British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Westmorland Geological Society
THE MILLENNIUM MAPPING PROJECT

Geology of the area between Lindale and Witherslack

Geology and Landscapes Northern Britain Programme

Internal Report IR/06/079

BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPES NORTHERN BRITAIN PROGRAMME

INTERNAL REPORT IR/06/079

Geology of the area between Lindale and Witherslack

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Keywords

Report; Cumbria; Kirkby Lonsdale; Silurian; Carboniferous.

Front cover

Outcrops of the Bannisdale Formation on Barrow Hollin looking eastwards to Whitbarrow Crag and the Yorkshire Dales. (Photo: M E Dewey)

Bibliographical reference

THOMAS, P R. 2005. Geology of the area between Lindale and Witherslack. *British Geological Survey Internal Report*, IR/06/079. 39pp.

Keyworth, Nottingham British Geological Survey 2006

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Foreword

This report, and the 1:10 000-scale geological sheet SD48SW which it describes, are the products of the Westmorland Geological Society's 'Millennium Mapping Project'. From 2000 until 2003 a team of over twenty members of the Society, supervised by P R Thomas and C R Rowley, completed the geological survey of the area between Lindale and Witherslack. The Project has been led throughout by P R Thomas. During the project, members of the Society sought advice on current BGS practice and standards from D Millward and M McCormac; they, and I C Burgess and N J Soper also participated in field workshops with the mapping team. To my knowledge this is the first time that a Geological Society has embarked upon such a venture with such a successful outcome. The project has been funded entirely by their members.

This area lies within the British Geological Survey 1:50 000-scale geological series Sheet 49, Kirkby Lonsdale. Resurvey of this district is currently underway as part of the Geology and Landscapes of Northern Britain Programme. The Westmorland Geological Society's original report forms the basis of this publication in the Internal Report series. The BGS acknowledges the contribution of the Society to the understanding of the geology of this area and recognises its copyright of the original documents. The BGS is also pleased to be able to incorporate information from this high quality work in the new edition of Sheet 49 and in the *Sheet Description* and *Sheet Explanation* that will accompany it. This published report has been edited by M McCormac and D Millward.

Dr Martin Smith
GLNB Programme Manager.

Note

In this report 'district' refers to the area covered by Ordnance Survey National Grid sheet SD48SW.

Numbers in square brackets are National Grid references. Unless otherwise indicated, all the references lie within the 100 km square SD.

Acknowledgements

This report was produced voluntarily by the Westmorland Geological Society, as their Millennium Mapping Project. It was funded by all those who contributed time and effort either in the field or at home to complete the project.

Twenty three members of the Westmorland Geological Society have contributed to the project. Most of this assistance was received at the mapping stage of the study. Key members of the Mapping Project have helped to review draft chapters of this report. Of the many members who have contributed to the project we would particularly like to thank the following: P R Thomas, J M Balderstone, M E Dewey, G V Dewey and C R Rowley, and also our Chairman, M H Parsons and our President, S K Monro for their continuous encouragement.

Useful help and advice was given by D Millward and M McCormac of BGS, Edinburgh, and N J Soper and I Burgess, who have been involved in mapping adjacent Sheets. BGS also supplied the base maps, provided borehole logs and original field maps for us to view at Murchison House and loaned the Society aerial photographs to cover the sheet.

We would also like to thank the Holker Estates, Halecat Estate and individual farmers of the Winster Valley for allowing access to their land.

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Summary

This report describes the bedrock and superficial deposits of the area between Lindale and Witherslack in Cumbria as depicted on 1:10 000-scale geological series sheet SD48SW, part of 1:50 000 geological series sheet 49 (Kirkby Lonsdale). The report should be read in conjunction with the map. The report and map were the result of a project undertaken by members of the Westmorland Geological Society.

The bedrock succession comprises almost 3000 m of upper Silurian strata belonging to the highest part of the Windermere Supergroup. The uppermost unit of this sequence, the Kirkby Moor Formation has been recognised in this district for the first time. The mudstone and sandstone turbidites were folded and cleaved during the Acadian Orogeny. These rocks are overlain unconformably by a succession of limestones assigned to the Lower Carboniferous Great Scar Limestone Group.

Bedrock is covered by a variable thickness of Quaternary deposits that range from sediments laid down as a result of melting of the Devensian ice sheet that covered the area, to the deposits of rivers and of Morecambe Bay. Deposits associated with a glacier within the Winster valley were influenced by the presence of a major rock barrier at its southern end. A late-glacial tufa deposit from the Whitbarrow Lodge area is described and interpreted to have filled an englacial tube.

1 Introduction

This report describes the bedrock geology and superficial deposits of the area around Lindale and Witherslack on the north side of Morecambe Bay in Cumbria. It accompanies 1:10 000 geological sheet SD48SW. This area is included within the 1:50 000 geological series sheet 49 (Kirkby Lonsdale). The rural landscape of the north and west of the Lindale and Witherslack district is dominated by north–south rocky ridges and intervening drift-filled valleys. To the south-east the ground is largely low-lying agricultural land, and formerly part of Morecambe Bay.

The village of Lindale lies at the southern end of a north-north-west trending rocky ridge reaching a maximum elevation of 214 m at Raven Crag. It is separated from the broad mass of Hampsfell to the south-west, by the Newton Gap and the A590, which follows the line of the Lindale Fault.

The River Winster, to the east of Newton Fell, forms a valley that drains southwards (currently at 4–7 m aOD) into the flat lowlands of the Morecambe Bay coast. Bleacrag [423 838], 2 km west of the small village of Witherslack, is the site of a rock barrier (maximum elevation 40 m above OD), only narrowly breached by the River Winster. Upstream, the bottom of the valley is also flat and was once occupied by a post-glacial lake, a remnant of which is Helton Tarn [419 849].

To the east of the Winster Valley the ground at first rises in a series of low scarps across the Halecat area and then steepens abruptly on to Yewbarrow [434 845], a north–south orientated limestone ridge reaching a maximum elevation of 128 m. To the south, the ridge drops in elevation and meets the former coastline of Morecambe Bay at Catcrag on the A590. It appears to rise again at Meathop [439 808] on the southern margin of the district.

The Yewbarrow fault line to the east of the ridge marks a further change in topography. Drumlinoid farmland in the north, gives way eastwards to hummocky rock outcrops at low elevations before the massive scarp of Whitbarrow Fell is reached in the far north-east corner of the district. The area, known as 'Rocky Common', is poorly drained although numerous, generally dry, channels have been carved by ice meltwater towards the south.

In the south-eastern part of the district, where the ground is no more than a few metres above sea level, large areas of peat have developed. Whereas many of these have been afforested in the past, they have recently started to be deforested in order to preserve the ecosystem represented by the raised peat bogs. Many of the peat areas would have been more extensive in the past, but a great deal of peat cutting has taken place.

1.1 PREVIOUS SURVEYS

Early work on the geology of the southern Lake District can be initially attributed to J Otley, who in 1823 published a guide book to the Geology of the Lake District. He recognised the presence of the three main groups of rocks, referring to them as 'clayslate' for what is now known as the Skiddaw Group, 'greenstone' for the Borrowdale Volcanic Group and 'greywacke' for the Windermere Supergroup. Sedgwick (1845) initially called the upper part of the latter group the Ireleth Slates, but later changed this to Bannisdale Slates, a name adopted by the Geological Survey in the memoir for the eastern part of the Kirkby Lonsdale Sheet (Aveline et al., 1872). However, it was not until later that Marr (1916), first described the banded nature of the Bannisdale Slates. More recently these rocks have been referred to formally as the Bannisdale Slate Formation (e.g. Lawrence et al., 1986) and the Bannisdale Formation (e.g. Kneller et al., 1994).

Both the Bannisdale 'slates' and the overlying Carboniferous limestones were mapped by the Geological Survey of England and Wales on the 1:10,560 Ordnance Survey base maps and published in 1869. Some data from the original field maps has been included on the current map. Descriptions by Aveline, McKenny-Hughes and Tiddeman appeared in the Kirkby Lonsdale and Kendal District Memoir of 1872, which covered much of the Old Series 1 inch quarter sheet 98 SE. The Carboniferous succession was later divided biostratigraphically by Garwood (1913), but much of the stratigraphical nomenclature adopted for the Dinantian rocks is currently based on the lithostratigraphical divisions of Rose and Dunham (1941, 1977) in the Furness area and Johnson et al. (2001) in the Ulverston district.

There is little published geomorphological work before that of Gresswell (1958), although investigations of the sediments in Helton Tarn by Smith (1959) provided evidence of a Holocene marine incursion. The effects of ice advance and retreat have been recorded during the present mapping, together with more recent post-glacial deposition associated with the Winster valley and Morecambe Bay.

To summarise, few detailed descriptions have been published on the geology of the area covered by Sheet SD48SW, prior to the present work.

1.2 GENERAL SUCCESSION

The oldest rocks in the district comprise folded and cleaved muddy siltstones and sandstones of the upper Silurian Bannisdale Formation. Whilst the succession is generally lithologically monotonous, sedimentary features are sporadically preserved which enable the sedimentology to be studied in more detail. It has also been possible to estimate the thickness of the succession in the district, which contains fewer coarse turbidite units than in the area to the west. The overlying Kirkby Moor Formation is recognised for the first time south of Whitbarrow.

The Silurian rocks are overlain unconformably by a succession of limestones belonging to the Great Scar Limestone Group. New exposures of several of the formations have been recorded in detail.

Apart from some joint fillings of probable Permo-Triassic age, no exposures of post-Carboniferous rocks have been found in the district.

Quaternary deposits, in the form of overconsolidated diamicton, have been differentiated from ablation tills and granular glaciofluvial deposits formed during the melting phases of the late Devensian ice-sheet. Postglacial alluvial and lacustrine deposits give way southwards to tidal flat deposits laid down during former sea-level highstands in the Morecambe Bay area.

Later, raised peat forms the youngest sediments, as many of the talus slopes are weakly cemented and of probable late-glacial to early postglacial origin.

2 Silurian rocks

2.1 BANNISDALE FORMATION

The Bannisdale Formation to the west and to the north of this area has been well documented by the work of Lawrence et al. (1986), Soper (1993), and Kneller et al. (1994). It is the thickest formation in the upper part of the Windermere Supergroup and is thought to be Ludlow in age.

In the Lindale–Witherslack district the formation is well exposed over more than 10 km^2 of outcrop. The most continuous exposures occur on the ridges running northwards from Lindale and High Newton, notably Newton Fell, Barrow Hollin, and the area south of Height Farm. In the Winster valley there are numerous small exposures and a well exposed rock barrier between the foot of Tow Top road and Blea Crag [4141 8337 to 4234 8384]. Good exposures also occur to the east of Yewbarrow, where upfaulted rocks near the top of the Bannisdale Formation dip eastwards under the Kirkby Moor Formation, at what appears to be a disconformable junction.

Exposure is lost to the south and east of the district under a thick blanket of postglacial deposits, although slaty mudstone was proved in one borehole [4454 8082] south of Meathop Moss. Proof of the continuous occurrence of the Bannisdale Formation is found near Low Meathop Farm [432 800] and north of Ulpha Farm [449 821], where the topmost Bannisdale sandstone is again exposed under the Kirkby Moor Formation. The base of this formation crops out immediately to the east, on the adjacent sheet (SD48SE).

