE OF POST-DEVENSIAN-DEGLACIATION DISSOLUTION SURFACE LOWERING

14.1: Introduction

Kinzl (1975) has proposed that 'karst tables' are of importance from the point of view of geochronology, as they provide a means for measuring the amount of corrosion (i.e. presumed surface lowering through dissolution) within a given time period. The theory behind the proposal is that the deposition of an erratic on a deglaciated limestone surface resets erosion of that surface to zero. Consequently, it follows that pedestal height, i.e. the elevation of the pedestal crown above rockhead, equates to the amount of surface lowering subsequent to erratic deposition. Furthermore, if the date of deposition is known then the mean rate of lowering can be determined as follows:

$r = h/t$ (Where r=mean rate of surface lowering (cm/ka), h=pedestal height (cm) and t=time since erratic deposition (ka))

Strictly speaking, assessing the amount and rate of post-Devensian-deglaciation dissolution surface lowering does not fall within the title of the thesis. Nevertheless, it has been included as the height of pedestals, especially at Norber, have been used to determine how much the Carboniferous limestone surface has been eroded since Devensian ice melted (e.g. Kendall and Wroot, 1924; Drew, 2001). Consequently, as the heights of pedestals and the dates of resetting the erosion surface to zero are known at Norber and at the sites outlined in Section 12.1, the work undertaken in Chapter 14 involves assessing the amount and rates of post-Devensian-deglaciation dissolution surface lowering.

14.2: Literature review

The majority of published measurements of pedestal height in England, Ireland and Wales are from Norber (Table 14.1). There are also some published measurements for sites other than Norber, as shown in Table 14.2. Several authors have used pedestal heights to determine rates of dissolution. For instance, about 25mm/ka over 12000 years at Norber (Goudie and Gardner, 1992), c.0.04mm/year over the past 12000years on the Burren (Drew, 2001), 3-13mm/ka in 15ka (Goldie, 2005) for selected English and Irish sites, and about 0.04mm/year in the Holocene, i.e. 10000 years, at Norber (Waltham, 2005). In addition, pedestal height and the rate of solution have been applied to dating regolith loss. Thus, Goldie (1994: 130; 1996: 4-5) has written that pedestals at Great Asby Scar are "…about 10cm in height [and] if calculated solution rates from elsewhere were applicable here (50cm in 10000 years, Sweeting, 1966), this pedestal depth would suggest exposure about 2000 years ago."

14.3: Aim and objective

The aim was to compare and contrast pedestal height measurements at the sampled thesis sites with the objective of assessing their use in determining post-Devensian-deglaciation dissolution lowering rates.

14.4: Method

Pedestal height was measured according to procedures outlined in Section 9.3. The only pedestals included in this assessment are:

1. Pedestals considered to have formed largely due to the lowering of the inter-pedestal surface in a sub-vegetation-covered regolith environment (i.e. pedestals bounded by vertical sidewalls only)

2. Pedestals considered to have formed largely due to the lowering of the inter-pedestal surface in a sub-aerial/sub-arboreal environment (i.e. pedestals bounded by sloping sidewalls only)

Many pedestals were excluded from this assessment, and they are:

1. Pedestals that partly owe their origin to glacial plucking (which, in any case, pre-dates deglaciation) or partly/wholly to anthropogenic removal of the surrounding surface

2. Pedestals that have foundered, as at Twyn Du, or whose caprocks have partly/wholly foundered, as at Norber for example, since their crowns may have undergone post-foundering dissolution

3. Pedestals bounded by both vertical and sloping sidewalls, since they have formed in two contrasting dissolution environments, i.e. sub-vegetation-covered regolith and subaerial/sub-arboreal

It is clear that although pedestals bounded by vertical sidewalls have essentially formed in a karstic environment, they have been modified by sidewall failure (Section 11.2). Nevertheless, vertical-walled pedestals were assessed, since sidewall failure does not alter or influence pedestal height.

It is important to understand when determining surface lowering rates that Devensian deglaciation occurred at different times in different places. Thus, England and Wales became ice-free in ca.14500BP (Section 3.4.1) and Ireland in ca.13700BP (Section 12.7.1). It is also important to understand that pedestal inception commenced at different times according to environment. Thus, the inception of pedestals bounded by sloping sidewalls probably begun soon after deglaciation (Section 12.5), which means that the commencement of surface lowering can be dated to ca.14500BP in England and Wales, and to 13700BP in Ireland. In contrast, the inception of pedestals bounded by vertical sidewalls probably did not commence until the Flandrian, which means that the commencement of surface lowering can be dated to ca.10000BP (Section 11.2.1).

14.5: Results

As vertical-walled and sloping-walled pedestals have formed in two contrasting dissolution environments they are assessed separately. The mean heights of pedestals bounded by vertical sidewalls (Table 14.3) and sloping sidewalls (Table 14.4) are respectively 46cm (range about 34-50 by site) and 15cm (range about 8-21cm by site). Moreover, it is apparent that the mean heights of the two types of pedestals are all but identical irrespective of province (Tables 14.5 and 14.6). It is also apparent that the surface surrounding vertical-sidewall pedestals has been lowered at rates of approximately 4.6cm/ka, and that the surface surrounding sloping-sidewall pedestals has been lowered at rates of approximately 1.0cm/ka in England and Wales, and 1.2cm/ka in Ireland (Table 14.7). In other words, although pedestals bounded by vertical sidewalls are roughly three times higher than pedestals bounded by sloping sidewalls, the rate of surface lowering is roughly four times greater once dates of pedestal inception are considered.

14.6: Analysis

The differences in the lowering rates of the inter-pedestal surfaces that surround pedestals bounded by vertical and sloping walls is attributed to the greater acidity of regolith water than rain water (Section 7.6.1). Furthermore, the difference in the inter-site heights of same-type pedestals is attributed to past and present variations in, for example, caprock decantation rates and decanted water acidity, arboreal interception rates, vegetation type, and soil water infiltration rates, pathways and acidity.

Although mean pedestal height at Norber (46cm) generally corresponds with published measurements (Table 14.1, range c.25 to <60cm excluding Goldie (2005)), it does not match well with Goldie's (2005) reassessment of height, which is 5-15cm. The reason for the disparity is very clear. Goldie (2005: 438) states re Norber that "…the few cases of solutional profile curves are discontinuous and measurement is difficult; none exceeds 15cm and several are lower, e.g. 5-12cm." Consequently, it is apparent that two very different 'heights' have been measured, i.e. from pedestal crown to bedrock (author) and "solutional profile curves" (Goldie, 2005). It is unclear exactly what "solutional profile curves" are (clarification was sought from Goldie by email, but no reply was received), but it is presumed that they and sloping sidewalls are one and the same. Nonetheless, the author has not noted any sloping sidewalls at Norber, and Goldie (2005) does not provide any visual evidence or grid references as proof of their existence. Accordingly, Goldie's (2005) reassessment of pedestal height cannot be accepted.

The calculation made by Goldie (1994; 1996) that the rate of solution at Norber may be used to determine the date of regolith loss at Great Asby Scar is considered invalid. This is because the calculation is based on the premise that the lowering of the inter-pedestal surface has proceeded at the same rate at both sites. This is patently not the case, since the surfaces at Norber and at Great Asby Scar have respectively been lowered at rates of about 4.6cm/ka in a sub-regolith setting and at about 1.0cm/ka in a subaerial/sub-arboreal setting. Besides, the calculation can equally be turned on its head, and pedestal height at Great Asby Scar could instead be extrapolated to show that pedestals at Norber are some 50000 years old, which is clearly not the case.

Williams (1966) has cited a mean pedestal height of 15cm in the Clare-Galway district, i.e. the Burren, whereas Drew (2001) has written that a typical pedestal height for the Burren is 40-60cm. The figure of pedestal height in Table 14.5 for the Burren is almost identical with that of Williams (1966), which means that Drew's (2001) figure is between about 3 and 4 times greater than either. Such a difference is not easy to explain, but it may be relevant to note that the only photograph of a pedestal in Drew (2001) is of B44, which is partly comprised of a glacial-scar downslope sidewall (Plate 12.16) that is about 59cm high. An upslope sloping sidewall, which is about 22cm high and which is much closer to the Burren 'norm', is also present. Consequently, it may well be that Drew's (2001) figure for the height of pedestals on the Burren is derived from a 'non-dissolution' measurement, and if so it cannot be accepted.

Williams (1966: 170) has asserted (Section 6.3) that the average pedestal heights of 15 and 51cm respectively on the Burren and in County Leitrim is suggestive of greater superficial denudation at higher levels "…where precipitation is more abundant". Could it be instead that the pedestals have formed in two contrasting environments, i.e. subaerial/sub-arboreal and sub-regolith, since their heights are close to the contrasting environmental mean elevations of 15 and 46cm? Moreover, SM4 and SM5 (Plate 12.5) are no more than 40m apart, which means that each must have received very similar amounts of precipitation, yet their respective heights are about 15 and >63cm because they have formed respectively in subaerial/sub-arboreal and sub-regolith environments.

14.7: Alternative methods for measuring surface lowering

Several authors have attempted to determine surface lowering rates experimentally by measuring weight loss of limestone tablets (e.g. Trudgill, 1983a) or employing micro-erosion meters (e.g. Trudgill *et al.* 1981; Nicholson, 1990) over periods of several years, and figures from Trudgill (1983a) (for Malham) are shown in Table 13.8. A comparison of the amount of extrapolated surface lowering based on Trudgill's (1983a) figures and the amount of lowering derived from measuring pedestal height is shown in Table 14.9.

The amount of lowering obtained by experimentation (extrapolated from Trudgill, 1983a) confirms the finding obtained from measuring pedestal height that sub-regolith dissolution proceeds at a greater rate than subaerial dissolution. Figures for the amount of subaerial lowering obtained by measuring pedestal height (15cm in England and Wales, and 16cm in Ireland) are at the upper end of the amount obtained by experimentation extrapolated from Trudgill (1983a) (5.4-19.5cm in England and Wales, and 5.1-18.5cm in Ireland). In contrast, figures for the amount of sub-regolith lowering obtained by measuring pedestal-height (46cm) is about two to five times greater than obtained by experimentation extrapolated from Trudgill (1983a) (8.4 -25.3). The exact reasons for the discrepancies are outside the scope of the thesis. Nonetheless, contributory aspects might include the facts that Trudgill's (1983a) figures are based solely on present-day dissolution rates and hence do not take into account any past changes in environment (as outlined in Chapters 10 and 11), and that Trudgill (1983a) warns against the validity of extrapolation through time.

Nicholson (1990) has also used micro-erosion meter results to determine surface lowering rates, and has written (p.100) that on the pavement just south of Alum Pot Beck micro-erosion measurements over a period of three years "…show an erosion rate of 0.33m per 1000 years. This agrees remarkably well with a rate of 0.40m per 1000 years as an average since deglaciation, estimated by Sweeting (1965) by measuring the height of pedestals under erratics left upstanding (at Norber, a few km to the south)". It is assumed that Nicholson's (1990) figure is an error, since it extrapolates into a pedestal height of about 4.8m assuming surface lowering commenced in 14500BP and because Sweeting's (1965) figure should read 0.04m per 1000 years. Nonetheless, Nicholson's (1990) figure has been reproduced in Huddart and Glasser (2002).

14.8: Conclusion

Williams (1968: 28) has pointed out (re The Burren) that the objective measurement "…of such poorly defined pedestals is difficult." There is no doubting that the validity of pedestal height evaluations is open to debate in almost every case for reasons outlined in Section 9.4. Furthermore, the absence of striae on the great majority of pedestal crowns means it cannot be taken for granted that they are Devensian in age. Consequently, Jennings' (1985: 85) comment that measuring pedestal height in order to ascertain surface lowering "…commands much confidence, if not a great deal of precision" has a ring of truth about it. Nevertheless, providing the pedestals are carefully chosen, i.e. if possible with flat/abraded crowns, but better still with striated crowns, it is considered that measuring pedestal height is a viable method of determining the amount/rate of post-glacial surface lowering. It must be acknowledged, though, that results are not to be used in a 'carte blanche' sense unless only vertical-walled or only sloping-walled pedestals occur at one site. Thus, it is possible to write with much confidence that the limestone surface at Norber has been lowered by a mean of about 46cm since Devensian deglaciation. This is because this figure was determined by measuring only the height of pedestals bounded by vertical sidewalls and because pedestals bounded by sloping sidewalls do not occur at the site. This figure ought not to be applied to other sites, though, especially where pedestals bounded by sloping sidewalls are present. For instance, parts of the surface of Scales Moor have been lowered by about 44cm, as indicated by the presence of vertical-walled pedestals, and parts have been lowered by about 20cm, as indicated by the presence of sloping-walled pedestals. Therefore, measuring the heights of pedestals at the sampled sites indicates that the post-Devensian-deglaciation surface has been lowered by a mean height of about 46cm in a sub-regolith environment and about 15cm in a subaerial/sub-arboreal environment.

Pedestal height (cm)	**Author and Year**
30-45	Phillips (in Hughes, 1886)
46	Kendall and Wroot, 1924
<60	Dunham *et al.*, 1953
c.25	Raistrick and Illingworth, 1965
c.30	Bell, 1966
30 to 50	Sweeting, 1966
40 to 45	Penny, 1974
<30	Talbot and Whiteman, 1991
30	Goudie and Gardner, 1992
40 to 50	Waltham *et al.*, 1997
5-15	Goldie, 2005

Table** Error! No text of specified style in document.**.1: Published measurements of pedestal heights at Norber

Site	Pedestal height (cm)	Author and Year
Cunswick Tarn	30-51	Hughes (1886)
Farleton Knot	8-18	Hughes (1886)
County Leitrim	51	Williams (1966)
Clare-Galway, i.e. the Burren	15	Williams (1966)
Twyn Du	20 to 40 (foundered)	Thomas (1970)
Great Asby Scar	10	Goldie (1994; 1996)
The Burren	40-60	Drew (2001)
Five sites (Scar Close/Scales Moor, Farleton Knott, Rock Forest, Gait Barrows and Arnside-Silverdale)	5-20	Goldie (2005)

Table** Error! No text of specified style in document.**.2: Published measurements of pedestal heights at sites other than Norber

Site	**Number of pedestals surveyed**	**Approximate mean pedestal height (cm)**
Cavan Burren	8	44
Cunswick Tarn	1	50
Farleton Knot	1	46
Gait Barrows	1	34
Gearstones	1	42
Hutton Roof Crags	1	34
Norber	17	46
Marlbank	1	47
Scales Moor	3	44
All	34	46

Table** Error! No text of specified style in document.**.3: Approximate mean height of pedestals bounded by vertical sidewalls

Site	**Number of pedestals surveyed**	**Approximate mean pedestal height (cm)**
The Burren	15	16
Farleton Knot	3	9
Great Asby Scar	9	11
Scales Moor	4	20
Scar Close	3	21
Underlaid Wood	1	8
Y Gogarth	1	18
All	36	15

Table *Error! No text of specified style in document.****.4: Approximate mean height of pedestals bounded by sloping sidewalls***

Geographical province	Number of pedestals surveyed	Approximate mean pedestal height (cm)
England	25	45
Ireland	9	44

Table** Error! No text of specified style in document.**.5: Approximate mean height of pedestals bounded by vertical sidewalls by province

Geographic province	**Number of pedestals surveyed**	**Approximate mean pedestal height (cm)**
England and Wales	21	15
Ireland	15	16

Table** Error! No text of specified style in document.**.6: Approximate mean height of pedestals bounded by sloping sidewalls by province

Environment of pedestal formation (and province)	**Pedestal form**	**Approximate mean pedestal height (cm)**	**Approximate years since pedestal inception (ka)**	**Approximate mean surface lowering rate (cm/ka)**
Sub-vegetation-covered regolith (England and Ireland)	Vertical sidewalls	46	10.0	4.6
Sub-aerial/sub-arboreal (England and Wales)	Sloping sidewalls	15	14.5	1.0
Sub-aerial/sub-arboreal (Ireland)	Sloping sidewalls	16	13.7	1.2

Table *Error! No text of specified style in document.****.7: Approximate mean rates of surface lowering***

Surface	Rate (mm/year)
Bare rock	0.0037 to 0.0135
Sub-acid brown soil	0.0084 to 0.0253

Table** Error! No text of specified style in document.**.8: Limestone surface lowering rates for Malham (after Trudgill, 1983a)

Environment (Trudgill, 1983a)	**Surface lowering obtained by experimentation (cm) (extrapolated from Trudgill, 1983a)**		**Environment**	**Surface lowering obtained by measuring pedestal height (cm)**	
	10000BP-present in England and Ireland re vertical- walled pedestals	**14500BP-present in England and Wales, and 13700BP-present in Ireland re sloping-walled pedestals**		**10000BP-present in England and Ireland re vertical-walled pedestals**	**14500BP-present in England and Wales, and 13700BP- present in Ireland re sloping-walled pedestals**
Bare rock	N/A	5.4-19.5 (England and Wales) 5.1-18.5 (Ireland)	Subaerial/sub-arboreal	N/A	15 (England and Wales) 16 (Ireland)
Sub-acid brown soil	8.4 to 25.3	N/A	Sub-vegetation -covered regolith	46	N/A

Table** Error! No text of specified style in document.**.9: Limestone surface lowering extrapolated from Trudgill (1983a) (columns 1, 2 and 3), and derived from pedestal height measurements (columns 4, 5 and 6)

CHAPTER 15: SUMMARY

15.1: Introduction

This thesis was initiated to investigate a Devensian glacial conundrum and a post-Devensian-deglaciation karstic landform that had not been previously subjected to comprehensive investigation. It therefore contributes the first detailed account of the provenance of the Norber erratics, and the formation of post-Devensian-deglaciation pedestal rocks with Carboniferous limestone pedestals in England, Ireland and Wales. Widely different accounts of the provenance of the *sensu stricto* Norber erratic and the formation of the Carboniferous limestone pedestals have been reported in literature. Thus, accounts of erratic provenance have placed their source area from as little as 1km away (Arthurton *et al.*, 1988) to as much as 160km away (British Isles: A Natural History, 2004). Furthermore, although rainfall is mostly claimed to be the prime process that has led to the formation of the pedestals (e.g. Goudie and Gardner (1992), a further nine processes have been also been advocated. Most of the accounts present little or no evidence to back up their claims. Thus, the only field evidence of erratic provenance comprises a photograph, and a brief description of plucked cliffs and an erratic trail in the Crummackdale Inlier by Dunham *et al*. (1953). Moreover, the only empirical data offered to support pedestal formation is five pH measurements of dripwater and one of precipitation by Jones (1965), and measurements of bedding inclines and topographic slope by Goldie (2005), both at Norber. Thus, the conclusions of the research presented in this chapter of the thesis are by far the most comprehensive with regard to the two respective fields of study. Apart from the thesis conclusions, sections on contributions to science and further research are also found in Chapter 15.

15.2: Conclusions of this research

15.2.1: The Provenance of the Norber erratics

Following a literature review (Chapter 3) nine potential geographical source areas for the *sensu stricto* Norber erratics were identified. Four of the source areas are specifically named, and they are:

1. The Crummackdale Inlier (e.g. Hughes, 1886; Waltham, 2005)
2. The Ribblesdale Inlier (Raistrick and Illingworth, 1965)
3. A hundred kilometres away (The Geography Programme, 1987)
4. Northumberland (British Isles: A Natural History, 2004)

One was identified from striae measurements (Tiddeman, 1872), and it is:

5. The Chapel-le-Dale Inlier

It is understood from the literature that Devensian ice moved towards Norber from the north (e.g. Goodchild, 1875; Arthurton *et al.* 1988; Mitchell, 1994) and that the erratics are comprised of Silurian rock (e.g. Hughes, 1886; Dunham *et al.*, 1953; Arthurton *et al.* 1988). Consequently, four further source areas were identified from a study of the geology to the north of Norber, and they are:

6. The Cross Fell Inlier
7. The Howgill Fells
8. The Lake District
9. The Teesdale Inlier

No field evidence is offered to support any of the literature potential source areas apart from by Dunham *et al*. (1953), as outlined in Section 15.1. Consequently, the first aim of this section of the thesis was to determine the geographical provenance of the Norber erratics. This is followed by two further aims, the first to determine the Lower Palaeozoic lithostratigraphical unit(s) that Devensian ice crossed in Crummackdale *en route* to Norber and the second to determine which of the Sowerthwaite, Crummack and Austwick unit(s) is/are the provenance of the *sensu stricto* Norber erratics. The findings of this research, which relate specifically to objectives 1-3 in Section 1.2.1, are as follows:

1: To map the dispersal of erratics and determine the geographical provenance of the Norber erratics

Mapping the dispersal of erratics was undertaken in a designated study area about 20km² (2000 hectares) that extended beyond the Crummackdale Inlier in all directions in order to allow sufficient clear ground between the inlier and study area boundaries. Thus, if mapping revealed that a train of *sensu stricto* Norber erratics crossed into the study area from outside its boundary and then continued onto Norber it would indicate that their provenance was external of the study area. Three indicator erratics were identified, and they were derived from Lower Palaeozoic strata of the Crummackdale Inlier in general, and more specifically from the Wharfe Conglomerate and conglomeratic basal units of the Kilnsey Formation. The indicator erratics had all been deposited to the south of *in situ* outcrops. This indicates that ice moved into the study area from the north, which confirms the long-held view (e.g. Hughes, 1886; Waltham *at al.*, 1997) that ice moved into Crummackdale from this direction. Moreover, as all the indicator erratics were present down-ice of the study area boundary it follows that their provenance is not Northumberland, a hundred kilometres away, the Lake District, the Howgill Fells, or the Cross Fell, Teesdale, Chapel-le-Dale or Ribblesdale inliers. In other words, the survey shows conclusively that the geographical provenance of the Norber erratics is the Crummackdale Inlier. Furthermore, the absence of exotic erratics in the study area revealed that Crummackdale ice was locally derived, as proposed by Mitchell (1994), for example.

2: To measure the trend of striae and determine the Lower Palaeozoic lithostratigraphical unit(s) Devensian ice crossed in Crummackdale *en route* to Norber

The trend of ninety striae was measured at thirteen separate locations to define better the direction of ice flow in the study area in order to narrow down erratic provenance within the Crummackdale Inlier. The erratic dispersal and striae strike surveys show that Devensian ice moved from a mean of 020 to 200º azimuth. Accordingly, it follows that Norber was by-passed by ice moving down eastern and central Crummackdale, but not by ice moving down western Crummackdale. Hence, Devensian ice crossed over only the Crummack, Sowerthwaite and Austwick formations of the Crummackdale Inlier *en route* to Norber, which means that only one or more of these lithostratigraphical units is the provenance of the *sensu stricto* Norber erratics. A western-Crummackdale provenance concurs with Dunham *et al.* (1953), Arthurton *et al.* (1988) and Waltham (1990), for example.

3: To compare and contrast the Norber erratics with strata of the Sowerthwaite, Crummack and Austwick formations in western Crummackdale in terms of their petrography and determine which of these lithostratigraphical unit(s) is/are the provenance of the Norber erratics.

The petrographical survey was undertaken in order to narrow down erratic provenance further. Thin sections and hand specimens of rock comprising the Norber erratics, and the Sowerthwaite, Crummack and Austwick formations were examined, and erratic size and bed thickness were measured. Grain-size analyses revealed that erratics comprised of arenaceous rock were derived only from arenaceous beds of the Austwick Formation, as Sowerthwaite and Crummack formation strata are composed of argillaceous rock only. This derivation is confirmed by the presence of mica visible to the naked eye in arenaceous erratic hand specimens but not in Sowerthwaite and Crummack formation hand specimens. An examination of argillaceous erratic hand specimens likewise revealed that mica was visible to the naked eye, which means that it too is not derived from the Sowerthwaite and Crummack formations. In contrast, mica was visible to the naked eye in argillaceous beds of the Austwick Formation. This means that the provenance of the *sensu stricto* Norber erratics is the Austwick formation, which concurs with Brumhead (1979) and Scrutton (1994), for example. Devensian ice passed over two outcrops of the Austwick Formation in Crummackdale *en route* to Norber, one at Capple Bank, and the other between Crummack and Norber Brow. Although there are no diagnostic textural or mineralogical differences between the rocks at the two outcrops, there are differences in bed thickness. Thus, beds are about a metre thick at Capple Bank but are up to 3.5m thick between Crummack and Norber Brow, this northward thinning being noted by McCabe and Waugh (1973). As many erratics at Norber have three axes greater than 1m in length it is clear that none of them are derived from the Austwick Formation at Capple Bank, since beds are too thin. Moreover, erratics are relatively sparse to the south of Capple Bank whereas they are relatively common between Crummack and Norber Brow. The greatest concentration of erratics between Crummack and Norber Brow emanates from a glacially-plucked ‘amphitheatre’ in the vicinity of the Old Limekiln (SD 770707), the erratics forming a distinctive train that strikes towards Norber. The ‘amphitheatre’ is backed by cliffs composed of arenaceous rock that are up to 3.5m in height, while argillaceous beds form part of the floor. It is clear that the bed comprising the walls of the ‘amphitheatre’ is thick enough to have produced the erratics at Norber with three axes greater than 1m in length. Nevertheless, it does not follow that this bed is the sole provenance of all the Norber erratics, since other plucked cliffs of similar stature occur nearby. Therefore, it follows that the provenance of the *sensu stricto* Norber erratics is outcrops of the Austwick Formation between Crummack and Norber Brow some 1.1 and 0.3km to the north of the northern boundary of Norber. The finding that the ‘amphitheatre’ is the main site of erratic provenance coincides with photographical and illustrative evidence of erratic provenance respectively found in Dunham *et al.* (1953: 102) and Waltham *et al.* (1997: 49). The finding contradicts the view held by Arthurton *et al.* (1988) and Scrutton (1994), however, that provenance is SD 770704.

15.2.2: The formation of post-Devensian-deglaciation pedestal rocks with Carboniferous limestone pedestals in England, Ireland and Wales

One hundred and fifty-one perched pedestal rocks and eleven mushroom pedestal rocks plus a mushroom-rock field were surveyed at nineteen different sites in order to establish the formation of post-Devensian-deglaciation pedestal rocks with Carboniferous Limestone pedestals in England, Ireland and Wales. The pedestal-rock sites visited were:

1. The Burren (Lat. 52º 58' to 53º 10'N, Long. 08º 58' to 09º 25'W), Co. Clare, Republic of Ireland
2. Cavan Burren (H 0735), Co. Cavan, Republic of Ireland
3. Cunswick Tarn (SD 4893), Cumbria, England
4. Dowkabottom (SD 9568), North Yorkshire, England
5. Farleton Knot (Farleton Fell/Newbiggin Crags/Holmepark Fell) (SD 5480), Cumbria, England
6. Gait Barrows (SD 4877), Cumbria, England
7. Gearstones (SD 7779), North Yorkshire, England
8. Great Asby Scar (NY 6510), North Yorkshire, England
9. Hutton Roof Crags (SD 5577), Cumbria, England
10. Marlbank (H1134), Co. Fermanagh, Northern Ireland
11. Norber (SD 7669), North Yorkshire, England
12. Runscar (SD 7679), North Yorkshire, England
13. Scales Moor (SD 7177), North Yorkshire, England
14. Scar Close (SD 7577), North Yorkshire, England
15. Semer Water (SD 9287), North Yorkshire, England
16. Twyn Du (SN 8316), Powys, Wales
17. Underlaid Wood (SD 4878), Cumbria, England
18. Winskill Stones (SD 8366), North Yorkshire, England
19. Y Gogarth (SH 7682), Gwynedd, Wales

Following a literature review (Chapter 6) nine potential pedestal-forming environments were identified at Norber, and these are:

1. Aeolian erosion (Wood, 1985)
2. Biogenic weathering and erosion (Goldie, 2005)
3. Freeze-thaw weathering (Goldie, 2005)
4. Glacial erosion (e.g. Waltham, 2005)
5. Induced tensile fracture weathering (Goldie, 2005)
6. Karstic erosion in a subaerial environment (e.g. Jones, 1965)
7. Karstic erosion in a sub-regolith environment (e.g. Hughes, 1886)
8. Soil-creep erosion (Sweeting, 1966)
9. Step-retreat erosion (Goldie, 2005)

Six potential pedestal-forming environments were identified from outside Norber, and these are:

1. Fluvial erosion (in France) (Martel, 1910)
2. Hydration weathering (in the Appalachians, USA) (Crickmay, 1935)
3. Insolation weathering (in Arizona, USA) (Leonard, 1927)
4. Lacustrine erosion (in Ireland) (Dunne and Feehan, 2003)
5. Marine erosion (in tropical seas) (Dunne and Feehan, 2003)
6. Salt-crystallization weathering (in Libya) (Peel, 1966)

Three potential pedestal-forming environments were identified in the field, and these are:

1. Anthropogenic erosion (at Farleton Knott)
2. Poaching erosion (at Norber)
3. Sidewall-failure weathering (at Norber)

In addition, Goldie (2005) has proposed that limestone fabric has played a role in pedestal formation at Norber and at other sites in England, Wales and Ireland, and Matsukura *et al.* (2007) have proposed likewise re limestone pedestals on Kikai-jima in Japan. With the exception of Jones (1965) and Goldie (2005), none of the published accounts of potential pedestal-forming environments provide any empirical data in support of their hypotheses.

Two types of pedestal rock are present in England, Ireland and Wales, perched pedestal rocks and mushroom pedestal rocks. The surveys revealed that all caprocks of perched pedestal rocks are erratics and that all caprocks of mushroom pedestal rocks have formed due to preferential weathering/erosion. Consequently, their origin within the context of pedestal rock formation is not considered further. The formation of the pedestals of perched pedestal rocks is accounted for before the pedestals of mushroom pedestal rocks, since the former are more abundant and occur at more sites.

15.2.2.1: The formation of pedestals of perched pedestal rocks

The first aim of this section of the thesis was to investigate at Norber which environments are eroding/weathering the inter-pedestal Carboniferous limestone surface and the second to determine whether fabric has played a role in pedestal formation. There is ample literature describing the changes that have occurred in the climate, soils and vegetation of England, Ireland and Wales following Devensian deglaciation (e.g. Roberts, 1989; Allen 1997; Bradshaw, 2001), all of which could have influenced pedestal evolution to a greater or lesser degree. Thus, an additional aim was to investigate the evidence for post-Devensian-deglaciation periglacial tundra and temperate arboreal environments at Norber. The present and past pedestal-forming environments are then combined in the final aim, which was to resolve the formation of pedestals of perched pedestal rocks through time. The investigations were largely undertaken at Norber due to author familiarity with the site, because more has been written about the site than any other (e.g. Hughes, 1886; Waltham, 2005) and because it has been used as a type site against which other sites are compared (e.g. Goldie, 1994; 1996). The findings of this research, which relate specifically to objectives 1-5 in Section 1.2.2, are as follows:

1: To investigate which environments are eroding/weathering the inter-pedestal Carboniferous limestone surface

There is no evidence to suggest that erosion of the inter-pedestal limestone surface by rivers, lakes, glaciers or the sea is occurring, since rivers are conspicuous by their absence, pedestals are not abutted by standing water, ice last covered sites at least ca.13700 years ago and no site is intertidal. There is also no evidence that anthropogenic removal of clints is taking place, despite its widespread incidence in the past (Goldie, 1993; 1995). Nor is there any evidence that weathering by hydration, insolation or salt crystallisation is occurring, since exposed limestone surfaces are indurated rather than crumbly. Furthermore, an examination of poaching erosion, and biogenic erosion and weathering at Norber revealed that both are inconsequential. There is also no evidence that wind and induced tensile fracture are eroding/weathering the inter-pedestal limestone surface. Thus, detailed studies at Norber showed that there is a distinct dearth of sand-sized particles to effect aeolian erosion and that stress imposed by caprocks on the underlying limestone is not nearly sufficient to cause induced tensile fracture weathering. Sweeting (1966) has suggested that soil-creep is a contributory agent in the downslope development of pedestals at Norber, a term that is normally applied to the movement of loose, superficial material rather than to well-indurated rock, such as limestone. As trails/concentrations of limestone clasts are not prevalent below downslope sidewalls, however, it is concluded that soil-creep is not eroding the inter-pedestal limestone surface. Goldie (2005) has proposed that the pedestals at Norber are the remains of steps that have been eroded back by mechanical processes. Goldie (2005) does not expand on the actual processes involved in step retreat other than citing (p. 438-439) "…frost action, and gravity fall…[and]…human and animal action." There is no climatic or field evidence to show that frost action is intense or rife enough to cause other than very limited retreat of the limestone steps at Norber, even in the very coldest of winters such as 1962-63. This is confirmed by the almost complete absence of clasts abutting pedestal sidewalls despite the fact that Goldie (2005) has cited no natural erosion process other than gravity fall for their removal. Nor is there any proof that anthropogenic/animal erosion has caused retreat of steps. Therefore, erosion of the inter-pedestal limestone surface due to step retreat via mechanical processes as envisaged by Goldie (2005) is not considered viable. Limestone blocks can, however, sometimes be visually 'jig-sawed' into adjacent pedestal sidewalls, and it is argued that they have failed due to undercutting of the pedestal sidewall by sub-regolith dissolution. Undercutting of pedestal sidewalls is apparent at sites where the sidewalls are abutted by vegetation-covered regolith, such as at Cunswick Tarn, Gearstones, Norber and Scales Moor. The actual rate of sidewall failure is hard to gauge because the lack of failed blocks infers that it happens infrequently. Many authors, such as Dunham *et al.* (1953), Sweeting (1966) and Bell (1996), have proposed that sub-regolith karstic erosion of the inter-pedestal limestone surface has occurred at Norber and other sites, and a detailed field investigation verified this. Thus, thirteen pre-weighed limestone tablets at Norber and twelve at Oxenber that had been buried below regolith for the 2004-2005 water year suffered weight loss. Other authors, from Hughes (1886) to Drew (2001), for example, have contended that sub-aerial karstic erosion of the inter-pedestal limestone surface by rainfall has occurred at Norber and at other sites. This was verified by an examination of pedestals at Norber, as decantation runnels a few millimetres deep and wide were recorded on seven of thirty pedestal sidewalls; runnels are also present on sidewalls at other sites, for example at the Cavan Burren. In addition, two pre-weighed limestone tablets tied to pedestal sidewalls below caprocks for the 2004-2005 water year at Norber suffered very slight weight loss. This was presumably due to dissolution by wind-blown rain and/or water vapour, since the tablets were sheltered from direct rainfall. Therefore, the investigations revealed that the erosion/weathering of the inter-pedestal Carboniferous limestone surface is essentially occurring only in sub-aerial and sub-regolith karstic environments, the latter abetted to a limited degree by sidewall failure.

2: To determine whether Carboniferous limestone fabric and composition have played a role in pedestal formation

Hughes (1886), King (1976) and Goldie (2005) contended that structure has played a role in pedestal formation at Norber and at other sites. Goldie (2005) suggested that discontinuity density may affect pedestal formation proposing that weathering of weak and strong limestone results respectively in relatively high and low pedestal height. There is no literature referring to limestone composition affecting pedestal formation, but Sweeting and Sweeting (1970) have suggested that biomicrites weather more rapidly than sparry limestones. The longest axes of pedestals at Norber rarely exceed 2-3m, which means that the thickness of beds within them will essentially be constant. If discontinuity density has affected pedestal formation, individual pedestals should therefore be of equal all-round height. This is clearly not the case, as the upslope and downslope height of N6 and N12, both of which occur on level ground, are respectively about 50 and 37cm, and about 48 and 62cm. Also, the downslope sidewall of N32 suddenly all but doubles in height from about 21 to 40cm; similar variations in the height(s) of individual pedestal are noted elsewhere. Moreover, Spearman's rank correlation coefficient of block surface area (i.e. surface discontinuity density) and exposed pedestal height of twenty-three pedestals at Norber was found to be +0.37, which is not statistically significant at the 95% level. An examination of thin sections of six pedestals was undertaken to establish the ratios of sparite cement to micrite matrix. The Spearman's rank correlation coefficient of the sparite cement/micrite matrix ratio and pedestal height is -0.26, which again is not statistically significant. Consequently, it is concluded that limestone fabric and composition have not played a role in pedestal formation.

3: To investigate the evidence for post-Devensian-deglaciation periglacial tundra and temperate arboreal environments at Norber

Evidence from literature shows that the time-span between Devensian deglaciation and the present man-made landscape can be grouped into two main environmental periods, an earlier periglacial tundra period lasting from deglaciation until ca.10000BP and a later temperate arboreal period lasting from ca.10000-3000BP. Both are different from the present day environment. Accordingly, it is important to confirm in the field that the periglacial/tundra and the temperate arboreal periods once existed. A landform survey of cold-climate features was undertaken in the Norber area, as well as a vegetation survey at the site. There is ample evidence of a past periglacial tundra period, since frost-shattered erratics occur at Norber while extensive scree deposits are widespread throughout the locale. Moreover, the scree deposits are not 'fresh' and are partly covered in vegetation, which is suggestive of senility and stability. In addition, relict tundra vegetation had previously been seen on Ingleborough and Pen-y-ghent. The vegetation survey disclosed that nine species are suggestive of an under-canopy arboreal environment and that a further four species either form or are part of the structure of hedgerows/scrubland/woods. All of the under-canopy species were growing in grykes, and it has been suggested that woodland plants have migrated to grykes and have become established in them because growth requirements are similar, i.e. relatively damp and shady. The seeds of five of the under-canopy plants discard onto the ground nearby. Consequently, it is difficult to imagine how the pavement at Norber, which is now isolated in a sea of sheep hostile to woodland plants, could have been colonised by these five species after grazing began. Therefore, the extensive scree deposits and the pavement under-canopy flora confirm literature evidence that a periglacial tundra environment and a temperate arboreal environment preceded the present grassland setting at Norber.