2.1.1 Lithology

The Bannisdale Formation is composed of mudstone, muddy siltstone and muddy sandstone in which layering ranges from fine lamination up to thick-bedded units. The sequence is characterised by the commonly changing occurrence of the following lithologies:

1. Muddy siltstone, which can have a massive appearance overprinted by a closely spaced, slaty cleavage.

2. Banded mudstone with siltstone or sandstone, which display a banded appearance in the form of laminations or centimetre-thick couplets of mudstone interbedded with either siltstone or sandstone. Grading and cross- laminations may develop in these regularly layered turbidites (Plate 1).

3. Sandstone is mapped as separate units within the Bannisdale Formation, either as thickly bedded units or thinner, units which contain more than 50% sand-size lithologies. Many of the distinct sandstone layers are impersistent, lenticular bodies, typically 10–30 m thick. They are commonly found to the west of Newton Fell and Barrow Hollin, but become less frequent towards the east, with the exception of (a) the area around the Bleacrag rock barrier [425 840], (b) the uppermost 100 m of the Formation at Bull Bridge [447 842] near Millside and (c) in the extreme east of the area, north-west of Ulpha Fell [450 821]. Notable localities of the massive sandstone units include those immediately south of the bypass at Lindale [4139 8071], in fields east of Bowes Lodge in the Winster valley [4257 8340] and on the east shore of High Newton reservoir [401 841]. The sandstone lenses may be interpreted as submarine channel deposits which are mainly concentrated in the northern and western parts of the area. There are some examples of incomplete Bouma-type turbidite sequences. One is exposed north of the road at Rocky Common [4447 8385] and another adjacent to the footpath south of the Lindale bypass, 0.5 km west of the roundabout [4274 8130] at Meathop. No proximal turbidite unit of coarse-grained sandstone or conglomerate has been found.

The only fossils found were gastropods in a thin shell bank, up to 8 cm thick, in unweathered banded mudstones on the Lindale bypass [4259 8129].

2.1.2 Sedimentary structures

There are numerous sedimentary structures within the Bannisdale Formation. Cross-lamination is common within the coarser units of the banded lithologies (Plate 1), but graded bedding is not as frequently observed as might be expected within the regularly bedded couplets. Where Bouma-type sequences occur, cross-bedding is sometimes found at quite low levels in sandstones which develop excellent flute casts at their base. This indicates that the depositional flows rapidly became subcritical.

One of the best examples of flute casts at the base of a thick turbidite unit occurs south of Height Farm, in a small quarry [4036 8434] by the side of the road to High Newton Reservoir (Plate 2). Here, the dip can be measured accurately, the fold plunge can be obtained from the cleavage/bedding intersection and the average plunge and pitch of the flute axes can be estimated. Hence all the elements are available to re-orientate the original flow direction on a stereonet. Although there are not enough locations to be of statistical value, Table 1 gives the results of three-dimensional observations taken from four localities where it has been possible to unfold the deformed bedding to reveal the original orientation of the current flows. Of those re-orientated, the flute and groove casts all gave flows towards the present west-south-west, whilst the single measurement of three-dimensional current-ripple laminations indicated a flow towards the south-south-west.

Table 1. Four locations in the Bannisdale Formation with current indicators, used as data on a stereonet to find the original direction of current flow.

Location	Grid Reference SD	Type of current indicator	Bedding dip and dip direction	Fold plunge	Current direction plunge	Reorientated current direction
Height	4036 8434	Flute casts	67/ 140	30/ 044	42/042 up	246^{o}
Barrow Hollin	4075 8425	Asymmetric ripples	66/ 338	57/ 026	70/045 up	205^{o}
Rock barrier	4158 8353	Flute casts	64/ 124	50/ 065	35/052 up	242^{o}
Lindale cut	4141 8085	Groove casts	56/ 001	20/ 075	32/058 up	236^{o}

One problem arising from the mapping was the necessity of checking the location of reported flute casts as these can easily be confused with a fluting effect developed as a result of spaced cleavage intersecting the base of coarser beds, as at a roadside exposure in Lindale village [4150 8057] and on the Bleacrag rock barrier just north of Holme Road [4163 8356].

2.1.3 Thickness

It is possible to produce approximate 200 m isopachs on the Bannisdale Formation within the district (Figure 1) because of the relatively regular bedding dips, the constant direction (if not angle) of the plunge of folds to the east-north-east, the control on the fault downthrow provided by the Carboniferous cover and the presence of the overlying Kirkby Moor Formation. Taking a carefully chosen transect (Figure 2), the maximum thickness of the formation can be estimated to be about 2600 m within the Lindale–Witherslack area.

2.2 KIRKBY MOOR FORMATION

At the eastern margin of the district the typically mixed lithologies of the Bannisdale Formation pass upwards into a cleaved, homogeneous silty sandstone about 100 m thick. This lithology crops out from Beck Head [447 847] southwards through Bull Bridge [447 841], until it is covered by postglacial sediments near the A590. It is seen again on the western flanks of Ulpha Fell [450 821] and may be the equivalent of the Underbarrow Flag Formation of Lawrence et al. (1986) below Scout Scar to the north-east. (Editor’s note: the term Underbarrow Formation has been abandoned recently; see Soper, 2006, appendix 1.) It is followed upwards, with evidence of some disconformity, by the younger, Kirkby Moor Formation, which is recorded initially south-west of the Lyth valley for the first time. The formation consists of laminated, pale grey sandstone in thick beds which sporadically display evidence of dewatering in the form of convolutions, but commonly only develops wavy laminations on a small scale (Plate 3). These rocks are well exposed immediately east of the road from Millside to Beck Head [4474 8453]. The base of the Kirkby Moor Formation is seen best in the garden of a house 100 m north-east of Bull Bridge [4475 8423]. The dip to the east is fairly constant at between 30 and 40 degrees and folds are rarely seen except in association with faulting. So the estimated stratigraphical thickness exposed in the area is about 150 m, whilst reconnaissance to the east has proved at least a further 300 m to be exposed below the shallowly dipping Carboniferous Martin Limestone which oversteps the sequence (Figure 4).

3 Carboniferous rocks

Whilst the general extent of the Carboniferous rocks was recognised in the first geological survey in the 1860s, there was no attempt to differentiate between limestone lithofacies. Dunham and Rose (1941) were the first to distinguish limestone units of differing lithological character within the Carboniferous of South Cumbria, but the formal division of the Dinantian rocks into five formations was introduced for the publication of the BGS memoir for 1:50 000 Ulverston Sheet 48 (Johnson et al., 2001). These units have been recognised and adopted during the current mapping (Figure 3).

3.1 MARTIN LIMESTONE FORMATION

Despite careful examination of the evidence for the character of the basal boundary of the Carboniferous succession in the district, it was not clear at first, whether the boundary was a fault or an unconformity. However, during reconnaissance of the ground below Whitbarrow Crag, immediately east of the district, the base of the Martin Limestone Formation was seen to overlie the Kirkby Moor Formation unconformably (Figure 4). The base is exposed in a small beck [4539 8448] flowing down from the crag immediately west of Whitbarrow Lodge. This can be located readily by the presence of tufa blocks on the surface of the field and wooded slopes nearby (5.1.3 and Plate 5).

The Martin Limestone Formation consists of well bedded units of various carbonate lithologies (Figure 5). To the west of Yewbarrow and at the foot of Whitbarrow the lowest members are thought to be masked by superficial deposits, although drainage ditches 0.5 km east of Helton Tarn [4250 8485] expose a strong, crystalline dolomitic grainstone very near to the base of the formation. In fact, one of the best natural exposures of this lithology lies beside an access track [4237 8534], just beyond the northern margin of the district. Here, dark brown, laminated and dune-bedded dolomitic calcarenite is well exposed.

Above these basal sandy dolomitic beds, the variable thickness of lithologies seen throughout the district and in 26 thin sections, are recorded on the stratigraphical logs in Figure 5. The main lithofacies consists of thin units of dark grey packstone interbedded with thicker units of buff coloured grainstone affected by varying degrees of dolomitisation.

The uppermost few metres of the Martin Limestone Formation is marked in many places by the appearance of very fine porcellanous units (calcrete), cross-stratified grainstone and sporadic lenses of breccia, marking possible emergence and even erosion prior to the deposition of the next formation (see Adams and Cossey, 1981; Adams et al., 1990).

The well documented Meathop Quarry section (Leviston, 1979), which exposes 41 m of Martin Limestone lies immediately south of the district. Its outcrop forms the base of the hill and is overlain by low dipping Red Hill Limestone Formation, which extends northwards to the hamlet of Meathop. Immediately to the north of the Yewbarrow Quarry faults, the formation is 46 m thick. However, abrupt variations in thickness of the Martin Formation seem to be related to the sites of east–west faults. Also, the Martin Limestone Formation thins to 10 m over a topographical high in the Bannisdale Formation just north-west of Key Moss [4282 8444] (Figure 5).

3.2 RED HILL LIMESTONE FORMATION

The base of the Red Hill Limestone Formation has been mapped at the first appearance of pale grey, shelly, peloidal grainstone. This has the appearance of being poorly bedded as a result of extensive bioturbation and the presence of numerous impersistent low-angle joints. Some lithological variation is seen, mainly in the size and frequency of occurrence of rounded faecal pellets, which in places give the rock a 'tapioca'-like appearance (Plate 4b). Sporadic units contain fewer pellets and more micritic cement, but most of the 50 thin sections studied display a sparry calcite cement.

One of the topographical characteristics of the Red Hill Limestone Formation to the west of Yewbarrow is the occurrence of small scarps, each between 1 and 5 m in height, which can be followed for some distance along the outcrop (Figure 6). There is a main scarp, approximately one third of the way up the sequence, underlain by several smaller scarps. A prominent scarp above, which has been found to contain the brachiopod *Delepinea carinata* near Yewbarrow Quarry is thought by I C Burgess (personal communication) to be indicative of the base of the Dalton Formation. However, this scarp dies out in the grounds of Halecat House [433 835] and is not now considered to represent that lithostratigraphical junction. Indeed, there are several scarps lying stratigraphically above this horizon which contain typical Red Hill facies.

It has also been reported from elsewhere (A E Adams, personal communication) that the brachiopod *Delepinea carinata* is Arundian in age, but not restricted to the lowest members of the Dalton Formation and could therefore be found in both Red Hill limestone and Dalton limestone. On lithostratigraphical grounds, the base of the succeeding Dalton Formation is placed nearer to the base of the main Yewbarrow scarp which is a very steep and prominent feature all the way along the west side of both Yewbarrow and Latterbarrow.

Whilst the stratigraphical thickness of the formation averages about 60 m, there is considerable variation within the district. As few as 40 m were recorded below Yewbarrow Quarry, whereas south of Halecat House 90 m are attained.

3.3 DALTON FORMATION

Lying with apparent conformity on the Red Hill Limestone Formation, well bedded packstone with thin mudstone units near the base of the Dalton Formation are exposed in the small quarry [4321 8422] opposite St Paul's Church in Witherslack. The church lies on the topmost scarp of the Red Hill Limestone Formation. Much of the lower part of the overlying Dalton Formation on Yewbarrow is covered in scree, but thin sections from several thick beds above this show dark grey, shelly packstone with micritic cement. Above the scree is a distinct crag which can be followed along the hillside. The rock here is rich in corals, brachiopods and gastropods and it is correlated with the massive limestone at the top of the Whitbarrow scarp above Beck Head [4499 8460].

A further 10 m of bedded limestone occur in scattered exposures above the crag on Yewbarrow, until at the top of the formation, the darker biomicrites give way to a much paler grainstone which marks the base of the Park Limestone Formation.

The thickness of the Dalton Formation on Yewbarrow averages 90 m around Witherslack, whilst above Beck Head on Whitbarrow it is almost 100 m.

3.4 PARK LIMESTONE FORMATION

Conformably overlying the Dalton Formation, the Park Limestone Formation has been recognised for the first time on Yewbarrow, where it follows the summit ridge. To the south of the east–west Yewbarrow Quarry Fault [4340 8460], it is confined to the higher ground, with the Dalton Formation appearing again on the eastern slopes, but near the northern margins of the district the formation occupies the whole of the eastern flanks and is followed down-dip by several crags of typical Urswick Limestone found during reconnaissance work to the north of the sheet boundary. Evidence for the Urswick Limestone exposures can be found just off the path, 300 m west of Hells Crag [4344 8533]. Small exposures of Park Limestone are also found to the west of Newton Fell [401 815], but because the base of the formation is not exposed hereabouts and some boundaries are faulted, its thickness is not known.

To the south of the aforementioned fault, the base of the Park Limestone Formation lies above the top of the steep Witherslack scarp, whereas to the north of the fault, the downthrown boundary is believed to be in the upper part of the crag [4310 8464] above Yewbarrow Quarry. The same boundary occurs on Whitbarrow crag above the highest scarp [449 846] and is displaced upwards to the south by the Beck Head Fault, which has been found to intersect the corner of Buckhouse Wood, immediately east of the area (Figure 4).

In general, the 11 thin sections of samples from the Park Limestone Formation indicate a pale grey, coarse, shelly grainstone (Plate 4a). These rocks are less well bedded than the Dalton Formation, characterised by numerous curved joints, which have promoted vigorous mechanical weathering in exposed places. Widely spaced master bedding planes are present locally and have led to karstic development of pavements in favourable locations such as the sunny eastern dip slope of the northern Yewbarrow ridge.

The thickness of the formation is difficult to establish, but where the Urswick Limestone Formation crops out above the Park Limestone Formation, it is estimated to be just over 100 m.

3.5 URSWICK LIMESTONE FORMATION

The Urswick Limestone Formation crops out south-west of the Lindale Fault. It is well exposed around Hampsfield, but becomes masked by glacial deposits in the Lindale Gap.

The rocks are composed of pale grey, bioclastic, fine to medium grainstone and packstone with development of darker grey, pseudobreccias giving the rock a mottled appearance. Thickly bedded units of limestone more than 3 m thick occur throughout the area, especially in the lower part of the formation; these are well exposed at Odding Crag [4037 8110]. The Woodbine ‘shale’, which normally occurs about 30 m above the base of the Urswick Limestone Formation was not seen during the survey. A rich assemblage of brachiopods, single and colonial rugose corals (mainly *Lithostrotion*), together with poorly preserved gastropods was found at Newton Heads [4018 8185].

Numerous well developed scarps, limestone pavement and other karstic features, including large sink holes, occur on the Hampsfield slopes running down to Lindale Village. The presence of these features may, in part, be due to the dip here being several degrees steeper than the slope of the hillside.

4 Permo-Triassic infills

Although no Permo-Triassic strata crop out in the district, a well exposed fault in a former (raised) coastal cliff close to the track [4340 8265] from Holy Well to Catcrag contains pockets of red thinly laminated siltstone. The fault could have been an open fissure during Permo-Triassic times and dust storms or flash floods may have deposited finer desert materials which filtered into it.

5 Structure

5.1 STRUCTURES AFFECTING THE SILURIAN ROCKS

Folding and cleavage are the dominant structures imposed on the Silurian rocks in this area. Within the main outcrops there is little evidence of the thrusting found on the adjacent sheet to the west and few major faults were found within the Bannisdale Formation.

5.1.1 Fold structures

The Bannisdale Formation is moderately deformed throughout the district, but no major fold of large amplitude or wavelength has been found. The largest and most clearly defined anticline plunges steeply into the south-west side of Barrow Hollin with its crest line at [4076 8465] marked by a sandstone unit almost 30 m thick. The limbs are asymmetrical with the dip to the north about 50^o and to the south-east at nearer 70^o (Figures 9 and 11).

5.1.1.1 FOLD PLUNGE

Plunge angles range from 20^o to 50^o for most folds and fold style is repeated in minor and intermediate folds throughout the district. Some fold pairs have persistent axes which can be traced for several kilometres, whereas others appear to die out abruptly. The angle and direction of plunge can be measured easily on exposures where the bedding planes stand out clearly at hinges. These are generally reflected in the stereonets of poles to bedding shown in Figure 10 for the three main areas where the Bannisdale Formation crops out, namely Height and Barrow Hollin, Newton Fell, and Town End to Beck Head. In the west the angle and direction data are similar at 20–50^o between 050^o and 055^o, although folds near Lindale plunge towards 070^o. To the east, in the Town End to Beck Head area, there are fewer folds and the plunges are less steep and also directed towards 068^o.

5.1.1.2 FOLD PROFILE

Figure 11 is a down-plunge profile showing the scale and similarity of the slightly asymmetrical folds in the district. The profile is about 4 km long and includes the eastern outcrop of the Bannisdale Formation by removing the effect of the Yewbarrow Fault. (The vertical downthrow of 400 m – see transect, Figure 1 – to the west and the estimated initial sinistral movement of 2 km have been removed).

The persistence of the folds in the direction of plunge and the shortness of their wavelength, may have some bearing on the position of the rock barrier in the Winster valley (Figure 8).

5.1.2 Cleavage

A pervasive slaty cleavage affects all the finer grained turbidite lithologies in the Bannisdale Formation, but the purer sandstone units in both the Bannisdale and the Kirkby Moor Formations have a poorly developed, spaced cleavage. Dips are steep to the north-north-west with only a small, clockwise angular transection to fold axial directions (less than 3 degrees). This is most noticeable on the stereonet for Newton Fell (Figure 10). However, the distribution of cleavage readings on Figure 9 indicates a more northerly dip in the Lindale–Meathop area. This is reflected in the Bannisdale Formation to the east of Yewbarrow fault and forms the basis of the supposed early sinistral slip of about 2 km on the fault.

5.1.3 Regional variations in structure of the Silurian rocks

An account of the tectonics history of the southern Lake District has been given by Soper in the Ulverston memoir (Johnson et al., 2001). However, it is necessary here to highlight some of the structural variations found in the Witherslack district.

1. In contrast to the Furness District the main Acadian folds are facing consistently towards the south-east or south (Figure 11).

2. Many of the fold plunges are steeper than those reported to the north-west. With angles of up to 50^{o}, easterly tilting of the Carboniferous strata by an average of 10^{o} indicates that the folds in the Bannisdale Formation had pre-Carboniferous plunges of up to 40^{o} to the north-east.

3. Most of the cleavage dips are steep to the north-west or vertical, and the change in cleavage strike towards the east in the south is repeated in the fold axial directions.

4. The amount of clockwise cleavage transection appears to be less than that to the north and west. It is hardly noticeable in field exposures, and is no more than 3^{o} on the stereonets.

In conclusion, the above structural details suggest that transpression may not have had so much influence on the southern margins of the Lake District and in the Yorkshire Dales and that late Caledonian tilting is likely, prior to Arcadian folding.

5.2 STRUCTURES AFFECTING THE CARBONIFEROUS ROCKS

There is a marked contrast between the structures affecting the Silurian and Carboniferous rocks of the district. The compressional and uplift phases of the Acadian Orogeny were followed by extension during Early Carboniferous times and then by transpression during Late Carboniferous times; though no folds formed at this time are seen within the district, this later event resulted in folding elsewhere in Northern England. Further fault reactivation occurred during Permo-Triassic, typically resulting in some drag associated with movement on fault planes.

5.2.1 Dip

Dip angles from 0 to 28^{o} have been recorded away from the influence of faults. The general dip in the Urswick Limestone at Hampsfield averages 15–20^{o} towards the east-north-east, whereas the dips in the underlying formations on Yewbarrow, Meathop and Whitbarrow vary from 0 to 22^{o} to the east with an average dip of 10^{o}.

5.3 FAULTS

Two major faults orientated north-north-west to south-south-east traverse the whole area. The movement on the Yewbarrow Fault has already been discussed in relation to the cleavage in the Silurian strata (Sections 5.1.1.2 as 5.1.2). Strike-slip displacement during the Acadian Orogeny was followed by large extensional displacements of around 400 m to the west or south-west during Permian times. This fault can be traced from the upper Winster valley through to Silverdale and Lunesdale.

The Lindale Fault is a major structure bringing upper Dinantian rocks in contact with Silurian rocks. The downthrow to the south-west must be close to 700 m, but the magnitude of any horizontal movement is not known. The fault bifurcates around the High Newton with the north-easterly branch trending north on the east side of Windermere and the south-western branch joining the Newby Bridge Fault up the centre of lake Windermere. The location of the western branch was clearly fixed by reference to the ground investigation borehole logs for the proposed Newton Bypass [401 825]. In the south of the district around Lindale the fault again bifurcates and exposures at Lindale church indicate the presence of the Park Limestone Formation between the two branches of the fault. The eastern branch continues into Morecambe Bay close to the Far Arnside coast and has been traced as far as Lunesdale.

Most of the other faults have a generally east–west orientation. The Beck Head Fault (Figure 4), east of Yewbarrow, has a throw down to the north estimated at 100 m near Beck Head and has now been found to continue through the crag above Buckhouse Wood as it curves towards the south-east with a diminishing downthrow. On the south-west corner of Whitbarrow Crag, above Buckhouse Wood the Dalton and Park formations are tilted by a few degrees on minor faults associated with the Beck Head dislocation.

Other east–west faults cut the Yewbarrow ridge and displace the outcrop of the Carboniferous unconformity together with all the minor scarps on the Red Hill platform (Figure 6). This provides some of the clues which allow the downthrow direction and amount to be calculated. The displacement to the north of the Yewbarrow Quarry Fault is estimated to be one of the largest at 20 m, and syn-depositional movements on this fault may explain the abrupt increase in thickness of the Martin Limestone Formation across it to the north. However, the fault possibly developed at the site of an earlier slope, which was present at the beginning of the Carboniferous Period.

The Pig Pen Fault, 300 m to the south has a southerly downthrow of about 15 m, bringing a thin Martin Limestone Formation against Bannisdale Formation at [4284 8445]. A clear displacement of the west Yewbarrow crag involves a downthrow to the north of 5–10 m on the Fern Hill Fault and, unusually, this fault can be traced into the Bannisdale Formation outcrop. The other faults to the south have small displacements of only a few metres. One further feature is worthy of note: the Lodge Fault (Figure 6) can be traced to the east of the Yewbarrow ridge where it appears in a small adit above the scree in the Dalton Formation.

Most of the east–west faults appear to terminate at the north–south Yewbarrow Fault and final movements may have been the result of stresses associated with the large downthrow on that fault. There was some discussion as to whether the Beck Head Fault was a continuation of the Yewbarrow Quarry Fault, but the downthrow on the Yewbarrow Fault was so large (at 400 m to the west) that this now seems unlikely.