4: To resolve the formation of Carboniferous limestone pedestals of perched pedestal rocks through time

All natural (i.e. non-anthropogenic) pedestals are bounded by vertical and/or sloping sidewalls. The former are abutted by vegetation-covered regolith (e.g. at the Cavan Burren and Norber), and the latter by open air and/or arboreal litter/organic mat/*Sphagnum* (e.g. on the Burren and at Gait Barrows). It follows, therefore, that the pedestals have formed in two contrasting environments. Consequently, resolving the formation of Carboniferous limestone pedestals of perched pedestal rocks through time is presented in two sections, as follows:

4.1: The formation of pedestals abutted by vegetation-covered regolith

After Devensian deglaciation in England and Wales in ca.14500BP, and in Ireland in ca.13700BP, little or no dissolution of the inter-erratic limestone surface occurred until ca. 10000BP because the ground was frozen due to a periglacial climate. This meant that water was unavailable to effect dissolution. Around 10000BP the permafrost thawed, and this allowed aggressive regolith water to corrode rockhead except where the limestone surface was protected by erratics resting directly on it. This marks the beginning of the erosion of the limestone surface by sub-regolith dissolution and hence of pedestal formation. At this stage the erratics 'morphed' into caprocks and the inter-erratic surface 'morphed' into the inter-pedestal surface. From ca.10000-3000BP sub-regolith dissolution occurred in an arboreal environment (the Wildwood). The trees were felled around 3000BP, and from that time until the present sub-regolith dissolution has taken place in a pastoral environment. It is not known whether dissolution rates were greater from ca.10000-3000BP when compared with ca.3000BP to the present day. The greater soil carbon dioxide production and the higher rainfall from ca.10000-3000BP should have led to an increase in dissolution rates. The buffering effect of leaf litter and the greater interception rates from ca.10000-3000BP should, however, have led to a reduction in dissolution rates. At some time post-ca.10000BP, pedestal sidewalls became exposed. This was caused by a reduction in height of the land surface as a consequence of dissolution of rockhead, since it follows that as rockhead is lowered the land surface must be lowered with it unless soil depth increases at a greater rate than bedrock dissolution. Subsequent to their exposure pedestal sidewalls underwent both lateral subaerial and lateral sub-regolith dissolution, the latter occurring at a greater rate than the former. This resulted in below-ground pedestal undercutting, which in turn led to above-ground failure of sidewall blocks about discontinuities due to the loss of below-ground support, both processes causing pedestal narrowing. Pedestals that have formed in the above sequence of environments are vertical-walled because a quantum leap occurs in the dissolution rate from 'insignificant' on the pedestal crown to 'significant' beyond its distal margin and/or because of sidewall failure about vertical discontinuities. Vertical-walled pedestals abutted by regolith that have a downslope sidewall comprised of a glacial scar have also formed in the same manner, except that the scar pre-dates the formation of the lateral and upslope sidewalls. Pedestals comprised of limestone clasts, which are essentially vertical-walled, have likewise formed in the same manner, except that there has been no input from sidewall failure.

4.2: The formation of pedestals abutted by open air and/or arboreal litter/organic mat/*Sphagnum*

Following Devensian deglaciation, dissolution of the inter-erratic limestone surface commenced in a sub-aerial environment as soon as rainwater was available to effect dissolution. Thus, due to the absence of regolith the erratics 'morphed' into caprocks and the inter-erratic Carboniferous limestone surface 'morphed' into the inter-pedestal Carboniferous limestone surface some time after ca.14500BP in England and Wales, and 13700BP in Ireland. It is unclear when or even if vegetation colonised the bare limestone, although the presence of arboreal plants in grykes and rundkarren on clints indicate that vegetation and soil were formerly more widespread than today. At some stage organic arboreal soils would have covered at least some of the inter-pedestal surface between ca.10000-3000BP, hence causing dissolution to occur under a relatively thin covering of arboreal litter/organic mat/*Sphagnum*. It is uncertain whether dissolution rates increased under the arboreal organic soils, since their nature is unknown. Smart *et al.* (1983) found, however, that the mean calcium concentrations of authigenic diffuse percolation waters draining thin organic-mat and bare-pavement (on the Burren) were very similar, which may mean that vegetation changes since ca.10000BP had little effect on dissolution rates. After deforestation around 3000BP the organic soils wasted away, and the inter-pedestal surface underwent dissolution in a sub-aerial environment. Pedestals that have formed in the above sequence of environments are bounded by sloping sidewalls if Carboniferous limestone caprocks overlie them. This is because rainwater is alkalised as it flows over the caprocks. Consequently, when it decants onto the surrounding limestone surface it forms a 'dissolution shadow' within which a gradual distal rise in the dissolution rate occurs due to ever-increasing neutralisation of the alkalised decanted water by more acid rainwater. Furthermore, the absence of regolith means that sidewall failure about vertical discontinuities does not occur. In contrast, pedestals that have formed in the above sequence of environments are bounded by vertical sidewalls if Carboniferous sandstone caprocks overlie them. This is because water decanting off the caprocks does not become alkalised, but is acidulated. Consequently, a quantum leap occurs in the rate of dissolution from 'insignificant' on the pedestal crown to 'significant' beyond its distal margin.

Some pedestals beneath Carboniferous limestone caprocks are bounded by sloping and vertical sidewalls, e.g. on the Burren, and at Farleton Knott and Scales Moor. It is argued that formation of the sloping sidewalls has occurred in a sub-aerial environment within a dissolution shadow and the vertical sidewalls have formed in a sub-regolith dissolution environment. Many of the sloping sidewalls are terminated abruptly by the vertical walls of grykes or solution areas, and it is envisaged that their retreat is caused by sidewall failure. Pedestals bounded only by vertical sidewalls can also form below Carboniferous limestone caprocks if they are abutted by vegetation-covered regolith. This is because acid water in the regolith neutralises the alkalinity of the decanted water prior to it reaching rockhead. Consequently, a quantum leap occurs in the rate of dissolution from 'insignificant' on the pedestal crown to 'significant' beyond its distal margin.

5: To resolve the formation of Carboniferous limestone pedestals of mushroom pedestal rocks through time

Two types of mushroom pedestal rocks were sampled, those which are not contiguous with bedrock, such as the Carlow Stone and the wave stones of the Burren, and those which are contiguous with bedrock at Great Asby Scar. Consequently, resolving the formation of Carboniferous limestone pedestals of mushroom rocks is presented in two sections, as follows:

5.1: Mushroom rocks that are not contiguous with bedrock

Dunne and Feehan (2003) have advocated that wave stones described in the Republic of Ireland show signs of erosion by wave action or dissolution suggestive of prolonged exposure to standing water in lake margins. Observations and experimentation at the site showed that this is clearly not the case. This is because adjacent lake water was saturated with respect to calcite as marl precipitation is occurring and because erosion/dissolution features were absent along lake margins. Moreover, pedestal crown lips should be more-or-less horizontal and should be of similar altitude in adjacent mushroom rocks if the pedestals beneath them have formed in lakes. Again, this is clearly not the case. Thus, on the Burren the height above water level of the lip of B53 ranged from about 31 to 67cm. Moreover, the heights of the caprock lips of B47, B51 and B52, which occur within about 250m of each other, were respectively about 13, 23cm and 59cm above an arbitrarily measured datum. Also, wave stone B56 is found on the side of a hill that could not possibly have been inundated by lake water. Furthermore erosion of two limestone erratics in Semer Water, North Yorkshire, had taken place not below water level but above. Consequently, it is argued that the 'wave stone' pedestals probably formed due to sub-regolith lateral dissolution under peat that has since shrunk or wasted away. It is also argued that the pedestal of the Carlow Stone has formed due to sub-regolith lateral dissolution under till that has been eroded by Semer Water. If dissolution by peat/till water has led to the formation of the pedestals, inception occurred after 10000BP. This is because Gascoyne *et al.*, (1983) found that the ground (in Craven) was frozen prior to this date.

5.2: Mushroom rocks that are contiguous with bedrock

Goldie's (1994) description of the mushroom rocks at Great Asby Scar suggests they have formed due to differential weathering/erosion, and that the pedestals, which are composed of well-fractured limestone, have undergone greater weathering/erosion than the caprocks, which are composed of massive limestone. It is argued by the author that this is the case. This is because greater discontinuity density increases the surface area open to weathering/erosion. Moreover, the inter-pedestal surface is littered with limestone clasts of similar size and shape to *in situ* loose pieces of limestone in pedestal sidewalls, some of which were re-fitted back into the sidewall or the base of adjacent pedestals. It is also argued by the author that the main phase of pedestal development took place in an arboreal environment, i.e. from ca.10000-3000BP.

15.2.3: The amount and rate of post-Devensian deglaciation Carboniferous limestone surface lowering in England, Ireland and Wales

Kinzl (1975) has proposed that 'karst tables' are of importance from the point of view of geochronology, as they provide a means for measuring the amount of corrosion within a given time period. The theory behind this proposal is that the deposition of an erratic on a deglaciated limestone surface resets erosion of that surface to zero. Consequently, pedestal height, i.e. the elevation of the pedestal crown above rockhead, equates to the amount of surface lowering following erratic deposition. Furthermore, if the date of deposition is known then the mean rate of lowering can be determined. The finding of this research, which relates specifically to objective 1 in Section 1.2.3, is as follows:

1: To measure the height of post-Devensian deglaciation Carboniferous limestone pedestals

The heights of 34 pedestals with vertical sidewalls and 36 with sloping sidewalls were measured to assess the amount and rate of post-Devensian deglaciation surface lowering of the Carboniferous limestone. Pedestals were divided into vertical- and sloping-sidewall groups because they have formed in contrasting environments. The results show that the amount of surface lowering indicated by pedestals bounded by vertical sidewalls and sloping sidewalls is respectively about 46cm and 15cm. It is important to understand when determining surface-lowering rates in England, Ireland and Wales that pedestal inception commenced at different times according to environment and/or place. Thus, the inception of pedestals bounded by sloping sidewalls probably began soon after deglaciation, which means that the commencement of surface lowering is ca.14500BP in England and Wales, and 13700BP in Ireland. In contrast, the inception of pedestals bounded by vertical sidewalls probably did not commence until the Flandrian, which means that the commencement of surface lowering is ca.10000BP. The results reveal that the surface surrounding pedestals bounded by vertical sidewalls has lowered at rates of approximately 4.6cm/ka, and that the surface surrounding pedestals bounded by sloping sidewalls has been lowered at rates of approximately 1.0cm/ka in England and Wales, and 1.2cm/ka in Ireland. In other words, although pedestals bounded by vertical sidewalls are roughly three times higher than pedestals bounded by sloping sidewalls, the rate of surface lowering is roughly four times greater once dates of pedestal inception are considered.

15.3: Contribution to science

As the only previous striae-strike survey in the Norber area was over 130 years ago (Tiddeman, 1872), the thesis survey provides an up-to-date assessment of the movement of Devensian ice in the locale. It also provides a permanent record of the strike of the striae, since it is foreseen that the striae will eventually be erased from the landscape by weathering and erosion. There is no record in the literature of a thin-section survey or of a physical survey of erratics and potential source rocks being used to determine erratic provenance. Consequently, these two techniques provide further tools for establishing the movement of ice elsewhere. In addition, the petrographical survey, especially the thin-section component, adds to the bank of knowledge of Lower Palaeozoic strata in the Crummackdale Inlier.

Only Hughes (1886) and Goldie (2005) have written articles that have essentially dealt solely with pedestal formation at Norber. Of the two, the thesis conclusion is more-or-less in accord with Hughes's (1886: 529) proposal that the time taken to reduce the surrounding limestone by the height of the pedestal "…is chiefly [due] to the action of the damp soil and vegetation, which has covered it all, up to the very base of the pedestal on which the boulder rests." In contrast, the conclusion does not accord with the respective proposals of Goldie (2004: poster) that most so-called pedestals are "…steps" and (Goldie, 2005: 439) that "…mechanical weathering results in step retreat", not least because there is little or no evidence that mechanical weathering of pedestals is occurring at the site.

The formation of the pedestals had not previously been examined through geological time, and this approach generated two important discoveries:

1. The inception of pedestals abutted by regolith is almost certainly not commensurate with Devensian deglaciation, which occurred in ca.14500BP, but instead is essentially commensurate with the start of the Flandrian in ca.10000BP. This premise is based largely on the lack of speleothem growth in the Craven area until the latter date, as shown by Gascoyne *et al.* (1983). This means that pedestals abutted by regolith are much younger than generally envisaged. Moreover, the inception of pedestals bounded by open air commenced in ca.14500BP in England and Wales, and ca.13700BP in Ireland. Both findings are of importance with regard to rates of post-Devensian-deglaciation surface lowering.

2. The umbrella theory is largely disproved where pedestals are abutted by regolith, as at Norber, as it is only since ca.3000BP following forest clearance that the caprocks have protected pedestal crowns from karstic erosion by rainwater, which is roughly three-tenths the age of the pedestals.

The thesis has shed new light on the former distribution of till, since it is apparent that where only pedestals bounded by sloping sidewalls occur the surface must have been till-free; otherwise pedestals bounded by vertical sidewalls would prevail. The thesis may also have shed new light on gryke formation and gryke age. It is possible that erratics composed of acid rock, such as grit or granite, overlying bare pavement might have caused gryke inception due to 'dissolution hotspots' forming about them. If erratics composed of acid rock have indeed caused gryke inception, it calls into question Rose and Vincent's (1985a) proposal that the Silurian erratics in Underlaid Wood were deposited by meltwater into, or onto, already opened grykes as the Devensian ice wasted. Instead, the 'dissolution hotspot' hypothesis infers that the grykes in Underlaid Wood post-date rather than pre-date Devensian deglaciation. The 'dissolution hotspot' hypothesis does not necessarily imply, though, that all grykes have formed in this setting or that all grykes post-date Devensian deglaciation. In addition, it is important it was found that many of the pedestals at Farleton Knott and Hutton Roof Crags are anthropogenic, because any future studies of pedestals at the two sites must take into account the fact that the pedestals there might not be natural.

15.3: Further research

There is perhaps little to discover with regard to the provenance of the *sensu stricto* Norber erratics. On the contrary, there is much that can be done to augment the findings of the thesis with regard to the formation of limestone pedestals. Thus, the emplacement of limestone tablets under a variety of vegetation/deposits in a woodland setting ought to throw new light on dissolution rates in the Flandrian, especially if more precise knowledge of Wildwood vegetation and clearance dates were known beforehand through pollen analyses. It is envisaged that Oxenber would provide a suitable site because the woods there are semi-natural and because a variety of micro-habitats ranging from *Sphagnum* moss, to leaf litter to under-canopy vegetation are present. Organic soils, weathered till and bare rock also occur at the site. A study of sub-weathered till dissolution rates at the site might also prove revealing re pedestal formation at Norber during the Flandrian.

CHAPTER 16: CONCLUSIONS

16.1: Introduction

This study investigates a Devensian glacial conundrum, the provenance of the Norber erratics, and the formation of a post-Devensian-deglaciation landform, pedestal rocks with Carboniferous limestone pedestals in England, Ireland and Wales.

16.2: The provenance of the Norber erratics

Investigations to determine erratic provenance were undertaken in a study area of about 2000ha, which included Norber and the Crummackdale Inlier. Mapping the dispersal of glacial indicator erratics showed that ice flowed into the survey area from a general northerly direction and that it brought with it glacial clasts derived solely from Carboniferous strata. Consequently, a provenance from Lower Palaeozoic outcrops to the north of the survey area is precluded. The provenance of the Norber erratics is thus Lower Palaeozoic rocks that crop out to the north of Norber within the Crummackdale Inlier. The strikes of ninety striae were measured at thirteen separate locations to define better the direction of ice flow. The erratic dispersal and striae strike surveys showed that Devensian ice moved from a mean of 020 to 200º azimuth. Norber was thus by-passed by ice moving down eastern and central Crummackdale, but not by ice moving down western Crummackdale. Hence, Devensian ice crossed over only the Crummack, Sowerthwaite and Austwick formations of the Crummackdale Inlier *en route* to Norber. A petrographical study of the Norber erratics and the three formations revealed that provenance is the Austwick Formation. Devensian ice passed over two outcrops of the Austwick Formation in Crummackdale *en route* to Norber, however, one at Capple Bank, and the other between Crummack and Norber Brow. Measurements of erratic sizes and numbers, and bed thicknesses at the two locations revealed that provenance is between Crummack and Norber Brow. The greatest concentration of erratics between Crummack and Norber Brow emanates from a glacially-plucked 'amphitheatre' in the vicinity of the Old Limekiln (SD 770707), the erratics forming a distinctive train that strikes southwards towards Norber. The siliclastic bed comprising the walls of the 'amphitheatre' is thick enough to have produced the largest erratics at Norber, but this bed is not the sole source of all the erratics, since other plucked cliffs of similar stature occur nearby. Therefore, the provenance of the *sensu stricto* Norber erratics is outcrops of the Austwick Formation between Crummack and Norber Brow some 1.1 and 0.3km to the north of the northern boundary of Norber.

16.3: The formation of post-Devensian-deglaciation pedestal rocks with Carboniferous limestone pedestals in England, Ireland and Wales

16.3.1: Perched pedestal rocks

Studies of nine erosion environments at Norber revealed that the lowering of the inter-pedestal limestone surface is taking place almost exclusively in a sub-regolith dissolution environment. Thus, pH gradients, limestone tablet weight loss and karstic landforms all indicate that sub-regolith dissolution of rockhead is occurring. Moreover, relatively fresh rundkarren on exposed pavement indicates that it has occurred in the recent past. It is argued that step-retreat erosion via mechanical processes, as envisaged by Goldie (2005), is not considered viable, largely because products of mechanical weathering do not abut pedestal sidewalls, as no erosion processes other than gravity fall is cited for their removal. Studies of eight modification environments showed that failure and subaerial dissolution of pedestal sidewalls are causing pedestal narrowing. There is no indication that limestone fabric and composition have played a role in pedestal formation. An examination of pedestal formation through time showed that little or no sub-regolith dissolution of rockhead occurred from ca.14500-10000BP principally due to a combination of frozen ground and lack of carbon dioxide generation. Thus, Gascoyne *et al*. (1983) found that abundant speleothem growth in the caves of Craven did not commence prior to ca.10000-9500BP, when an abrupt climatic improvement occurred. This period marks the beginning of pedestal inception, the thawing and increased carbon dioxide generation, the latter as a consequence of afforestation, allowing regolith-water to corrode rockhead. As every caprock at Norber rests directly on rockhead and is/was encased in regolith, it follows that a quantum leap occurs in the dissolution rate from what is essentially insignificant below caprocks to significant beyond their distal margins under the surrounding regolith. This causes pedestals with vertical sidewalls to form. It also follows that as rockhead is lowered the land surface is lowered with it. This eventually leads to the exposure of pedestal sidewalls, and once this has occurred sidewalls are subject to lateral sub-regolith undercutting and subaerial dissolution, the former process augmenting the vertical nature of the sidewalls due to failure along joints. It is argued that, on balance, pedestal development probably proceeded at an ever-increasing rate from ca.10000-3000BP due to increased rainfall and soil acidification, and that rates fell back to present-day levels following deforestation. Therefore, the pedestals at Norber are residuals of Flandrian age that have formed due to erosion of the inter-pedestal surface in a sub-regolith dissolution environment augmented by sidewall failure and subaerial dissolution.

One hundred and nineteen perched pedestal rocks were surveyed at seventeen extra-Norber sites in England, Ireland and Wales. Pedestal formation was examined at Scales Moor first, as a greater range of pedestal rocks and surroundings occurs there than at than any other site. Unlike Norber all caprocks are composed of Carboniferous limestone, and some overlie subaerial pedestals bounded by sloping sidewalls. A study of the pH of rainwater and water that had decanted from the caprocks showed that water trickling over them is alkalised, and that this causes a dissolution shadow to occur about them. Consequently, sloping sidewalls form due to a gradual increase in dissolution occurring from sidewall head to sidewall toe resulting from mounting acidulation of the alkalised decanted water by acid rainwater. An examination of pedestal formation through time revealed that pedestal inception occurred in ca.14500BP, as Lauritzen (2005) has recorded subaerial pedestals in Arctic Spitzbergen. It is unclear whether pedestal development proceeded at an increased rate from ca.10000-30000BP, since neither the extent nor timing of pavement afforestation is known. Rates would, however, have fallen back to present-day levels following any deforestation. Therefore, the pedestals on Scales Moor are residuals that have formed due to erosion of the inter-pedestal surface in a subaerial/sub-arboreal dissolution environment, inception occurring soon after erratic deposition. All caprocks at the surveyed perched-pedestal-rock sites are erratics.

It is argued that like-pedestals occurring in like-environments have formed in a like-manner. Thus, all vertical-walled regolith-abutted pedestals, such as those at the Cavan Burren, have formed in the same manner as those at Norber. Similarly, all sloping-walled subaerial pedestals, such as those on the Burren, have formed in the same manner as those at Scales Moor. Inception occurred in ca.13700BP on the Burren, though, due to its later deglaciation. It is argued also that the 'Umbrella Theory' is not applicable through time to pedestals bounded by vertical sidewalls. Thus, little or no dissolution of rockhead occurred from ca.14500-10000BP, and even after pedestal inception caprocks protected pedestal crowns from regolith water until sidewalls became exposed. Moreover, pedestal crowns were protected from inundation by arboreal litter from ca.10000-3000BP. Thus, it is only for the past 3000 years at most, that caprocks have protected the underlying limestone from dissolution by direct rainfall, i.e. for three tenths of their age at most. In contrast, the 'Umbrella Theory' is applicable through time to pedestals bounded by sloping sidewalls. Thus, caprocks protected crowns from dissolution by rainwater from inception until 10000BP, for an indeterminate period in the Flandrian until afforestation and from ca.3000BP subsequent to deforestation, i.e. for more than half the age of the pedestals.

16.3.2: Mushroom pedestal rocks

Eleven mushroom rocks and a mushroom rock field were surveyed at three sites in England and Ireland. It is argued that mushroom rocks have formed due to differential erosion, the subaerial caps undergoing dissolution at a lower rate than the sub-regolith-abutted pedestal sidewalls. This applies to the so-called Burren 'wave stones', which Dunne and Feehan (2003) envisaged forming in lakes.

16.4: The amount and rate of post-Devensian-deglaciation dissolution surface lowering

Measuring pedestal height revealed that the inter-pedestal post-deglaciation surface has been lowered by c.46cm about vertical-walled pedestals and c.15cm about sloping-walled pedestals. This translates into mean lowering rates of c.4.6cm/ka about pedestals with vertical sidewalls, since dissolution commenced in ca.10000BP, and c.1.0cm/ka about pedestals with sloping sidewalls in England and Wales, and c.1.2cm/ka in Ireland, since dissolution respectively commenced in ca.14500 and 13700BP.

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APPENDIX 1: LOCALITIES

Ailladie: M 0903: area of the Burren, Republic of Ireland.
An Carn (Carran): R 2898: hamlet on the Burren, Republic of Ireland.
Appleby: NY 6820: market town in Cumbria, England.
Arnside: SD 4578: seaside town backed by Arnside Knott on the Kent estuary, Cumbria, England.
Ash Spring wood: SD 4894: wood occurring 0.3km to the north-west of Cunswick Tarn in Cumbria, England.
Askrigg Block: geological fault block bounded to the south by the Craven Faults and to the west by the Dent fault, England.
Austwick: SD 7668: village to the mouth of Crummackdale, England.
Austwick Beck Head: SD 777709: resurgence of Austwick Beck in northern Crummackdale, England.
Berwick-upon-Tweed: (NT 9953): town bordering the North Sea in Northumbria, England.
Bewaldreth (NY 2034): hamlet in Cumbria 10km to the north-east of Cockermouth, England.
Burton-in-Kendal: SD 5376: large village in Cumbria, England.
The Burren: Lat. 53 3N Long. 8 49W: an expanse of Carboniferous Limestone in Co. Clare in the Republic of Ireland.
Caddroun Burn near Saughtree: (NY 5696): stream and hamlet 12km north-east of Newcastleton in Nortumbria, England.
Cairngorms: eastern Highlands of Scotland.
Capple Bank: SD 782721: locality in north-eastern Crummackdale, England.
Cavan Burren: H0735: area found 3km to the south of the town of Blacklion in Co. Cavan, the Republic of Ireland.
Chapel-le-Dale: valley of Chapel Beck/the River Doe found to the west of the survey area, England.
Clapham: SD 7469: village at the foot of Clapdale, England.
Colt Park: SD 776776: ancient wood in northern Ribblesdale, England.
River Coquet: NT 7908: river in Northumbria rising on the Anglo-Scottish border 6km north of Byrness, England.
Craven: regional term for areas found immediately to the north of the Craven Faults, England.
Craven Lowlands: regional term for areas found immediately to the south of the Craven Faults, England.
Creehaun: R 3395: area of the Burren, Republic of Ireland.
Cross Fell: NY 6834: the highest point of the Pennines, England.
Crummack: SD 772714: locality in western Crummackdale, England.
Crummack Dale: SD 775721: locality in north-western Crummackdale.
Crummackdale: valley of Austwick Beck occurring 1km to the east of Norber, England.
Crummack Lane: SD 772697: track running along western Crummackdale, England.
Cunswick Tarn: SD 4893: small lake found some 4km to the north-west of the market town of Kendal in Cumbria, England.
Dan-yr-Ogof: SN 8315: cave system near Glyntawe (SN 8416), a hamlet in Cwm Tawe-Uchaf (Upper Swansea Valley) in Powys, Wales.
Dowkabottom: (SD 9568): limestone shoulder to the south-west of Littondale in North Yorkshire, England.
Eglwyseg: SJ 2346: mountain composed of Carboniferous limestone in the Bryniau Clwyd 11km to the west-south-west of Wrecsam (Wrexham) in Clwyd, Wales.
Eshton: SD 935562: hamlet in the Aire Valley 21km to the south-east of Norber, England.
Fahee North: R 3000: are of the Burren found some 3km to the north-east of the hamlet of Carran (An Carn), Republic of Ireland.
Fanore Bridge: M 1409: area of the Burren, Republic of Ireland.
Gait Barrows: SD 4877: National Nature Reserve found 3km to the south-east of Arnside, England.
Gaping Ghyll: SD 751727: swallow hole found above Clapdale on the southern slopes of Ingleborough, England.
Gortlecka: R 3094: area of the Burren, Republic of Ireland.
Harry Hallam's Moss: SD 7375: limestone pavement on the north-western flanks of Ingleborough.
Holme Fen: TL 1987: Nature Reserve 11km south of Peterborough, England.
Hunterstye: SD 7871: locality in north-eastern Crummackdale.
Hutton Roof village: SD 5778: hamlet in east Cumbria, England.
Ingleborough Fell: SD 740745: mountain 5km to the north of the survey area, England.
Ingram: (NU 1106): village in Northumbria 20km west-north-west of Alnwick, England.
Kilnsey Crags: SD 9768: glacially eroded cliffs found on the west bank of the River Wharfe, England.
Lancelot Clark Storth: SD 5477: Cumbria Wildlife Trust Reserve on Hutton Roof Crags, England.
Leeds: SE 3033: city in West Yorkshire, England.
Littondale: SD 9470: valley of the River Skirfare in North Yorkshire, England.
Long Scar: SD 765719: interfleuve to the west of Crummackdale separating it from Clapdale, England.
Lonsdale: valley of the River Lune (SD 6082), England.

Lough Gealáin: R 3194: Lough (unnamed on Sheet 51 Ordnance Survey, Ireland) in Gortlecka on the Burren, Republic of Ireland.
Lowland Lonsdale: some 40km² of mosses and low limestone hills to the north of Carnforth (SD 4870), England.
Lissylisheen: R 2099: area of the Burren, Republic of Ireland.
Malham Cove: SD 8964: large 'amphitheatre' of Carboniferous Limestone cliffs about 2km to the south of Malham Tarn, England.
Malham Tarn: SD 6689: small lake 13km to the east-south-east of Norber
Malham Tarn Field Studies Council Centre. SD 6689: field studies centre adjacent to Malham Tarn, England.
Marlbank: H1134: National Nature Reserve in Co. Fermanagh, Northern Ireland found some 5km to the south-east of Blacklion, Republic of Ireland.
The Mendips: A range of Carboniferous Limestone hills in Somerset, England.
Moughton: SD 791719: interfleuve to the east of Crummackdale separating it from Ribblesdale, England.
Moughton Scar: SD 788699: Carboniferous limestone cliff found to the north of Wharfe, England.
Moughton Scars: SD 782722: Carboniferous limestone cliff found immediately to the north of Capple Bank, England.
Moughton Whetstone Hole: SD 785720: spring in north-east Crummackdale, England.
Nappa Scars: SD 769698: Carboniferous limestone cliff found immediately to the south-east of Norber, England.
Norber: SD 764699: the southern extremity of Long Scar, England.
Norber Brow: SD 772697: a spur of Carboniferous Limestone that projects eastwards into the south-western extremity of Crummackdale, England.
Norber Syke: SD 7669: intermittent stream emanating above the Lower Palaeozoic-Carboniferous unconformity below Nappa Scars, England.
North Craven Fault: a major east-west trending fault found approximately 0.5km to the south of Norber, England.
Old Limekiln: SD 770707: locality on the western flank of Crummackdale, England.
Oxenber: SD 782683: woodland occurring 2km to the east of Austwick, England.
Pen-y-ghent: SD 8373: mountain 8km to the north-east of the survey area, England.
Ribblehead: SD 7678: headwater area of the River Ribble, England.
Ribblesdale: SD 8072: valley of the Ribble found immediately to the east of the survey area, England.
Rinnemona Lough: R 2994: Small lough on the Burren located about 1km to the south-west of Gortlecka, Republic of Ireland.
Robin Proctor's Scar: SD 763697: Carboniferous Limestone cliff found immediately to the south of Norber, England.
Runscar Great Scar: SD 7679: area of scars and pavement a kilometre or so to the north-east of the Ribblehead Viaduct, England.
Scales Moor: SD 7277: limestone pavement on the southern flank of Whernside, England.
Scar Close: SD 7577: limestone pavement on the north-western flanks of Ingleborough, England.
The Screes, Wasdale: NY 1504: well-developed screes found above the southern shore of Wastwater in the Lake District, England.
Semer Water: SD 9287: a natural lake situated some 6km to the south-east of Hawes in North Yorkshire, England.
Settle: SD 8163: Market town found to the south-east of Norber in Ribblesdale, England.
Sheshy More (Sheshymore): R 2495: area of the Burren, Republic of Ireland.
Somerset Island: Lat. 73 30N Long. 93 0W: Arctic island located between Baffin Bay to the east and the Beaufort Sea to the west.
Sowerthwaite Farm: SD 7769: farm in south Crummackdale, England.
Studrigg: SD 780708: locality in eastern Crummackdale, England.
Studrigg Scar: SD 782706: Carboniferous Limestone cliff in eastern Crummackdale, England.
Sulber: SD 781733: area of limestone pavement and moorland to the north of Crummackdale, England.
Tarn Moss: SD 6688: Field Studies Council/National Trust nature reserve on the western shore of Malham Tarn, England.
The Allotment: SD 7673: area of sinks on the south-east flank of Ingleborough 3.5km north of Norber, England.
Thieves Moss: SD 777731: location in northern Crummackdale, England.
Thwaite Lane: SD 763692: track to the south of Crummackdale, England.
Thwaite Scars: SD 758709: part of Long Scar, England.
Thwaite Top: SD 754692: locality to the south of Thwaite Lane, England.
Upper Wharfedale: the valley of the River Wharfe north of SD 9769, England.
Victoria Cave: SD 838651: excavated cave found approximately 2.5km to the north-east of Settle, England.
Wharfe: SD 783696: hamlet at the south-eastern end of Crummackdale, England.
Wharfedale: SD 0162: valley of the River Wharfe in North Yorkshire, England.
Wharfe Gill Syke: SD 783692: stream to the south of Wharfe, England.
Wharfe Mill-Dam: the locality of this site is unknown, but it may be the same as Mill Bridge (SD 777696), which is located to the south of Wharfe, England.

Whernside: SD 739814: mountain 12km to the north of Norber, England.
Whitbarrow: SD 4584: Carboniferous limestone hill by the Kent Estuary, Cumbria, England.
White Moss: SD 791546: location some 7km to the south-west of Hellifield, England.
White Stone: SD 778705: locality in south-eastern Crummackdale, England.
Winskill: SD 8366: locality some 2km to the north-east of Langcliffe in Ribblesdale, England.
Yealand Hall Allotment: SD4876: locality 2km north-west of the village of Yealand Redmayne, Cumbria, England.
Y Gogarth (The Great Orme): SH 7682: Carboniferous limestone headland immediately to the north-west of Llandudno in Gwynedd, Wales.

APPENDIX 2: GLOSSARY AND ABBREVIATIONS

Appendix 2.1: Glossary

Ablation: the disappearance of glacial snow and ice by melting and evaporation.
Abrasion: the wearing down of relatively cohesive material by bombardment with particles such as sand or pebbles. In an aeolian environment the process is often known as sand-blasting.
'Acid': a general geological term applied to rocks that contain a relatively high percentage of siliceous minerals, very often in the form of quartz e.g. sandstone.
Active layer: the top layer of soil in a permafrost zone subjected to seasonal freezing and thawing, which becomes very mobile during the melt season.
Allochems: the particles or grains other than matrix or cement that comprise a limestone.
Argillaceous: a sedimentary rock composed of clay- and/or silt-sized particles (<0.0625mm).
Arenaceous: a sedimentary rock composed of sand-sized particles (0.0625-2mm).
Authigenic: originating where found.
Azimuth: the horizontal angle measured in degrees in a clockwise direction from north.
'Basic': a general geological term applied to rocks that contain a relatively high percentage of carbonate minerals, very often in the form of calcite e.g. limestone.
Bio-: a prefix denoting that a rock contains skeletal remains.
Birefringence colour: the colour of a mineral when viewed in light with crossed polars (XPL) in a petrographic microscope.
Boulder: a clast with at least one axis greater than 256mm in length.
Bronze Age: an archaeological term dated as lasting from ca.5000 to 3000BP
Brown earths: a wide range of brown soils occurring in humid temperate latitudes, often forming on Pleistocene glacial deposits in Britain.
Calcrete: a brecciated limestone cemented by calc-tufa.
Calcicole: a plant liking lime in the soil.
Calcifuge: a plant disliking lime in the soil.
Carboniferous: a system of the Upper Palaeozoic that lasted from ca.345 to 280Ma.
Chert: a siliceous mineral found in some limestones.
Clast: a piece of fractured mineral or rock or skeleton.
Cockly: a term used by Sweeting (1966) to describe the crinkly appearance of limestone erratics caused by the direct atmospheric action of rainwater.
Conductivity: a measurement of the amount of salts in solution.
Corestone: a rounded boulder produced by subsurface weathering. If the weathered rock (saprolite) is removed by erosion the corestone becomes exposed at the ground surface.
Creep: the imperceptible but continuous movement of material, such as rock debris and soil, down a slope in response to gravity.
Cryosphere: the cold envelope encircling the earth that is partly in contact with the lithosphere, especially at high altitudes and latitudes at the present.
Damp flush: a small area of seepage often marked by a bright green patch of vegetation due to mineral enrichment of the ground water.
Detrital: a term applied to a mineral that has been derived from a pre-existing rock.
Devensian: the last glacial stage of the Pleistocene epoch occurring from ca.120000 to 10000BP. It precedes the Flandrian.
Denudation: the combined processes of weathering and erosion that wear down landscapes.
Discontinuity: a break, such as a bedding plane or joint, within a rock.
Dissolution: the dissolving of limestone in water.
Dolomitised: a limestone where calcium ions have been partially replaced by magnesium ions.
Drift: all unconsolidated rock debris transported from one place to another, usually applied to movement by ice.
Erosion: that part of the processes of denudation whereby the land surface is worn away mechanically such as by the flow of water, ice or wind, or chemically such as by solution.
Erratic: a glacially transported clast.
Erratic provenance: the source area of a glacial clast.
Evapotranspiration: the water lost to the atmosphere by two processes, evaporation and transpiration. Evaporation is the loss from open bodies such as lakes, bare soil and snow cover; transpiration is the loss from living plant surfaces.
Extraclasts: material derived from an older rock that has become incorporated into a younger one.