6 Quaternary deposits

6.1 GLACIAL FEATURES AND LANDFORMS

Features of glacial erosion such as roches moutonées and glacial striations were measured on rock surfaces. Larger, commonly subparallel, gouges in rock form dry valleys, orientated north–south. They are most common in the rocky area between Town End and Beck Head, east of Yewbarrow. These features confirm that ice had flowed from the north, although some deflections towards the south-west were also recorded.

The material forming glacial deposits was observed not only in ditches, riverbanks and other exposures, but also by the samples recovered from the use of hand augers. However, much of the mapping of the superficial deposits depended on a geomorphological approach. The glacial deposits within the district were classified on the basis of the materials and landforms:

those deposited during glacial advance – lodgement tills

those deposited during glacial retreat – ablation tills

those deposited in meltwater – glaciofluvial deposits.

6.1.1 Lodgement Till

Overconsolidated, firm to stiff diamicton (boulder clay) is distributed over parts of the area, either as a thin veneer, commonly patchy, or in places as a sheet with sporadic, isolated rocks exposed. Where a considerable thickness of till accumulated below the ice and where ice-flow conditions were favourable, drumlins developed. These are well formed in the Lindale Gap between High Newton and Lindale, where two large drumlins, each 2 km in length, have an average trend of 160˚. Till thickness within the more northerly drumlin is estimated at 7–12 m, based on ground investigation boreholes drilled for the proposed Newton bypass (Figure 7b). Smaller drumlins are also well developed on the eastern side of Yewbarrow, where they have long axes trending between 170˚ and 180˚ and are between 150 and 500 m in length. Here, at least five drumlins obscure the outcrop of the Yewbarrow Fault for a distance of almost 2 km. Elsewhere, there are a few isolated examples worthy of note. An isolated drumlinoid structure has been preserved on the upstream side of the Winster rock barrier at [418 838], but there is no indication of the thickness of the till. Very small drumlinoid ridges trending 200˚ near the top of the Tow Top road [405 833] are parallel to the flow direction indicated by glacial striae and have been mapped as diamicton, but only excavation could prove whether or not they are medial moraines or even eskers. Finally, there are several important drumlinoid ridges at the northern margin of the area, just north of Barrow Hollin. Their trend is west to west-south-west upslope, as if diverted by the mass of Barrow Hollin.

The lodgement tills are taken to represent deposits formed at the final stages of ice advance about half way through the Late Devensian (Dimlington) Stadial (26000-13000 years BP) and would incorporate much of the previously deposited glacial materials. A reconstruction of the glacial history of this area is included in the glacial summary below.

6.1.2 Ablation Till

Although melting may have taken place throughout much of the Ice Age, once the advance of ice from the Lake District ceased around 15 000 years ago, melting would have succeeded ice cap accumulation as the dominant process and a new regime of material deposition would have taken over. Although ablation involves meltwater, some processes simply resulted from ice dwindling, so that material such as supraglacial moraine was dumped as the ice retreated. Many of the superficial materials left behind by such processes are poorly sorted, commonly angular or subangular and poorly consolidated, with a low clay content. This reflects the transport mode on the ice, where material which initially fell on to glaciers, subsequently underwent very little attrition apart from further mechanical weathering. Some moraine which starts as supraglacial may become englacial during transport and clasts therefore undergo some rounding. Both will be dumped on retreat of the ice to form irregular mounds, the axes of which may be subparallel to the valley sides (as in lateral and medial moraines), or they may be the result of dumping during a standstill phase which often leads to irregular cross-valley ridges (end moraines).

Many of the glacial deposits forming subdued ridges, irregular in plan, on the west side of the Winster valley are considered to be ablation till moraines (Figure 7a). Exposures in ditches and elsewhere are mainly of grey or grey-brown, loose to medium-dense sandy silts with subangular cobbles and boulders, few of which contain striated surfaces. Whilst a few of the ridge lines are parallel to the valley sides, others are at right angles; notably at [414 835] near the Bleacrag rock barrier, just north of the junction of Holme road and Tarn Green road. South-west of Helton Tarn around [417 846] there is a complex of low ridges which may represent a further standstill of the valley ice. Similarly, on the north-east side of the Bleacrag rock barrier, there are several hummocky moraines. Away from the Winster valley, between Height Farm and Barrow Wife [406 848], there is hummocky ground south-west of the drumlins already mentioned.

6.1.3 Glaciofluvial deposits

6.1.3.1 SAND AND GRAVEL

Sand and gravel deposits are relatively sparse in the district and only two outcrops of waterborne glacial materials having been mapped.

A smooth mound containing subrounded, sandy gravel forms a curved ridge with broad, convex slopes just south of the rock barrier [417 831]. At first it was not certain whether this was a recently landscaped, man-made fill area, covered with gravelly material, or a natural deposit, but reference to old air photographs and especially the original Geological Survey field maps of the 1860s, showed that the mound had existed for at least 140 years and is almost certainly natural. It has been interpreted as a glaciofluvial ice-contact fan deposit laid down at the snout of the Winster Glacier, presumably during a prolonged standstill before the Windermere Interstadial.

Similar, but thinner and laterally confined waterborne deposits are found east of Height Farm, where a large dry channel descends towards Barrow Wife [4035 8463].

6.1.3.2 TUFA DEPOSITS

Another product of the melting phase is quite rare. Immediately east of the district, the mapping team found exposures of calcareous tufa detached from bedrock and lying loose on both Carboniferous and Silurian strata in woods, and on superficial deposits in the fields, south of Whitbarrow lodge [452 841] (Figures 4 and 8). This is interpreted as a linear tufa tube that has been fragmented into large blocks (typically 3 x 2 x 2 m) with some smaller, more scattered, fragments. The blocks are clearly not cemented to the ground, unlike the recently deposited fine buff tufa, which strongly adheres to the bed of the beck. The coarse tufa lies on the present slopes of Whitbarrow Crag in two distinct trains: an upper line of three blocks on a slope of 35^o at an elevation between 70 and 80 m above sea level, and at least seven blocks on the lower slopes of around 10^o at an elevation of 16 to 30 m above sea level (Figure 8a). All blocks are composed of grey tufa containing numerous subparallel small tubes, typically a few centimetres in diameter. The linear orientation of the larger blocks is between 130^o and 140^o, with flow lineations in the form of tubes and grooves, within each block, mainly in the same direction, although some blocks have been tilted. The source of the tufa is a former cave lined with the older grey tufa and now filled with recent fine, buff tufa, lying in a vertical crag at an elevation of 90 m above sea level [4530 8465] (Plate 5).

The angular shape and alignment of most of the fragments and the low slope angle, rules out recent rocksliding or downslope rolling and, although friction could have been reduced under periglacial conditions when slopes may have been permanently frozen, the alignment would surely be lost when sliding occurred. It is unlikely to have been deposited in situ as there is no sign of a river channel beyond its abrupt south-east termination. Therefore, this has been interpreted as a tufa deposit emerging from the cave in the crag during the waning phase of ice melting and possibly being deposited in an englacial ice tunnel prior to the final melting of the ice, when little advance was taking place. During the final stages of melting, the tufa bed would be progressively extended and lowered to the ground, to be distributed as found today (Figure 8b). However, it is possible that some of the tufa around Whitbarrow Lodge may have been removed during construction work.

6.1.4 Glacial history

An interpretation of the late Dimlington Stadial, during melting of the ice as the Winster valley glacier was in retreat, is given in Figure 7a. The Bleacrag rock barrier probably continued to have some influence at this stage of the Pleistocene and it is suggested that the Winster ice was less thick and powerful than that in the valleys to the west. It was also loaded with more morainic material than that in the Witherslack Hall valley, where no retreat deposits have been found.

During ice-sheet advance, in Devensian times, the rock barrier may have been higher than at present and probably had the effect of slowing down the glacial advance sufficiently to force some of the ice flow to the west of Barrow Hollin, over the top of the Height area and down to the larger Lindale–Cartmel glacier at High Newton.

Towards the end of the Dimlington Stadial, melting on the larger, more bulky Cartmel ice may have caused meltwater to overflow into the Height–Barrow Wife depression, where it was diverted and occasionally dammed by the snout of the westerly spur of the Winster Glacier. Temporarily impounded water could have overflowed at various levels to leave terraces, but the lowest are not level and are more indicative of river terraces formed when the flow was not impeded. The present river channel was cut into the lodgement till and was partly filled with sand and gravel. Today, there is no catchment for this dry channel, although slight depressions connect with the Saskills plateau immediately west of the district [399 847] (Figure 7a).

Prolonged standstills associated with the Bleacrag rock barrier in the Winster valley resulted in glaciofluvial fan deposits and there is evidence from a borehole near Meathop [4454 8082] that rockhead is covered by several metres of dense gravel which may represent proglacial outwash, deposited well beyond the ice (Figure 7b).

During the Loch Lomond Stadial towards the end of the Pleistocene Ice Age, the ice would have had very little influence on the Winster valley, since it was confined when readvancing in the Lake District to combes and hanging valleys. By 10,000 years BP all signs of permanent ice had gone.

6.2 POSTGLACIAL DEPOSITS

The final removal of all ice from the upper Winster valley occurred during the Windermere Interstadial and it is suggested that water accumulated in the rock basin, north of the rock barrier, giving rise to the formation of ‘Lake Winster’.

6.2.1 Lacustrine deposits and alluvium

Since we have not mapped the north Winster valley, the full extent of any lake is not known in detail, but it is estimated to have been at least 3 km long. A remnant of it remains today in Helton Tarn [419 849]. Smith (1959) reported laminated lake silts and clays to a depth of over 10 m with some intermediate layers, thought to be due to marine incursions during the Flandrian when sea level was at its postglacial maximum (now known to be approximately +6 m aOD at 6000 years BP). During the highstand, the marine incursions into and beyond the rock barrier may have eroded some of the moraines on the western side of the Winster valley. This could explain the rather low, subdued nature of the hummocky ground, although it could also be accounted for by the removal of the material by man.

Most other alluvial deposits in the district are either associated with small stream beds and fans, or are the result of poor drainage between moraines or in glacial gouges. There are three larger areas of alluvial silt and clay associated with the poor drainage around the drumlins in the Lindale Gap. They lie between the drumlins and the Bannisdale Formation rocks of the western slopes of Newton Fell at [440 828, 407 819 and 411 816].

6.2.2 Raised Tidal Flat Deposits

The rapidly rising sea level associated with the start of the Holocene Epoch led to flooding of the lower ground and establishment of a coastline below which much of the glacial outwash was redistributed. Before vegetation cover was fully restored there would also have been much river erosion of the till and transportation of finer silts and clays into the Morecambe Bay area, so that thick accumulations of grey and brown clayey silt could be achieved. These sediments were later affected by slow isostatic changes during the Flandrian, which took the coastline seawards once again.

More than 38 m of soft brown silty clay have been recorded in a borehole on the banks of the Winster between Stripe Bridge and the roundabout [4301 8352] at Meathop (Figure 7b), whilst a very informative site investigation borehole [4454 8082], east of Meathop gave the following sequence:

Depth		Thickness
0 - 10 m	Sand with shells	10 m
10- 37m	Very soft brown and grey laminated silty clay	27m
37- 39m	Dense grey sandy gravel and cobbles	2m
39m TD	Slaty mudstone	

Not only did this borehole prove rockhead within the Bannisdale Formation, and the overlying thin glaciofluvial sandy gravel and cobbles, but it also gave the thickness of the soft, finer grained tidal flat clays, this time overlain by a blanket of Morecambe Bay sands. Sandy deposits have also been found in auger holes west of the present banks of the River Winster near Low Green [4234 8240] and Watery Lane.

6.2.3 Peat

Once the raised tidal flats became established, large areas of vigorous vegetation growth resulted in the accumulation of organic matter which developed into peat deposits raised a further two metres above the surrounding flats. The main areas of raised peat today are Nichol’s Moss and Meathop Moss which were possibly once joined, Bellart How Moss and Cushatt Wood. The areas have been reduced over the centuries by man’s need for fuel.

Smaller accumulations of peat in depressions on the tidal flats are less clear, but were mapped using a peat probe at [420 826] and [426 848], and in the Bleacrag barrier overflow at [415 835].

6.2.4 Talus (scree)

Scree deposits are common below the main limestone scarps of Yewbarrow and Whitbarrow. More recent accumulations of talus are loose angular cobbles and gravel, but weakly cemented talus, possibly dating back to the late Devensian, is also found. Yewbarrow Quarry [4315 8464] is almost exclusively a working in this material, and part of the smaller Halecat Quarry [4288 8358] contains cemented talus of Martin Limestone.

7 Artificial deposits

7.1 MADE GROUND

Major fill areas were built up during the construction of embankments for the Lindale bypass on the A590 trunk road, but most other areas of made ground are found on local farms or in large foundation areas for buildings. Only the largest of these deposits have been mapped.

8 Geotechnical information

Since metamorphism has not hardened the lithologies in the Bannisdale Formation, good drilling rates should be possible in the thin-bedded facies using diamond bits. This is also true of the limestones in the Carboniferous formations. Much more difficult drilling conditions may be expected near the base of the Martin Limestone Formation, where crystalline dolostone forms a strong fabric, and also in the more massive units of turbiditic sandstone within the Bannisdale Formation.

The presence of joints in both the Silurian and the Carboniferous rocks means that, although blasting is necessary to remove large quantities of rock, excavation could be relatively straight forward for a few metres, using rock peckers in more weathered rock.

Foundations directly on the Bannisdale Formation should not pose any problems, but the karstic condition of the Carboniferous rocks always requires caution, because of the possible presence of open underground chambers. Drilling or probing methods should be employed at any ground investigation stage.

The main geotechnical problems associated with the soils (superficial deposits) are found in the soft to very soft silty clay of the former estuary. Not only are these soils highly compressible, because of the lack of consolidation, but they are usually found in flat, low lying areas liable to flooding. Any substantial structures built on them will require piling to the underlying till or rock. All fields on the raised tidal flats of the estuary form difficult ground except where sandy layers predominate.

The areas of diamicton, although muddy in wet weather, form much better foundations due to their overconsolidation during the former advance of the ice sheets.

With few areas of glaciofluvial sands and gravels, there are not many free draining soils in the area, with the possible exception of the areas underlain by ablation moraines.

No areas of major landslip where found during the mapping although all steeper slopes which have been glaciated may have some landslip potential.

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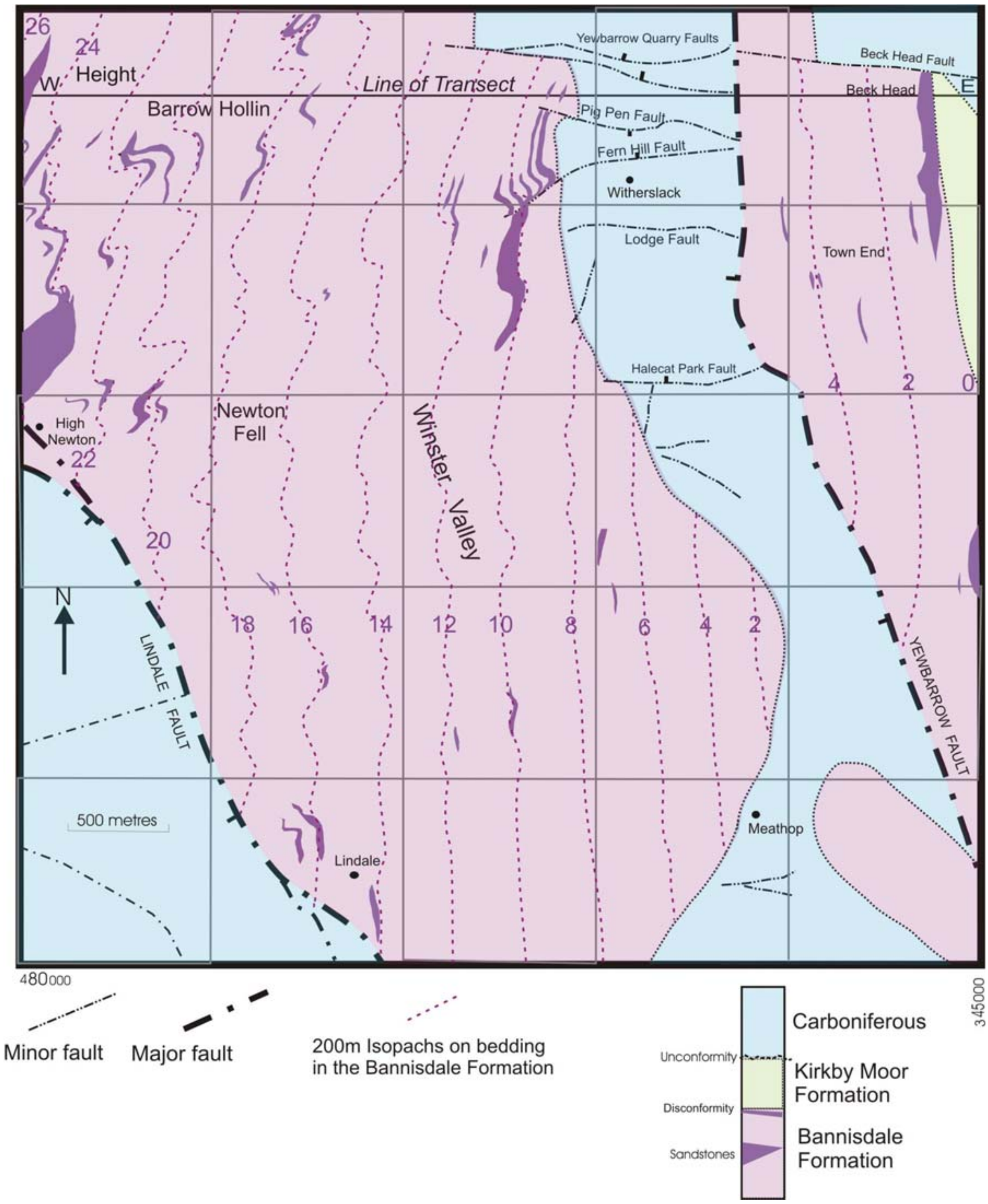

Figure 1. Isopachs for the Bannisdale Formation

Isopachs shown at 200 m intervals; mapped sandstone units are also shown.

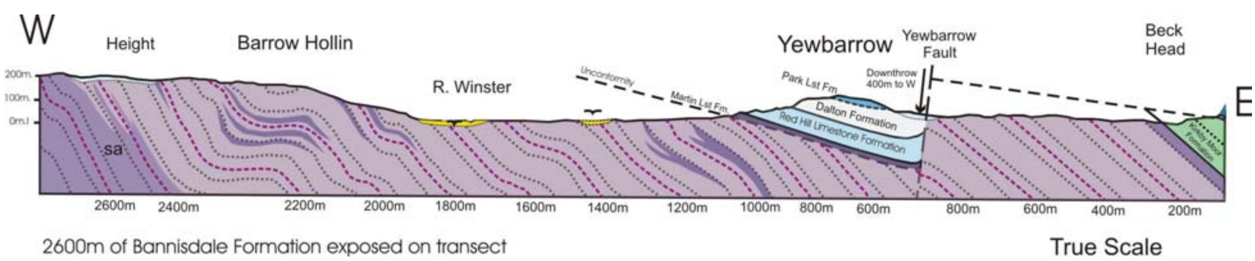

Figure 2. West to east cross-section along Northing 845

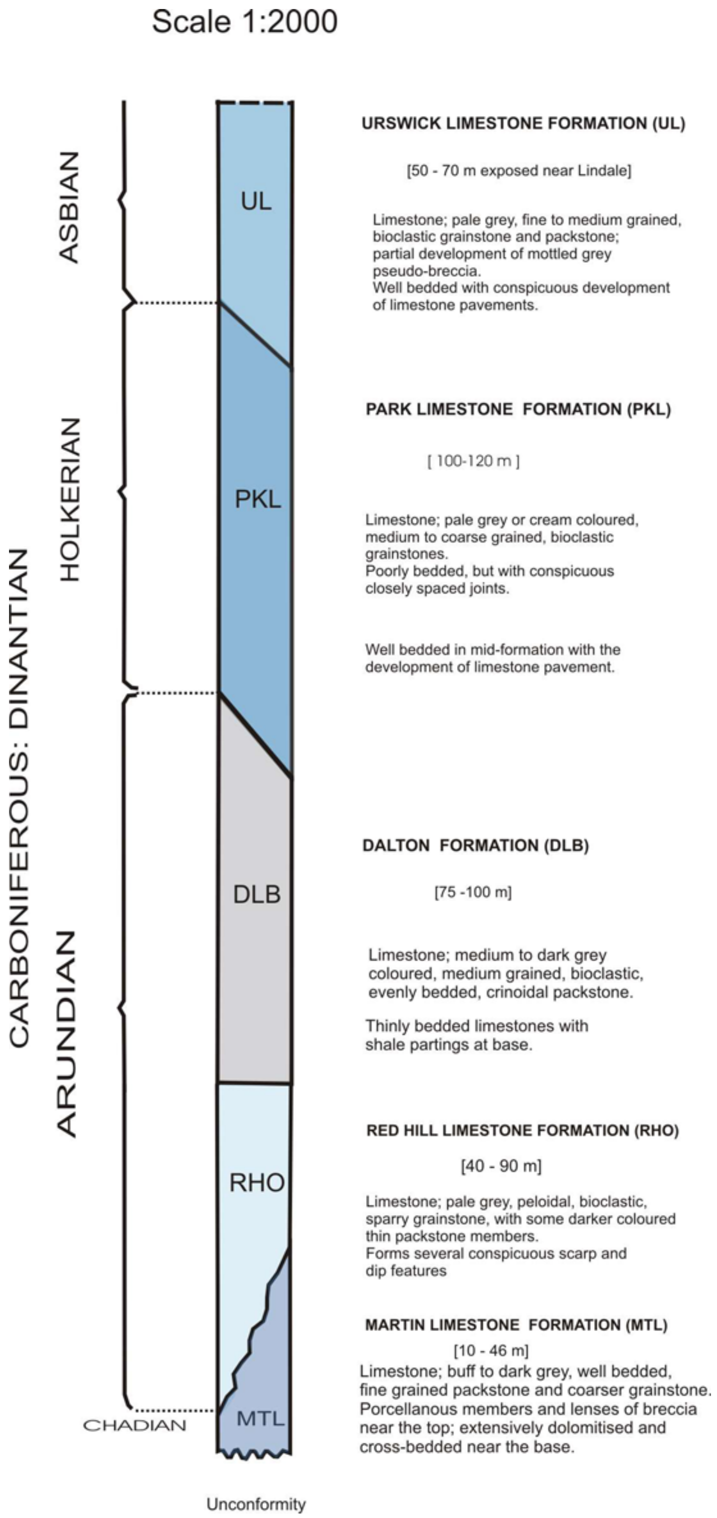

Figure 3. Generalised vertical section for the Carboniferous rocks of the Lindale - Witherslack district