Fabric: the total of all the textural and structural features of a rock.
Flandrian: the most recent warm (interglacial) stage of the Quaternary. It is roughly equivalent to the Holocene Epoch and commenced approximately ca.10000BP.
Frost action: a weathering process that occurs in the cryosphere during freeze-thaw cycles when water in discontinuities and pores expands upon freezing, thus wedging the rock apart thereby creating landforms such as scree and blockfields (shillow).
Fluvial: formed or produced by the action of rivers.
Glaciokarst: a type of karst modified by glacial erosion.
Gritstone: a coarse sandstone.
Holocene: the most recent geological epoch, which dates from ca.10000BP.
Hydration: the process whereby minerals, mainly silicates and clays, take up water into their structure causing them to swell and to become vulnerable to future break down.
Indicator erratic: a distinctive glacial clast that can be traced back to a relatively well-defined *in situ* bedrock source on the basis of its lithology.
Insolation: the amount of diffuse and direct solar radiation that reaches the earth's surface.
Insolation weathering: the break-up of rocks due to their expansion and contraction as diurnal temperatures rise and fall thus inducing disintegrative stress.
Interception: the amount of precipitation that does not reach the ground and that evaporates directly from plant canopies.
Interfluve: the area of higher ground separating two rivers that flow into the same drainage system.
Interstadial: a single period of warmer climate or retreating ice, as a subdivision of a longer glacial period.
Iron Age: an archaeological term dated as lasting from after ca.3000BP
Karst: a kind of topography characteristic of areas of relatively soluble rock (usually limestone) and mainly underground drainage, which is marked by surface features such as limestone pavements, karren, swallow holes and caverns.
Karstic erosion: the dissolution and removal of soluble rock, primarily limestone, by natural water.
Kamenitza: a generally flat-bottomed depression only tens of centimetres in diameter and a few centimetres deep formed by dissolution upon an exposed limestone surface.
Lacustrine: pertaining to lakes.
Late-glacial: relating to the cold period (ca.14500 to 13000BP) between Devensian deglaciation and Windermere Interstadial amelioration.
Lautrido event: 9-10 hours of -5°C.
Leaching: the removal by downward-percolating soil water of humus, soluble bases and sesquioxides from the a-horizon and their deposition in the underlying b-horizon.
Lithic: a qualifying term denoting that a rock contains extraclasts.
Lithology: a term usually applied to sedimentary rocks, referring to their general characteristics; it generally relates to descriptions based upon hand-specimens and outcrops.
Little Ice Age: A period of cooling from about the middle of the sixteenth and nineteenth centuries.
Loch Lomond Stadial: a term used primarily in Britain to describe a short-lived deterioration (or stadial event), which occurred between 11000 and 10000BP, towards the end of the last glacial period (the Devensian Period). It is often considered to be equivalent to the Younger Dryas event of north-west Europe.
Lower Palaeozoic: the older sub-era of the Palaeozoic Era that includes the Cambrian, Ordovician and Silurian systems and which lasted from ca.600 to 395Ma.
Mafic: a general term used to describe ferro-magnesian minerals; they are normally dark in colour.
Mass movement: the downslope transport of soil and rock material under the influence of gravity.
Matrix: a microcrystalline 'paste' of clay and other minerals including chlorite and quartz.
Mechanical processes: the breakdown of rock into smaller fragments without alteration of the minerals that form it, the rock fracturing along lines of weakness. Such processes are usually associated with weathering e.g. freeze-thaw, but they may also be associated with erosion e.g. plucking by ice.
Mesolithic: an archaeological term used to define the middle division of the Stone Age that is broadly dated from ca.12000 to 10000BP
Micrite: microcrystalline calcite.
Mor: the humus found in poor soils where organic material decays slowly and sometimes incompletely; it has a very acid character.
Mudrock: a type of argillaceous rock consisting of >75% matrix.
Mull: the humus found in good soils where organic material decays rapidly; it has a neutral pH.
Neolithic: an archaeological term used to define the last division of the Stone Age that is broadly dated from ca.10000 to 5000BP.

Orthoquarzite: a quartz-rich sandstone.
Packstone: a limestone with allochems (of which less than 10% are >2mm in diameter) in contact, and with a matrix (usually micrite) present (Dunham, 1962).
Palaeokarst: a karstified surface and the karst features associated with it that have been buried by younger rocks.
Palaeolithic: an archaeological term used to define the first division of the Stone Age that is broadly dated from ca.2.5 million to 12000BP.
Pedestal crown: the upper surface of a pedestal.
Pedestal sidewall: the lateral surface of a pedestal, which may be sloping or vertical.
Pellet: a peloid of faecal origin.
Pelmicrite: a limestone containing peloids in which micrite predominates over sparite (Folk, 1959).
Pelsparite: a limestone containing peloids in which sparite predominates over micrite (Folk, 1959).
Peloid: a spherical, cylindrical or angular grain composed of micrite, but with no internal structure.
Periglacial: a type of climate and the climatically controlled surface features adjacent to ice sheets.
Permeable: a rock is said to be permeable if water can pass through from its upper to its lower surface.
Petrography: the systematic description of rocks in hand specimen and in thin section.
pH: a scale used to denote the acidity (pH <7) or alkalinity (pH >7) of the soil.
Phenoclast: a relatively large fragment found in a sedimentary rock.
Pleistocene: an epoch lasting from about 1.6Ma to 10000BP composed of alternations of great cold (stadials) and relative warmth (interstadials). It is sometimes referred to as the 'Ice Age'.
Pleochroism: a phenomenon restricted to certain coloured minerals in thin section which exhibit a variation in colour when rotated in plane-polarized light.
Pluvial: pertaining to rain.
Poaching: a farming term applying to an area of ground, which is usually located near to gates or feeding troughs, where livestock have trampled away the vegetation and compacted/turned to mud/removed the surface layer of soil.
Podsol: a type of soil formed in cool, humid climatic regions where leaching is a dominant process.
Quaternary: a geological period ranging from ca.1.6Ma to the present. It is divided into two epochs, the Pleistocene and the Holocene.
Regolith: the layer of loose, broken and rocky material mantling the surface of the undecomposed bedrock. It comprises all types of rock waste together with the superficial deposits of, for example, peat, wind-blown sand and glacial drift, in addition to the soil layers.
Röhrenkarren: an upward tapering dissolutional tube
Ruderal: growing in 'waste' places – a weed.
Rudstone: a limestone with allochems (of which more than 10% are >2mm in diameter) in contact, and with a matrix (usually micrite) present (Dunham, 1962).
Rundkarren: a minor limestone solution feature with rounded crests that forms beneath superficial material such as till or soil, or beneath a vegetation cover.
Rupestral: growing among rocks.
Saltation: a mechanism by which sediment is transported by bouncing or hopping along the surface of the ground.
Sink hole: a funnel-shaped depression often several metres or more in diameter in calcareous terrain; it is usually dry and is formed by subterranean collapse of a cave or by surface solution.
Soil-creep: the slow down-slope movement of superficial soil or loose rock which is usually imperceptible except to observations of long duration.
Sparite: clear equant calcite cement.
Spearman's rank test: a non-parametric statistical method of correlation analysis based on ordinal data, which produces a coefficient known as r_s.
Speleothem: a general term for all cave mineral deposits, mostly formed of calcite by precipitation from lime-saturated groundwater.
Stadial: a single period of colder climate or advancing ice, as a subdivision of a longer glacial period.
Stria: a scratch on the surface of an ice-abraded rock produced by the scoring action of a rock fragment frozen into the base of a moving glacier or ice sheet.
Texture: the grain size, grain shape, grain relationship and degree of crystallinity of a rock.
Tufa: a soft, porous chemical sedimentary rock of calcium carbonate formed by evaporation or precipitated by algae and bacteria.
Tundra: treeless plain of the Arctic or Antarctic characterized by low-growing vegetation.
Turbidite: the sediment deposited from a turbidity current, often a greywacke-sandstone.

Turlough: a grassy depression in the surface, sometimes small, sometimes extending over many acres, which during wet weather fill with water through subterranean passages in the rock and empties by the same means.
Unconformity: a major break in sedimentation often caused by denudation.
Wacke: a type of arenaceous rock composed of 15%-75% matrix, the remainder consisting of clastic particles of which quartz is the most common.
Water cycle (also known as the hydrological cycle): the continuous movement of water on, above and below the surface of the earth.
Weathering: that part of the processes of denudation whereby rocks are broken down and decomposed by the action of external agencies such as water, temperature changes and plants; the term does not infer any transportation of the weathered material.
'Wellekarren': a karren feature akin in form to rundkarren that has resulted from wave action at lake margins.
Windermere Interstadial: a term used primarily in Britain to describe a short-lived amelioration (or interstadial event), which occurred between 13000 and 11000BP, towards the end of the last glacial period (the Devensian Stage).

Appendix 2.2: Abbreviations

BGS: British Geological Survey
BP: (years) Before Present (actually meaning years before 1950)
ca.: about
GPS: Global Positioning System
Ka: Thousand years ago
Ma: Million years
OD: Ordnance Datum (~ Mean sea level)
OS: Ordnance Survey
sp.: species

APPENDIX 3: RESULTS

Appendix 3A: Aeolian erosion results

Pedestal number	0m	10m	20m	30m	40m	50m	Mean (m)
N5	7c	6	45	28	37e	13	22.7
N11	3	53	26	6	11	19	19.7
N12	4	4	9	12	21	4	9.0
N14	8	63	51	14	10	18	27.3
N15	5	8	13	6	3	10	7.5
N17	15c	11	7	13	54	4	17.3
N19	10	7	9	63	30g	12c	16.8
N21	14c	3	8	49	11	7	15.3
N25	10	7	64	7	9	59	26.0
N27	13c	46	11	1	19	31	20.2

Key: c = clasts (limestone); e = erratic (greywacke); g = gryke depth

Table 3A.1: Height (cm) of vegetation (and other obstacles) along south-west striking transect lines from selected pedestals at Norber

Cap-rock number	045° azimuth (distance in cm)	225° azimuth (distance in cm)
N5	-43	-64
N11	-52	-17
N12	-21	+17
N14	-23	-32
N15	-24	-23
N17	-41	0
N19	-9	-23
N21	-25	-51
N25	0	-6
N27	+7	-61
Mean	-23.1	-26.1

Table 3A2: Undercut (-) and extension (+) of pedestals 5, 11, 12, 14, 15, 17, 19, 21, 25 and 27 in relation to overlying cap-rocks at Norber to the leeward (045° azimuth) and windward (225° azimuth) of the prevailing wind.

Sample	Granules (>2mm)	Sand (0.63-2mm)	Silt/Clay (<0.63mm)
1	4.93	37.33	57.74
2	11.34	33.88	54.78
3	0.09	42.46	57.45
4	4.0	22.68	73.31
5	2.61	19.32	78.07
Mean	4.59	31.13	64.33

Table 3A.3: Surface soil sieving results (%) from five molehills at Norber

Cap-rock number	045° azimuth (distance in cm)	225° azimuth (distance in cm)
N1	-69	-38
N2	-30	-11
N3	-11	-47
N4	-61	-84
N5	-43	-64
N7	-15	-14
N9	-21	-27
N10	-12	-29
N11	-52	-17
N12	-21	+17
N14	-23	-32
N15	-24	-23
N16	-63	-28
N17	-41	0
N19	-9	-23
N20	-31	-20
N21	-25	-51
N23	-52	-74
N24	-54	0
N25	0	-6
N27	+7	-61
N28	-9	-26
Mean	-29.95	-29.91

There are no readings for pedestals E6, E13, E26 and E29 as it was not possible to measure either one or both undercuts, and for E8 and E22 since their cap-rocks have partially foundered.

Table 3A.4: Undercut (-) and extension (+) of pedestals in relation to overlying cap-rocks at Norber to the leeward (045° azimuth) and windward (225° azimuth) of the prevailing wind.

Appendix 3D: Discontinuity spacing survey results

Pedestal number	Joint spacing (cm) from lateral sidewall to lateral sidewall	Bedding spacing (cm) from pedestal crown to regolith
N1[1]	50/7/50/50/50/7/20/10	14/30/10
N2[1]	17/36	10/25
N3[1]	30/8/9/27	23/7/5
N4[2]	16/11/17/22/20/12/9	26/11/6
N5[2]	4/15v/16/2-13v/24	29/5 (to rock-head)
N6[2]	11/17/12/7/30/17/21	9/11/17
N7[2]	14/2v/13/28v/21/9v/10/20	18/11/23
N8[2]*	23/8v/26/11/7/32	18/15/27
N9[2]	20/7/12/21/27/10/15/10/10/21/9/23/32/17/18/10/14	4/17/12/10
N10[2]	13/20/2v/6	41/28
N11[2]	50/11/21	18
N12[2]	41/91/22/17/12/24	62
N13[2]	7/9/7/11/7/8/19/4/20	26/14/6
N14[2]	27/21/19/16/5/41	22/36
N15[2]	54/21/20	20/12/32
N16[2]	21/7/9/22/16	13/9/8
N17[2]	5/11/16	36
N18[2]	49/70	16/2v/31/6/7
N19[2]	40/43/31/20/2v/55	15/30
N20[2]	22/2v/77	18/12/9/11/11
N21[2]	6/15/6/6v/18/12/2v/20/34	30
N22[2]*	37/2v/4/24	34
N23[2]	20/17	22/7/7
N24[1]	48/19/12/40	17/15/2/45
N25[2]	47/2v/82	46
N26[2]	17/4v/7/8/6v/4/4v/14/39/14	62/5
N27[2]	13/23/7/7/5/14/40/14	46
N28[2]	30/8/9	27
N29[2]		32/21

[1] Pedestal composed of Kilnsey Limestone v: void
[2] Pedestal composed of Cove Limestone
* Strictly speaking this is not a pedestal rock since the cap-rock has partly foundered

Table 3D.1: Pedestal discontinuity spacing of easterly-facing sidewalls at Norber

Pedestal number	Downslope (SE) pedestal height (cm)	Upslope (NW) pedestal height (cm	Mean pedestal height (cm)	Bedding spacing of SE sidewall from pedestal crown to regolith (cm)	Mean bed thickness (cm)
N2[1]	35	33	34	10/25	18
N5[2]	34	35	35	29/5 (to rock-head)	17
N6[2]	37	50	44	9/11/17	12
N7[2]	52	50	51	18/11/23	17
N9[2]	43	47	45	4/17/12/10	11
N10[2]	69	53	61	41/28	35
N11[2]	18	–	–	18	18
N12[2]	62	48	55	62	62
N13[2]	46	43	45	26/14/6	15
N14[2]	58	65	62	22/36	29
N15[2]	64	68	66	20/12/32	18
N16[2]	40	40	40	13/19/8	13
N17[2]	36	51	44	36	36
N18[2]	62	62	62	16/2v/31/6/7	15
N19[2]	45	49	47	15/30	23
N20[2]	61	39	50	18/12/9/11/11	10
N21[2]	30	48	39	30	30
N23[2]	36	20	28	22/7/7	12
N24[1]	79	29	54	17/15/2/45	20
N27[2]	46	–	–	46	46
N28[2]	27	51	44	27	27
N29[2]	53	52	53	32/21	27
N30[2]	40	21	31	40	40

[1] Pedestal composed of Kilnsey Limestone   v: void
[2] Pedestal composed of Cove Limestone

Table 3D.2: Pedestal height and discontinuity spacing at Norber

Appendix 3IF: Induced fracture weathering survey results

	1st	2nd	3rd	4th	5th	Total	Mean	R	MPa
E1	45	30	45	34	30	184	36.8	39.23	43.7
E2	26	38	38	46	44	192	38.4	40.93	47.3
E3	22	55	47	54	29	207	41.4	44.13	52.9
E4	40	40	46	49	46	221	44.2	47.12	58.4
E5	50	48	50	50	48	246	49.2	52.44	69.8
E6	42	40	50	46	55	233	46.6	49.68	63.6
E7	54	60	41	48	44	247	49.4	52.66	70.2
E9	54	51	52	44	49	250	50.0	53.30	71.4
E10	52	51	51	52	44	250	50.0	53.30	71.4
E11	42	51	41	45	46	225	45.0	47.97	60.3
E12	45	43	32	40	42	202	40.4	43.07	51.1
E13	22	22	33	40	32	149	29.8	31.77	31.5
E14	50	42	40	41	45	218	43.6	46.48	57.5
E15	43	42	53	50	50	238	47.6	50.74	66.4
E16	42	44	45	34	35	200	40.0	42.64	50.3
E17	47	46	50	50	41	234	46.8	49.89	64.0
E18	40	33	36	51	47	207	41.4	44.13	53.1
E19	39	46	50	56	45	236	47.2	50.32	64.6
E20	34	46	33	46	33	192	38.4	40.93	47.3
E21	40	43	38	43	39	203	40.6	43.28	51.5
E23	42	52	35	39	53	221	44.2	47.12	58.7
E24	42	50	52	50	45	239	47.8	50.95	66.9
E25	46	48	52	45	46	237	47.4	50.53	66.0
E26	55	49	50	40	41	235	47.0	50.10	65.2

There is no reading for pedestals E8 and E22 since their cap rocks have foundered.

Table 3IF.1: Schmidt Hammer Rebound (R) values on pedestal sidewalls at Norber.

Appendix 3M: Moisture survey results

Gauge	Water (ml)	% re pptn.	Distance from cap-rock lip (cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)	pH
1 (C)	100 (Pptn.)	100	In open – 16	–	332	5.01
2	27	27	Lip – 0	18	012	5.26
3	0	0	Under – 22	36	120	–
4	75	75	Lip – 0	44	148	5.56
5	0	0	Under – 24	18	192	–
6	91	91	Lip – 0	15	225	5.00

(C): Control. Wind: 120° azimuth – gentle breeze.
Table 3M.1: Pedestal rock N5 *(09/09/2003)*

Gauge	Water (ml)	% re pptn.	Distance from cap-rock lip (cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	186 (Pptn.)	100	In open – 68	–	142
2	94	51	Lip – 0	17	142
3	+600*	+323	Under – 9	15	202
4	4	2	Under – 6	10	008
5	+600*	+323	Under – 13	29	068
6	0	0	Under – 44	10	068

(C): Control. Wind: 300° azimuth – gale. *Gauge located under sloping overhang.
+ Gauge full to the brim and overflowing.
Table 3M.2: Pedestal rock N11 *(07/10/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock lip (cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	81(Pptn.)	100	In open – 14	–	234
2	178	220	Under – 7	16	290
3	3	4	Under – 30	1	302
4	29	36	Under – 23	49	050
5	24	30	Under – 47	35	122
6	15	19	Under – 26	15	200

(C): Control. Wind: 305° azimuth – strong breeze.
Table 3M.3: Pedestal rock N12 *(22/09/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock lip (cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	102 (Pptn.)	100	In open – 31	–	190
2	292*	286	Under – 9	13	258
3	3	3	Under – 19	7	306
4	0	0	Under – 17	28	006
5	74	73	Under – 10	32	072
6	3	3	Under – 27	32	144

(C): Control. Wind: 180° azimuth – moderate breeze. *Gauge collected run-off from dipping erratic surface.
Table 3M.4: Pedestal rock N14 *(30/09/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock lip (cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	379 (Pptn.)	100	In open – 34	–	180
2	197	52	Under – 15	42	180
3	+600	+158	Lip – 0	57	088
4	211	57	Under – 12	52	108
5	+600	+158	Under – 13	66	140
6	0	0	Under – 47	47	144

(C): Control. Wind: 200° azimuth – fresh breeze. + Gauge full to the brim and overflowing.
Table 3M.5: Pedestal rock N15 *(21/09/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock lip (cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	76 (Pptn.)	100	In open – 43	–	144
2	166	218	Lip – 0	27	180
3	76	100	Under – 6	32	252
4	22	29	Under – 32	25	336
5	4	5	Under – 42	13	74
6	2	3	Under – 6	28	108

(C): Control. Wind: 355° azimuth – moderate breeze.
Table 3M.6: Pedestal rock N17 *(26/10/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock edge(cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	146 (Pptn.)	100	In open – 41	–	304
2	23	16	Lip – 0	22	360
3	222	152	Lip – 0	19	068
4	0	0	Under – 52	25	130
5	0	0	Under – 27	19	190
6	184	126	Lip – 0	21	276

(C): Control. Wind: 205° azimuth – light breeze.
Table 3M.7: Pedestal rock N19 *(29/10/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock edge(cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1(C)	68 (Pptn.)	100	In open – 50	–	318
2	0	0	Under – 10	31	360
3	6	9	Under – 36	28	044
4	52	76	Under – 31	57	090
5	0	0	Under – 69	19	118
6	78	115	Under – 51	28	232

(C): Control. Wind: 215° azimuth – fresh breeze.
Table 3M.8: Pedestal rock N21 *(02/11/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock edge(cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	135 (Pptn.)	100	In open – 62	–	168
2	10	7	Under – 11	18	168
3	400	296	Lip – 0	25	224
4	218	161	In open – 18 *	–	268
5	63	47	Under – 17	28	328
6	26	19	Lip – 0	23	080

(C): Control. Wind: 270° azimuth – strong breeze. *Pedestal extends beyond the cap rock edge
Table 3M.9: Pedestal rock N25 *(10/10/2003)*

Gauge	Water (ml)	% *re* pptn.	Distance from cap-rock edge(cm)	Distance below cap-rock under-surface (cm)	Azimuth (°)
1 (C)	134 (Pptn.)	100	In open – 75	–	220
2	0	0	Under – 19	7	315
3	0	0	Under – 27	15	045
4	196	146	Lip – 0	60	112
5	34	25	Under – 20	58	160
6	69	51	Under – 20	46	214

(C): Control. Wind: 250° azimuth – light breeze.
Table 3M.10: Pedestal rock N27 *(19/09/2003)*

Pedestal rock	Wet weight (gms)	Dry weight (gms)	Moisture (gms)	% moisture	Distance to cap-rock edge (cm)	Direction facing
N5	227	223	4	1.8	32	N,E,S,W.
N11	250	216	34	13.6	44	NE
N12	803	302	501	62.4	0	SW
N14	494	221	273	55.3	0	S
N15	227	220	7	3.1	38	SE
N17	316	216	100	31.6	24	NE and SE
N19	232	221	11	4.7	52	E
N21	237	223	14	5.9	28	NW and NE
N25*	452	221	231	51.1	0	SW
N27	252	223	29	11.5	20	E

*Covering erosion decantation runnels as seen in Plate 8.4.
Fabric weighed on a Mettler PE24 balance.
Table 3M.11: Fabric moisture retention

Pedestal rock	Decantation runnels present/absent
N1	✓[2]
N2	–
N3	–
N4	–
N5	–
N6	–
N7	✓[1]
N9	–
N10	✓[1]
N11	–
N12	–
N13	–
N14	✓[1]
N15	✓[1]
N16	–
N17	–
N18	–
N19	–
N20	–
N21	–
N23	–
N24	–
N25	✓[1]
N26	–
N27	✓[2]
N28	–
N29	–

There are no results for pedestals N8 and N22 since their cap-rocks have toppled off.
[1]Dissolution runnels on proximal pedestal sidewalls.
[2] Dissolution runnels on interior pedestal sidewalls.
Table 3M.12 Decantation runnels at Norber

Appendix 3pH: pH results

Pedestal rock	Root zone pH	Maximum augur depth pH
N3	6.62	5.89
N4	5.81	7.85
N5	5.83	6.99
N10	5.60	7.18
N12	6.30	6.39
N14	6.08	7.81
N19	5.87	7.18
N24	6.29	7.81
N25	6.00	7.22
N26	5.93	4.66
N28	5.28	6.02
N29	5.08	6.80
N30	5.81	6.58
Mean	5.88	6.8

Table 3pH.1: Norber: Regolith pH from 1m to the west of pedestals

Caprock	pH
N3	7.74
N4	6.49
N5	7.23
N10	7.62
N12	7.44
N14	7.64
N19	7.19
N24	6.77
N25	7.05
N26	7.95
N28	7.02
N29	7.89
N30	8.13
Mean	7.4

Table 3pH.2: Norber: Regolith pH from adjacent to limestone tablets at the regolith/pedestal-sidewall interface

Tablet	pH
31	7.53
32	7.24
33	7.25
35	7.33
36	6.43
40	6.96
41	7.09
42	6.75
54	7.11
56	6.56
57	7.10
60	7.47
Mean	7.1

Table 3pH.3: Oxenber: Regolith pH from adjacent to limestone tablets at the regolith/rock-head interface

Sampling event and site	Water type	Rock type	pH
1 Norber	Precipitation	–	5.6
	Decanted (N5)	Silurian grit	5.3
		"	5.6
		"	5.0
		"	5.4
	Decanted mean	"	5.3
2 Norber	Precipitation	–	4.8
	Decanted (Boulder 1)	Carb. Lst.	7.0
	(Boulder 2)	"	6.8
	Decanted mean	"	6.9
3 Norber	Precipitation	–	7.2
	Decanted (N5)	Silurian grit	6.7
	(N6)	"	5.3
	(N27)	"	6.7
	Decanted mean	"	6.2
	Decanted (N26)	Carb. Lst.	8.1
	(N26)	"	8.0
	(Boulder 1)	"	7.7
	(Boulder 2)	"	7.8
	(Boulder 3)	"	7.7
	Decanted mean	"	7.9
4 Norber	Precipitation	–	6.3
	Decanted (N5)	Silurian grit	5.1
	(N6)	"	5.2
	(N27)	"	5.7
	Decanted mean	"	5.3
	Decanted (N26)	Carb. Lst.	7.1
	(Boulder 1)	"	8.0
	(Boulder 2)	"	7.2
	Decanted mean	"	7.4
5 Norber	Precipitation	–	5.9
	Decanted (N5)	Silurian grit	5.1
	(N6)	"	4.7
	(N27)	"	5.1
	Decanted mean	"	5.0
	Decanted (N26)	Carb. Lst.	7.3
	(Boulder 1)	"	8.0
	(Boulder 2)	"	7.2
	Decanted mean	"	7.5
6 Gearstones	Precipitation	–	5.6
	Decanted (G1)	Carb. Lst.	5.9
	(G2)	"	6.0
	(G3)	"	5.7
	Decanted mean	"	5.9

Table 3pH.4: Precipitation and decantation pH results for Norber and Gearstones

Site	Water type	pH
Scales Moor (SM1)	Precipitation	5.6
	Decanted from clints	6.4
		6.7
		6.4
		6.4
		6.8
	Decanted mean	6.5

Table 3pH.5: Precipitation and clint decantation pH results for Scales Moor

Appendix 3S: Striae survey results

Location 1 : SD 76861 71230

022/102	020/200	024/204	024/204	010/190	028/208	026/206	020/200	026/206	030/210
030/210	022/212								

Location 2 : SD 76864 71039

014/194

Location 3: SD 76810 70903

020/200	016/196	016/196	018/198	016/196	020/200	110/290	010/190	016/196	016/196
006/186	010/190	004/184	014/194	152/332	012/192	160/340	008/188	012/192	014/194
012/192	002/182	030/210	014/194	008/188	022/202	018/198	018/198	012/192	130/310
004/184	006/186	030/210	012/192	008/188	004/184	152/332	014/194	174/354	014/194

Location 4 : SD 76746 71118

026/206	026/206	024/204	032/212	026/206	026/206	020/200	026/206	024/204	028/208

Location 5 : SD 77492 70526

032/212

Location 6 : SD 77090 70652

026/206	026/206	018/198	032/212	024/204	018/198	022/202	022/102	022/202	020/200

Location 7 : SD 76899 70778

034/214	045/225

Location 8 : SD 76762 71153

020/200

Location 9 : SD 78023 70666

028/208

Location 10 : SD 78898 69812

028/208	028/208	034/214	036/216	042/222	038/218	038/218	040/220	040/220

Location 11 : SD 76689 69945

036/216

Location 12: SD 76684 69869

040/220

Location 13: SD 76731 69926

040/220

Table 3S.1: Results of the measurements of the trend of striae for locations 1-13 in degrees azimuth for grid north (magnetic north estimated 5° west of grid north for 1999)

Stria(e) location and grid reference	Circular mean. (°azimuth)	Circular variance	Mean resultant	Circular standard deviation (°)	Maximum % (in 15° azimuth sector)	Number of stria(e) measured	Altitude (m)
1: SD 76861 71230	204°	0.0	1.0	5	91.7 (195/210°)	12	321
2: SD 76864 71039	194°	0.0	1.0	0	100 (180/195°)	1	314
3: SD 76810 70903	189°	0.05	0.95	19	60 (180/195°)	40	316
4: SD 76899 70778	206°	0.0	1.0	3	90 (195/210°)	10	281
5: SD 77090 70652	212°	0.0	1.0	0	100 (210/225°)	1	242
6: SD 77492 70526	203°	0.0	1.0	4	90 (195/210°)	10	242
7: SD 76746 71118	220°	0.0	1.0	6	100 (210/225°)	2	357
8: SD 76762 71153	200°	0.0	1.0	0	100 (195/210°)	1	350
9: SD 78023 70666	208°	0.0	1.0	0	100 (195/210°)	1	270
10: SD 78898 69812	216°	0.0	1.0	5	77.8 (210/225°)	9	274
11: SD 76689 69945	216°	0.0	1.0	0	100 (210/225°)	1	296
12: SD 76684 69869	220°	0.0	1.0	0	100 (210/225°)	1	300
13: SD 76731 69926	220°	0.0	1.0	0	100 (210/225°)	1	299
Survey area	200°	0.04	0.96	16	48.3 (195/210°)	90	--

Table 3S.2: Trend of striae statistics for locations 1-13 *(The circular mean and the maximum % within a 15° azimuth sector are for the direction that Devensian ice moved towards)*

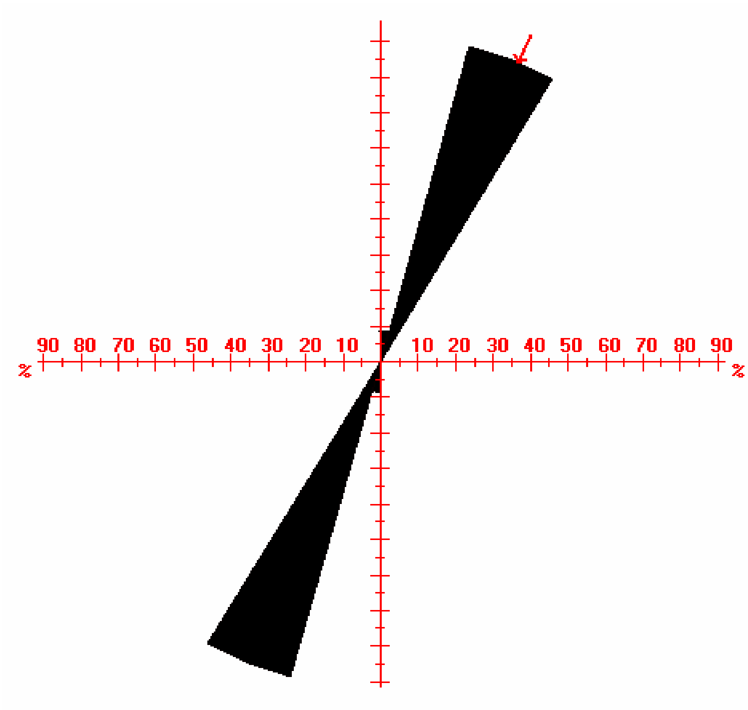


Fig. 3S.1.1: Rose diagram of the trend (Grid North) of 12 striae for Location 1 (sector size 15° azimuth).

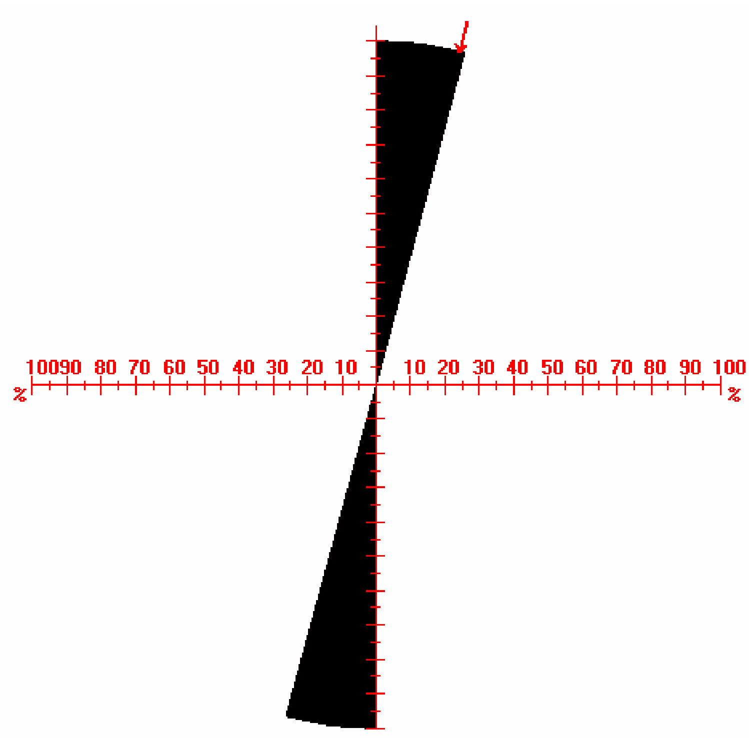


Fig. 3S.1.2: Rose diagram of the trend (Grid North) of 1 stria for Location 2 (sector size 15° azimuth).

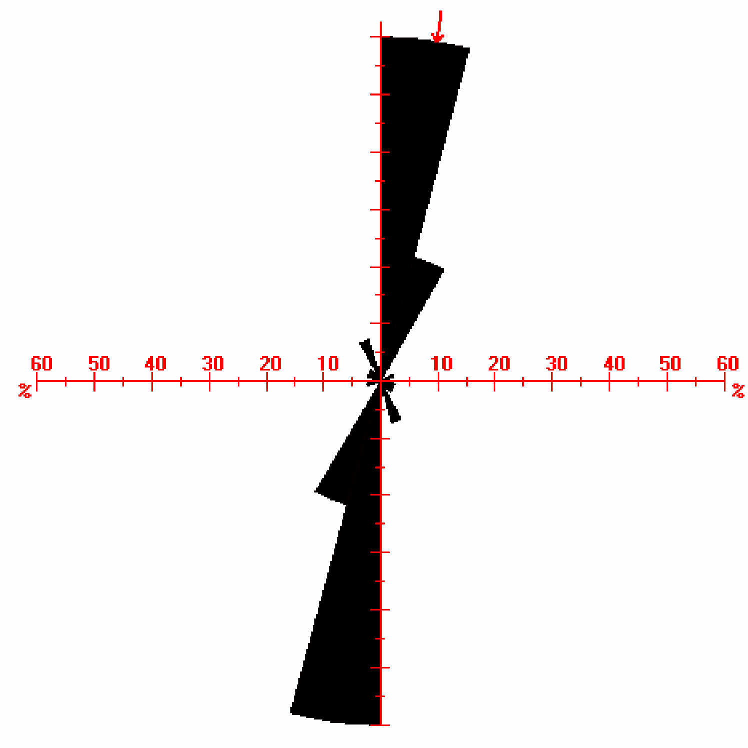


Fig. 3S.1.3: Rose diagram of the trend (Grid North) of 40 striae for Location 3 (sector size 15° azimuth).

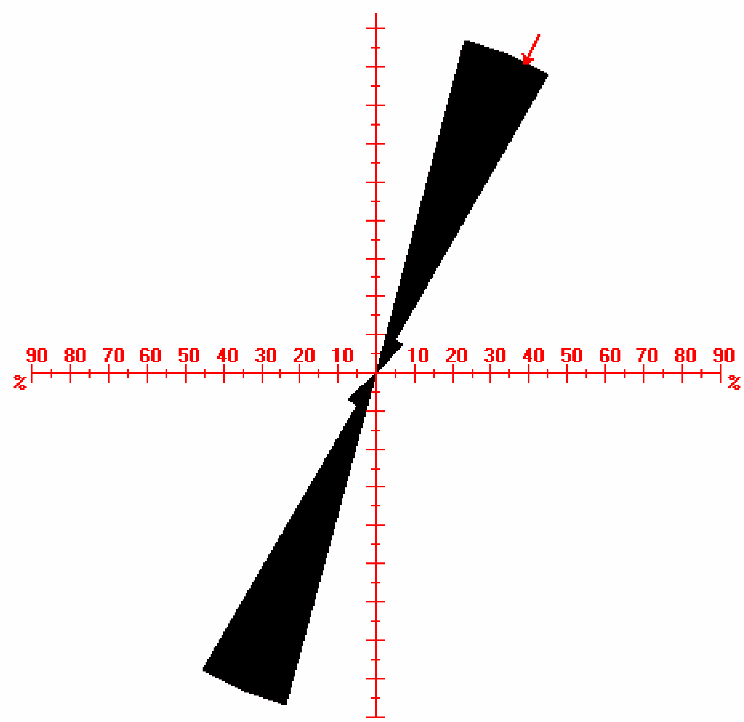


Fig. 3S.1.4: Rose diagram of the trend (Grid North) of 10 striae for Location 4 (sector size 15° azimuth).

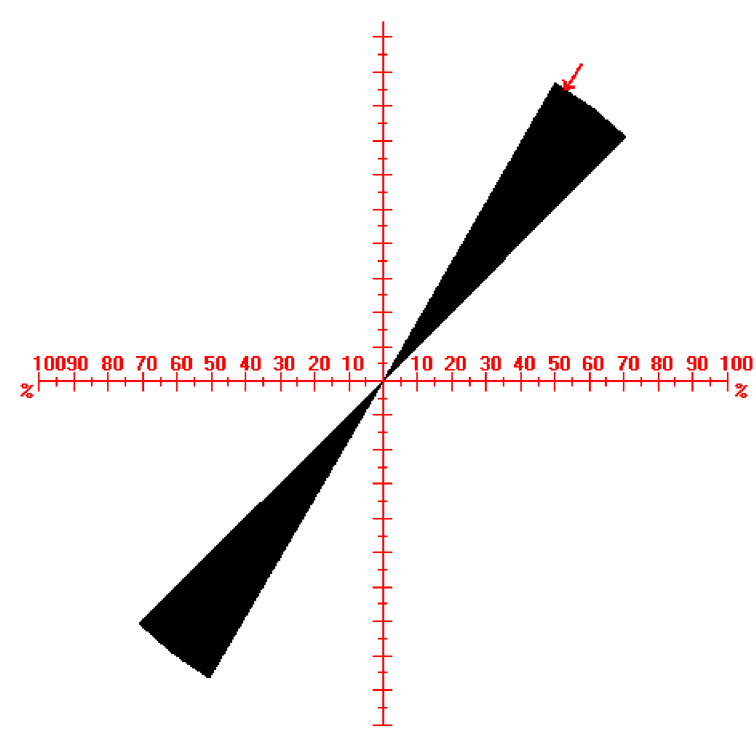


Fig. 3S.1.5: Rose diagram of the trend (Grid North) of 1 stria for Location 5 (sector size 15° azimuth).

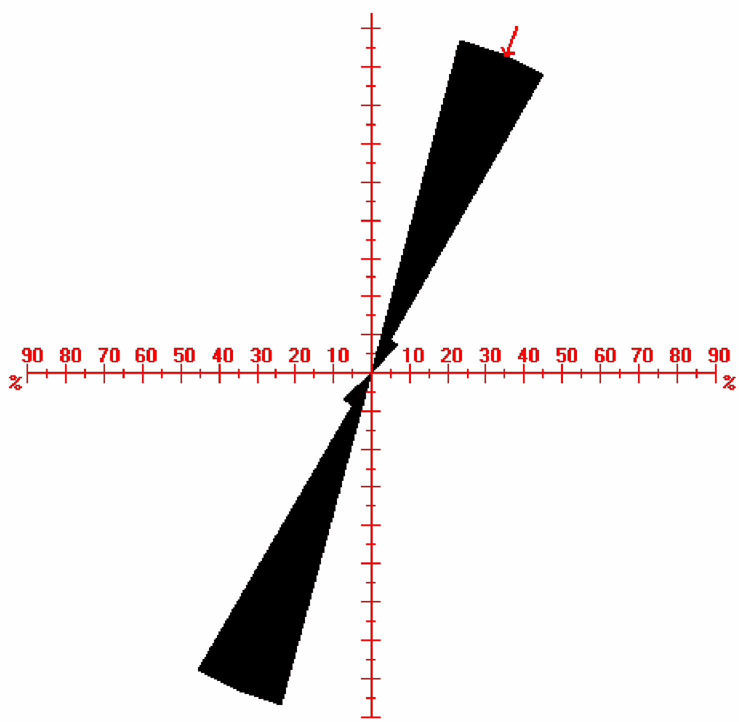


Fig. 3S.1.6: Rose diagram of the trend (Grid North) of 10 striae for Location 6 (sector size 15° azimuth).

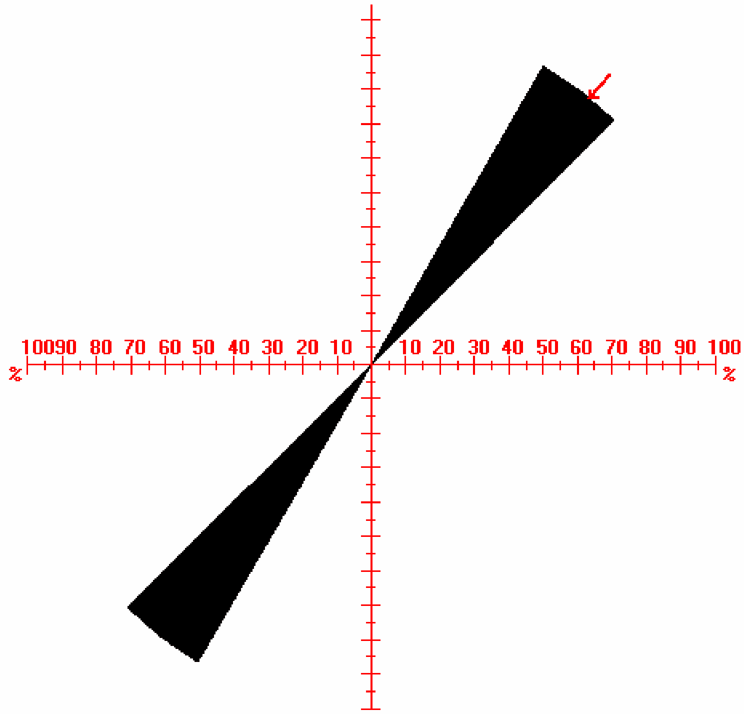


Fig. 3S.1.7: Rose diagram of the trend (Grid North) of 2 striae for Location 7 (sector size 15° azimuth).

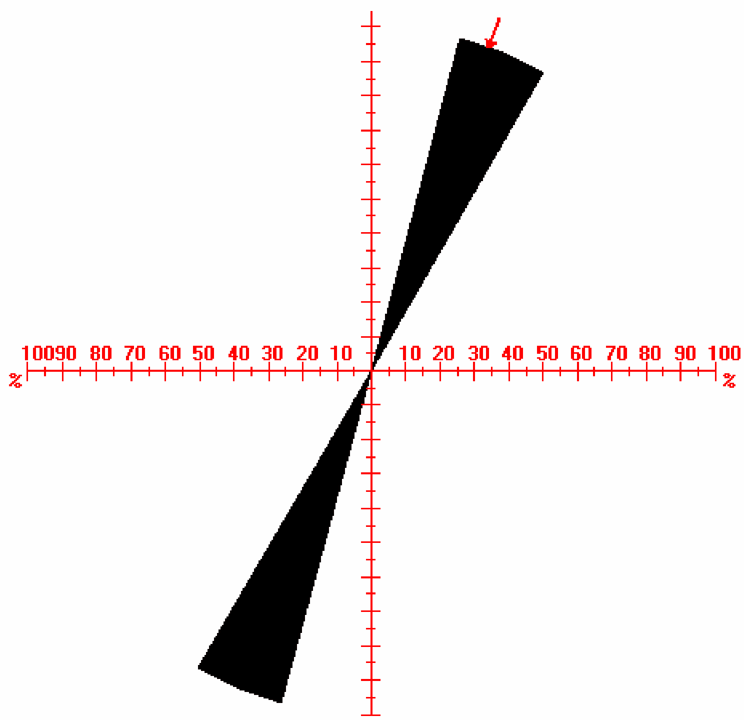


Fig. 3S.1.8: Rose diagram of the trend (Grid North) of 1 stria for Location 8 (sector size 15° azimuth).

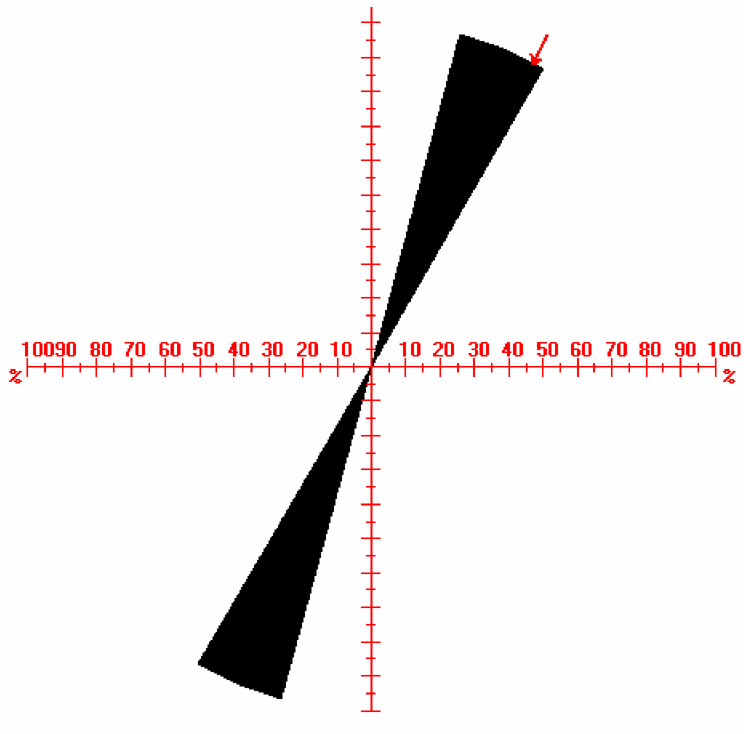


Fig. 3S.1.9: Rose diagram of the trend (Grid North) of 1 stria for Location 9 (sector size 15° azimuth).

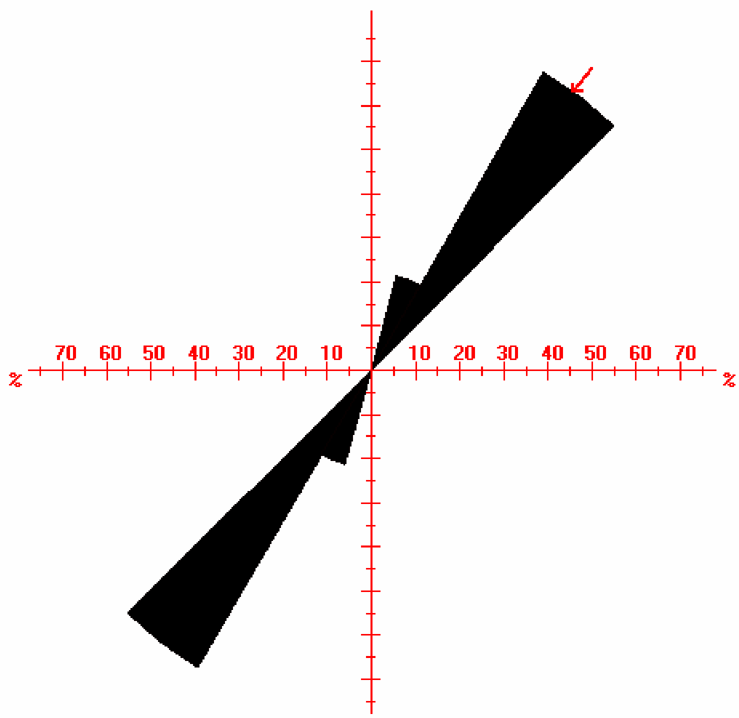


Fig. 3S.1.10: Rose diagram of the trend (Grid North) of 9 striae for Location 70 (sector size 15° azimuth).

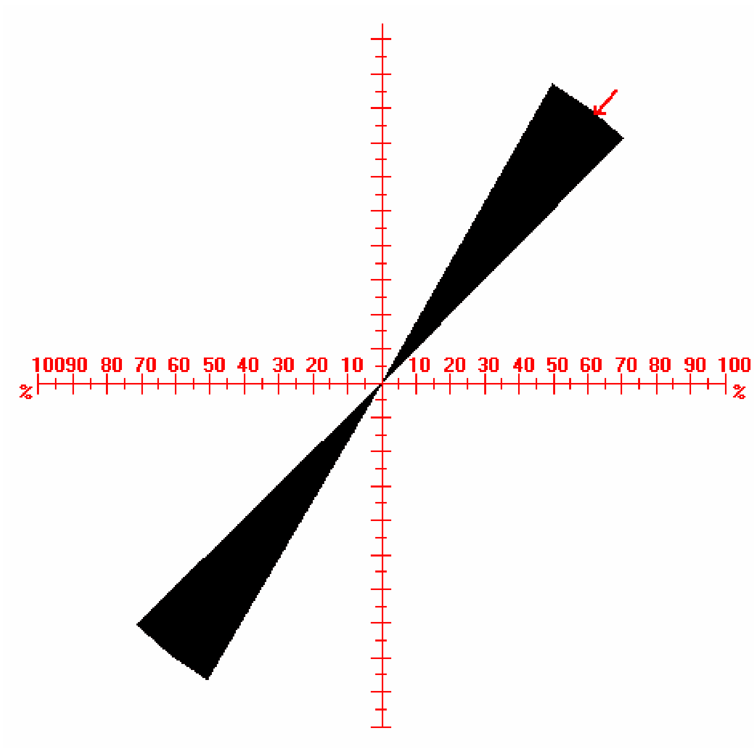


Fig. 3S.1.11: Rose diagram of the trend (Grid North) of 3 striae for locations 11, 12 and 13 (Norber) (sector size 15° azimuth).

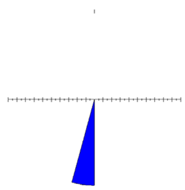


Fig. 3S.2.1: Location 1 ice flow cursor

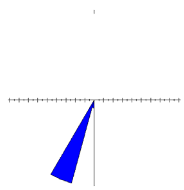


Fig. 3S.2.2: Location 2 ice flow cursor

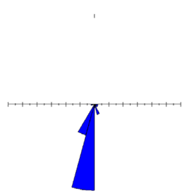


Fig. 3S.2.3: Location 3 ice flow cursor

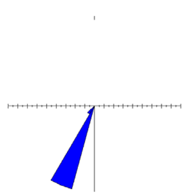


Fig. 3S.2.4: Location 4 ice flow cursor

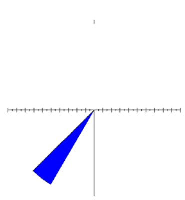


Fig. 3S.2.5: Location 5 ice flow cursor

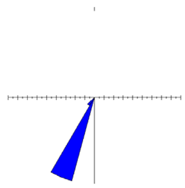


Fig. 3S.2.6: Location 6 ice flow cursor

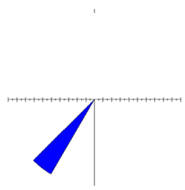


Fig. 3S.2.7: Location 7 ice flow cursor

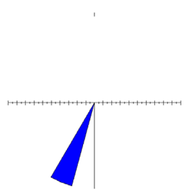


Fig. 3S.2.8: Location 8 ice flow cursor

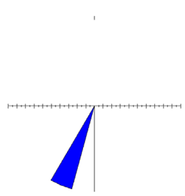


Fig. 3S.2.9: Location 9 ice flow cursor

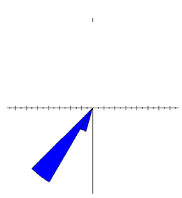


Fig. 3S.2.10: Location 10 ice flow cursor

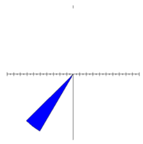


Fig. 3S.2.11: Locations 11, 12 and 13 (Norber) ice flow cursor

Appendix 3T: Tablet survey results

Tablet number	**d (cm)**	**h (cm)**	**Area (cm²)**
1	4.55	0.64	41.67
2	4.54	0.52	39.79
3	4.53	0.41	38.07
4	4.55	0.57	40.67
5	4.53	0.60	40.77
6	4.56	0.50	39.65
7	4.54	0.62	41.22
8	4.54	0.46	38.94
9	4.55	0.42	38.53
10	4.55	0.55	40.38
11	4.54	0.55	40.22
12	4.53	0.60	40.77
13	4.55	0.47	39.24
14	4.53	0.60	40.77
15	4.55	0.46	39.09
16	4.55	0.53	40.10
17	4.53	0.44	38.50
18	4.55	0.53	40.10
19	4.55	0.52	39.95
20	4.53	0.44	38.50
21	4.55	0.44	38.81
22	4.53	0.52	39.63
23	4.54	0.64	41.50
24	4.54	0.50	39.51
25	4.53	0.44	38.50
26	4.52	0.45	39.48
27	4.51	0.40	37.62
28	4.55	0.55	40.38
29	4.54	0.56	40.36
30	4.52	0.54	39.76

Table 3T.1: Norber: Tablet dimensions

Tablet number	Area (cm²)	Pre-burial weight (gm)	Post-burial weight (gm)	Weight loss (gm)	Weight loss (%)	Thickness loss (mm/yr)
1	41.67	25.45412	– (missing)	–	–	–
2	39.79	20.86418	– (not *in situ*)	–	–	–
3	38.07	15.91245	15.90279	0.00966	0.06071	0.00096
4	40.67	23.21384	23.19897	0.01487	0.06406	0.00139
5	40.77	23.96500	23.93617	0.02883	0.12030	0.00268
6	39.65	19.73002	– (not *in situ*)	–	–	–
7	41.22	24.74774	– (missing)	–	–	–
8	38.94	18.88250	– (missing)	–	–	–
9	38.53	16.01257	– (missing)	–	–	–
10	40.38	22.16014	22.11807	0.04207	0.18985	0.00395
11	40.22	21.78244	– (missing)	–	–	–
12	40.77	23.06275	22.99889	0.06386	0.27690	0.00594
13	39.24	18.98164	– (missing)	–	–	–
14	40.77	23.99296	23.97237	0.02059	0.08582	0.00191
15	39.09	18.71214	– (missing)	–	–	–
16	40.10	19.99013	– (missing)	–	–	–
17	38.50	17.13873	– (not *in situ*)	–	–	–
18	40.10	21.41934	– (in two)	–	–	–
19	39.95	20.45314	20.44234	0.00108	0.05280	0.00010
20	38.50	17.86458	– (not *in situ*)	–	–	–
21	38.81	17.33747	– (missing)	–	–	–
22	39.63	20.58788	– (missing)	–	–	–
23	41.50	26.39911	– (missing)	–	–	–
24	39.51	19.38635	19.18877	0.19758	1.01920	0.01895
25	38.50	18.17165	18.10089	0.07076	0.38940	0.00697
26	39.48	17.69633	17.69290	0.00343	0.01938	0.00033
27	37.62	16.09305	– (not *in situ*)	–	–	–
28	40.38	22.87754	22.80054	0.07700	0.33657	0.00723
29	40.36	22.79090	22.78473	0.00617	0.02707	0.00058
30	39.76	22.50950	22.49523	0.01427	0.06340	0.00136
Mean	= 5.8435cm in 14500yrs and 6.045 in 15000yrs					0.00403

Table 3T.2: Norber: Buried tablet survey results

Tablet number (and pedestal number)	Pre-burial weight (gm)	Post-burial weight (gm)	Weight loss (gm)	Weight loss (%)
61 (N1)	25.81248	25.80688	0.00560	0.02169
62 (N25)	28.07274	27.96196	0.11078	0.39462
63 (N5)	47.72028	– (not *in situ*)	–	–
64 (N5)	37.94328	– (missing)	–	–
65 (N21)	37.60205	37.58772	0.01433	0.03811
66 (N24)	25.63945	– (missing)	–	–
67 (N24)	22.33560	– (missing)	–	–
68 (N24)	27.89912	– (missing)	–	–
69 (N5)	62.98329	– (missing)	–	–
70 (N5)	15.79469	– (missing)	–	–
71	27.67907	– (void)	–	–
72 (N6)	51.25937	– (missing)	–	–

Table 3T.3: Norber: Exposed tablet survey results

Tablet number	d (cm)	h (cm)	Area (cm²)
31	4.94	0.38	44.23
32	4.96	0.44	45.50
33	4.96	0.52	46.75
34	4.95	0.48	45.95
35	4.95	0.37	44.24
36	4.96	0.40	44.88
37	4.96	0.53	46.90
38	4.96	0.45	45.66
39	4.96	0.45	45.66
40	4.96	0.42	45.19
41	4.96	0.44	45.50
42	4.96	0.46	45.81
43	4.97	0.53	47.08
44	4.97	0.41	45.20
45	4.97	0.50	46.61
46	Discarded		
47	4.91	0.49	45.43
48	4.94	0.40	44.54
49	4.98	0.47	46.31
50	4.96	0.47	45.97
51	4.94	0.42	44.86
52	4.97	0.43	45.51
53	4.97	0.42	45.36
54	5.00	0.55	47.91
55	4.95	0.42	45.02
56	4.97	0.45	45.83
57	4.94	0.46	45.47
58	4.98	0.40	45.21
59	4.96	0.48	46.12
60	4.97	0.39	44.89

Table 3T.4: Oxenber: Tablet dimensions

Tablet number	**Area (cm²)**	**Pre-burial weight (gm)**	**Post-burial weight (gm)**	**Weight loss (gm)**	**Weight loss (%)**	**Thickness loss (mm/yr)**
31	4.94	17.75408	16.71351	0.04057	0.24251	0.00348
32	4.96	20.44620	20.33881	0.10739	0.52523	0.00894
33	4.96	22.70396	22.59097	0.11299	0.49767	0.00916
34	4.95	20.90096	– (not *in situ*)	–	–	–
35	4.95	16.84496	16.72020	0.12476	0.74064	0.01069
36	4.96	18.40934	18.33894	0.07040	0.38241	0.00594
37	4.96	25.81380	– (missing)	–	–	–
38	4.96	22.00528	– (missing)	–	–	–
39	4.96	20.20216	– (missing)	–	–	–
40	4.96	21.60942	21.47987	0.12955	0.59951	0.01087
41	4.96	21.52893	21.49558	0.03335	0.15491	0.00278
42	4.96	23.03771	22.93559	0.10212	0.44327	0.00845
43	4.97	25.56131	– (missing)	–	–	–
44	4.97	19.60762	– (missing)	–	–	–
45	4.97	22.91837	– (missing)	–	–	–
46	–	–	– (discarded)	–	–	–
47	4.91	22.77880	– (missing)	–	–	–
48	4.94	16.99637	– (missing)	–	–	–
49	4.98	22.47449	– (missing)	–	–	–
50	4.96	21.82237	– (missing)	–	–	–
51	4.94	19.50185	– (not *in situ*)	–	–	–
52	4.97	20.67522	– (not *in situ*)	–	–	–
53	4.97	19.77030	– (not *in situ*)	–	–	–
54	5.00	26.67488	27.57871	0.09617	0.34750	0.00761
55	4.95	20.90863	– (missing)	–	–	–
56	4.97	21.49536	21.38955	0.10581	0.49225	0.00875
57	4.94	22.59558	22.56725	0.02833	0.12538	0.00236
58	4.98	19.60129	– (missing)	–	–	–
59	4.96	21.93473	– (missing)	–	–	–
60	4.97	18.20090	18.15524	0.04566	0.25087	0.00385
MEAN	=10.0195cm in 14500yrs and 10.365cm in 15000yrs					0.00691

Table 3T5: Oxenber: Buried tablet survey results

Appendix 3TL: Transect lines: pedestal rock survey at norber

Transect line	Start grid reference	End grid reference
1	SD 76735 69561	SD 76948 70149
2	SD 76681 69663	SD 76853 70187
3	SD76600 69686	SD 76761 70200
4	SD 76491 69710	SD 76653 70229
5	SD 76372 69577	SD 76547 70211
6	SD 76260 69700	SD 76400 70111
7	SD 76211 69827	SD 76266 70083
8	SD 76137 69948	SD 76171 70081
9	SD 76049 70010	SD 76061 70065

Table 3TL.1: Grid references of transect start and end points

Appendix 3TS: Thin section descriptions

Appendix 3TS.1: Descriptions 1-8: Norber Erratic samples

SAMPLE 1 (Slide 1/1: NE1) (N27)
Location
SD 76746 70010
Field description
A well weathered erratic, especially in its upper parts. It contains two sets of discontinuities, a major set of parallel joints and bedding planes 5-30cm apart cut by a minor set at an angle of 45° that are approximately 60cm apart. It is not possible to deduce the 'way-up'. The erratic is approximately 2x1x1m in size.
Hand description
A homogeneous, mid-grey rock in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amounts of a vitreous mineral that is probably mica. It is well-indurated.
Thin section description
Overall - the thin section is grey-brownish in colour. The rock is poorly sorted and there appears to be a complete range of grain sizes upwards to 1mm. Grain shape varies from angular to sub-rounded, with the former dominant. The majority of grains consist of a colourless mineral surrounded by a 'dirty', pale grey-brown matrix. The distribution of grains and matrix are uneven as a band containing a higher proportion of the colourless mineral (approximately 80% compared to 50% elsewhere) is present.
Mineral 1: PPL. The grain size extends upwards to 0.5mm and the shape is predominantly angular. The mineral is colourless, clean and has no cleavage. It appears to be of low relief.
XPL. The birefringence colours are first order greys and the mineral passes into extinction quickly; undulose grains do not appear to be present. It comprises 55% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 1.0mm, and the shape varies from platy to acicular, with the latter dominant. The mineral is colourless to very pale brown; one cleavage plain occurs in some of the acicular grains. It appears to be of low relief.
XPL. The mineral has bright second order blue, green and pink birefringence colours; extinction is straight. It comprises 5% of the constituents. The mineral is muscovite mica.
Other minerals - there is approximately 2% of isotropic opaque minerals and traces of brown biotite mica, multiple twinned plagioclase feldspar and ice-green chlorite (either individual plates or found as intergrowths with muscovite mica).
Matrix - this comprises 37% of the constituents.
Rock type
The specimen is an immature arenaceous **feldspathic wacke**.

SAMPLE 2 (Slide 2/1: NE2) (N18)
Location
SD 76655 70228
Field description
The erratic has been split into four by frost action. It is massively bedded, as it contains few discontinuities apart from one joint and a set of bedding planes that are approximately 60cm apart. It is not possible to deduce the 'way-up'. The erratic is approximately 2x2x2m in size.
Hand description
A homogeneous mid-grey, well-indurated rock, in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amount of a vitreous mineral that is probably mica.
Thin section description.
Overall - the thin section is grey-brown in colour. The rock is poorly sorted and there appears to be a complete range of grain sizes upwards to and including 0.5mm; grain shape is largely angular. The specimen is not totally homogeneous as a 'lens' containing finer grains of similar composition to the remainder of the section occurs; this is approximately 8x2mm in size. The most abundant mineral is colourless while the matrix is a 'dirty' pale brown colour.
Mineral 1: PPL. The grain size extends upwards to 0.3mm and the shape is largely angular. The mineral is colourless, clean, and has no cleavage. It appears to be of low relief.
XPL. The birefringence colours are first order greys and it passes into extinction quickly; no undulose grains are present. It comprises 50% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.5mm in size and the shape is largely acicular, though laths are also present. The mineral is very pale brown in colour and appears to be of low relief. Acicular grains show alignment.

XPL. Birefringence colours are mainly bright second order pinks and yellows. One set of cleavage planes is visible in some grains. It comprises 10% of the constituents. The mineral is muscovite mica.
Other minerals - there is approximately 1% of isotropic opaque minerals as well as traces of brown biotite mica, of pale green chlorite and of multiple twinned plagioclase feldspar.
Matrix - this comprises 38% of the constituents.
<u>Rock type</u>
The specimen is an immature arenaceous **feldspathic wacke**.

SAMPLE 3 (Slide 3/1: NE3) (N15)
<u>Location</u>
SD 76622 69984
<u>Field description</u>
The erratic has been split into two by frost action. It consists of massive rock. There are only two indistinct and very poorly weathered out discontinuities present, one vertical and the other horizontal. It is not possible to deduce the 'way-up'. The erratic is approximately 4x3x2m in size.
<u>Hand description</u>
A homogeneous, well-indurated, mid-grey coloured rock, in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amount of a vitreous mineral that is probably mica.
<u>Thin section description</u>
Overall - the thin section is grey-brownish in colour. The rock is very poorly sorted and the grain size ranges upwards to 0.5mm. Most of the grains are angular and are of a colourless mineral that are incorporated within a pale brownish matrix.
Mineral 1: PPL. The grain size extends upwards to 0.5mm and most grains are angular. The mineral is colourless, clean and has no cleavage. It appears to be of low relief.
XPL. Birefringence colours are first order greys and it passes into extinction quickly, although some grains are undulose. It comprises 50% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.5mm; most grains are acicular in shape and show alignment. The mineral is colourless to pale brown. One plane of cleavage is visible in some grains and relief appears to be low.
XPL. Birefringence colours are commonly bright second order yellows and pinks, though greens also occur; extinction is straight. It comprises 5% of the constituents. The mineral is muscovite mica.
Other minerals - these include 2% of isotropic opaque minerals and traces of greenish chlorite, of dark brown biotite mica and multiple twinned plagioclase feldspar.
Rock fragments - these are dark-coloured and they consist of fine-grained minerals; they comprise 2% of the constituents.
Matrix - this comprises 40% of the constituents.
<u>Rock type</u>
The specimen is an immature arenaceous **lithic wacke**.

SAMPLE 4 (Slide NE8)
<u>Location</u>
SD 76339 69691
<u>Field description</u>
This erratic is only partly exposed. It has a surface area of approximately 1.3x0.45m. It is not possible to deduce the 'way-up'. No discontinuities are present.
<u>Hand description</u>
A mid-grey rock that is well-indurated. Some individual grains are visible to the naked eye but it is not possible to determine the presence of any minerals apart from small amounts of a vitreous mineral that is probably mica.
<u>Thin section description</u>
Overall - this is mid grey-brown in thin section. The rock is poorly sorted and the grain size ranges upwards to 0.7mm. The grain shape is largely angular. It consists mostly of colourless clastic grains. The rock is homogeneous.
Mineral 1: PPL. This is largely angular and the grain size ranges upwards to 0.4mm. The mineral is colourless, clean and has no cleavage. Relief appears to be low.
XPL. Birefringence colours are low first order greys and extinction occurs quickly. It comprises 40% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.5mm; most grains are acicular in shape and are relatively well aligned. The mineral is colourless to pale brown. One plane of cleavage is visible in some grains and relief appears to be low.
XPL. Birefringence colours are commonly bright second order yellows, pinks and greens. Extinction is straight. It comprises 5% of the constituents. The mineral is muscovite mica.

Other minerals - there is approximately 1% each of brown biotite mica and isotropic opaque minerals, with traces of multiple-twinned plagioclase feldspar, 'twinkling' calcite and green chlorite.
Rock fragments - these are dark in colour, fine grained and comprise a trace of the constituents.
Matrix - this comprises 51% of the constituents.
Rock type
The specimen is an immature arenaceous **feldspathic/lithic wacke**.

SAMPLE 5 (Slide 5/1: NE5)
Location
SD 76549 69775
Field description
A jagged and frost-shattered erratic with many discontinuities up to several centimetres apart; there is a little evidence of cleavage. It is not possible to deduce the 'way-up'. It is approximately 2x1x1m in size.
Hand description
A mid-grey, well-indurated rock, in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amount of a vitreous mineral that is probably mica.
Thin section description
Overall - this is a greyish-brown thin section. The rock is very poorly sorted and the grain size ranges upwards to 0.5mm; the grain shape is largely angular. It consists mostly of colourless clastic grains set in a greyish-brown matrix. The rock is homogeneous.
Mineral 1: PPL. This is largely angular and grain size extends upwards to 0.5mm. The mineral is colourless, clean and has no cleavage. Relief appears to be low.
XPL. Birefringence colours are low first order greys. Extinction normally occurs quickly; it is rarely undulose. It comprises 50% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.3mm; most grains are acicular in shape and show alignment. The mineral is colourless to pale brown; relief appears to be low.
XPL. Birefringence colours are commonly bright second order yellows and pinks, though blues and greens also occur; extinction is straight. It comprises 3% of the constituents. The mineral is muscovite mica.
Other minerals - there is approximately 2% of isotropic opaque minerals and 1% of brown biotite mica together with traces of multiple twinned plagioclase feldspar and greenish chlorite.
Rock fragments - these are dark in colour, fine grained and comprise 2% of the constituents.
Matrix - this comprises 41% of the constituents.
Rock type
The specimen is an immature arenaceous **lithic wacke**.

SAMPLE 6 (Slide NE6)
Location
SD 76460 70139
Field description
No discontinuities are present and it is not possible to deduce the 'way-up'. The erratic is approximately 0.5x0.5x0.5m in size.
Hand description
A mid-grey rock that is well-indurated. Some individual grains are visible to the naked eye but it is not possible to determine the presence of any minerals apart from small amounts of a vitreous mineral that is probably mica.
Thin section description
Overall - this is pale brownish in thin section. The rock is poorly sorted and the grain size ranges upwards to 0.4mm; the grain shape is largely angular. It consists mostly of colourless clastic grains set in a greyish-brown matrix. The rock is homogeneous.
Mineral 1: PPL. This is largely angular and it extends upwards in grain size to 0.2mm. The mineral is colourless, clean and has no cleavage. Relief appears to be low.
XPL. Birefringence colours are low first order greys. Extinction normally occurs quickly; it is rarely undulose. It comprises 45% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.3mm and grains are platy in shape. The mineral is pale to dark brown in colour and some grains are weakly pleochroic; relief appears to be low.
XPL. Birefringence colours are shades of brown and grains close to extinction become mottled. It comprises 3% of the constituents. The mineral is biotite mica.

Other minerals - there is approximately 1% each of colourless muscovite mica and isotropic opaque minerals, together with traces of multiple twinned plagioclase feldspar.
Matrix - this comprises 49% of the constituents.
Rock type
The specimen is an immature arenaceous **feldspathic wacke**.

SAMPLE 7 (Slide NE7)
Location
SD 76121 70023
Field description
A partly exposed erratic with a surface area of approximately 1.1x0.7m. It is not possible to deduce the 'way-up'. No discontinuities are present.
Hand description
A mid-grey rock that is well-indurated. Some individual grains are visible to the naked eye but it is not possible to determine the presence of any minerals apart from small amounts of a vitreous mineral that is probably mica.
Thin section description
Overall - this is pale brown-grey in thin section. The rock is moderately well sorted and the grain size ranges upwards to 0.3mm with 90% of the grains being siltstone size (<0.0625mm) or finer. The grain shape is largely angular. It consists mostly of colourless clastic grains. The rock is homogeneous.
Mineral 1: PPL. This is largely angular and it extends upwards in grain size to 0.0625mm. The mineral is colourless, clean and has no cleavage; relief appears to be low. It includes one grain containing 'needles' of rutile (?).
XPL. Birefringence colours are low first order greys and extinction occurs quickly. It comprises 55% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.3mm and most grains are acicular in shape and they generally show alignment. The mineral is colourless to pale brown. One plane of cleavage is visible in some grains; relief appears to be low.
XPL. Birefringence colours are commonly bright second order yellows and pinks, though azure also occurs. Extinction is straight. It comprises 5% of the constituents. The mineral is muscovite mica.
Other minerals - there is 10% of isotropic opaque minerals and 1% of brown biotite mica.
Matrix - this comprises 29% of the constituents.
Rock type
The specimen is an immature argillaceous **wacke**.

SAMPLE 8 (Slide 4/1: NE4) (N12)
Location
SD 76684 69869
Field description
A well-cleaved erratic, the distance between individual planes being about a centimetre or less; fissility is poor. The erratic also has well-developed discontinuities from 10-70cm apart. It is not possible to deduce the 'way-up'. It is approximately 2x1x2m in size.
Hand description
A mid-grey rock that is well-indurated. Some individual grains are visible to the naked eye but it is not possible to determine the presence of any minerals apart from small amounts of a vitreous mineral that is probably mica.
Thin section description
Overall - this is pale brownish in thin section. The rock is poorly sorted and the grain size ranges upwards to 0.5mm but with 90% of the grains being siltstone size (<0.0625mm) or finer. Clasts coarser than 0.1mm consist largely of an angular colourless mineral, whereas the remainder is composed of a 'dirty' brownish matrix. The specimen is not homogeneous, as there are lenses and bands up to 4mm in width, consisting almost entirely of matrix.
Mineral 1: PPL. This is acicular and colourless to very pale brown. Some grains show one set of cleavage planes. The grain size extends upwards to 0.5mm and relief appears to be low.
-XPL. Birefringence colours vary, but are mainly bright second order yellows, pinks and greens. Extinction is straight. Under XPL it is possible to see that although many of the acicular grains show alignment this is by no means always the case. It comprises 20% of the constituents. The mineral is muscovite mica.
Mineral 2: PPL. Most grains are angular in shape and its grain size extends upwards to 0.2 mm. It is colourless, clean and it has no cleavage. Its relief appears to be low.
XPL. The birefringence colours are first order greys and the mineral moves into extinction quickly. It comprises 15% of the constituents. The mineral is quartz.

Other minerals - there is 1% of isotropic opaque minerals and there are traces of greenish chlorite, brown biotite mica and red augite.
Rock fragments - these are dark in colour and comprise 1% of the constituents.
Matrix - this comprises 62% of the constituents.
Rock type
The specimen is an immature argillaceous **lithic wacke**.

Appendix 3TS.2: Descriptions 9-22: In situ lithostratigraphical unit samples

SAMPLE 9 (Slide 1/7: AF1)
Location
SD 76860 71232 (Striated pavement by Crummack Farm)
Field description
A glacial pavement with 1m high plucked cliffs along its eastern and southern edges. Many striae striking SSW-NNE are present and some are traceable for several metres. There are widely spaced vertical discontinuities and the dip of the beds is 20°/100°.
Hand description
A mid-grey, well-indurated rock, in which some individual grains are just visible to the naked eye. It is not possible to determine mineral content except for a few percent of a vitreous mineral that is probably mica. The rock contains irregularly shaped, elongate voids up to 2mm in length that are randomly orientated.
Thin section description
Overall - the thin section is pale brown in colour. It consists largely of colourless, clastic grains enclosed in a cloudy brown matrix. The rock is very poorly sorted and the grain size ranges upwards to 0.4mm; most grains are angular in shape. It is a homogeneous.
Mineral 1: PPL. Although this mineral varies in grain size upward to 0.3mm most of the grains are 0.1mm or coarser. The grain shape ranges from sub-rounded to angular, with the latter dominant. The mineral is colourless and has no cleavage. It is not possible to determine its relief but it appears to be low.
-XPL. The birefringence colours are first order greys and the mineral normally passes into extinction quickly although some grains are undulose. It comprises 50% of the constituents. The mineral is quartz.
Mineral 2: PPL. The grain size extends upwards to 0.4mm but most grains are 0.05mm or finer. Grain shape varies from laths to acicular, with the latter being more common. It is not possible to determine any cleavage; relief appears to be low.
XPL. The mineral has bright second order blue and pink birefringence colours and straight extinction. Under XPL it is clear that most of the acicular grains are aligned in the same direction. It comprises 5% of the constituents. The mineral is muscovite mica.
Other minerals - there is 2% of isotropic opaque minerals and 1% each of greenish chlorite and dark brown biotite mica. There is also a trace of multiple twinned plagioclase feldspar.
Rock fragments - these are dark in colour, fine grained and comprise 1% of the constituents.
Matrix - this comprises 39% of the constituents.
Rock type
The specimen is an immature arenaceous **lithic wacke.**

SAMPLE 10 (Slide 4/7: AF2)
Location
SD 76902 70788(Striated pavement by the Old Limekiln)
Field description
A glacial pavement with many striae striking SSW-NNE and with a cliff 2-3m in height facing SSW (220° azimuth). The ground to the forefront of the cliff appears to be the source of the erratic train that extends to the SSW. The dip of the strata is 011°/136°**.**
Hand description
A homogeneous, mid-grey rock in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amount of a vitreous mineral that is probably mica. It is well-indurated.
Thin section description
Overall - the thin section is pale grey-brown in colour. It consists largely of colourless clastic grains set in a "dirty" greyish matrix. The rock is poorly sorted and the grain size ranges upward to 0.7mm; most grains are angular in shape. The specimen is homogeneous.
Mineral 1: PPL. The grain size extends upwards to 0.5mm but appears bi-modal, with some 75% of the grains averaging 0.1mm and the remainder averaging 0.25mm or coarser. The shape varies from sub-rounded to angular but is mostly the latter. The mineral is colourless, generally clean and has no cleavage. It is not possible to determine the actual relief, but it appears to be low.
XPL. Birefringence colours are first order greys. Most of the grains pass into extinction quickly, but some are undulose. It comprises 55% of the constituents. The mineral is quartz.

Mineral 2: PPL. The grain size extends upwards to 0.7 mm, but most grains are 0.1mm or finer. The shape varies from laths to acicular, the latter being more common. One set of cleavage planes is visible in some of the coarser grains. Relief is not determinable and it is not pleochroic.