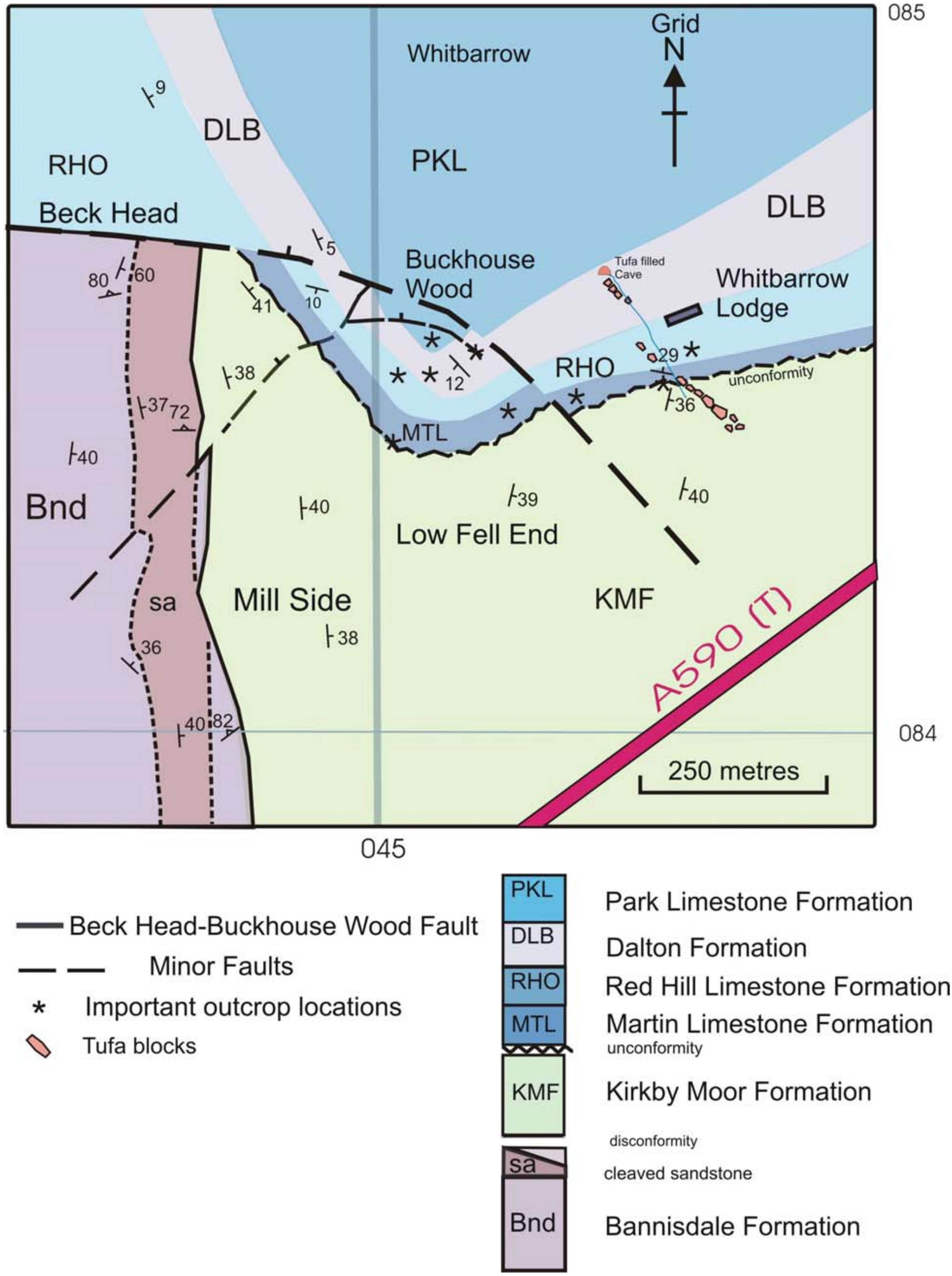

Figure 4. Geological map of the north-east of the district, showing critical relationships of the Dinantian strata

Locations are given illustrating details of the unconformity at the base of the Carboniferous succession, the formation boundaries and for the Beck Head – Buckhouse Wood Fault.

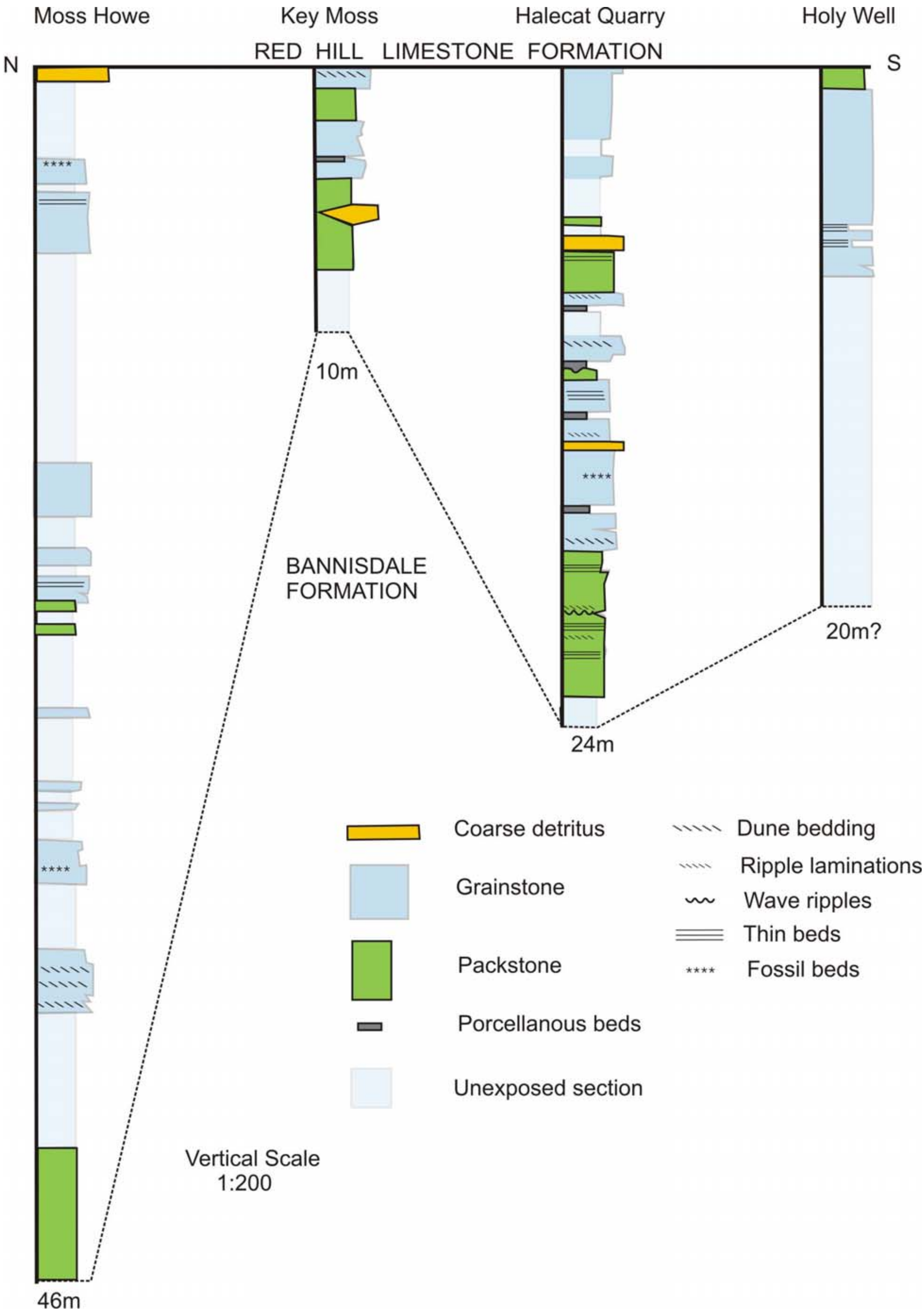

Figure 5. Stratigraphical logs at four locations within the Martin Limestone Formation

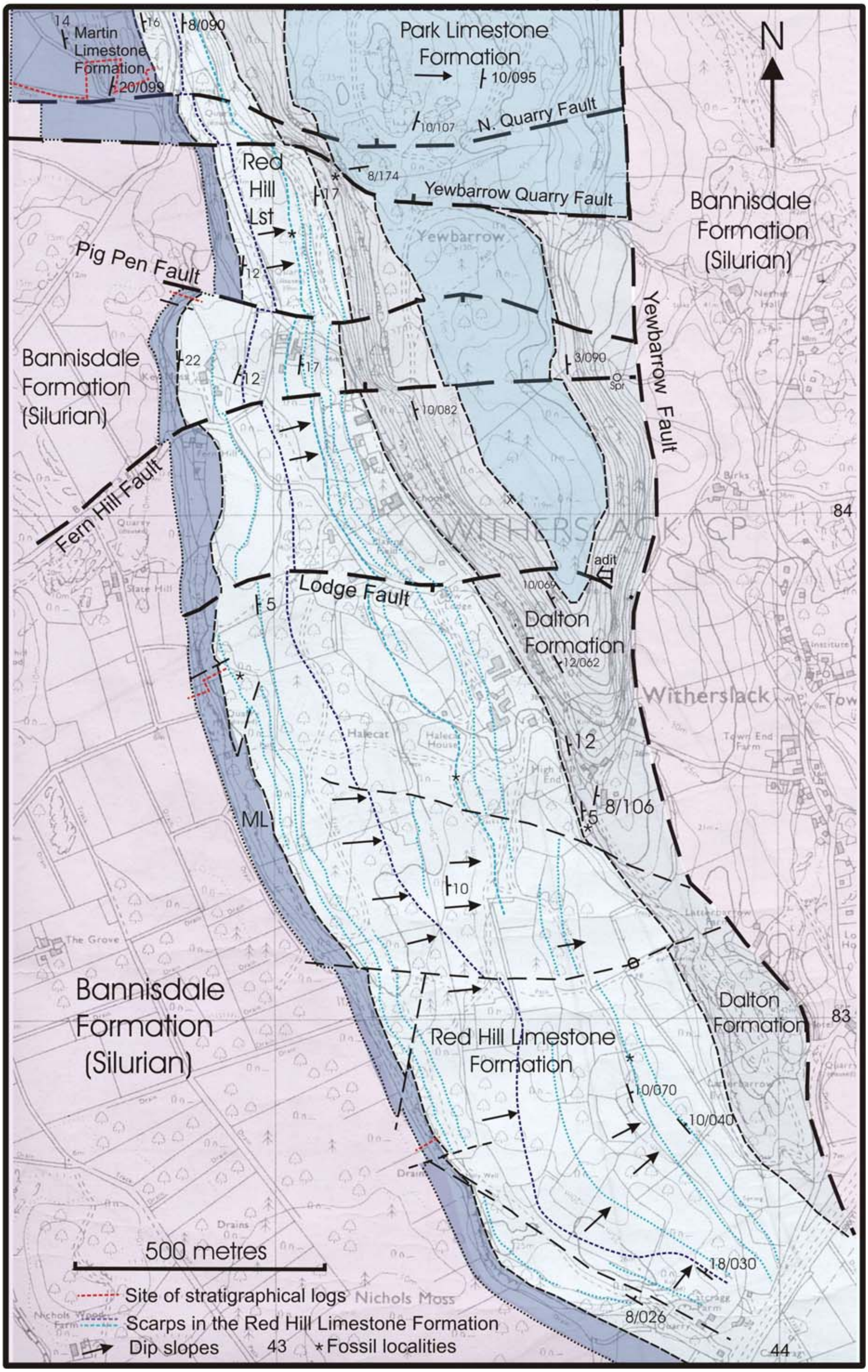

Figure 6. Geological map of the Carboniferous succession at Witherslack and Yewbarrow

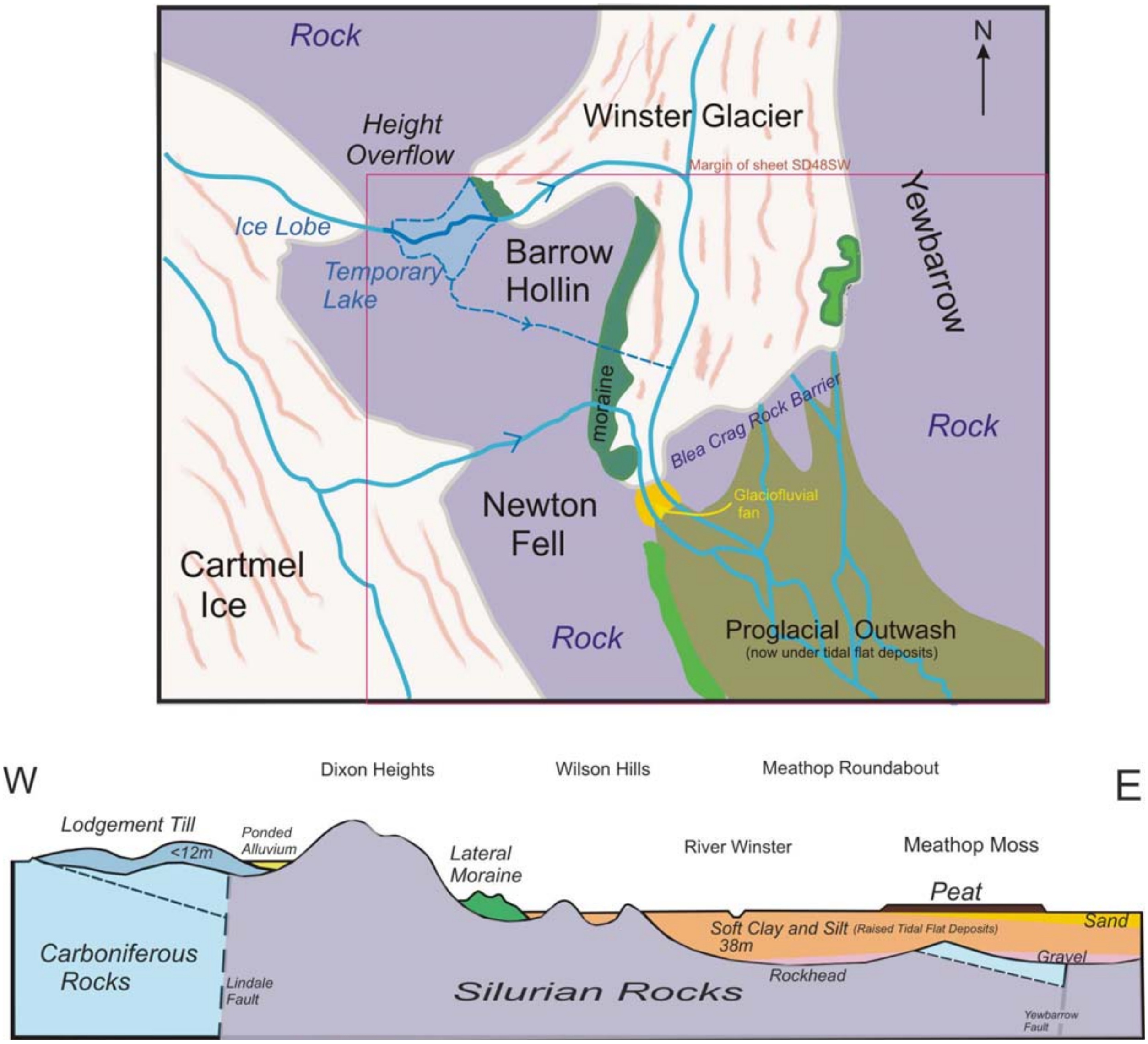

Figure 7. Reconstruction and relationships of the Quaternary deposits

The map (at top) is a reconstruction of the Winster ice during a late stage standstill in the Dimlington Stadial (about 14 000 years BP), when the Bleacrag rock barrier had a major influence on ice termination and overflow was taking place from higher Cartmel ice.

Below is a cross-section (not to scale) along northing 815, illustrating the relationship between the Quaternary deposits.

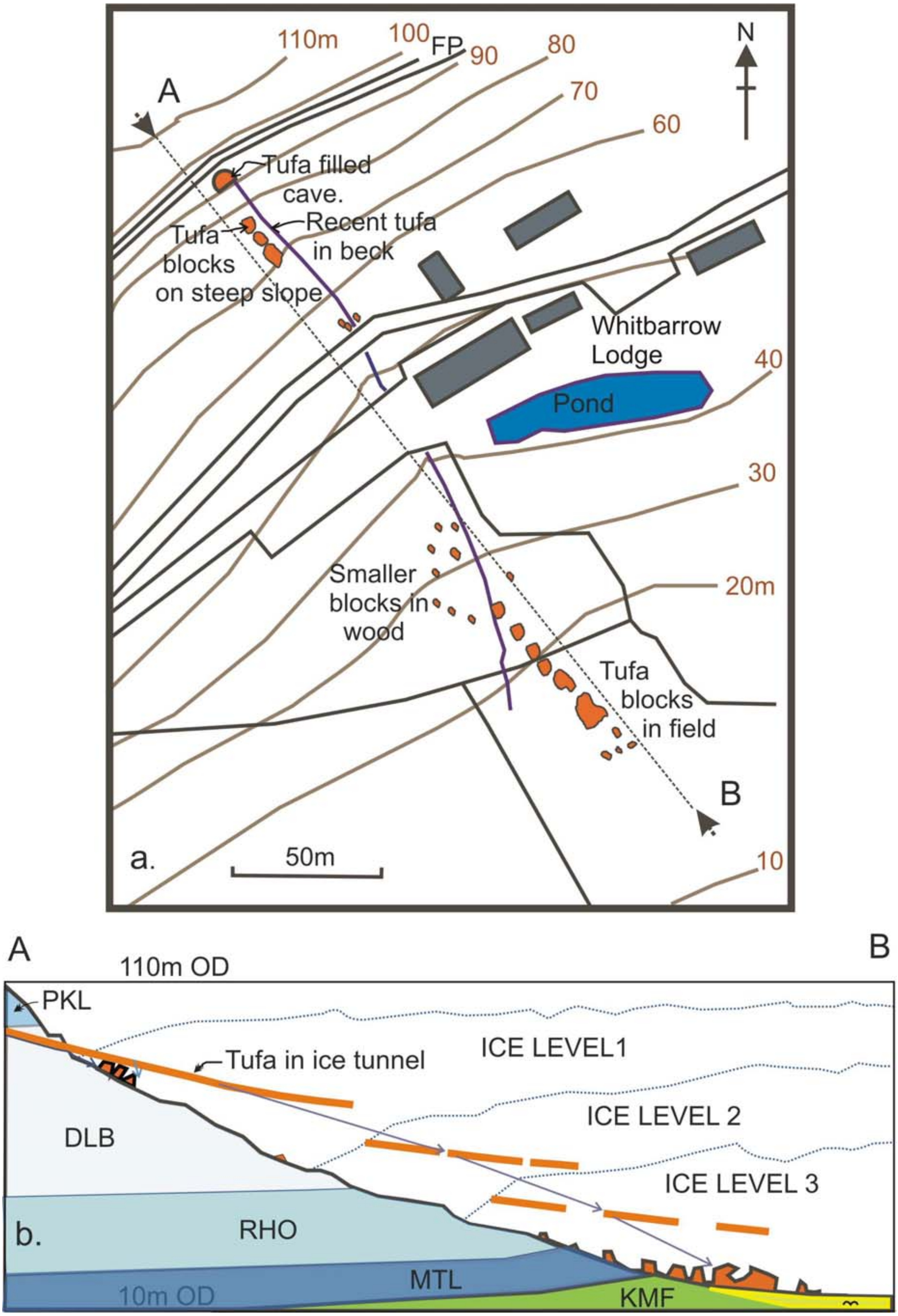

Figure 8. Map and interpretative cross-section of the late-glacial tufa deposit at Whitbarrow Lodge

Map (above) showing the distribution of the tufa blocks and true-scale cross-section A–B (below) giving an explanation of its late glacial origin.

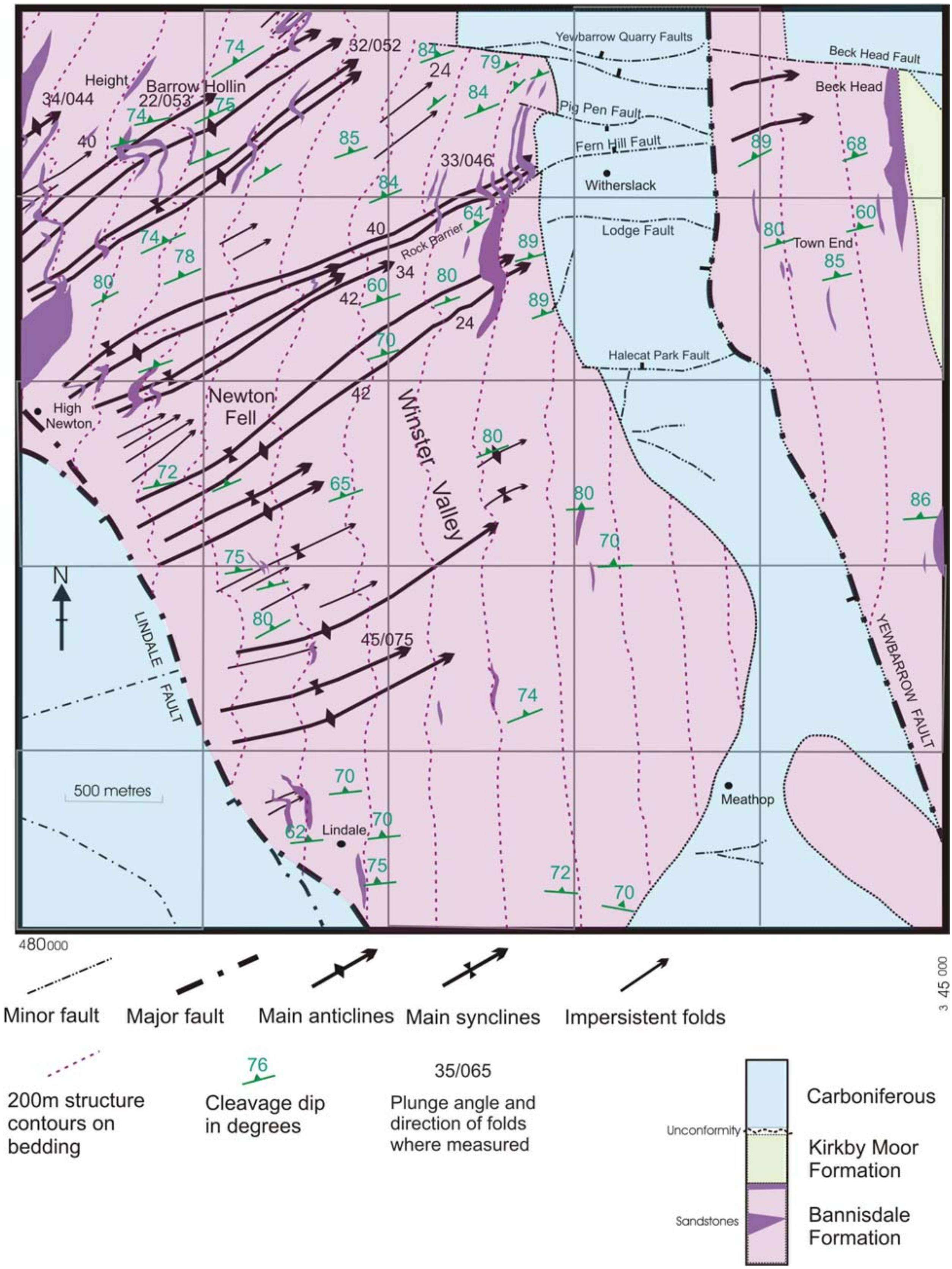

Figure 9. Map showing fold axial plane traces and cleavage orientation within the Windermere Supergroup strata