XPL. The mineral shows bright second order orange, pink, green and blue birefringence colours. Extinction is straight, with mottling beforehand. There is alignment of the acicular grains. It comprises 5% of the constituents. The mineral is muscovite mica.

Other minerals - these comprise 5% of isotropic opaque minerals and 1% of greenish chlorite, together with traces of dark brown biotite mica and of feldspar (simple and multiple twinned grains are evident).

Rock fragments –these consist of fine-grained minerals and they comprise 1% of the constituents.

Matrix - this comprises 32% of the constituents.

Rock type

The specimen is an immature arenaceous **lithic wacke.**

SAMPLE 11 (Slide 6/7: AF3)

Location

SD 77091 70650 (Improved field by Crummack Lane)

Field description

A glacial pavement with a well-weathered surface. One stria is present and this has a SSW-NNE strike. The plucked cliffs are 2m in height and face to the west. The dip of the strata is 006°/130°**.**

Hand description

A uniformly grey, well-indurated rock, in which some individual grains are just visible to the naked eye. The only mineral that can be identified has a vitreous lustre; it comprises a low percentage of the total content and is probably mica.

Thin section description

Overall - the thin section is pale grey-brown in colour. It is very poorly sorted and the grain size ranges upwards to 2mm with particles finer than 0.5mm consisting of mineral fragments and those coarser than 0.5mm consisting of lithic fragments. It consists largely of colourless, clastic grains enclosed in a 'dirty' brownish matrix; most grains are angular. The specimen is homogeneous.

Mineral 1: PPL. The grain size extends upwards to 0.5mm and most grains are angular; there is a complete range of shapes from angular to sub-rounded. The mineral is colourless, generally clean and has no cleavage. It is not possible to determine the relief but it appears to be low.

XPL. The mineral has first order grey birefringence colours. It passes into extinction quickly; no undulose grains appear to be present. It comprises 50% of the constituents. The mineral is quartz.

Mineral 2: PPL. The grain size extends upwards to 1mm and the shape is predominantly acicular, though platy grains also occur. One set of cleavage planes is seen in some of the coarser grains. Some grains are weakly pleochroic while the relief appears to be low.

XPL. The birefringence colours are mainly bright second order pinks, but yellows and blues also occur. Under XPL these colours show that the acicular grains are aligned in some areas, but randomly orientated in others. The mineral has a mottled appearance and straight extinction. It comprises 5% of the constituents. The mineral is muscovite mica.

Other minerals – these comprise 5% isotropic opaque minerals and 1% of brown biotite mica together with a trace of multiple twinned plagioclase feldspar.

Rock fragments - some 5% of the constituents consist of rock fragments up to 2mm in grain size. These are darker in colour than the matrix and mineral clasts. The rock fragments are lineated, which suggests a metamorphic origin; they appear to be composed of particles that are of a fine grain size.

Matrix - this comprises approximately 33% of the constituents.

Rock type

The specimen is an immature arenaceous **lithic wacke**.

SAMPLE 12 (Slide AF.Sst: AF4)

Location

SD 76743 71002 (Top south corner of Crummack Farm field)

Field description

A plucked cliff some 2-3m in height that faces to the east that is located just south of the crest of the Crummack Anticline. The dip of bedding is 18°/150° and poor cleavage is evident.

Hand description

A uniformly grey, well-indurated rock, in which most individual grains are not visible to the naked eye, except for a vitreous mineral that is probably mica, this comprising a few percent of the overall content but up to 25% on a bedding plane.

Thin section description

Overall - the thin section is grey-brownish in colour. It is poorly sorted and the grain size ranges upwards to 1.0mm. Most of the grains are angular and are of a colourless mineral that is incorporated within a pale brownish matrix. The sample is homogeneous.

Mineral 1: PPL. The grain size extends upwards to 0.5mm and most grains are angular. The mineral is colourless, clean and has no cleavage. It appears to be of low relief.

XPL. Birefringence colours are first order greys and it passes into extinction quickly, although a few grains are undulose. It comprises 40% of the constituents. The mineral is quartz.

Mineral 2: PPL. The grain size extends upwards to 1.0mm and most grains are acicular in shape and show alignment. The mineral is colourless to pale brown. One plane of cleavage is visible in some grains and relief appears to be low.

XPL. Birefringence colours are commonly bright second order yellows, greens and pinks although blues also occur; extinction is straight. It comprises 10% of the constituents. The mineral is muscovite mica.

Other minerals - these include 3% of isotropic opaque minerals as well as traces of dark brown biotite mica and multiple twinned plagioclase feldspar.

Matrix - this comprises the remainder (46%) of the constituents.

Rock type

The specimen is an immature arenaceous **feldspathic wacke.**

SAMPLE 13 (Slide AF8)

Location

SD 77100 70451 (Nearest exposure to Arthurton *et al.*'s (1988) provenance).

Field description

This is a partially exposed plucked cliff some 0.5 m in height that faces north. No discontinuities are exposed except for one bedding plane which has a dip of 10°/220°.

Hand description

This is a uniformly grey, well-indurated rock, in which individual grains are not visible to the naked eye, except for a vitreous mineral that is probably mica which comprises some 10% of the overall content.

Thin section description

Overall - the thin section is pale brown in colour. It is poorly sorted and the grain size ranges upwards to 1.0mm. Most of the grains are angular and are of a colourless mineral that is incorporated within a pale brownish matrix. It is homogeneous.

Mineral 1: PPL. The grain size extends upwards to 0.1 mm and grains are angular to sub-rounded . The mineral is colourless, clean and has no cleavage. It appears to be of low relief.

XPL. Birefringence colours are first order greys and it passes into extinction quickly. It comprises 40% of the constituents. The mineral is quartz.

Mineral 2: PPL. The grain size extends upwards to 0.2mm and grains are acicular in shape. One cleavage plane is evident in some grains; long-axis alignment is good. The mineral is colourless to pale brown. Relief appears to be low.

XPL. Birefringence colours are commonly bright second order pinks and azure blues; extinction is straight. It comprises 15% of the constituents. The mineral is muscovite mica.

Other minerals - these include 7% of isotropic opaque minerals and 1% of brown biotite mica; traces of green chlorite are also present.

Rock fragment – this consists of a single dark grey and fine-grained (metamorphic?) clast that is 1.0mm in length.

Matrix - this comprises the remainder (36%) of the constituents.

Rock type

The specimen is an immature arenaceous **lithic wacke.**

SAMPLE 14 (Slide AF6)

Location

SD 76973 71018 (In Crummack Farm field by the cattle grid)

Field description

A plucked cliff some 1.5m in height. The rock is massive with a minimum of 1.0m between bedding planes and 25cm between joints. The dip of bedding is 20°/105°.

Hand description

A uniformly grey, well-indurated rock, in which individual grains are not visible to the naked eye, except for a vitreous mineral that is probably mica which comprises a few percent of the overall content.

Thin section description

Overall - the thin section is pale brown in colour. The rock is very poorly sorted and the grain size ranges upwards to 0.3 mm. Most of the grains are angular and are of a colourless mineral that is incorporated within a pale brownish matrix. The grain shape is angular to sub-rounded. The section is homogeneous.

Mineral 1: PPL. The grain size extends upwards to 0.3 mm and although most grains are angular some are also sub-rounded. The mineral is colourless, clean and has no cleavage. It appears to be of low relief.

XPL. Birefringence colours are first order greys and it passes into extinction quickly, although a few grains are undulose. It comprises 60% of the constituents. The mineral is quartz.

Mineral 2: PPL. The grain size extends upwards to 0.1mm and grains are acicular in shape; alignment is poor. The mineral is colourless to pale brown. Relief appears to be low.

XPL. Birefringence colours are commonly bright second order pinks and yellows. Extinction is straight. It comprises 3% of the constituents. The mineral is muscovite mica.

Other minerals - these include 5% of isotropic opaque minerals and 1% of brown biotite mica, and traces of multiple twinned plagioclase feldspar and ice-green chlorite.

Matrix - this comprises the remainder (30%) of the constituents.

Rock type

The specimen is an immature arenaceous **feldspathic wacke.**

SAMPLE 15 (Slide AF7)

Location

SD 76813 70543 (Below the Carboniferous-Lower Palaeozoic unconformity in the Old Limekiln field)

Field description

A well-cleaved rock with an average of 1cm between planes; it is poorly fissile. It is not possible to determine the dip angle or direction due to the poor exposure and good cleavage.

Hand description

A uniformly grey, well-indurated rock, in which individual grains are not visible to the naked eye, except for a vitreous mineral that is probably mica which comprises a few percent of the overall content.

Thin section description

Overall - the thin section is medium brown in colour. The rock is moderately sorted and the grain size ranges upwards to 0.2 mm, though 95% of grains are finer than silt size (<0.0625mm). Most of the grains are angular and are of a colourless mineral that is incorporated within a pale brownish and cloudy matrix. A degree of lineation is present.

Mineral 1: PPL. The grain size extends upwards to 0.0625mm and grain shape ranges from angular to rounded. The mineral is colourless, clean and has no cleavage. It appears to be of low relief.

XPL. Birefringence colours are first order greys and it passes into extinction quickly. It comprises 40% of the constituents. The mineral is quartz.

Mineral 2: PPL. The grain size extends upwards to 0.2mm and grains are acicular in shape; there is a general degree of alignment. The mineral is colourless to pale brown. Relief appears to be low.

XPL. Birefringence colours are commonly bright second order pinks yellows and blues. Extinction is straight. It comprises 3% of the constituents. The mineral is muscovite mica.

Other minerals - these include traces of isotropic opaque minerals and of brown biotite mica.

Matrix - this comprises the remainder (56%) of the constituents.

Rock type

The specimen is an immature argillaceous **wacke.**

SAMPLE 16 (Slide AF.Slt : AF5)

Location

SD 76821 70707 (Siltstone in the Old Limekiln field)

Field description

This is a plucked cliff some 1m in height that is well weathered and partly overgrown. The strata are well bedded and cleaved and dip at a moderate angle to the north.

Hand description

This is a mid-grey coloured rock that is well-indurated and well cleaved, the distance between cleavage planes being some 1-2cms. No minerals are visible to the naked eye.

Thin section description

Overall – this is pale brown in colour. It is moderately sorted as although the grain size ranges upwards to 0.5mm 95% of grains are finer than silt size (<0.0625mm). Clasts coarser than 0.1mm consist of an acicular pale brown mineral, the remainder comprising a colourless, angular mineral and 'dirty' brownish matrix. The specimen is not homogeneous as a band some 4mm in width consisting almost entirely of matrix as well as 'veins' of a dark brown or black mineral up to a few millimetres in length occur.

Mineral 1: PPL. Most grains are angular in shape and its grain size extends upwards to 0.1mm. It is colourless, clean and it has no cleavage. Its relief appears to be low.

XPL. The birefringence colours are first order greys and the mineral moves into extinction quickly. It comprises 30% of the constituents. The mineral is quartz.

Mineral 2: PPL. This is acicular and colourless to very pale brown. Some grains show one set of cleavage planes. The grain size extends upwards to 0.5mm; relief appears to be low.

XPL. Birefringence colours vary, but are mainly bright second order yellows and oranges, though pinks and blues are also present. Extinction is straight. Under XPL it is possible to see that two sets of alignment of the acicular grains occur at right angles to each other. It comprises 20% of the constituents. The mineral is muscovite mica.

Other minerals - there is 5% of isotropic opaque minerals. The dark bands are also isotropic and they anastomise in part; this suggests that they may be composed of an iron compound and that they are of secondary origin.

Matrix - this comprises the remainder (45%) of the constituents.

Rock type

The specimen is an immature argillaceous **wacke.**

SAMPLE 17 (Slide 7/1: AFCB1)

Location

SD 77820 72100 (Capple Bank).

Field description.

An ice-plucked outcrop of well-jointed rock. The dip of bedding is 65°/027°. Discontinuity spacing is moderately wide.

Hand description.

A homogeneous, mid-grey rock in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amount of a vitreous mineral that is probably mica. It is well indurated.

Thin section description.

Overall - the thin section is brownish grey in colour. It is very poorly sorted and the grain size ranges upwards to 0.75mm. It consists largely of angular grains set within a 'dirty' brownish matrix. It is homogeneous.

Mineral 1 - PPL. The grain size extends upwards to 0.5mm and most of the grains are angular. The mineral is clean, colourless and has no obvious cleavage. It appears to be of low relief.

-XPL. The birefringence colours are first order greys. The mineral moves quickly into extinction, though some of the grains are undulose. It comprises 60% of the constituents. The mineral is quartz.

Mineral 2 - PPL. The crystals are mostly acicular in shape and the grain size extends upwards to 0.75 mm. The mineral is colourless to very pale brown. The grains show some degree of alignment.

- XPL. The birefringence colours are bright second order greens, yellows, reds and blues. One set of cleavage planes is visible in planar sections. Extinction is straight. It comprises 10% of the constituents. The mineral is muscovite mica.

Other minerals – these include 5% of isotropic opaque minerals and 1% of brown biotite mica. There are also traces of dark green chlorite and multiple twinned plagioclase feldspar.

Rock fragments – these comprise 5% of the constituents consisting of brown and black clasts, which appear to be present in approximate equal proportions.

Matrix - this comprises 18% of the constituents.

Rock type

The specimen is an immature arenaceous **lithic wacke.**

SAMPLE 18 (SlideAF(CB)2: AFCB2)

Location

SD 77861 72081 (Capple Bank).

Field description.

An ice-plucked outcrop of well-jointed rock. The bedding dip is 59°/023°. Discontinuity spacing is moderately wide.

Hand description.

A homogeneous, mid-grey rock in which some individual grains are just visible to the naked eye. It is not possible to determine any minerals present apart from small amount of a vitreous mineral that is probably mica. It is well indurated.

Thin section description.
Overall - the thin section is pale brownish-grey in colour. It is very poorly sorted and the grain size ranges upwards to 0.8mm. It consists largely of angular grains within a 'dirty' brownish matrix. It is homogeneous.
Mineral 1 - PPL. The grain size extends upwards to 0.4mm and most of the grains are angular. The mineral is clean, colourless and has no obvious cleavage. It appears to be of low relief.
-XPL. The birefringence colours are first order greys. The mineral moves quickly into extinction, though some of the grains are undulose. It comprises 60% of the constituents. The mineral is quartz.
Mineral 2 - PPL. The crystals are mostly acicular in shape and the grain size extends upwards to 0.8 mm. The mineral is colourless to very pale brown. The grains show a good degree of alignment.
- XPL. The birefringence colours are bright second order oranges and reds, though some greens, yellows, and blues are also present. One set of cleavage planes is present in some sections. Extinction is straight, though mottling may occur beforehand. It comprises 8% of the constituents. The mineral is muscovite mica.
Other minerals - there is 5% each of isotropic opaque minerals and of brown biotite mica. Traces of green chlorite and multiple twinned plagioclase feldspar are also present.
Matrix - this comprises 21% of the constituents.
Rock type
The specimen is an immature arenaceous **feldspathic wacke.**

SAMPLE 19 (Slide 6/1: SF1)
Location
SD 77769 71813 (Austwick Beck Head)
Field description
This is a plucked exposure with joints ranging from 5-20cm apart and cleavage from 1-3cm apart. It is poorly fissile. The dip of bedding is 48°/238°.
Hand description.
This is a mid-grey, well-indurated, homogeneous rock, in which individual grains are not visible to the naked eye.
Thin section description.
Overall - this is a brown thin section. The rock is not homogeneous, as two incomplete units of graded bedding are present. The base of the unit consists largely of angular clasts up to 0.5mm in grain size, whereas the top of the unit consists almost entirely of material finer than 0.01mm. The boundary between the two is sharp. Only one mineral, which is transparent and angular, appears to be unaltered, as the remaining minerals are all very 'dirty' and/or speckled in appearance.
Mineral 1: PPL. This is angular in shape, colourless, clean and has no obvious cleavage. It appears to exhibit low relief.
XPL. Birefringence colours are first order greys and the mineral goes into extinction quickly. It comprises some 30% (and thus approximately 15% of the total) of the coarser portion of a graded unit; it is not possible to tell whether it is present in the top of a unit due to the fine grain size. The mineral is quartz.
Other constituents - the remainder of the material is so altered that it is possible to determine only the presence of 1% of isotropic opaque minerals together with traces of rock fragments and muscovite mica.
Matrix – this comprises 83% of the constituents and consists of an amorphous mixture of ‘cloudy’ brown and blackish material.
Rock type
The specimen is an immature **graded wacke**.

SAMPLE 20 (Slide SF2: SF2)
Location
SD 77661 71887 (Austwick Beck Head cave directly below the Carboniferous-Lower Palaeozoic unconformity)
Field description
The exposure forms part of the northern bank of Austwick Beck. Joint spacing is 15-70cm and cleavage spacing is 5-15cm. It is poorly fissile. The dip of bedding is 08°/294°.
Hand description.
A mid-grey, well-indurated rock, in which individual grains are not visible to the naked eye but in which laminations are clearly visible.
Thin section description.
Overall - this is a brown thin section. The rock is not homogeneous as it consists of a number of relatively fine darker brown units and relatively coarse paler brown units. The latter comprise some 20% of the total and individual units range in thickness from 0.3 to >3mm. The junction between the units is either sharp or it may merge to form graded beds; four of the latter are present. A scattering of sub-rounded rock fragments that are 0.1-0.8mm in size, fine grained and which may be of

metamorphic origin are present; these are not evenly distributed occurring most commonly in the fine units. It is not possible to identify any minerals (even at x10 magnification) other than a trace of muscovite mica, which has bright birefringence colours and which is much altered around its edges. The remainder of the constituents (99%) would appear to be composed of matrix.

<u>Rock type</u>

The specimen is an immature **graded mudrock**.

SAMPLE 21 (Slide H: Hm)

<u>Location</u>

SD 77935 71300 (Hunterstye – 100m to the north of King and Wilcockson's (1934) trench)

<u>Field description</u>

This consists of well-cleaved and fissile rock, the cleavage being flat and parallel and with less than 1cm between the planes. The exposure is poor as it is in the bank and bed of a stream, and largely covered in rank vegetation. It was thus not possible to measure either the dip or the strike of the bedding.

<u>Hand description</u>

This is a dark grey to black coloured rock that is slightly friable to the finger. Individual grains are not visible to the naked eye.

<u>Thin section description</u>

Overall - this is a mid to dark brown thin section. It appears to be bi-modal in grain size as it consists largely of a 'dirty' and veined matrix that is finer than silt size (0.0625mm) admixed with a scattering of grains ranging upwards to 0.04mm in size.

Mineral 1: PPL. This is angular in shape, colourless, clean and has no obvious cleavage. It appears to exhibit low relief.

XPL. Birefringence colours are second order greys and the mineral goes into extinction quickly. It comprises some 8% of the constituents. The mineral is quartz.

Other minerals - this includes 1% of isotropic opaque minerals, together with traces of muscovite and biotite micas and of multiple twinned plagioclase feldspar.

Matrix - this comprises the remainder (90%) of the constituents and consists of cloudy unidentifiable minerals admixed with wavy and sub-parallel 'veins' of an opaque mineral.

<u>Rock type</u>

The specimen is an immature **mudrock.**

SAMPLE 22 (Slide CB: CBm)

<u>Location</u>

SD 7794 7130 (Hunterstye – 100m to the east of King and Wilcockson's (1934) trench).

<u>Field description</u>

An ice-plucked outcrop consisting of well-jointed rock that is poorly exposed. It has well-developed cleavage, with planes some 1-2cms apart, and is moderately fissile. The dip of bedding is 45°/202°.

<u>Hand description</u>

A mid-grey coloured rock that is well indurated and homogeneous. Individual grains are not visible to the naked eye.

<u>Thin section description</u>

Overall - this is a mid-brown thin section. It is generally moderately sorted and all grains are silt sized (0.0625mm) or finer. It is not a homogeneous rock as patches of slightly coarser grain size occur.

Mineral 1: PPL. This is angular in shape, colourless, clean and has no obvious cleavage. It appears to exhibit low relief.

XPL. Birefringence colours are second order greys and the mineral goes into extinction quickly. It comprises some 10% of the constituents. The mineral is quartz.

Other minerals - 1% each of isotropic opaque minerals and of ragged muscovite mica is discernable.

Matrix - this comprises the remainder (88%) of the constituents and consists of cloudy unidentifiable material.

<u>Rock type</u>

The specimen is an immature **mudrock**.

Appendix 3TS.3: Descriptions 23-34: Carboniferous Limestone pedestal samples

Limestones are classified on the basis of texture (Folk, 1959) and on composition (Dunham, 1962) (cited in Tucker, 2001).

SAMPLE 23 (Slide 1) (N1)
Location, altitude and limestone
SD 76802 69768: 263m: Kilnsey
Field description
The exposure consists of grey near-horizontal rock. Two bedding planes 30cm apart are present as is a set of vertical sub-planar joints; individual joints are 7-50cm apart. Maximum exposed pedestal height is approximately 54cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface, but pale-grey anastomising veins several centimetres in length and approximately 1mm in width are perceptible in cut section; they give the rock a somewhat marbled appearance. The rock is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5-1mm in diameter, and as sizes range from fines to coarse (<5mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in crystals that occur in the internal portion of some shell fragments denoting that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent allochems/cement/matrix alike. Birefringence colours, which are high first order whites, pinks and blues, are indicative of calcite. Allochems comprise 70% of the rock and they consist of an assemblage of micritic peloids (65%), which include well-rounded pellets and amorphous grains, and a variety of bioclasts (5%). The latter are somewhat micritized and degraded but multiple-chambered foraminifera, massive compound coral (*Syringopora* sp.?) and punctuate brachiopods, together with other unidentifiable skeletal remains, are present. Some bioclast chambers have been infilled with drusy sparite, and micrite envelopes are present on some shell margins. Some 10% of terrigenous extraclasts is also present; these consist of Lower Palaeozoic angular arenaceous greywacke rock fragments as well as traces of allogenic quartz and mica. Sparite cement and micrite matrix respectively comprise 20% and a trace of the rock.
Rock type
The specimen is a **lithic bio-pelsparite** (Folk, 1959) or a **lithic pellet packstone** (Dunham, 1962).

SAMPLE 24 (Slide 3) (N3)
Location, altitude and limestone
SD 76711 69760: 263m: Kilnsey
Field description
The exposure consists of grey horizontally bedded rock. Two bedding planes 7cm apart and a set of vertical joints that are 8->30cm apart are present. Maximum exposed pedestal height is approximately 35cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are mottled steely-grey in colour. No individual grains are visible to the naked eye on either type of surface, but a few pale-grey blotches up to 2mm across are perceptible in cut section. The rock is crystalline in appearance and is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5-1mm in diameter, and as sizes range from fines to coarse (<6mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in some grains indicating that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in calcite cement, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites, pinks and greens, and which are almost entirely confined to the cement, are indicative of calcite. Allochems comprise 50% of the rock and they consist of an assemblage of micritic peloids (45%), which include well-rounded pellets and amorphous grains, and a variety of bioclasts (5%). The latter are often micritized, but multiple-chambered foraminifera (*Plectogyra* sp.?), massive compound coral (*Syringopora* sp.?) and pseudopunctuate brachiopods are present, together with other unidentifiable skeletal remains. Some bioclast chambers have been infilled with drusy sparite, and micrite envelopes are present on some shell margins. Some 30% of terrigenous extraclasts consisting of Lower Palaeozoic arenaceous angular and ragged rock fragments of greywacke and of micaceous siltstone is also present as

are traces of allogenic subangular quartz and mica. The clasts and grains are sometimes partly enveloped by peloids. Sparite cement and micrite matrix respectively comprise 20% and a trace of the rock.
Rock type
The specimen is a **lithic bio-pelsparite** (Folk, 1959) or a **lithic pellet packstone** (Dunham, 1962).

SAMPLE 25 (Slide 5) (N5)
Location, altitude and limestone
SD 76796 70083: 298m: Cove
Field description
The exposure consists of four separate weathered grey horizontally-bedded blocks of rock. A single bedding plane is present as is a set of joints 16>34cm apart. Maximum exposed pedestal height is approximately 38cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface, but a paler grey vein a centimetre in length and less than 1mm in width and a scattering of voids with a yellowish-brown coating (limonite?) up to 1mm across are perceptible in cut section. The rock is crystalline in appearance and is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has very partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5-1mm in diameter, and as sizes range from fines to coarse (<7mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in the coarsely-crystalline cement and in crystals that occur in the internal portion of some shell fragments denoting that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites, pinks, greens and blues, are indicative of calcite. A sutured stylolite, which is stained brown by an opaque residue (limonite?) and which cuts through pelloids and bioclasts alike is also present. Allochems comprise 80% of the rock and they consist of an assemblage of micritic peloids (75%), which include well-rounded pellets and amorphous grains, and a variety of bioclasts (5%). The latter have been micritized and degraded, but multiple-chambered foraminifera, massive compound coral, a solitary corallite, crinoid ossicles and punctuate brachiopods are discernible. Other unidentifiable skeletal remains are also present, and as some consist of drusy sparite it is likely that they were composed initially of aragonite. Micrite envelopes are present on some shell margins. Micrite and sparite cement respectively comprise 15% and 5% of the rock.
Rock type
The specimen is a **bio-pelmicrite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 26 (Slide 7) (N7)
Location, altitude and limestone
SD 76744 69987: 292m: Cove
Field description
The exposure consists of weathered grey horizontally-bedded rock. Two bedding planes 11cm apart and a set of vertical sub-planar joints which are 10-21cm apart are present. Maximum exposed pedestal height is approximately 43cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface, but pale-grey anastomising veins several centimetres in length and approximately 1mm in width, and several voids up to 1mm across are perceptible in cut section. The rock is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5-1mm in diameter, and as sizes range from fines to coarse (<4mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in some shell fragments indicating that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites, pinks, greens and blues, are indicative of calcite. Allochems comprise 70% of the rock and they consist of an assemblage of micritic peloids (65%), which include well-rounded pellets and amorphous grains, and a variety of bioclast remains (5%). The latter have been largely altered to micrite but multiple-chambered foraminifera, the wall of a solitary coral, an articulate brachiopod and a gastropod are discernible. Other unidentifiable skeletal remains, some of which were almost certainly composed initially of aragonite since they now consist of drusy sparite, are also

present. Micrite envelopes occur on some shell margins. Sparite cement and micrite matrix respectively comprise 20% and 10% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 27 (Slide 13) (N13)
Location, altitude and limestone
SD 76519 69771: 286m: Cove
Field description
The exposure consists of weathered grey horizontally-bedded rock. Two bedding planes 14-cm apart and a set of vertical joints 4->20cm apart are present. Maximum exposed pedestal height is approximately 42cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface, but pale-grey anastomising veins several centimetres in length and approximately 0.5mm in width, and a few voids that are coincident with the veins are perceptible in cut section. The rock is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5-1mm in diameter, and as sizes range from fines to coarse (<4mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in some grains indicating that they are composed of calcite. Rhombohedral cleavage is also present; this is almost entirely confined to the cement but sometimes passes into pellets indicating that some post-depositional recrystallization has taken place. Birefringence colours, which are high first order whites, greens and blues, are indicative of calcite. Allochems comprise 80% of the rock and they consist of an assemblage of micritic peloids (75%), which include well-rounded pellets and amorphous grains, and a variety of bioclast remains (5%). The latter have been largely altered to micrite and only multiple-chambered foraminifera, punctuate brachiopod shells, the odd crinoid plate and a massive compound coral can be identified with certainty. An occasional bioclast chamber has been infilled with drusy sparite, and micrite envelopes are present on some shell margins. Sparite cement and micrite matrix respectively comprise 15% and 5% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 28 (Slide 19) (N19)
Location, altitude and limestone
SD 76660 70203: 312m: Cove
Field description
The exposure consists of weathered grey horizontally-bedded rock. One bedding plane and a set of vertical joints 20->55cm apart are present. Maximum exposed pedestal height is approximately 7cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface and the rock is homogeneous in cut section apart from the presence of a few voids approximately 0.5mm in diameter. The rock is crystalline and well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone..
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5mm in diameter, and although sizes range from fine to coarse (<3mm) the rock is moderately well-sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in some shell fragments indicating that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites and blues, are indicative of calcite. Allochems comprise 85% of the rock and consist almost entirely (83%) of an assemblage of micritic peloids, which include well-rounded pellets and amorphous grains, together with an occasional intraclast. A limited number of micritized and degraded bioclasts (2%) composed of multiple-chambered foraminifera, massive compound coral, crinoid plates and unidentifiable skeletal remains are also present. An occasional bioclast chamber has been infilled with drusy calcite while micrite envelopes are present on some shell margins. Sparite cement and micrite matrix respectively comprise 12% and 3% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 29 (Slide 21) (N21)
Location, altitude and limestone
SD 76646 70111: 304m: Cove
Field description
The exposure consists of grey horizontally-bedded rock. Bedding is absent but a set of vertical joints that are 6-24cm apart are present. Maximum exposed pedestal height is approximately 45cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface. The rock is heterogeneous as pale-grey anastomising veins several centimetres in length and approximately 0.5mm in width are perceptible in cut section; this imparts a 'crazy-paving' appearance to the rock. The rock is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of coarse grain size as the majority of grains are >2mm in diameter, and as sizes range from fines to coarse (<6mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in crystals that occur in the internal portion of some shell fragments denoting that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites, oranges and blues, are indicative of calcite. Allochems comprise 60% of the rock and they consist of a variety of bioclast remains (40%) and an assemblage of micritic peloids (20%), which include well-rounded pellets and amorphous grains. The fossil remains have been only partly altered to micrite, and multiple-chambered foraminifera, punctuate and pseudopunctate brachiopod shells, a solitary coral (*Palaeosmilia* sp.?) (septa and dissepiments are discernible) and a massive compound coral (*Lithostrotian* sp.?) can be identified. The presence of replacement drusy sparite in some shells indicates that mollusc shells may also be present. Micrite envelopes are present on some shell margins. Sparite cement and micrite matrix respectively comprise 35% and 5% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **bioclastic rudstone** (Dunham, 1962).

SAMPLE 30 (Slide 23) (N23)
Location, altitude and limestone
SD 76577 70035: 310m: Cove
Field description
The exposure consists of grey horizontally-bedded rock. Two bedding planes 10cm apart and a vertical joint are present. Maximum exposed pedestal height is approximately 42cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface. The rock is heterogeneous as a few pale-grey anastomising veins several centimetres in length and which are approximately 0.5mm in width are perceptible in cut section. The rock is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5mm in diameter, and as sizes range from fines to coarse (<3mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in some shell fragments indicating that they are composed of calcite. Rhombohedral cleavage is also present; this is largely confined to the cement but it also passes into pellets indicating that some post-depositional recrystallization has taken place. Birefringence colours, which are high first order whites and blues, are indicative of calcite. Allochems comprise 65% of the rock and they consist of an assemblage of micritic peloids (60%), which include well-rounded pellets and amorphous grains, and a variety of bioclast remains (5%). The latter have undergone a degree of micritization but multiple-chambered foraminifera, punctuate and pseudopunctuate brachiopod shells and a massive compound coral (*Lithostrotian* sp.?) can be identified. Micrite envelopes are present on some shell margins. Sparite cement and micrite matrix respectively comprise 30% and 5% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 31 (Slide 25) (N25)
Location, altitude and limestone
SD 76800 69934: 285m: Cove
Field description
The exposure consists of weathered grey horizontally-bedded rock. One bedding plane and a vertical joint are present. Maximum exposed pedestal height is approximately 49cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface. The rock is homogeneous and is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are approximately 0.5mm in diameter, and as sizes range from fines to coarse (<4mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in crystals that occur in the internal portion of some shell fragments denoting that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites and blues, are indicative of calcite. Allochems comprise 75% of the rock. They consist of an assemblage of micritic peloids (70%), which include well-rounded pellets and amorphous grains, and a variety of bioclast remains (5%). The latter have been mostly altered to micrite and only multiple-chambered foraminifera, punctuate brachiopod shells and a massive compound coral can be identified with certainty. Micrite envelopes are present on some shell margins. Sparite cement and micrite matrix respectively comprise 20% and 5% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 32 (Slide 26) (N26)
Location, altitude and limestone
SD 7677 6989: 287m: Cove
Field description
The exposure consists of weathered grey horizontally-bedded rock. One bedding plane and a set of joints 7-39cm apart are present. Maximum exposed pedestal height is approximately 67cm.
Hand description
Weathered surfaces are creamy-grey but cut-sections are steely-grey in colour. No individual grains are visible to the naked eye on either type of surface. The rock is heterogeneous as a few pale-grey sub-parallel veins several centimetres in length and approximately 0.5mm in width are perceptible in cut section. The rock is well-indurated. It effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.
Thin section description
The section is pale brown in colour in both PPL and XPL and it has partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are 0.5-1mm in size, and as sizes range from fines to coarse (<4mm) the rock is poorly sorted. Rotating the polarizer in PPL produces a 'twinkling' effect in crystalline cement and in crystals that occur in the internal portion of some shell fragments denoting that they are composed of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is often evident in the calcite, occasionally passes into adjacent pelloids. Birefringence colours, which are high first order whites and blues, are indicative of calcite. Allochems comprise 80% of the rock. They consist of an assemblage of micritic peloids (70%), which include well-rounded pellets and amorphous grains, and a variety of bioclasts (10%). The latter are not well-preserved as they have been largely altered to micrite and/or partially recrystallized. Few remains can thus be identified with certainty, although crinoid plates together with fragments of possible pseudopunctate brachiopods shells and a solitary rugose coral are discernible. Micrite envelopes are present on some shell margins. Sparite cement and micrite matrix respectively comprise 15% and 5% of the rock.
Rock type
The specimen is a **bio-pelsparite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

SAMPLE 33 (Slide 29) (From an *in situ* exposure 4m to the east of N31)
Location, altitude and limestone
SD 76045 70048: 346m: Gordale
Field description

The exposure consists of weathered grey rock. Bedding is absent (nearby exposures are horizontally-bedded) but a single joint is present. Maximum exposed pedestal height is approximately 13cm.

Hand description

Weathered surfaces and cut-sections are pale grey in colour. The rock is well-indurated and has a porcellaneous appearance; some vitreous crystals are visible to the naked eye on fresh surfaces. It is heterogeneous as a white anastomising veins several centimetres in length and which are less than 0.5mm in width are perceptible in cut section. The rock effervesces strongly when 0.5M hydrochloric acid is applied revealing that calcite is present and that the rock is limestone.

Thin section description

The section is pale grey-brown in colour in both PPL and XPL and it has very partially been altered to neomorphic spar. The rock is of medium grain size as the majority of grains are 0.1-0.5mm in size, and as sizes range from fines to coarse (<2mm) the rock is poorly sorted.. The rock is heterogeneous as a pair of pale-grey sub-parallel veins about a centimetre in length and approximately 0.1mm in width is perceptible in cut section. Some irregularly-shaped voids approximately 0.5mm in diameter are also present; these are lined with an opaque mineral that is probably limonite. Rotating the polarizer in PPL produces a 'twinkling' effect in the finely-crystalline cement and in crystals that occur in the internal portion of some shell fragments indicating that they are composed of calcite. Birefringence colours are mainly high first order whites but infrequent blues also occur; they are also indicative of calcite. Some post-depositional recrystallization has taken place since rhombohedral cleavage, which is sometimes evident in the calcite, occasionally passes into adjacent pelloids. Allochems comprise 80% of the rock. They consist of an assemblage of peloids (75%), most of which are amorphous in shape and much micritized, an occasional well-rounded pellet, and a variety of bioclasts (5%). Most of he latter are not well-preserved as they have been largely altered to micrite, but complete foraminifera shells, pentameroid and spherical crinoid plates, and brachiopod/bivalve skeletal débris are discernible. Micrite envelopes are very occasionally present on some shell margins. Micrite matrix and sparite cement respectively comprise 15% and 5% of the rock.

Rock type

The specimen is a **bio-pelmicrite** (Folk, 1959) or a **pellet packstone** (Dunham, 1962).

APPENDIX 3: RESULTS

Appendix 3TS.4: Descriptions of the Kilnsey, Cove and Gordale limestones (after Arthurton et al., 1988: 26 (i), 29 (ii) and 32, and 30 (iii))

(i) KILNSEY LIMESTONE (KILNSEY FORMATION)
"The Kilnsey Limestone consists of well bedded, thin and thick beds of medium-dark to medium-light grey limestones, with characteristic lithologies being fine to coarse calcarenite packstones and grainstones. The limestones are dominantly bioclastic, common grains being crinoid plates, algae (*Koninckopora*, kamenids and aoujgalids) and shell fragments. Peloids, generally micritised bioclasts, are common throughout. The passage into the overlying Malham Formation is gradational and taken at the change from darker to paler lithologies."

(ii) COVE LIMESTONE (MALHAM FORMATION)
"Petrologically the Cove Limestone consists of medium and coarse calcarenites, bioclastic and peloidal packstones and grainstones. These are generally unevenly grained. The dominant bioclasts are crinoid fragments, foraminifera, algae (particularly *Koninckopora* but with kamenids also present), and brachiopod fragments. Peloids (interpreted as micritised bioclasts) are ubiquitous." "In the Moughton-Long Scar area grainstone is more abundant."

(iii) GORDALE LIMESTONE (MALHAM FORMATION)
"The member is a well bedded (varying from thick- to very-thick bedded), medium-light grey to very light grey limestone in which lithological alternations are conspicuous. Petrologically the limestones consist of fine to medium, and some coarse, calcarenites bioclastic packstones, wackestones and grainstones. Principal grains in these are foraminifera, algae, ostracods and peloids. Kamenids dominate the algae, and at some levels are the most dominant grains, *Koninckopora* being less abundant than in the underlying Cove Limestone. Partial or complete matrix neomorphism to spar is almost ubiquitous in the packstones and wackestones."

Appendix 3V: Vegetation survey results

Appendix 3V.1: Norber

Transect 1: Rough grassland that slopes a few degrees to the north-east with a scattering of erratics and with a limited exposure of Malham Formation limestone.

Date	Start	End
13-06-2003	SD 76546 69941	SD 76742 70149

Species present:

Quadrat 1: *Cerastium fontanum* (Common mouse-ear chickweed)
Potentilla erecta (Common tormentil)
Crataegus monogyna (Common hawthorn)
Plantago lanceolata (Ribwort plantain)
Galium sterneri (Sterneri's bedstraw)
Carex flacca (Glaucous sedge)
Festuca ovina (Sheep's fescue)
Briza media (Common quaking grass)

Quadrat 2: *Galium sterneri* (Sterneri's bedstraw)
Festuca ovina (Sheep's fescue)

Quadrat 3: *Galium sterneri* (Sterneri's bedstraw)
Festuca ovina (Sheep's fescue)

Quadrat 4: *Galium sterneri* (Sterneri's bedstraw)
Carex flacca (Glaucous sedge)
Festuca ovina (Sheep's fescue)

Quadrat 5: *Potentilla erecta* (Common tormentil)
Galium sterneri (Sterneri's bedstraw)
Hieracium sp. (Hawkweed)
Festuca ovina (Sheep's fescue)

Quadrat 6: *Polygala vulgaris* (Common milkwort)
Lotus corniculatus (Bird's-foot trefoil)
Thymus praecox (Wild thyme)
Festuca ovina (Sheep's fescue)
Briza media (Common quaking grass)

Quadrat 7: *Lotus corniculatus* (Bird's-foot trefoil)
Potentilla erecta (Common tormentil)
Galium sterneri (Sterneri's bedstraw)
Carex flacca (Glaucous sedge)
Festuca ovina (Sheep's fescue)
Briza media (Common quaking grass)

Quadrat 8: *Minuartia verna* (Vernal sandwort)
Lotus corniculatus (Bird's-foot trefoil)
Galium sterneri (Sterneri's bedstraw)
Hieracium sp. (Hawkweed)
Thymus praecox (Wild thyme)
Briza media (Common quaking grass)
Festuca ovina (Sheep's fescue)

Quadrat 9: *Potentilla erecta* (Common tormentil)
Galium sterneri (Sterneri's bedstraw)
Festuca ovina (Sheep's fescue)

Quadrat 10: *Minuartia verna* (Vernal sandwort)
Potentilla erecta (Common tormentil)
Vaccinium myrtillus (Bilberry)
Galium sterneri (Sterneri's bedstraw)
Carex flacca (Glaucous sedge)
Festuca ovina (Sheep's fescue)

Quadrat 11: *Cerastium semidecandrum* (Little Mouse-ear chickweed)
Festuca ovina (Sheep's Fescue)

Quadrat 12: *Ranunculus acris* (Meadow buttercup)
Cerastium semidecandrum (Little Mouse-ear chickweed)
Urtica dioica (Stinging nettle)
Veronica chamaedrys (Germander speedwell)
Galium sterneri (Sterneri's bedstraw)
Festuca ovina (Sheep's fescue)

Transect 2: Intermittent limestone pavement of the Malham Formation. The clints, which have degraded rundkarren on their surface, reach 1m² in area while grykes may attain 1m in depth.

Date	**Start**	**End**
13-06-2003	SD 76633 70024	SD 76499 69869

Species present:

Quadrat 1: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Geranium robertianum (Herb Robert)
Oxalis acetosella (Wood sorrel)
Mycelis muralis (Wall lettuce)

Quadrat 2: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Geranium robertianum (Herb Robert)
Oxalis acetosella (Wood sorrel)
Hedera helix (Ivy)
Sanicula europea (Sanicle)
Mycelis muralis (Wall lettuce)

Quadrat 3: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Geranium robertianum (Herb Robert)

Quadrat 4: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Geranium robertianum (Herb Robert)

Cratagus monogyna (Common hawthorn)
Thymus praecox (Wild thyme)

Quadrat 5: *Dryopteris filix-mas* (Male fern)
Asplenium scolopendrium (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Anemone nemorosa (Wood anemone)
Geranium robertianum (Herb Robert)
Fragaria vesca (Wild strawberry)
Mercuralis perennis (Dog's mercury)
Mycelis muralis (Wall lettuce)

Quadrat 6: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Geranium robertianum (Herb Robert)
Oxalis acetosella (Wood sorrel)

Quadrat 7: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Anemone nemorosa (Wood anemone)
Cratagus monogyna (Common hawthorn)
Fraxinus excelsior (Ash)
Thymus praecox (Wild thyme)

Quadrat 8: *Asplenium scolopendrium* (Hart's tongue fern)
Oxalis acetosella (Wood sorrel)
Thymus praecox (Wild thyme)
Mycelis muralis (Wall lettuce)

Quadrat 9: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Geranium robertianum (Herb Robert)
Oxalis acetosella (Wood sorrel)
Mercuralis perennis (Dog's mercury)

Quadrat 10: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Cratagus monogyna (Common hawthorn)
Mercuralis perennis (Dog's mercury)

Quadrat 11: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Geranium robertianum (Herb Robert)
Mercuralis perennis (Dog's mercury)

Quadrat 12: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Geranium robertianum (Herb Robert)
Cratagus monogyna (Common hawthorn)
Mercuralis perennis (Dog's mercury)
Mycelis muralis (Wall lettuce)

Quadrat 13: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Geranium robertianum (Herb Robert)

Quadrat 14: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Cratagus monogyna (Common hawthorn)

Quadrat 15: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort)
Oxalis acetosella (Wood sorrel)
Urtica dioica (Stinging nettle)
Primula vulgaris (Primrose)
Mycelis muralis (Wall lettuce)

Quadrat 16: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Geranium robertianum (Herb Robert)
Mercuralis perennis (Dog's mercury)

Quadrat 17: *Dryopteris filix-mas* (Male fern)
Asplenium scolopendrium (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Asplenium ruta-muraria (Wall rue spleenwort
Geranium robertianum (Herb Robert)
Oxalis acetosella (Wood sorrel)
Mercuralis perennis (Dog's mercury)
Urtica dioica (Stinging nettle)

Quadrat 18: *Asplenium scolopendrium* (Hart's tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Geranium robertianum (Herb Robert)
Oxalis acetosella (Wood sorrel)

Appendix 3V.2: The Burren

Phyllitis scolopendrium (Harts-tongue fern)
Asplenium trichomanes (Maidenhair spleenwort)
Ceterach officianarum (Rusty-back fern)
Polipodium australe (Polypody fern)
Pteridium aquilinum (Bracken)
Heliathemum canum (Hoary rock rose)
Polygala vulgaris (Common milkwort)
Viola riviniana (Dog violet)
Silene vulgaris var. maritime (Sea campion)
Geranium robertianum (Herb Robert)
Lotus corniculatus (Bird's-foot trefoil)
Prunus spinosa (Sloe)
Alchemila vulgaris (Lady's mantle)
Potentilla fruticosa (Shrubby cinquefoil)
Fragaria vesca (Wild strawberry)
Rubus saxitalis (Stone bramble)
Dryas octopetela (Mountains avens)
Rosa pimpinellifolia (Burnet rose)
Sorbus sp. (Whitebeam)
Sorbus aucuparia (Rowan)
Geranium robertianum (Herb Robert)
Crataegus monogyna (Hawthorn)
Fraxinus excelsior (Ash)
Hedera helix (Ivy)
Lonicera periclymenum (Honeysuckle)
Antennaria dioca (Cat's foot)
Bellis perennis (Daisy)
Senecio jacobea (Ragwort)
Carlina vulgaris (Carline thistle)
Mycelis muralis (Wall lettuce)
Erica/Calluna sp. (Heather)
Primula vulgaris (Primrose)
Primula veris (Cowslip)
Gentiana verna (Spring gentian)
Pingicula vulgaris (Common butterwort)
Teucrium scorodinia (Wood sage)
Plantago sp. (Plantain)
Urtica dioica (Stinging nettle)
Coryllus avellana (Hazel)
Orchis mascula (Early-purple orchid)
Neotinea maculate (Dense-flowered orchid)
Menyanthes trifoliate (Bogbean)
Schoenus nigricans

APPENDIX 4: PROCEDURES

Appendix 4.1: Tablet survey procedures

Prior to burial, all tablets were prepared by Kirkstall Laboratories in accordance with instructions outlined by Trudgill (1975). The dimensions of tablets were measured on 14/09/2004 using EB callipers to an accuracy of two visual decimal points and pre-burial weighing was undertaken on 22/09/2004 using a Pi Oxford A2205D balance (calibrated on 23/06/2004). Post-burial preparation of the tablets was also that of Trudgill (1975). Re-weighing was undertaken on 18/10/2005 using a Metler AT 261 Range self-calibrating balance in the Instrumental Balance Laboratory at the University of Huddersfield. (Two balances were used as Kirkstall Laboratories went out of business during the 2004-2005 water year). Tablets were transported from the desiccator to the respective balances in newly opened plastic bags and as weighing generally took no longer than a minute there was little time for them to absorb moisture from either the air in the laboratory or the balance weighing compartment.

All measurements were undertaken in the Geochemistry Department at the University of Leeds. The dimensions of tablets were measured on 14/09/2004 using EB callipers (made in Germany) to an accuracy of two visual decimal points. The pre- and post-field emplacement weights of tablets were respectively measured on 22/09/2004 and 00/10/2005 using the same Pi Oxford A2205D weighing machine (calibrated on 23/06/2004 and 00/06/2005). The tablets were taken from the desiccation jar and immediately placed in the weighing compartment. The weighing pan was allowed to settle and the weight noted some twenty seconds following the appearance of a “g” on the display screen. Therefore, the weighing process generally took no longer than a minute, which meant that there was little time for the tablets to absorb moisture from either the air in the laboratory or from the weighing compartment.

Appendix 4.2: Soil and water sample ph survey procedures

The pH of soil samples was measured in the laboratory following procedures outlined in 'A composite method for the measurement of soil pH' of the University of Huddersfield using a Jenway 3010 pH Meter as follows:

1. Fill a sampler tube either ¼-full – or up to the 5ml mark – with soil.
2. Add de-ionised water until the level of liquid reaches ½-full or 10ml in a graduated tube.
3. Put the cap on the tube, shake it vigorously for 10 seconds, and allow it to stand for 10 minutes.
4. After 10 minutes, shake the tube vigorously again to re-suspend the soil, and lower the pH probe into the suspension until the whole of the glass electrode and its 'junction' are below the liquid surface and take the pH reading.

The pH of water samples was measured according to standard procedure either in the field using a Jenway 3071 pH meter or in the laboratory at the University of Huddersfield using a Jenway 3010 pH Meter.

All analyses in the laboratory were carried out as soon as possible after collection in the field.

Appendix 4.3: Induced fracture survey procedures

A minimum of five to ten impact tests should be carried out on each surface being investigated and ‘off shots’, i.e. those that deviate from the mean by more than 5 units, be eliminated and replaced by a further impact test. The Schmidt Hammer is calibrated on an anvil, and if the rebound number (Ra) deviates from the nominal value 80 then the rebound number (R) measured on rock in the field will be falsified in the same proportion. Thus the following formula applies for the test evaluation:

$R = \Sigma r/n \times 80/Ra$

(Where: Σr = sum of rebound tests, n = number of tests, 80 = nominal rebound value and Ra = calibrated rebound value (= 75 in this instance))

The (cube) compressive strength is determined as a function of R. For R values below 50 a table is used to evaluate results but for R values above 50 the equation $\sigma c = 1.94r-36.99$ is used. In addition, a value of 5MPa is added for rocks with a dry density of $2.6t/m^3$ or greater.

The hammer used in the testing was calibrated on 23/06/03 and employed in the field on 29/06/03.

APPENDIX 5: PEDESTAL ROCK SITES

Appendix 5B: The Burren (Lat. 52º 58' to 53º 10'N, Long. 08º 58' to 09º 25'W)

Site OSI and GSI maps, and location

Ordnance Survey Ireland Discovery Sheet 51 Clare, Galway 1:50000 (2002)
Ordnance Survey Ireland Discovery Sheet 52 Clare, Galway 1:50000 (2003)
Geological Survey of Ireland (2003): Geology of Galway Bay. Sheet 14. 1:100000 Scale Sheet
The central part of the Burren is located about 20km to the north of the market town of Ennis (53º 3'N, 8º 49'W) in the west of the Republic of Ireland.

Closest locality (i) Pedestal rock No. (ii) Irish GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (ii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) height (cm) and facing direction (e: exposed and u: unexposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
Gortlecka (R 3094) (i) B1 (ii) R 31803 94799 (iii) 40	(i) Carboniferous limestone (ii) 1.5x1x1 (iii) P>Cr	(i) Sloping/stepped (ii) Smooth (iii) 18 in all directions	Thinly bedded with moderately wide joints. Burren Formation: Maumcaha member	Much dissected and clast-strewn pavement with small kamenitzas but no sign of rundkarren. Ground more-or-less horizontal. Thin patches of organic (?) soil. Woodland vegetation present in turf and in grykes.
(i) B2 [1] (ii) R 31772 94773 (iii) 40	(i) Carboniferous limestone (ii) [2] (iii) P>Cr	(i) Sloping/stepped (ii) Dissected (iii) 20 in all directions	Thinly bedded with wide joints. Burren Formation: Maumcaha member	
(i) B3 (ii) R 31899 94786 (iii) 40	(i) Carboniferous limestone (ii) [2] (iii) P>Cr	(i) Sloping/stepped (ii) Not exposed (iii) 21 in all directions	Thinly bedded with moderately wide joints. Burren Formation: Maumcaha member	
(i) B4 (ii) R 31777 94872 (iii) 40	(i) Carboniferous limestone (ii) [2] (iii) P>Cr	(i) Sloping/stepped (ii) Smooth with <2cm clasts (iii) 21 in all directions	Thinly bedded with wide joints. Burren Formation: Maumcaha member	
(i) B5 (ii) R 32702 94745 (iii) 35	(i) Carboniferous limestone (ii) 1.3x1x1.5 (iii) P>Cr to N, S and W but Cr>P to E	(i) Sloping to N, S and W and vertical to E (ii) Smooth (iii) 20 to N, S and W but >20 to E	Thinly bedded with very wide joints. Burren Formation: Hawkhill member	Similar to B1-B4 but with better developed grykes and with larger

(i) B6 (ii) R 32496 94513 (iii) 38	(i) Carboniferous limestone (ii) 1x0.5x1 (iii) P>Cr	(i) Sloping (ii) Not exposed (iii) 16 in all directions	Thickly bedded (?) with very wide joints. Burren Formation: Hawkhill member	islands of vegetation
Parknabinnia Megalithic Tombs (R 2593) (i) B7 (ii) R 26546 93570 (iii) 138	(i) Carboniferous limestone (ii) 3x2.5x2 (iii) P>Cr to N, E and S, but Cr >P to W	(i) Sloping to N, E and S, and vertical to W (ii) Not exposed but appears flat (iii) 41 in all directions	Medium bedded. Joints not exposed. Slievenaglasha Formation: Ballyelly member	Mostly pasture but also isolated areas of intact rectangular pavement with worn rundkarren and small kamenitzas. Ground more-or-less horizontal. Thin organic (?) soils at B7 but thicker at B8. Soil pH: 6.1.
(i) B8 (ii) R 26628 93881 (iii) 145	(i) Carboniferous limestone (ii) 1.5x1x0.8 (iii) C-r>P	(i) Vertical (ii) Uneven (iii) 14 in all directions	Thinly bedded. Joints not exposed. Slievenaglasha Formation: Ballyelly member	
Sheshy More (R 2495) (i) B9 (ii) R 24152 95869 (iii) 112	(i) Carboniferous limestone (ii) 1x1x0.5 (iii) P>Cr	(i) Sloping (ii) Not exposed (iii) 10 in all directions	Very thickly bedded with extremely wide joints. Slievenaglasha Formation: Ballyelly member	Large expanses of smooth lichen-covered bare clint with deep kamenitzas in places separated by 'bottomless' grykes up to 30cm wide. Ground more-or-less horizontal. Rundkarren absent except on gryke edges. Spreads of moss under low-growing horizontal trees (pH: 6.6) and of thin organic (?) soils; also island mounds of peaty soils (pH: 5.3 sub-root to 7.1 on clint).
(i) B10 (ii) R 24373 96078 (iii) 115	(i) Carboniferous limestone (ii) 1.5x1x0.5 (iii) P>Cr	(i) Sloping (14º) (ii) Not exposed (iii) 13 in all directions	Very thickly bedded with extremely wide joints Slievenaglasha Formation: Ballyelly member.	
(i) B11 [1] (ii) R 24190 96066 (iii) 114	(i) Carboniferous limestone (ii) 1.3x1x0.5 (iii) P>Cr	(i) Sloping (15º) (ii) Fretted – fossil remains proud of surface (iii) 15 to S, N and E.	Very thickly bedded with extremely wide joints. Slievenaglasha Formation: Ballyelly member	
(i) B12 (ii) R 24118 95848 (iii) 115	(i) Carboniferous limestone (ii) 1.5x1x0.3 (iii) P>Cr	(i) Sloping (18º) (ii) Not exposed (iii) 12 in all directions	Very thickly bedded with very wide joints. Slievenaglasha Formation: Ballyelly member	

(i) B13 (ii) R 24022 95868 (iii) 111	(i) Carboniferous limestone (ii) 1.5x1.5x1.5 (iii) P>Cr	(i) Sloping (ii) Flattish with chippings (iii) 5 in all directions	Very thickly bedded with extremely wide joints. Slievenaglasha Formation: Ballyelly member	
Meggagh East (R 2698) (i) B14 (ii) R 26711 98650 (iii) 188	(i) Carboniferous limestone (ii) 1.3x0.8x0.8 (ii) P=Cr	(i) Not exposed (ii) Not exposed (iii) >30	Not exposed. Slievenaglasha Formation: Ballyelly member	Pasture but with residual areas of much-eroded pavement Ground more-or-less horizontal. Soils in solution hollows are mostly brown earths developed on drift; moss-covered clasts plentiful. Soil pH: 7.2.
(i) B15 (ii) R 26731 98634 (iii) 184	(i) Carboniferous limestone (ii) [2] (iii) P=Cr	(i) Not exposed (ii) Not exposed (iii) >31	Not exposed. Slievenaglasha Formation: Ballyelly member	
Ailladie (M 0903) (i) B16 (ii) M 08726 02075 (iii) 17	(i) Carboniferous limestone (ii) 1.8x1x1 (iii) Cr>P to S, W and N, but P>Cr to E	(i) Vertical (ii) Not exposed (cap-rock cemented to pedestal by calcrete) (iii) 12 to N, 37 to S	Medium bedded with very wide joints. Burren Formation: Aillwee member	Bare pavement comprising large slabs of clint, some smooth and some broken, divided by relatively shallow grykes. Ground more-or-less horizontal. Kamenitzas are plentiful while rundkarren are restricted to gryke edges. Patches of drift and organic (?) soils occur.
(i) B17 (ii) M 08689 02032 (iii) 20	(i) Carboniferous limestone (ii) 1.3x1x0.8 (iii) P>Cr to N and S, but Cr=P to W	(i) Vertical to W, but slopes at 18º to N and S. (Turf to E). (ii) Not exposed (iii) 13 to N, S and W	Very thickly bedded with very wide joints. Burren Formation: Aillwee member	

Lissylisheen (R 2099) (i) B18 (ii) R 20117 99374 (iii) 176	(i) Carboniferous limestone (ii) 1.5x1.5x1.7 (iii) P>Cr to SE, SW and NW, but Cr=P to NE	(i) Sloping (12º) to SE, SW and NW, but vertical to NE (ii) Not exposed but appears flat (iii) 12 to SE, SW and NW, and 50e and 7u to NE	Medium bedded with very wide joints. Slievenaglasha Formation: Lissylisheen member	Pasture with residual areas of pavement; plentiful rundkarren with a few incipient kamenitzas on clints. Ground more-or-less horizontal. Soils in solution hollows are mostly brown earths developed on drift. Thin organic soils are present on clint tops. Woodland vegetation present. Soil pH: 5.9.
(i) B19 (ii) R 20063 99406 (iii) 176	(i) Carboniferous limestone (ii) 1.5x1x0.8 (iii) Cr=P except to SE where P>Cr	(i) Sloping to SE (ii) Flat (iii) 13 to SE, and 30e and >33u elsewhere	Thickly bedded with very wide joints. Slievenaglasha Formation: Lissylisheen member	
(i) B20 (ii) R 20173 99356 (iii) 176	(i) Carboniferous limestone (ii) [2] (iii) Cr=P except to S where P>Cr	(i) Sloping to S and vertical elsewhere (ii) Not exposed but appears flat (iii) 13 to S, and 13e and 17u elsewhere	Medium bedded with very wide joints. Slievenaglasha Formation: Lissylisheen member	
Fanore Bridge (M 1409) (i) B21 (ii) M 14813 10187 (iii) 62	(i) Carboniferous limestone (ii) 1x0.8x0.7 (iii) P>Cr to N and S, but P =Cr	(i) Sloping (10º) to the N and S, and vertical to the W and E (ii) Flat (iii) 13 to N and S, 20 to W and 31 to E	Thinly bedded with very wide joints. Burren Formation: Black Head member	Mostly bare pavement of uneven and elongate clint sloping at about º to the south-west. Rundkarren are absent and kamenitzas worn. Patchy thin organic soils occur on some clints.
(i) B22 (ii) M 14544 09997 (iii) 32	(i) Carboniferous limestone (ii) [2] (iii) [2]	(i) Sloping (ii) [2] (iii) 10	[2] Burren Formation: Black Head member	
Fanore (M 1308) to Lackaniska (M 1206) (i) B23 to B38 (ii) M 13675 07986 to M 13255 07278 (iii) 6 to 15	(i) Carboniferous limestone (ii) Not measured (iii) mostly P>Cr	(i) Sloping/stepped (ii) Not noted (iii) From 6 to 17 (Mean of 12)	Mostly thinly bedded with wide joints. Burren Formation: Fanore member	Approximately 60% pasture and 40% eroded bare rock
East of Knockanes (R 3297) (i) B39 (ii) R 33577 97724 (iii) 59	(i) Carboniferous limestone (ii) [2] (iii) P>Cr to E but P=Cr to W and S	(i) Sloping (6º) to E, and vertical to W and S. N not exposed. (ii) Not exposed (iii) 17 to E and >46 to W and S	Medium bedded with very wide joints. Burren Formation: Lower Aillwee member	Pasture with outcrops of eroded and broken pavement. Poorly preserved rundkarren

(i) B40 (ii) R 33575 97727 (iii) 65	(i) Carboniferous limestone (ii) [2] (iii) P>Cr	(i) Sloping (ii) Not exposed (iii) 17 in all directions	Bedding unexposed: wide joints. Burren Formation: Lower Aillwee member	with fresher kamenitzas at B39 and B40. Rundkarren better preserved and more common than kamenitzas at B 41-42. Mostly thin organic soils but some patches of drift. Woodland vegetation present, including thick stands of trees at B41-42.
(i) B41 and B42 (ii) R 34033 97463 (iii) 41	(i) Carboniferous limestone (ii) B41 4x3x3 B42 1x0.8x0.5 (iii) P>Cr	(i) Sloping, especially clear to the N and S parallel with the major joint set (ii) Flat (iii) 24 in all directions	Very thickly bedded with very wide joints. Burren Formation: Lower Aillwee member	
Creehaun (R 3395) (i) B43 (ii) R 34366 95664 (iii) 29	(i) Carboniferous limestone (ii) Cap-rock complex (iii) P>Cr	(i) Sloping (ii) Obscured by drift, but appears flat (iii) 20 in all directions	Thinly bedded with very wide joints. Burren Formation: Maumcaha member.	Mostly well-dissected lichen-covered pavement with well-developed kamenitzas in parts. Rundkarren restricted to gryke edges. Woodland vegetation present.
Caher Upper (M 1508) (i) B44 (ii) M 15053 09057 (iii) 60	(i) Carboniferous limestone (ii) 2.5x1.5x1.5 (iii) Cr>P to N, E and W, but P>Cr to S	(i) Vertical to N, E and W, but sloping to S (ii) Uneven (iii) 59 to N and 22 to S	Medium bedded with very wide joints. Burren Formation: Maumcaha member	Steeply sloping valley side with scars remnants and fallen blocks partly covered in thin organic/drift soil. Woodland vegetation present.
Doonyvardan (M 1901) (i) B45 (ii) M 19751 01964 (iii) 213	(i) Carboniferous limestone (ii) 2x2x1.5 (iii) Cr>P	(i) Sloping in all directions (ii) Not recorded [3] (iii) 19	Not recorded [3]. Slievenaglasha Formation: Lissylisheen member	Pasture with residual areas of pavement. Ground more-or-less horizontal. Woodland vegetation present

Carran (R2898) (i) B46 (ii) R 29369 99538 (iii) 126 (perfumery)	(i) Carboniferous limestone (ii) 2x2x0.5 (iii) Cr>P	(i) Sloping (ii) Flat (iii) 13 in all directions	No bedding planes exposed but very wide joints. Burren Formation: Aillwee member	Large expanses of clints, with more rundkarren than kamenitzas, partly covered in pasture. Ground sloping at 4º to the north. Woodland vegetation present.

[1] Strictly speaking this is not a pedestal rock since the cap-rock has partially toppled off
[2] Water-sodden notes unreadable
[3] Didn't linger as wearing Welsh rugby jersey and bull approaching

Table 5B.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Location (i) Wavestone No. (ii) Irish GR (iii) Altitude (to within 10m)	Description	Surrounding environs
Rinnamona Lough (R 2994) (i) B47 (Rinnamona 2) [1] (ii) R 29759 94232 (iii) 42	Three lips are present. The most pronounced is more-or-less entire and has an undercut of about 10cm; it is horizontal, and occurs some 40cm below the apex of the wavestone. The pedestal sidewall below the lip it is smooth and slopes outwards at an ever decreasing angle. Higher and lower incomplete lips respectively occur on the SE and NE corners of the wavestone, and a passage has been cut through it.	Sodden peat with sedges, moss, damp-loving herbs, heather and tussocky grasses. Soil pH: 6.7. The mean pH and conductivity of Rinnemona Lough (some 10m from RS1, RS4 and RS5) and its exit stream (RS6) was respectively 8.2 and 352 in May 2005 and was 6.8 and 279 in October 2006. The floor of the lough is covered with a soft pelletal lime precipitate. No lips are present on limestone scars close to RS2 and RS3 or at water level of RS6, which is situated in the middle of the exit stream. In October 2006 lip height above an arbitrary datum was measured using instrumentation and that of RS1 was 12.5 (lower lip) and 28cm (upper lip), of RS5 was 22.5cm and of RS6 was 59cm. The site was flooded at the time and the distance of lips above water level of RS1 was 21 (lower lip) and 40cm (upper lip), of RS5 was 12.5cm and of RS6 was 16cm.
(i) B48 (ii) R 29779 94184 (iii) 37	A not quite horizontal lip only to the NNE is present and it occurs some 50cm below the apex of the wavestone.	
(i) B49 (ii)R 29192 94182 (iii) 36	A more-or-less horizontal lip that is entire except to the NNE is present and it occurs some 5cm below the apex of the wavestone.	
(i) B50 (ii) R 29730 94102 (iii) 32	A not quite horizontal lip only to the NE is present. The wavestone was too worn to determine with accuracy the depth of the lip below its apex.	
(i) B51 (ii) R 29710 94075 (iii) 35 PHOTO 5	A more-or-less horizontal lip that is entire is present, though undercut is greater to the NE and SW (10cm) than to the NW and SE (5cm); it occurs some 5cm below the apex of the wavestone	
(i) B52 (Rinnamona 3) [1] (ii) R 29602 93957 (iii) 33	A more-or-less horizontal lip that faces in a northerly direction is present and it occurs some 15cm below the apex of the wavestone.	
Lough Gealáin (R 3194) (i) B53 (Gortlecka 2) [2] (ii) R 32028 94985 (iii) 37	A wavy lip that is entire except to the lakeside W is present; it occurs some 50cm below the apex of the wavestone. Maximum overhang is some 20cm to the E (i.e. up-lake), and the pedestal sidewall, which is approximately 1m in height, is vertical below the lip but tapers outwards near ground level. The wavestone is pock-marked to the west.	A sere grading from limestone vegetation just inland from the wavestones, to sodden peat with sedges, moss, tussocky grasses, and damp-loving herbs and shrubs surrounding them to standing water with mere vegetation lakewards. The mean pH and conductivity levels of the lake water were respectively 8.2 and 310 in May 2005 and were 7.1 and 368 in October 2006. The Lough floor is covered with a soft pelletal lime precipitate. No lips are present on the many erratics that ring Lough Gealáin shoreline or on limestone outcrops that form cliffs in the vicinity of the lake and the wavestones. Lip to water-level distances for G2
(i) B54 (Gortlecka 1) [1] (ii) R 32011 94965 (iii) 37	A more-or-less horizontal entire lip is present; it occurs some 50cm below the apex of the wavestone. Maximum overhang is some 40cm to the E (i.e. up-lake). The pedestal sidewall, which is approximately 1.2m in height, is vertical below the lip but gradually tapers outwards until some 50cm above ground level. Here, it once again becomes vertical; it is also scalloped rather like the walls of some grykes. A passage akin to a phreatic tube has been cut through the wavestone; this extends both above and below ground level. A similar passage that is entirely below ground level occurs in a nearby erratic. The wavestone is pock-marked to the west.	

(i) B55 (ii) R 31991 94958 (iii) 37	A lip that faces only to the SW is present; it appears to be more-or-less level with the lips of G1 and G2.	from its NW to S corners when the site was flooded are 31, 36, 45, 48, 50, 53, 67, 56, 46, 45, 47, 45, 46 and 50cm.
Fahee South (R 2998) (i) B56 (ii) R 29866 98934 (iii) 140	Five slots are apparent, the lowest and main one having an indent of about 22cm and measuring some 20cm from top to base. The remaining four are considerably shallower. The main slot is exposed to the NE only, but it also occurs at soil level up-slope to the SE.	A relatively steep hillside comprising pasture on till.

[1] Dunne and Feehan (2003:11 and 20)
[2] Dunne and Feehan (2003:11)

Table 5B.2: Mushroom pedestal rock (wavestones) locations, salient features and surrounding environs

Appendix 5CB: Cavan Burren (H 0735)

Site OSNI and GSI maps, and location

Ordnance Survey of Northern Ireland Sheet 26 Lough Allen 1:50000 (1984))
British Geological Survey (1991): Derrygonnelly and Marble Arch. Northern Ireland Sheets 44, 56 and 43. 1:50000 Series
The Cavan Burren is located about 3km to the south of the town of Blacklion (H 0737) in Co. Leitrim, the Republic of Ireland. It is best approached on the minor road that runs from Blacklion to the hamlet of Legeelan (H 0633), and is reached along a rough track that bears east about 1km before the hamlet.

(i) Pedestal rock No. (ii) Irish GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (ii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) height (cm) and facing direction (e: exposed and u: unexposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) CB1 (ii) H 07600 35149 (iii) 250	(i) Carboniferous sandstone (ii) 2.7x1.6x1.9 (iii) Cr>P to E, S and W, and P>Cr to N	(i) Vertical to E, S and W, and sloping 16º (?) to N. (ii) Uneven: varies in height by c.17cm (iii) 44e and 8u to E, S and W	Thinly bedded with very wide joints. Dartry Limestone Formation: Knockmore Limestone	Largely coniferous over-canopy with litter, moss, ferns and herbs on woodland floor. Sub-root soil pH 6.9 at CB1
(i) CB2 (ii) H 07586 35063 (iii) 251	(i) Carboniferous sandstone (ii) 2.6x1.2x1.6 (iii) C-r>P	(i) Vertical (ii) Uneven: no striae present (iii) 30e to N, 40e and 11u to E, and 47e to W. Up to 12cm of undercutting at soil level.	Medium bedded with very wide joints. Dartry Limestone Formation: Knockmore Limestone	
(i) CB3 (ii) H 07450 34772 (iii) 260	(i) Carboniferous sandstone (ii) 1.6x1.2x0.5 (iii) Cr>P	(i) Vertical (ii) Uneven: no striae present (iii) 45e to N, 33e and 17u to S, and 17e to W	Medium bedded with wide joints. Dartry Limestone Formation: Knockmore Limestone	
(i) CB4 [1] (ii) H 07643 34707 (iii) 258	(i) Carboniferous sandstone (ii) 2x1.7x0.7 (iii) Cr>P	(i) Vertical (ii) Blocky (iii) 20e and 12u (?) in all directions	Moderately wide joints. Dartry Limestone Formation: Knockmore Limestone	
(i) CB5 [2] (ii) H 07771 34557 (iii) 255	(i) Carboniferous sandstone (ii) 1.7x1.3x1.2 (iii) Cr>P to N, S and W, and P>C-r to E	(i) Vertical to N, S and W, sloping to E (ii) Uneven: no striae present (iii) 40e, 5u to N and 45e to S. Up to 37cm of undercutting at soil level.	Moderately wide joints. Dartry Limestone Formation: Knockmore Limestone	

(i) CB6 [1] (ii) H 07774 34557 (iii) 252	(i) Carboniferous sandstone (ii) 1.3x1.2x0.5 (iii) Cr>P to NE, SW and NW, and P>Cr to SE	(i) Vertical to NE, SW and NW, and sloping 16º(?) to SE (ii) Flattish, but poorly exposed. (iii) 23e to NE, 31e 10u to SW, 30e 10u to NW	(Sidewalls largely moss- largely covered.) Dartry Limestone Formation: Knockmore Limestone	
(i) CB7 (ii) H 07833 34412 (iii) 252	(i) Carboniferous sandstone (ii) 1.7x1.6x1.2 (iii) Cr>P	(i) Vertical (ii) Very uneven (iii) 29e 16u (?) to N, 23e 7u (?) to E, 67e 5u to S and 55e 17u to W	Medium bedded with wide joints.	Pasture with Sphagnum, heather, juniper, sedges, herbs and grasses Sphagnum Soil sub-root pH 5.7 at CB7
(i) CB8 (ii) H 07887 34431 (iii) 252	(i) Carboniferous sandstone (ii) 2x1.4x0.6 (iii) Cr>P	(i) Vertical (ii) Very uneven: (iii) 29e 16u to N, 26e 9u to E, 40e 9u to S and 6e 19u to W. Up to 8cm of undercutting at soil level.	Medium bedded with wide joints. Dartry Limestone Formation: Knockmore Limestone	
(i) CB9 (ii) H 07905 34535 (iii) 251	(i) Carboniferous sandstone (ii) 1.7x1.4x1.1 (iii) Cr>P	(i) Vertical (ii) Very uneven (iii) 36e 9u to N, 38e 10u to E, 38e 7u to S and 8u to W. Up to 10cm of undercutting at soil level.	(Sidewalls largely moss- largely covered.) Dartry Limestone Formation: Knockmore Limestone	As GB1-6
(i) CB10 (ii) H 08003 34544 (iii) 257	(i) Carboniferous sandstone (ii) (Not recorded) (iii) Cr>P to N, E and W, and P>C-r to S	(i) Vertical to N, E and S, but sloping 28º (?) to W. (ii) Uneven: no striae present (iii) 23e 22u to E, and 28e 22u to S. Up to 24cm of undercutting at soil level.	Thinly bedded with wide joints. Dartry Limestone Formation: Knockmore Limestone	
(i) CB11 [3] (ii) H 07986 34789 (iii) 239	(i) Carboniferous sandstone (ii) 2.9x2.3x0.6 (iii) Cr>P	(i) Vertical (ii) Uneven: no striae present (iii) 21e 24u to N, 31e 14u to E, 49e 10u to S and 30e 15u to W	Thinly to medium bedded with wide joints. Dartry Limestone Formation: Knockmore Limestone	Largely coniferous over-canopy but with litter only.

[1] Caprock partially toppled off
[2] The Rocking Stone (Burns, n.d)
[3] The Lightening Stone (?) (Burns, n.d.)

Table 5CB.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5CT: Cunswick Tarn (SD 4893)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998)
British Geological Survey (1887): Kendal. England and Wales Sheet 39. 1:63360 Old Series
Cunswick Tarn is located about 4km to the north-west of the town of Kendal (SD 5291) in Cumbria. It is best approached on the B5284 Kendal to Bowness-on-Windermere (SD 4096) road, and is reached by about a 1km walk/scramble along footpaths to the south of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (ii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) height (cm) and facing direction(e: exposed and u: unexposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) CT1 (ii) SD 48771 93830 (iii) 144	(i) Silurian grit (ii) 2x1.5x0.7 (iii) Cr>P	(i) Vertical (ii) Ice-abraded (iii) 49e+13u to SW, 44-55e to NE	Medium bedded with wide joints. Carboniferous limestone (undifferentiated)	Mainly level ground of pasture on till

Table 5CT.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5D: Dowkabottom (SD 9568)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997)
British Geological Survey (1989): Settle. England and Wales Sheet 60. 1:500000 Series
Dowkabottom is located about 7km to the north-west of the tourist town of Grassington (SD 0064) in North Yorkshire. It is reached by about a 1km scramble over rough pasture from the minor road on the south-west side of Littondale (SD 9470).

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative cap-rock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) D1 (ii) SD 95380 68975 (iii) 379	(i) Carboniferous limestone (ii) 4.5x3.0x2.6 (iii) Cr>P	(i) Vertical (ii) N/A (iii) 50e+15u	N/A Malham Formation: Gordale Limestone	Gently sloping ground of pasture on till

Table 5D.1: Perched pedestal rock location, salient features and surrounding environs

Appendix 5FK: Farleton Knot (farleton fell/newbiggin crags/ holmepark fell) (SD 5480)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998)
British Geological Survey (1892): Kirkby Lonsdale. England and Wales Sheet 49. 1:63360 Old Series
Farleton Knot is located about 4km to the north-north-east of the town of Burton-in-Kendal (SD 5376) in Cumbria. It is best approached from the minor road that runs between the hamlets of Clawthorpe (SD 5377) and Hutton Roof (SD 5778), and is reached by about a 2km walk over tracks to the north-west of the road.

(i) Pedestal rock No. (ii) O.S. GR (iii) Altitude (to within 10m)	(i) Caprock rock type (ii) Caprock size (m) (iii Relative caprock (Cr) and pedestal (P) sizes	Pedestal (i) sidewall and (ii) crown surface forms, and (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)	Pedestal rock mass description and solid geology	Surrounding environs
(i) FK1 (ii) SD 54503 80106 (iii) 249	(i) Carboniferous limestone (ii) N/A (iii) N/A	(i) Vertical (ii) Smooth with striae (042/222) (iii) N/A	N/A Carboniferous Limestone (undifferentiated)	Horizontal ground with clasts, grass and herbs
(i) FK2 (ii) SD 54486 80098 (iii) 247	(i) Carboniferous limestone (ii) N/A (iii) N/A	(i) Vertical (ii) Not exposed (iii) N/A	N/A Carboniferous Limestone (undifferentiated)	Horizontal ground with soil/till, grass and herbs
(i) FK3 (ii) SD 54479 80121 (iii) 240	(i) Carboniferous limestone (ii) 1.8x1x0.4 (iii) Cr>P	(i) Vertical (ii) Smooth with striae (042/222) (iii) 30e+16u	Thinly bedded with moderately wide joints. Carboniferous Limestone (undifferentiated)	Horizontal ground with soil/till, grass and herbs
(i) FK4 (ii) SD 54422 80134 (iii) 244	(i) Carboniferous limestone (ii) 1.8x1.3x2.2 (iii) P>Cr	(i) Sloping, dip 18º (ii) Smooth (iii) 13 in all directions	Very thickly bedded with wide joints. Carboniferous Limestone (undifferentiated)	Bare pavement with rundkarren (but not on pedestal)
(i) FK5 (ii) SD 54182 80112 (iii) 258	(i) Carboniferous limestone (ii) 2x2x1 (iii) P>Cr	(i) Sloping (ii) Smooth (iii) 6 in all directions	Medium bedded with very wide joints. Carboniferous Limestone (undifferentiated)	Bare pavement dipping at 016/140º
(i) FK6 (ii) SD 54182 80112 (iii) 258	(i) Carboniferous limestone (ii) 2x2x1 (iii) P>Cr	(i) Sloping , but cut by gryke with extremely wide aperture (ii) Smooth (iii) 8 in all directions	Medium bedded with very wide joints. Carboniferous Limestone (undifferentiated)	Bare pavement dipping at 016/140º
(i) FK7 (ii) SD 54914 79588 (iii) 242	(i) Carboniferous limestone (ii) 1x1x1 (iii) P>Cr to SE Cr>P to NE	(i) Sloping to SE, vertical to NE (ii) Uneven (iii) 15 to SE and 42 to NE	Thickly bedded with wide joints. Carboniferous Limestone (undifferentiated)	Much dissected Pavement. Some grykes 1m wide

(i) FK8 (ii) SD 54372 79295 (iii) 214	(i) All Carboniferous limestone (ii) All N/A (iii) Cr>P mostly	(i) Some evidence of sloping sidewalls, but mostly vertical (ii) Smooth (iii) N/A	N/A Carboniferous Limestone (undifferentiated)	Horizontal ground with rough pavement, upturned clint and cap rocks in two partially covered in grass and herbs
(i) FK9 (ii) SD 54342 79442 (iii) 217				
(i) FK10 (ii) SD 54374 79342 (iii) 214				
(i) FK11 (ii) SD 54334 79307 (iii) 205				

Table 5FK.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5G: Gearstones (SD 7779)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997)
British Geological Survey (1997): Hawes. England and Wales Sheet 50. 1:50000 Provisional Series
Gearstones is located about 2km to the east-north-east of Ribblehead (SD 7678) in North Yorkshire. It is best approached from the B6255 Ingleton (SD 6973) to Hawes (SD 8789) road, and is reached by about a 1km walk over pasture to the south of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative cap-rock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) G1 (ii) SD 77810 79481 (iii) 298	(i) Carboniferous limestone (ii) 2.5x2.5x1.2 (iii) Cr>P	(i) Vertical (ii) Ice-abraded (iii) 78e to W, 47e to N and 43e+8u to S, 22u to E	Thinly bedded with wide joints. Malham Formation: Danny Bridge Limestone	Steeply sloping hillside (12º) of pasture-covered till. pH: 5.8
(i) G2/G3 (ii) SD 77843 79502 (iii) 303	(i) Carboniferous limestone (ii) Both 2x1.5x1.5 (iii) Cr>P	(i) Vertical (ii) G2: Abraded G3: Eroded (iii) 35e+27u to SW, 17e+23u to NW and 37e+6u to NE	Medium bedded with wide joints. Malham Formation: Danny Bridge Limestone	Mainly level ground with pasture on till
(i) G4 (ii) SD 78043 79714 (iii) 306	(i) Carboniferous limestone (ii) 2x1.5x1.1 (iii) Cr>P	(i) Vertical (ii) (Not exposed) (iii) > 59e to W	(Not exposed) Malham Formation: Danny Bridge Limestone	Steeply sloping hillside (25º) of pasture-covered till
(i) G5 (ii) SD 77676 79311 (iii) 288	(i) Carboniferous limestone (ii) 2.5x1.2x1.4 (iii) Cr>P	(i) Vertical (ii) Undulating (iii) 147 (130e+17u) to W	Medium bedded with wide joints. Malham Formation: Danny Bridge Limestone	Steeply sloping hillside (12º) of pasture-covered till pH: 4.2 (G6) pH: 5.2 (G7)
(i) G6 and G7 (ii) SD 77725 79378 (iii) 286	(i) Carboniferous limestone (ii) G6: 2x1.8x2.2 G7: 1.8x1.4x0.7 (iii) Cr>P	(i) Vertical (ii) (Not exposed) (iii) > 2e+43u to W	(Not exposed) Malham Formation: Danny Bridge Limestone	
(i) G8 (ii) SD 77741 79401 (iii) 290	(i) Carboniferous limestone (ii) 1.8x1.0.25 (iii) Cr>P	(i) Vertical (ii) (Not exposed) (iii) > 5e+35u in all directions	(Not exposed) Malham Formation: Danny Bridge Limestone	Pasture/till-covered ledge

Table 5G.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5GAS: Great Asby Scar (SD 6510)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 19 Howgill Fells and Upper Eden Valley 1:25000 (1995)
British Geological Survey (1892): Kirkby Lonsdale. England and Wales Sheet 49. 1:63360 Old Series
Great Asby Scar is located about 11km to the south-south-west of the market town of Appleby-in-Westmorland (SD 6720) in Cumbria. It is best approached from the B6260 Appleby-in-Westmorland to Orton (SD 6208) road, and is reached by about a 2km walk along rough tracks to the east of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative cap-rock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) GAS1-9 (ii) NY 64595 09812 south to NY 64626 10003 [1] (iii) 365	(i) Carboniferous limestone (ii) Mean of 1.1x0.7x0.4 (iii) P>Cr	(i) Sloping (ii) Flat (glacially planed (?)) (iii) 8 to 19 (mean 11) in all directions	Thickly bedded with wide to very wide joints. Carboniferous Limestone (undifferentiated)	Dissected limestone bench with sparse vegetation and fresh rundkarren

[1] Area 8 (Goldie, 1994: 3)

Table 5GAS.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

(i) Mushroom rock number (ii) GR (iii) Altitude (to within 10m)	**Description**	**Surrounding environs**
(i) Mushroom rock field centred on (ii) NY 64836 09263[1] (iii) 409	Cap-rock area varied greatly as it was dependent on joint density. Cap-rocks formed of relatively massive bed and pedestals of relatively well-fractured bed. Pedestals more-or-less vertical from the ground upwards but flare outwards underneath their cap-rocks, the latter extending from as little as a few centimetres to as much as 48cm beyond the pedestal sidewall. Pedestal height ranges from 16 to 28cm with a mean of 22cm.	Much dissected lichen-covered pavement of well-developed grykes and cushion-shaped clints with well-weathered rundkarren and poorly-formed kamenitzas. Vegetation and organic soil restricted mainly to grykes.

[1] Area 13 (Goldie, 1994: 4)

Table 5GAS.2: Mushroom pedestal rocks: location and salient features

Appendix 5GB: Gait Barrows (SD 4877)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998)
British Geological Survey (1892): Kirkby Lonsdale. England and Wales Sheet 49. 1:63360 Old Series
Gait Barrows is located about 3km to the north-east of the coastal town of Silverdale (SD 4675) in Cumbria. It is best approached from the minor road that runs from Silverdale to Yealand Redmayne (SD 5075), and is reached by about a 0.5km walk over tracks to the south-east of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative cap-rock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) GB1 (ii) SD 48082 77339 (Gait Barrows NNR) (iii) 38	(i) Carboniferous limestone (ii) 1.2x1x0.6 (iii) P>Cr	(i) Sloping (ii) Not exposed (iii) 12 in all directions	Medium bedded with extremely wide joints. Carboniferous Limestone (undifferentiated)	Mostly bare undissected level pavement
(i) GB2 (ii) SD 48071 77324 (Gait Barrows NNR) (iii) 37	(i) Carboniferous limestone (ii) (Not accessible but similar to GB1) (iii) P>Cr	(i) Sloping (ii) Not exposed (iii) 15 in all directions	(Not exposed) Carboniferous Limestone (undifferentiated)	Organic soil on level pavement under trees
(i) GB3 (ii) SD 48509 76308 (Field to the west of Yealand Hall Allotment) (iii) 47	(i) Carboniferous limestone (ii) 2x1.6x1.8 (iii) Cr>P	(i) Vertical (ii) Abraded (iii) 25e+9u to north	Medium bedded with moderately wide joints. Carboniferous Limestone (undifferentiated)	Level pasture on till

Table 5GB.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5HRC: Hutton Roof Crags (SD 5577)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern area 1:25000 (1998)
British Geological Survey (1892): Kirkby Lonsdale. England and Wales Sheet 49. 1:63360 Old Series
Hutton Roof Crags is located about 4km to the north-east of the town of Burton-in-Kendal (SD 5376) in Cumbria. It is best approached from the minor road that runs between the hamlets of Clawthorpe (SD 5377) and Hutton Roof (SD 5778), and is reached by about a 2km walk over rough ground to the south-east of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative cap-rock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) HRC1 (ii) SD 55004 78201 (iii) 219	(i) Silurian grit (ii) 1.3x0.8x0.4 (iii) P>Cr	(i) Vertical (ii) Glacially abraded (iii) 19 (19e) to N, 56 (56e) to S	Thinly bedded with wide joints. Urswick Limestone [2]	Dissected bare clint with thin rendzinas/ brown earths in solution hollows
(i) HRC2 (ii) SD 54868 77937 (iii) 207	(i) Carboniferous limestone (ii) 1.7x1.2x1.3 (iii) P>Cr	(i) Vertical and sloping (ii) Plucked (iii) 13 (13e)	Medium bedded with wide joints. Urswick Limestone [2]	
(i) HRC3 (ii) SD 54870 77963 (iii) 206	(i) Carboniferous limestone (ii) 1.8x1.4x0.8 (iii) P>Cr	(i) Vertical and sloping (ii) Uneven (iii) 16 (16e) where sloping (S), 56 (42e,14u) where vertical (N)	Medium bedded with very wide joints. Urswick Limestone [2]	
(i) HRC4 The Cuckoo Rocking Chair (Milligan, 2003) (ii) SD 56868 78267 (iii) 176	(i) Carboniferous limestone (ii) 4x3x3 (iii) Cr>P	(i) Vertical (ii) Part abraded and part plucked (iii) 34 (17e,17u) to S	Medium bedded with wide joints. Urswick Limestone [2]	Ground covered in soil/till

[2] Milligan (2003)

Table 5HRC.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5M: Marlbank (H 1034)

Site OSI and BGS maps, and location

Ordnance Survey of Northern Ireland Sheet 26 Lough Allen 1:50000 (1984)
British Geological Survey (1991): Derrygonnelly and Marble Arch. Northern Ireland Sheets 44, 56 and 43. 1:50000 Series
Marlbank, which is a National Nature Reserve, is located about 6km to the south-east of the town of Belcoo (H 0839) in Co. Fermanagh, Northern Ireland. It is best approached on minor roads from Blacklion (H 0737), in Co. Leitrim, the Republic of Ireland, and M1 is found to the south of the road about 2km before the turnoff to Marble Arch Caves (H 1234).

(i) Pedestal rock No. (ii) Irish GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) M1 (ii) H 10352 34141 (iii) 188	(i) Carboniferous sandstone (ii) 1.6x1.2x0.6 (iii) Cr>P to S and W	(i) Vertical to S and W (ii) Undulating (iii) 36e and 9u to S, and 45e and 3u W	Thinly bedded with wide joints. Dartry Limestone Formation: Knockmore Limestone	Pasture/till covered pavement. Soil pH 5.7

Table 5M.1: Perched pedestal rock location, salient features, solid geology and surrounding environs

Appendix 5N: Norber (SD 7669)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997)
British Geological Survey (1989): Settle. England and Wales Sheet 60. 1:500000 Series
Norber is located about 1.5km to the north-north-west of the village of Austwick (SD 7668) in North Yorkshire. It is best approached from Austwick along the minor road (Crummack Lane (SD 7769)) that terminates at Crummack (SD 7771), and is reached by about a 1km walk over footpaths to the west of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) N1 (ii) SD 76802 69768 (iii) 263	(i) Silurian grit (ii) n/a (cap-rock in several pieces) (iii) Cr>P	(i) Vertical (ii) Uneven/plucked (iii) SE: 43 (43e) NW: n/a (not exposed)	Thinly bedded with wide joints. Kilnsey Formation: Kilnsey Limestone	Above glacial scar and surrounded by regolith
(i) N2 (ii) SD 76748 69699 (iii) 251	(i) Silurian grit (ii) 1.5x1.2x0.7 (iii) Cr>P	(i) Vertical (ii) Uneven/plucked (iii) SE: 35 (16e,19u) NW: 33 (33u)	Moderately bedded with wide joints. Kilnsey Formation: Kilnsey Limestone	Level ground surrounded by regolith
(i) N3 (ii) SD 76711 69760 (iii) 263	(i) Silurian grit (ii) 3.0x1.8x1.9 (iii) Cr>P	(i) Vertical (ii) Smooth (iii) SE: 40 (28e,12u) NW: n/a (not exposed)	Thinly bedded with moderately wide joints. Kilnsey Formation: Kilnsey Limestone	Above glacial scar and surrounded by regolith
(i) N4 (ii) SD 76872 70042 (iii) 288	(i) Silurian grit (ii) 2.8x1.4x1.2 (iii) Cr>P	(i) Vertical (ii) Uneven/plucked (iii) SE: n/a (not exposed) NW: 45 (45e)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N5 (ii) SD 76796 70083 (iii) 298	(i) Silurian grit (ii) 2.3x2.0x1.2 (iii) Cr>P	(i) Vertical (ii) Rough (iii) SE: 34 (34e) NW: 35 (35e)	Thinly bedded with wide joints. Malham Formation: Cove Limestone	Gently sloping ground surrounded by regolith
(i) N6 (ii) SD 76747 70006 (iii) 296	(i) Silurian grit (ii) 3.0x1.1x2.0 (iii) Cr>P	(i) Vertical (ii) Smooth/undulating (iii) SE: 37 (37e) NW: 50 (50u)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N7 (ii) SD 76744 69987 (iii) 292	(i) Silurian grit (ii) 1.8x1.2x0.7 (iii) Cr=P	(i) Vertical (ii) Smooth/undulating (iii) SE: 52 (52e) NW: 50 (50u)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N8* (ii) SD 76737 69982 (iii) 295	(i) Silurian grit (ii) 1.8x1.6x0.7 (iii) Cr>P	(i) Vertical (ii) Plucked [1] (iii) SE: 57 (56e,1u) NW: 62 (24e,38u)	Medium bedded with moderately wide joints. Malham Formation:	Level ground surrounded by regolith

			Cove Limestone	
(i) N9 (ii) SD 76740 69969 (iii) 293	(i) Silurian grit (ii) 3.3x1.0x1.2 (iii) Cr=P	(i) Vertical (ii) Smooth (iii) SE: 43 (34e,9u) NW: 47 (47u)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N10 (ii) SD 76717 69957 (iii) 292	(i) Silurian grit (ii) 1.3x1.1x0.8 (iii) Cr>P	(i) Vertical (ii) Smooth/undulating (iii) SE: 69 (69e) NW: 53 (41e,12u)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N11 (ii) SD 76689 69945 (iii) 297	(i) Silurian grit (ii) 2.2x1.6x0.6 (iii) Cr>P	(i) Vertical (ii) Abraded with striae (iii) SE: 18 (18e) NW: n/a (not exposed)	Thinly bedded with wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N12 (ii) SD 76684 69869 (iii) 289	(i) Silurian grit (ii) 2.6x1.4x1.4 (iii) Cr>P	(i) Vertical (ii) Abraded with striae (iii) SE: 62 (56e,6u) NW: 48 (37e,11u)	Moderately bedded with wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N13 (ii) SD 76519 69771 (iii) 286	(i) Silurian grit (ii) 2.7x1.6x1.8 (iii) Cr>P	(i) Vertical (ii) Uneven/plucked (iii) SE: 46 (39e,7u) NW: 43 (43e)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N14 (ii) SD 76610 69955 (iii) 301	(i) Silurian grit (ii) n/a (cap-rock in several pieces) (iii) Cr>P	(i) Vertical (ii) Smooth/undulating (iii) SE: 58 (41e,17u) NW: 65 (35e,30u)	Moderately bedded with wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N15 (ii) SD 76622 69984 (iii) 302	(i) Silurian grit (ii) n/a (cap-rock in two pieces) (iii) Cr>P	(i) Vertical (ii) Uneven (iii) SE: 64 (64e) NW: 68 (68u)	Thinly bedded with wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N16 (ii) SD 76599 70041 (iii) 307	(i) Silurian grit (ii) 3.8x1.7x1.2 (iii) Cr>P	(i) Vertical (ii) Even (iii) SE: 40 (40e) NW: 40 (40e)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N17 (ii) SD 76617 70146 (iii) 310	(i) Silurian grit (ii) 2.3x1.0x1.2 (iii) Cr>P	(i) Vertical (ii) Plucked (iii) SE: 36 (36e) NW: 51 (41e,10u)	Medium bedded with moderately wide joints. Malham Formation: Cove Limestone	Gently sloping ground surrounded by regolith
(i) N18 (ii) SD 76655 70228 (iii) 318	(i) Silurian grit (ii) n/a (wall built over it) (iii) Cr>P	(i) Vertical (ii) Uneven (iii) SE: 62 (51e,11u) NW: 62 (41e,21u)	Thinly bedded with wide joints. Malham Formation: Cove Limestone	Sloping ground surrounded by regolith
(i) N19 (ii) SD 76660 70203 (iii) 312	(i) Silurian grit (ii) 2.4x1.7x1.2 (iii) C-r>P	(i) Vertical (ii) Undulating (iii) SE: 45 (20e,25u) NW: 49 (16e,33u)	Thinly bedded with wide joints. Malham Formation: Cove Limestone	Sloping ground surrounded by regolith
(i) N20	(i) Silurian grit	(i) Vertical	Thinly bedded	Sloping ground

(ii) SD 76642 70135 (iii) 306	(ii) 1.8x1.4x0.5 (iii) Cr>P	(ii) Uneven/plucked (iii) SE: 61 (43e,18u) NW: 39 (19e,20u)	with wide joints. Malham Formation: Cove Limestone	surrounded by regolith
(i) N21 (ii) SD 76646 70111 (iii) 304	(i) Silurian grit (ii) 2.0x0.7x1.1 (iii) Cr>P	(i) Vertical (ii) Smooth (iii) SE: 30 (30e) NW: 48 (36e12u)	Medium bedded with moderately wide joints. Malham Formation: Cove Limestone	Sloping ground surrounded by regolith
(i) N22* (ii) SD 76582 70007 (iii) 306	(i) Silurian grit (ii) 1.3x0.5x0.7 (iii) Cr>P	(i) Vertical (ii) Uneven [1] (iii) SE: 33 (33e) NW: 32 (32e)	Medium bedded with wide joints. Malham Formation: Cove Limestone	Level ground on hill top surrounded by regolith
(i) N23 (ii) SD 76577 69707 (iii) 310	(i) Silurian grit (ii) 1.5x0.9x0.6 (iii) Cr>P	(i) Vertical (ii) Undulating (iii) SE: 36 (36e) NW: 20 (20e)	Thinly bedded with moderately wide joints. Malham Formation: Cove Limestone	Sloping ground with regolith to NW and rock- head to SE
(i) N24 (ii) SD 76727 69707 (iii) 244	(i) Silurian grit (ii) 2.6x1.6x0.7 (iii) Cr>P	(i) Vertical (ii) Uneven/plucked (iii) SE: 79 (58e,21u) NW: 29 (29u)	Thinly bedded with wide joints. Kilnsey Formation: Kilnsey Limestone	Sloping ground surrounded by regolith
(i) N25 (ii) SD 76800 69934 (iii) 285	(i) Silurian grit (ii) 2.1x0.5x2.0 (iii) Cr>P	(i) Vertical (ii) Smooth/plucked (iii) SE: 42 (42e) NW: 35 (35u)	Medium bedded with very wide joints. Malham Formation: Cove Limestone	Above glacial scar and surrounded by regolith
(i) N26 (ii) SD 76767 69889 (iii) 287	(i) Carboniferous limestone (ii) 1.6x1.1x0.7 (iii) Cr>P	(i) Vertical (ii) Uneven (iii) SE: 50 (50e) NW: 20 (20u)	Medium bedded with moderately wide joints. Malham Formation: Cove Limestone	Above glacial scar and surrounded by regolith
(i) N27 (ii) SD 76746 70010 (iii) 296	(i) Silurian grit (ii) 2.6x1.7x1.2 (iii) Cr>P	(i) Vertical (ii) n/a (not exposed) (iii) SE: 46 (46e) NW: n/a (not exposed)	Thickly bedded with moderately wide joints. Malham Formation: Cove Limestone	Sloping ground surrounded by regolith
(i) N28 (ii) SD 76147 70014 (iii) 342	(i) Silurian grit (ii) 2.3x1.6x0.5 (iii) Cr>P	(i) Vertical (ii) Smooth (iii) SE: 27 (27u) NW: 51 (51u)	Medium bedded with moderately wide joints Malham Formation: Cove Limestone.	Level ground surrounded by regolith
(i) N29 (ii) SD 76690 69859 (iii) 294	(i) Silurian grit (ii) 1.5x1.1x1.3 (iii) Cr>P	(i) Vertical (ii) Uneven (iii) SE: 53 (30e,23u) NW: 52 (16e,36u)	Medium bedded with moderately wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith
(i) N30 (ii) SD 76714 69970 (iii) 299	(i) Silurian grit (ii) 4.0x0.8x1.5 (iii) Cr>P	(i) Vertical (ii) Smooth/plucked (iii) NE: 21(21e) SE: 40 (40e) NW: 21 (21e)	Medium bedded with wide joints. Malham Formation: Cove Limestone	Level ground surrounded by regolith to NW and rock- head to SE
(i) N31 (ii) SD 76045 70048 (iii) 355	(i) Carboniferous limestone (ii) 1.3x?xo.9 (iii) ?	(i) Vertical (ii) ? (iii) Pedestal barely exposed, and	N/A	Wall built over it. Level ground surrounded by regolith

		composed of clasts?		
(i) N32 (ii) SD 76714 69969 (iii) 300	(i) Silurian grit (ii) 4x0.9x1.5 (iii) Cr>P	(i) Vertical (ii) Smooth/plucked (iii) SE: 21 (21e) and +40 (40e) NW: 22 (22e)	Medium bedded with wide joints. Malham Formation: Cove Limestone	Level ground partly surrounded by regolith and partly by bare rock

* Strictly speaking this is not a pedestal rock since the cap-rock has partially foundered

Table 5N.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5R: Runscar (SD 7679)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997)
British Geological Survey (1989): Settle. England and Wales Sheet 60. 1:500000 Series
Runscar is located about 1km to the north-east of Ribblehead (SD 7678) in North Yorkshire. It is best approached from the B6255 Ingleton (SD 6973) to Hawes (SD 8789) road, and is reached by about a 0.5km walk over soggy moorland to the north of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) R1 (ii) SD 76563 79638 (iii) 311	(i) Carboniferous limestone (ii) 1.3x1.3x0,7 (iii) Cr>P	(i) Vertical (ii) Gently undulating and smooth (iii) 54e+2u to NW	Medium bedded with moderately wide joints. Malham Formation: Gordale Limestone	Relatively steeply sloping hillside of scars and pasture-covered till

Table 5R.1: Perched pedestal rock location, salient features, solid geology and surrounding environs

Appendix 5SC: Scar Close (SD 7577)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997)
British Geological Survey (1997): Hawes. England and Wales Sheet 50. 1:50000 Provisional Series
Scar Close is located about 2km to the south-west of Ribblehead (SD 7678) in North Yorkshire. It is best approached from the B6255 Ingleton (SD 6973) to Hawes (SD 8789) road, and is reached by about a 1km walk over tracks to the south-east of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) SC1 (ii) SD 74840 77152 (iii) 358	(i) Carboniferous limestone (ii) 1.9x1.2x0.9 (iii) P>Cr	(i) Sloping (ii) Uneven (iii) 18e all round	Very thickly bedded with extremely wide joints. Malham Formation: Danny Bridge Limestone	Flat pavement partially covered in organic mat pH: 6.8 (SC1) pH: 6.9 (SC2). Many lily of the valley (*Convallaria majalis*) in solution hollows and grykes
(i) SC2 (ii) SD 74863 77208 (iii) 359	(i) Carboniferous limestone (ii) 1.3x1.1x0.5 (iii) P>Cr	(i) Sloping (ii) Flat (iii) 21e all round		
(i) SC3 (ii) SD 74963 77292 (iii) 354	(i) Carboniferous limestone (ii) 1.2x1.2x1.0 (iii) P>Cr	(i) Sloping (ii) Gently undulating (iii) 23e all round		
(i) SC4 (ii) SD 74472 77607 (iii) 358	(i) Carboniferous limestone (ii) 1.8x1.1x1.2 (iii) P>Cr	(i) N/A (ii) N/A (iii) N/A Carboniferous limestone clasts up to 30cm in size		Pasture-covered till

Table 5SC.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5SM: Scales Moor (SD 7177)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western area 1:25000 (1997)
British Geological Survey (1997): Hawes. England and Wales Sheet 50. 1:50000 Provisional Series
Scales Moor is located about 4km to the south-west of Ribblehead (SD 7678) in North Yorkshire. It is best approached from the hamlet of Chapel-le-Dale (SD 7377) immediately to the north of the B6255 Ingleton (SD 6973) to Hawes (SD 8789) road, and is reached by about a 2km walk over tracks and soggy moorland.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) SM1 (ii) SD 73253 78009 (iii) 323	(i) Carboniferous limestone (ii) 1.5x0.6x0.7 (iii) Cr>P to N, E and S, and P>Cr to W	(i) Vertical to N, E and S, and sloping 24º to W (ii) Planar (iii) 28e and 24u to N, E and S, and 13 to W	Medium bedded with very wide joints. Malham Formation: Danny Bridge Limestone	Dissected pavement of clint (up to 1.7m across), grykes (up to 0.5m across) and often vegetation-filled rundkarren surrounded by peat. Soil pH: 6.1
(i) SM2 (ii) SD 73246 78007 (iii) 323	(i) Carboniferous limestone (ii) 1x1x1 (iii) Cr>P to N, E and S, and P>Cr to W	(i) As above, but slope 20º (ii) As above (iii) 35e and 13u to N, E and S, and 13 to W		
(i) SM3 (ii) SD72451 77370 (iii) 375	(i) Carboniferous limestone (ii) 2x1x0.5 (iii) Cr>P to N and S, and P>Cr to E and W	(i) Vertical to N and S, and sloping 22º to E and W (ii) Not exposed (iii) 55e+15u to N and S, and 15 to E and W	Medium bedded with very wide joints. Malham Formation: Danny Bridge Limestone	Dissected pavement of clint (up to 0.8m across), grykes (up to 0.5m across) and often vegetation-filled rundkarren
(i) SM4 (ii) SD 71929 77303 (iii) 396	(i) Carboniferous limestone (ii) 1.3x1.3x1 (iii) P>Cr	(i) Sloping (ii) Smooth (iii) 15 in all directions	Medium bedded with wide joints Malham Formation: Danny Bridge Limestone	Dissected pavement with rounded edges. Clints cockly in parts
(i) SM5 (ii) SD 71907 77275 (iii)394	(i) Carboniferous limestone (ii) 1.5x1x0.5 (iii) Cr>P	(i) Vertical, though sometimes stepped (ii) Flattish (iii) 63e and ?u in all directions	Medium bedded with very wide joints. Malham Formation: Danny Bridge Limestone	Solution hollow covered in pasture

(i) SM6 (ii) SD 71159 76437 (iii) 398	(i) Carboniferous limestone (ii) 2x1.5x2 (iii) P>Cr	(i) Sloping (8-12º) (ii) Flattish (iii) 26 in all directions	Thinly bedded with very wide joints. Malham Formation: Danny Bridge Limestone	Dissected pavement with wide flattish clint. Indistinct rundkarren and few kamenitzas
(i) SM7[1] (ii) SD 72549 77227 (iii) 369	(i) Carboniferous sandstone (ii) 1x0.7x0.7 (iii) Cr >P	(i) Vertical in part, gryke sidewall to S and runnel to N, E and W (ii) Uneven (iii) 15 to N, E and W	Thinly bedded with very wide joints. Malham Formation: Danny Bridge Limestone	Dissected pavement with wide flattish clint. No rundkarren or kamenitzas within vicinity
(i) SM8 (ii) SD 71781 77164 (iii) 393	(i) Carboniferous limestone (ii) 3x2.1x0.7 (iii) Cr>P to N, S and W, and P>r to E	(i) Vertical (but flares out at rock-head). (ii) Flat (iii) 46 to N, S and W, and 22 to E	Medium bedded with very wide joints. Malham Formation: Danny Bridge Limestone	At the bottom of a shake hole some 1m deep
(i) SM9 (ii) SD 72889 77730 (iii) 345	(i) Carboniferous limestone (ii) 1.7x1.2x0.8 (iii) Cr=P to N, E and W, but Cr>P to S	(i) Vertical to N, E and W, but sloping (10º) to S (ii) Flat with possible striae 082/262º (iii) Up to 99 (84e and +15u) to N, up to 76 (61u and +15u) to E and W, and 10 to S.	Very thickly bedded with wide joints. Malham Formation: Danny Bridge Limestone	Much divided clint with solution hollows (both may be several meters across) surrounded by peat. Soil pH: 4.22
(i) SM10 (ii) SD 71404 76635 (iii) 396	(i) Carboniferous limestone (ii) 0.7x0.7x0.6 (iii) P>Cr	(i) Sloping (ii) Not exposed (iii) 16 (?).	Malham Formation: Danny Bridge Limestone	
(i) SM11[2] (ii) SD 71404 76635 (iii) 396	(i) Carboniferous sandstone (ii) 0.4x0.4x0.4 (iii) No pedestal	N/A	Malham Formation: Danny Bridge Limestone	In gryke
(i) SM12 (ii) SD 70684 75997 (iii) 406	(i) Carboniferous limestone (ii) 1.5x1.1x1.1 (iii) Cr >P	(i) Vertical (ii) Flat (iii) 22e 4u to E, 29e to NW.	Malham Formation: Danny Bridge Limestone	
(i) SM13 (ii) SD 71347 76592 (iii) 388	(i) Carboniferous limestone (ii) 1.5x1x1.3 (iii) P>C-r	(i) Sloping (ii) Not exposed (iii) 23	Very thickly bedded with extremely wide joints. Malham Formation: Danny Bridge Limestone	Dissected pavement with wide flattish clint. Indistinct rundkarren and few kamenitzas
(i) SM14 (ii) SD 71438 76552 (iii) 398	(i) Carboniferous limestone (ii) 3.5x2.1x1 (iii) P>Cr	(i) Sloping (22º) and vertical (ii) Not exposed (iii) vertical 34e and 11u, and sloping 13	Barely exposed. Malham Formation: Danny Bridge Limestone	Nettles

[1] Strictly speaking this is not a pedestal rock since the cap rock has partly toppled off its pedestal
[2] This is not a pedestal rock but a Carboniferous sandstone erratic in a gryke

Table 5SM.1: Perched pedestal rock locations, salient features, solid geology and surrounding environrons

Appendix 5SW: Semer Water (SD 9287) – The Carlow Stone

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 30 Yorkshire Dales: Northern and Central areas 1:25000 (1984)
British Geological Survey (1997): Hawes. England and Wales Sheet 50. 1:50000 Provisional Series
Semer Water is located about 3km to the south-west of the market town of Bainbridge (SD 7678) in North Yorkshire. It is best approached from the minor road that runs from Bainbridge to the hamlet of Countersett (SD 9287). The Carlow Stone is situated next to the road that runs along the moraine at the northern end of the lake

Location **(i) Mushroom rock number** **(ii) O.S. GR** **(iii) Altitude (to within 10m)**	**Salient features**	**Surrounding environs**
(i) SW1 (ii) SD 92173 87558 (iii) 260	The Carlow Stone is approximately 4x2x1.8m in size. It is mushroom-shaped to the W, N and E with vertical pedestal sidewalls some 70cm in height. Its cap overhangs the pedestal by about 1m to the W and E, and 30cm to the N; the cap under-surface is more-or-less horizontal. The S wall is water-worn at its base.	Surrounded by soil/till and some rank vegetation, and a car-park. The shore of Semer Water is some 25m to the south. The ph of water samples analysed at Leeds University on 13-11-04 was 6.3, 6.4, 6.4.

Table 5SW.1: Mushroom pedestal rock location, salient features and surrounding environs

Appendix 5TD: Twyn Du (SN 8316)

Site OS and BGS maps, and location

Ordnance Survey Explorer OL12 Parc Cenedlaethol Bannau Brycheiniog: Ardaloedd gorllewinol a chanalog 1:25000 (2002)
British Geological Survey (1979): Merthyr Tydfil. England and Wales Sheet 231. 1:50000 Series
Twyn Du is located about 5km to the north-east of the village of Abercraf (SN 8212) in Powys, close to Dan-yr-Ogof Caves (SN 8315). It is best approached from the A4067 Abercraf to Defynnog (SN 9227) road, and is reached by about a 1.5km walk over rough tracks to the north-west of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) TD1 [1] (ii) SN 83242 17038 (iii) 437	(i) Devonian conglomerate (ii) 1.4x1x0.7 (iii) Cr = P (?)	(i) vertical (ii) N/A (ii) 65e+3u in all directions	Medium bedded with wide joints. Main Limestone Group: Cil-yr-ychen Limestone	Undulating ground dipping some 10º to the S with bare dissected pavement and pasture on drift. No rundkarren present
(i) TD2 [2] (ii) SN 83398 17010 (iii) 444	(i) Devonian conglomerate (ii) 0.9x0.9x0.6 (iii) N/A	(i) N/A (ii) N/A (iii) N/A	Medium bedded with moderately wide joints. Main Limestone Group: Cil-yr-ychen Limestone	

[1] Strictly speaking TD1 not a pedestal rock since the cap-rock has partly toppled off
[2] TD2 is not a pedestal rock

Table 5TD.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5UW: Underlaid Wood (SD 4878)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern area 1:25000 (1998)
British Geological Survey (1892): Kirkby Lonsdale. England and Wales Sheet 49. 1:63360 Old Series
Underlaid Wood is located about 2km to the south-east of the coastal town of Sandside (SD 4780) in Cumbria. It is best approached from the minor road that runs southwards from Sandside to Hazelslack (SD 4778), and is reached by about a 1km walk over tracks to the east of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) UW1 (ii) SD 48485 78861 (iii) 73	(i) Carboniferous limestone (ii) 1.5x1.1x1.1 (iii) P>Cr	(i) Sloping (ii) Even (ii) 8cm in all directions	Thickly bedded with wide joints Carboniferous Limestone (undifferentiated)	Mainly wooded with *Sphagnum* and arboreal litter

Table 5UW.1: Perched pedestal rock location, salient features, solid geology and surrounding environs

Appendix 5W: Winskill (SD 8366)

Site OS and BGS maps, and location

Ordnance Survey Outdoor Leisure 2 Yorkshire Dales: Southern and Western areas 1:25000 (1997)
British Geological Survey (1989): Settle. England and Wales Sheet 60. 1:500000 Series
Winskill is located about 2km to the north-east of the village of Langcliffe (SD 8265) in North Yorkshire. It is best approached from the minor road that runs from Langcliffe to Malham (SD 9063), and is reached by about a 0.5km walk along a track to the north-west of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) W1 (ii) SD 83178 66228 (iii) 340	(i) Silurian grit (ii) 3x3x1.5 (iii) Cr>P	(i) Vertical (ii) Gently undulating and smooth (iii) 63e+3u to SW 16e to NE	Thinly bedded with moderately wide joints. Malham Formation: Gordale Limestone	Relatively steeply sloping hillside of scars and pasture-covered till. pH: 6.1

Table 5W.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

Appendix 5YG: Y Gogarth (SH 7682)

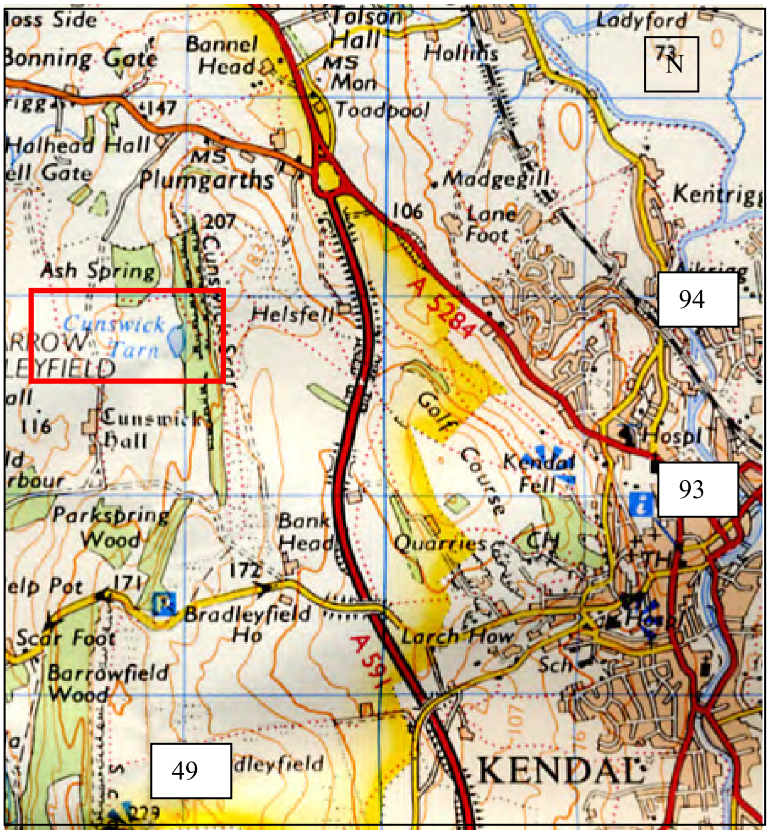
Site OS and BGS maps, and location

Ordnance Survey Explorer OL17 Yr Wyddfa: Taflen y Gorllewin 1:25000 (2006)
British Geological Survey (1989): Llandudno. England and Wales Sheet 94. 1:50000 Series
Y Gogarth is located about 2km to the north-west of the coastal resort of LLandudno (SH 7882) in Gwynedd. It is best approached from the minor road that crosses Great Orme (SH 7683), and is reached by about a 1km walk along a track to the north-west of the road.

(i) Pedestal rock No. (ii) British GR (iii) Altitude (to within 10m)	**(i) Caprock rock type (ii) Caprock size (m) (iii) Relative caprock (Cr) and pedestal (P) sizes**	**Pedestal (i) sidewall and (ii) crown surface forms (iii) approximate height (cm) and facing direction (u: unexposed and e: exposed)**	**Pedestal rock mass description and solid geology**	**Surrounding environs**
(i) YG1 (ii) SH 76858 82916 (iii) 202	(i) Carboniferous limestone (ii) 1.8x1.7x1.4 (iii) Cr>P to S but P>Cr to N	(i) Sloping steeply (32°) to S but gently (9°) to N (ii) Smooth (iii) 18 all round	(Bedding barely exposed). Very wide joints. Dyserth Limestone Group: Great Orme Limestone	Undulating ground dipping 10°/316° with pasture on thin regolith
(i) YG2 (ii) SH 76120 84029 (iii) 158	(i) Carboniferous limestone (ii) 2.3x2.1x1.7 (iii) N/A	(i) Vertical to W (ii) Smooth (iii) Maximum of 15u	(Bedding barely exposed). Very wide joints. Dyserth Limestone Group: Great Orme Limestone	Undulating ground dipping 10°/108° with pasture on thin regolith pH: 7.6

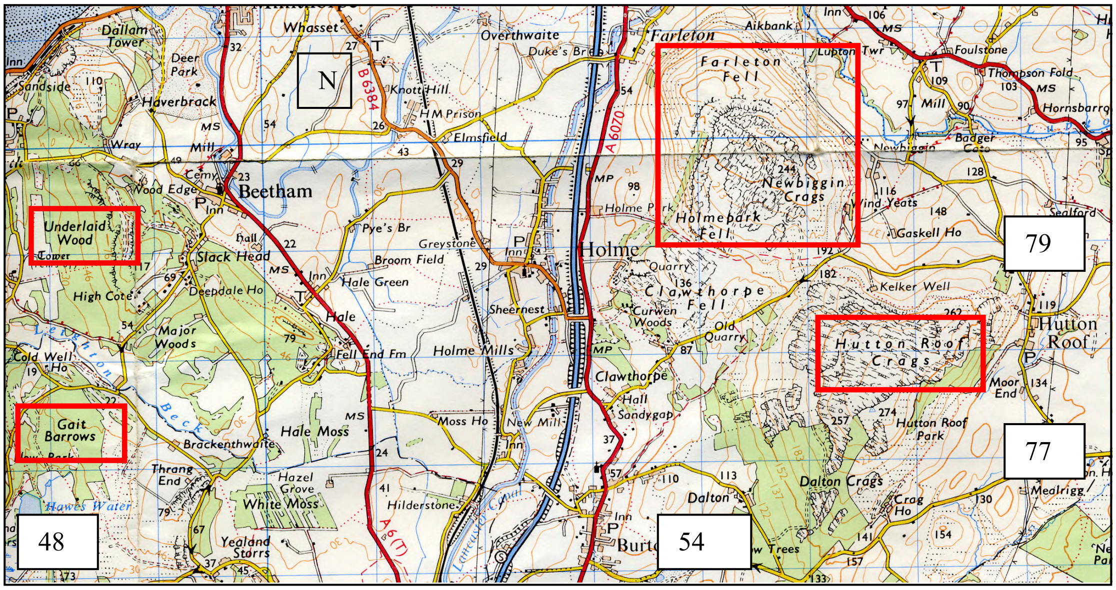
Table 5YG.1: Perched pedestal rock locations, salient features, solid geology and surrounding environs

APPENDIX 6: PEDESTAL-ROCK SITE LOCATION MAPS



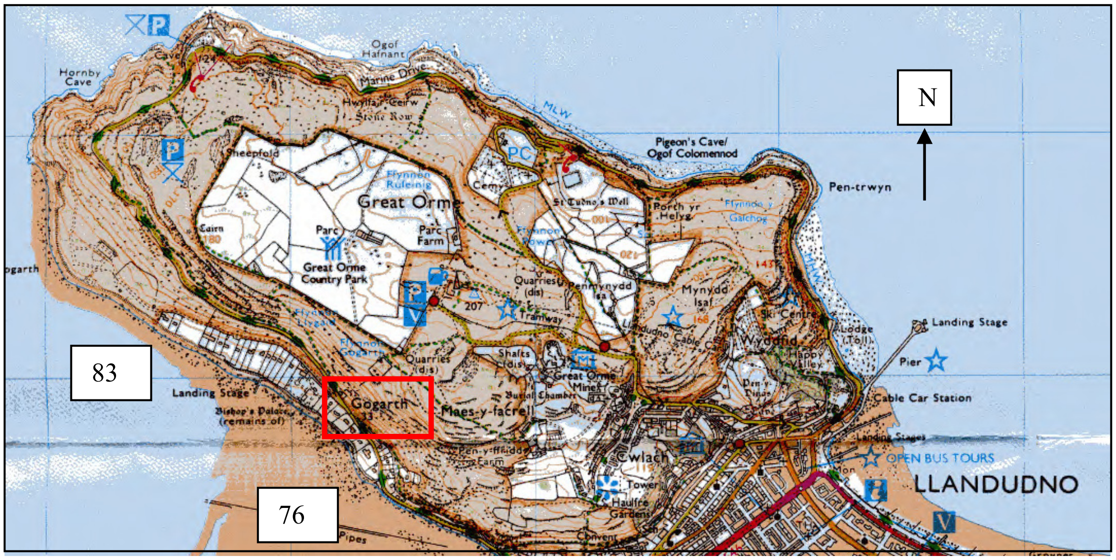
Ordnance Survey Outdoor Leisure 7 The English Lakes: South Eastern areas 1:25000 (1998)

Fig. A6.1: Location of Cunswick Tarn (SD 4893), Cumbria, England (courtesy of the Ordnance Survey, Southampton)



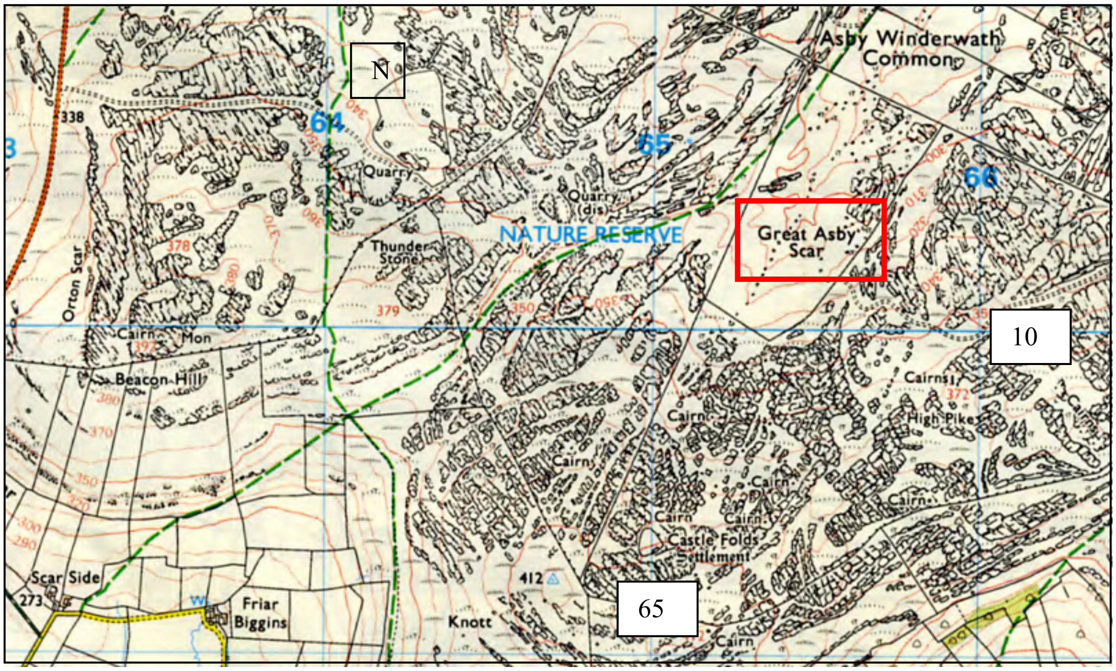
Ordnance Survey Sheet 97 Kendal and Morecambe 1:50000 (1974)

Fig. A6.2: Locations of Farleton Knot (Farleton Fell/Newbiggin Crags/Holmepark Fell) (SD 5480), Hutton Roof Crags (SD 5577) and Underlaid Wood (SD 4878), Cumbria, and Gait Barrows (SD 4877), Lancashire, England (courtesy of the Ordnance Survey, Southampton)



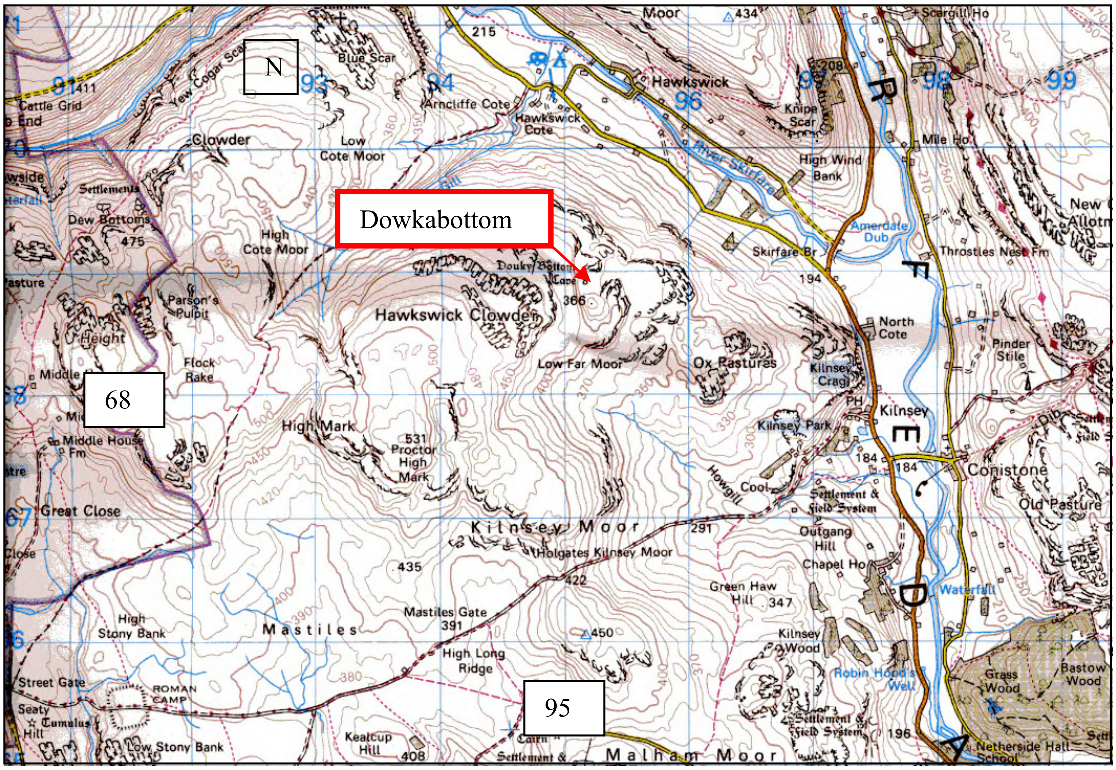
Ordnance Survey Explorer OL17 Yr Wyddfa: Taflen y Gorllewin 1:25000 (2006)

Fig. A6.11: Location of Y Gogarth (SH 7682), Gwynedd, Wales (courtesy of the Ordnance Survey, Southampton)



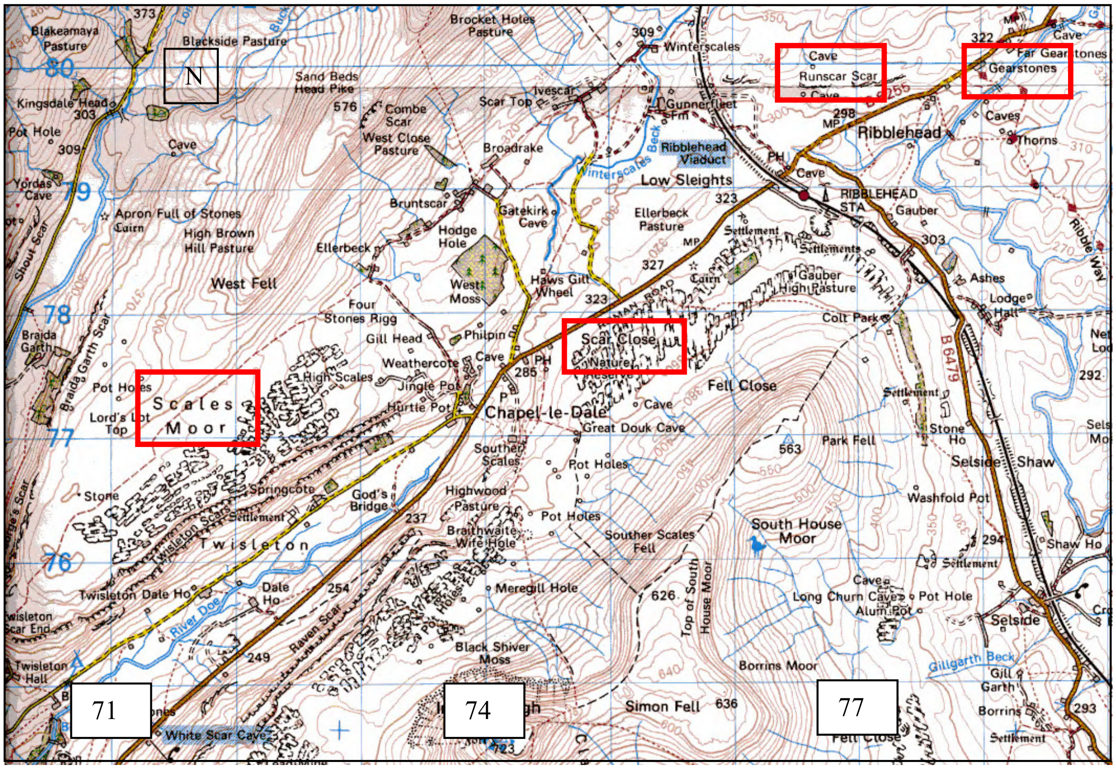
Ordnance Survey Outdoor Leisure 19 Howgill Fells and Upper Eden Valley 1:25000 (1995)

Fig. A6.3: Location of Great Asby Scar (NY 6510), Cumbria, England (courtesy of the Ordnance Survey, Southampton)



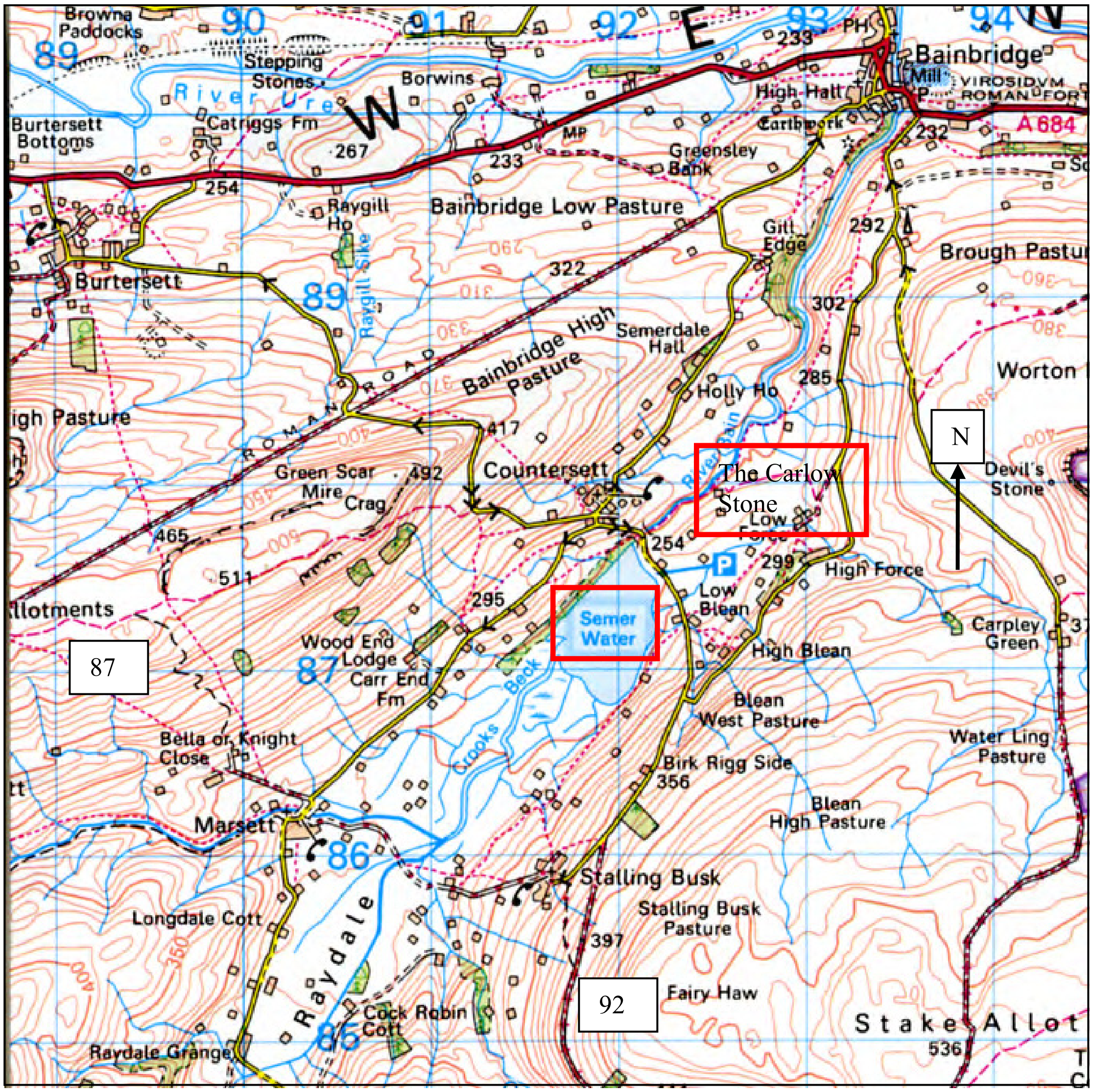
Ordnance Survey sheet 98 Wensleydale and Upper Wharfedale 1:50000 (1999)

Fig. A6.4: Location of Dowkabottom (SD9568), North Yorkshire, England (courtesy of the Ordnance Survey, Southampton)



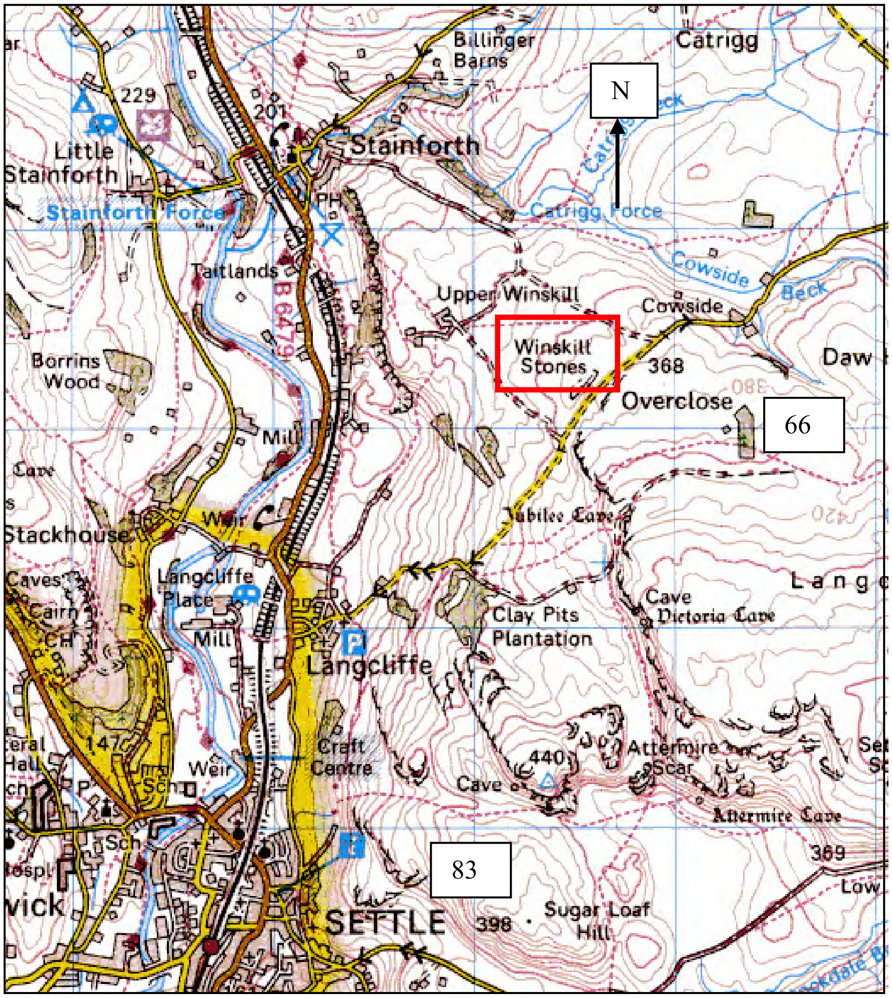
Ordnance Survey sheet 98 Wensleydale and Upper Wharfedale 1:50000 (1999)

Fig. A6.5: Locations of Gearstones (SD 7779), Runscar (SD 7679), Scales Moor (SD 7177) and Scar Close (SD 7577), North Yorkshire, England (courtesy of the Ordnance Survey, Southampton)



Ordnance Survey sheet 98 Wensleydale and Upper Wharfedale 1:50000 (1999)

Fig. A6.6: Location of Semer Water: the Carlow Stone (SD 9287), North Yorkshire, England (courtesy of the Ordnance Survey, Southampton)

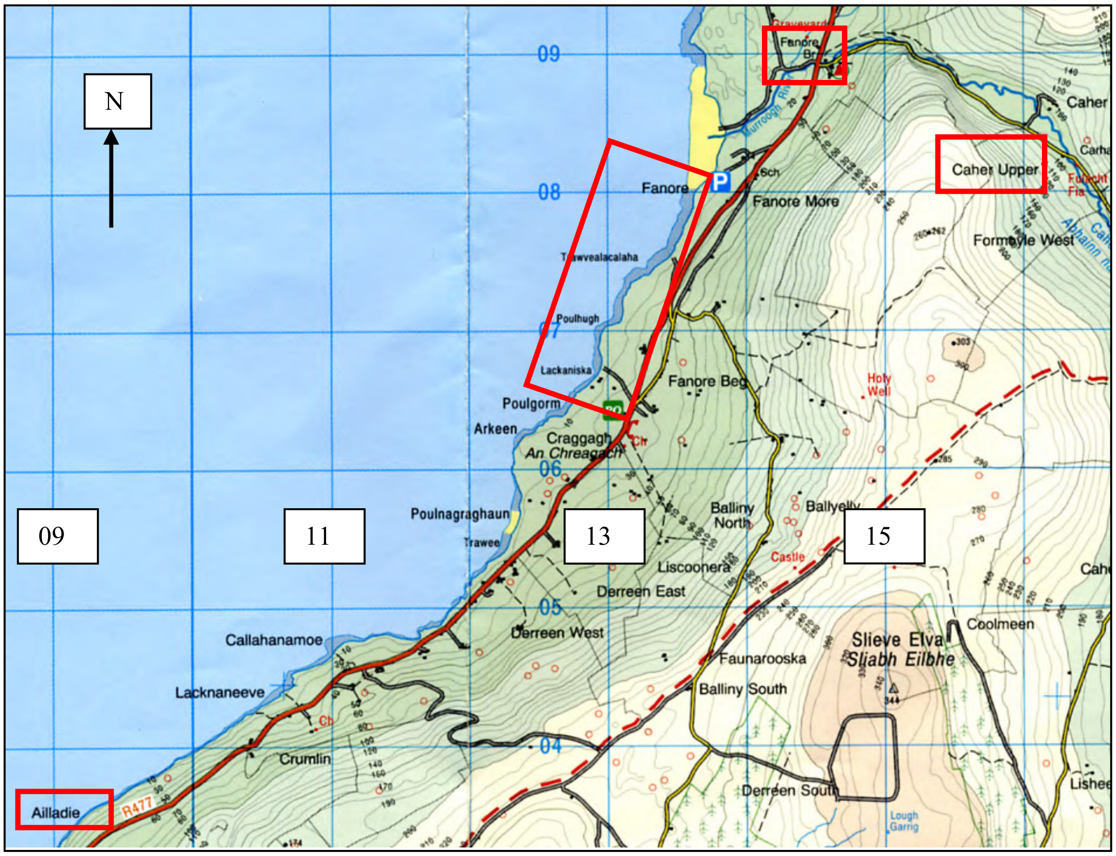


Ordnance Survey sheet 98 Wensleydale and Upper Wharfedale 1:50000 (1999)

Fig. A6.7: Location of Winskill Stones (SD 8366), North Yorkshire, England (courtesy of the Ordnance Survey, Southampton)

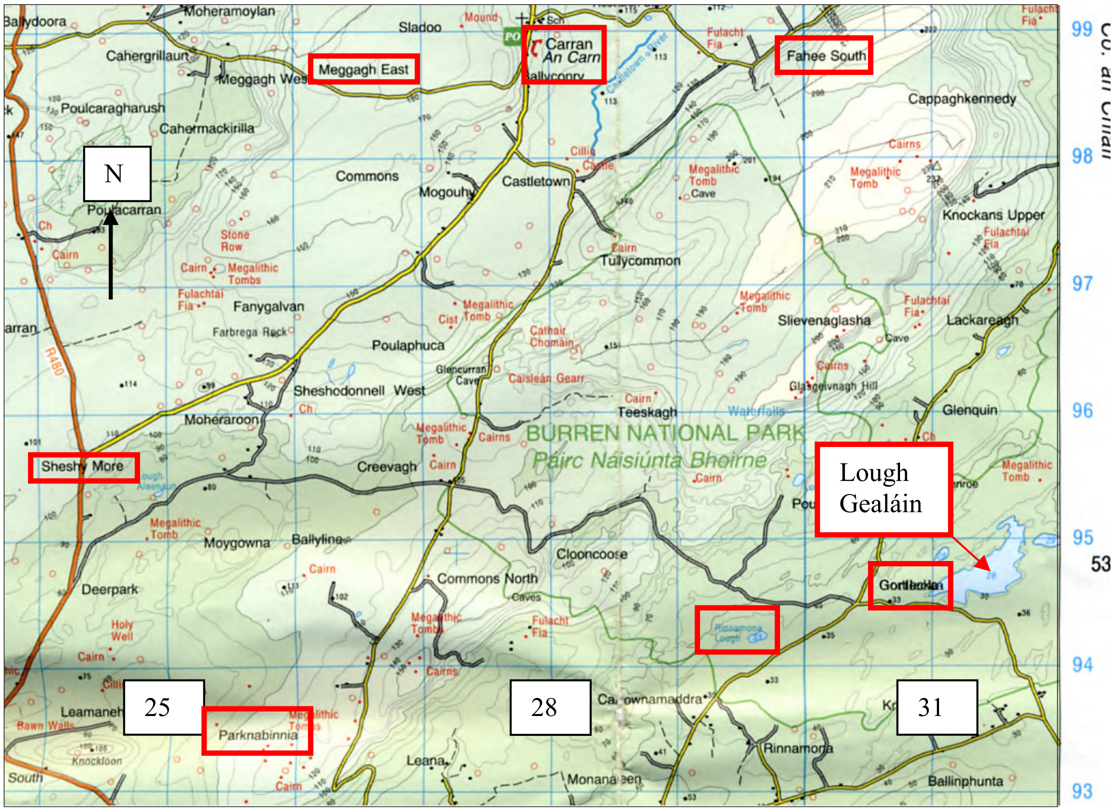
Ordnance Survey of Northern Ireland Sheet 26 Lough Allen 1:50000 (1984)

Fig. A6.8: Location of Marlbank (H 1034), Co. Fermanagh, Northern Ireland, and the Cavan Burren (H 0735), Co. Cavan, the republic of Ireland (courtesy of the Ordnance Survey of Northern Ireland, Belfast)



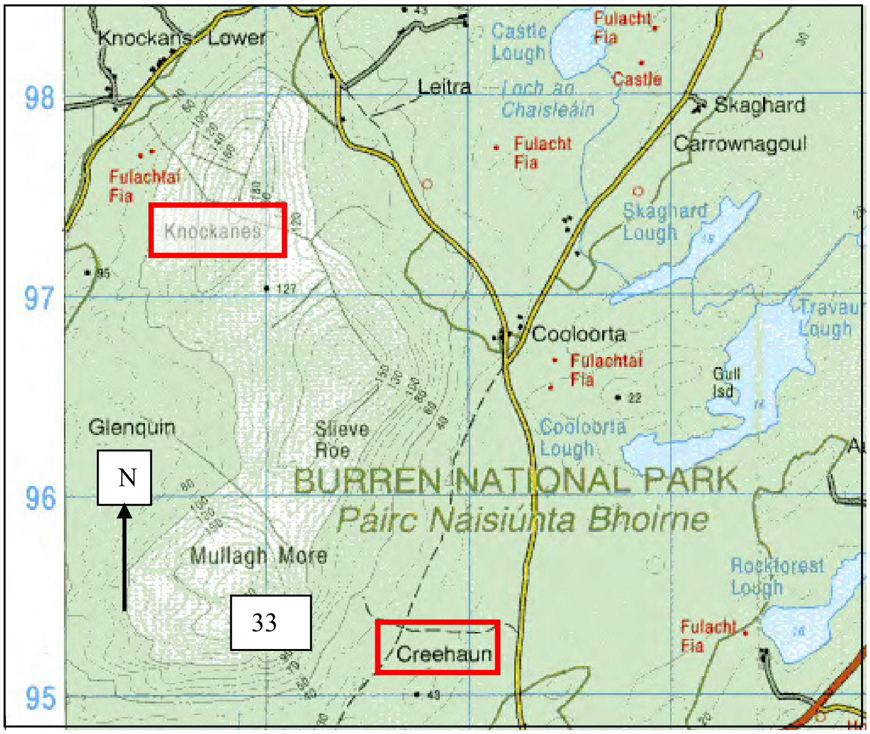
Ordnance Survey Ireland Discovery Sheet 51 Clare, Galway 1:50000 (2002)

Fig. A6.9.1: Locations of Ailadie (M 0903), Caher Upper (M 1508), Fanore to Lackaniska (M 1308-M 1206) and Fanore Bridge (M 1409), the Burren, Co. Clare, Republic of Ireland (courtesy of Ordnance Survey Ireland, Dublin)



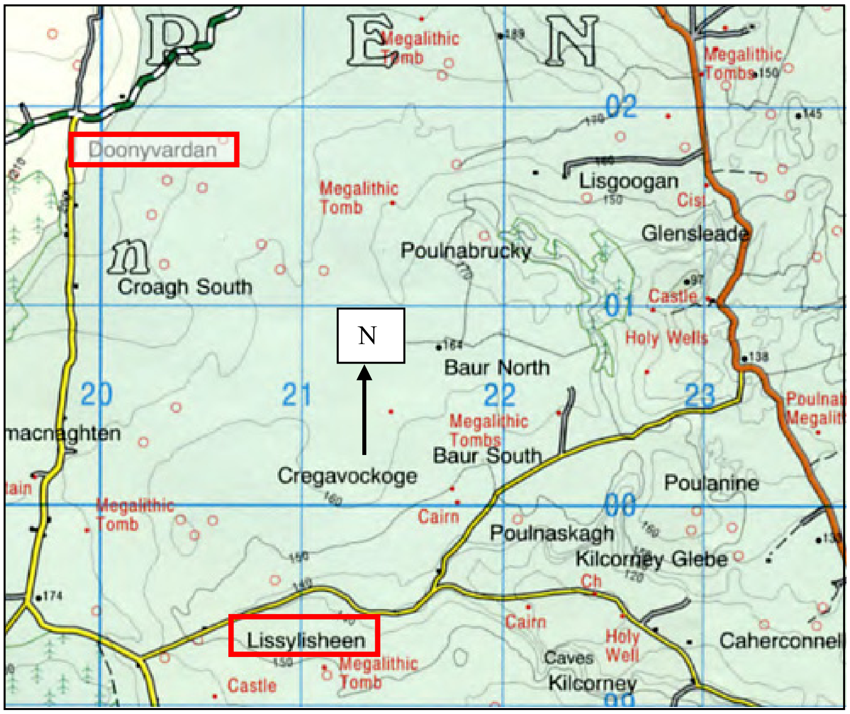
Ordnance Survey Ireland Discovery Sheet 51 Clare, Galway 1:50000 (2002)

Fig. A6.9.2: Locations of Carran (R 2898), Fahee South (R 2998), Gortlecka (R 3094), Lough Gealáin (R 3194), Meggagh East (R 2698), Parknabinnia (R 2593), Rinnemona Lough (R 2994) and Sheshymore (R2495), the Burren, Co. Clare, Republic of Ireland (courtesy of Ordnance Survey Ireland, Dublin)



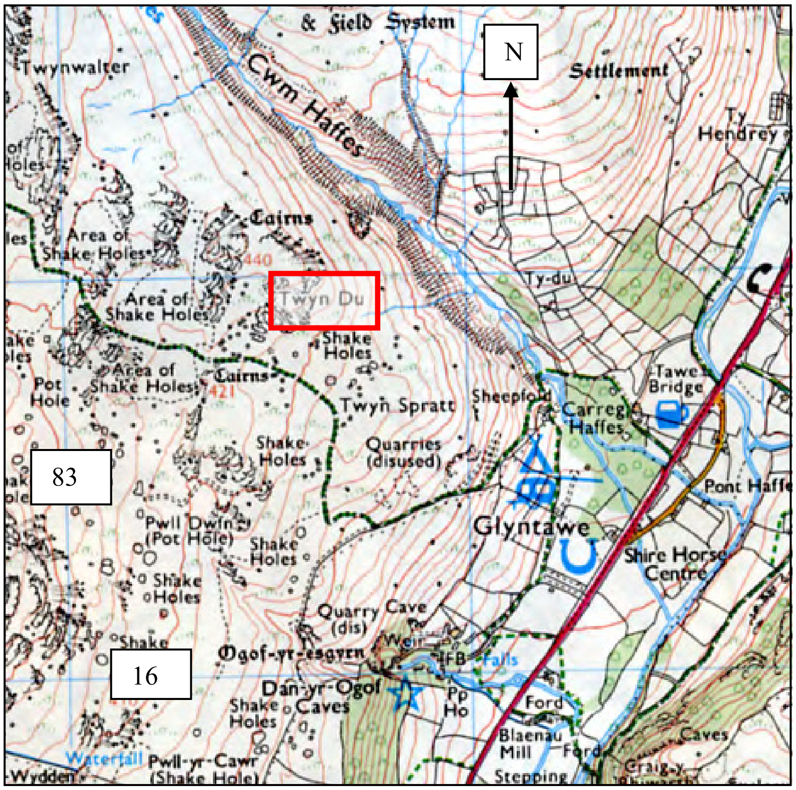
Ordnance Survey Ireland Discovery Sheet 52 Clare, Galway 1:50000 (2003)

Fig. A6.9.3: Locations of Creehaun (R 3395) and Knockanes (R 3297), the Burren, Co. Clare, Republic of Ireland (courtesy of Ordnance Survey Ireland, Dublin)



Ordnance Survey Ireland Discovery Sheet 51 Clare, Galway 1:50000 (2002)

Fig. A6.9.4: Locations of Doonyvardan (M 1901) and Lissylisheen (R 2099), the Burren, Co. Clare, Republic of Ireland (courtesy of Ordnance Survey Ireland, Dublin)



Ordnance Survey Explorer OL12 Parc Cenedlaethol Bannau Brycheiniog: Ardaloedd gorllewinol a chanalog 1:25000 (2002)

Fig. A6.10: Location of Twyn Du (SN 8316), Powys, Wales (courtesy of the Ordnance Survey, Southampton)