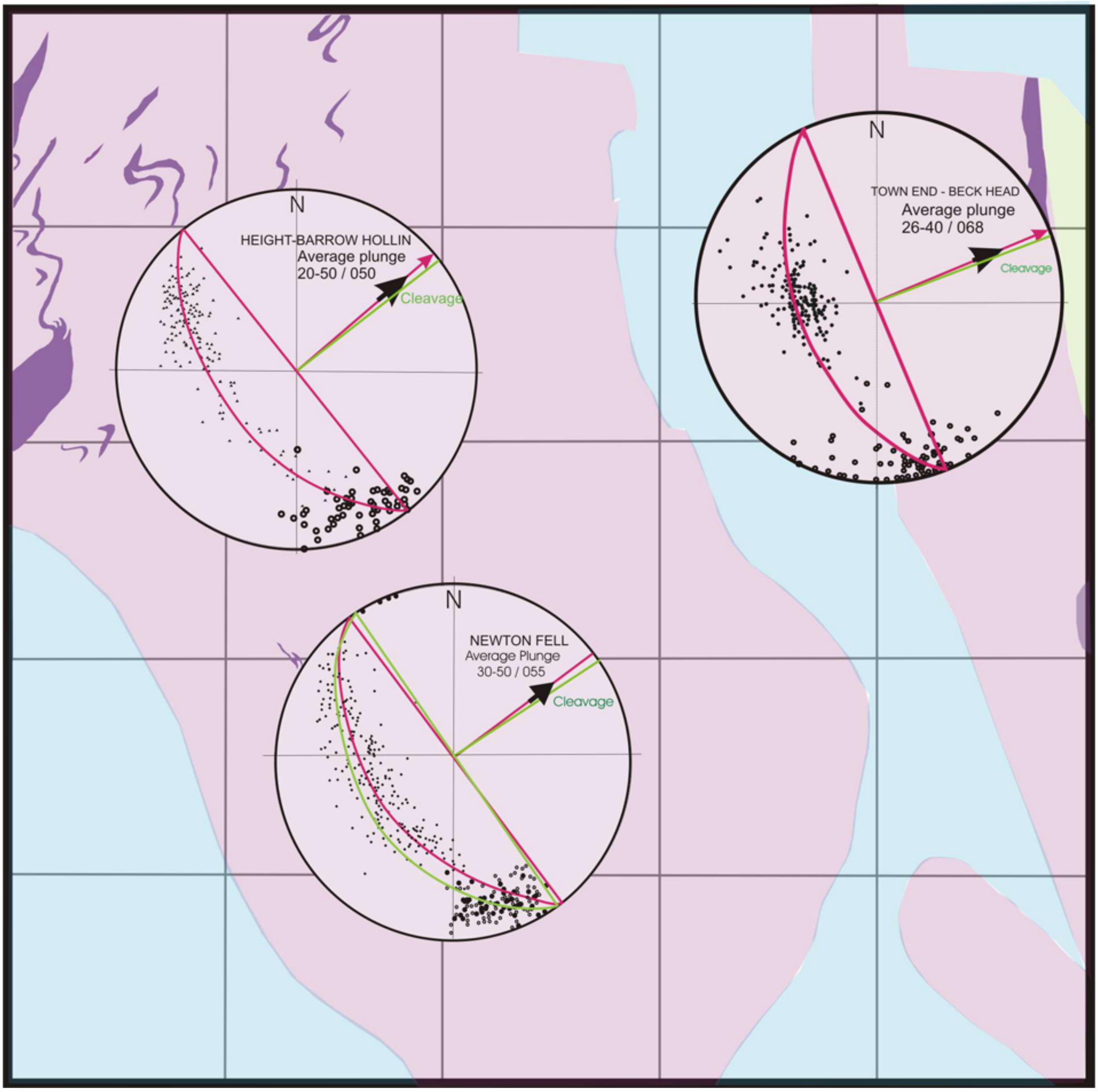

Figure 10. Stereonets of poles to bedding and cleavage for three zones within the Bannisdale Formation

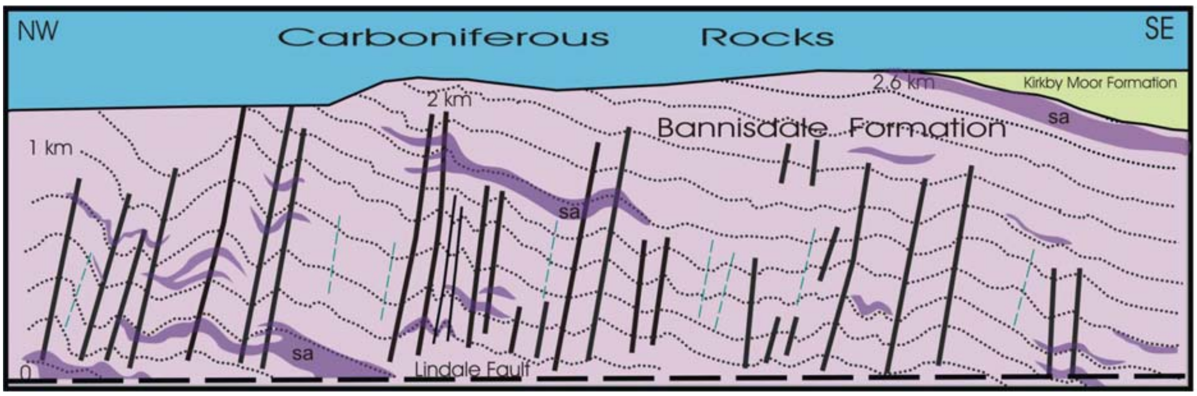

Figure 11. Down-plunge profile of folds in the Bannisdale Formation

The thickness of the Formation is illustrated by the isopachs, shown at 200 m intervals. Profile base line is 4 km long. Axial planes shown as thick black lines. Broken green lines indicate cleavage dip. Sandstone units – sa.

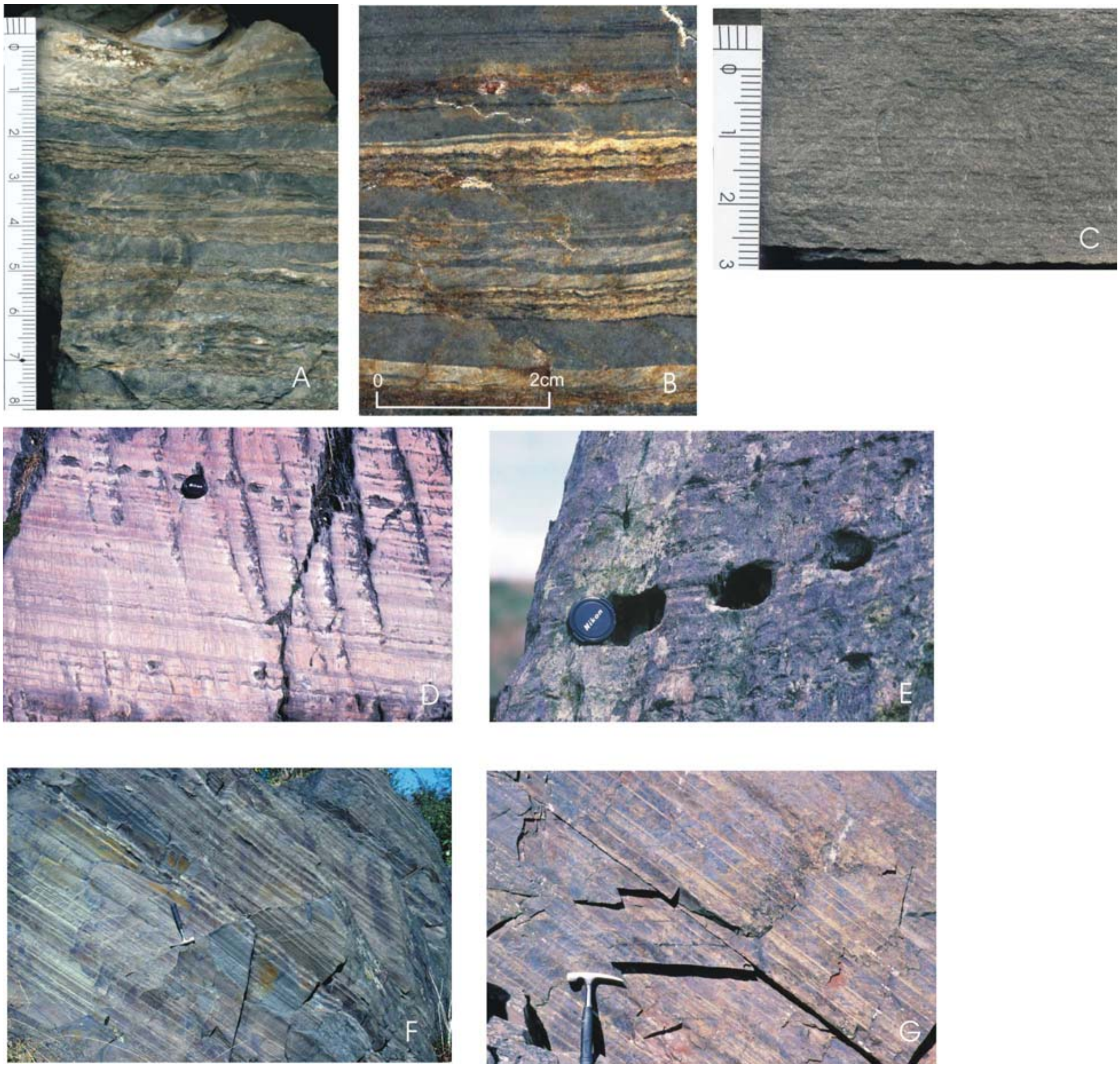

Plate 1. Lithofacies in the Bannisdale Formation

A, B. Banded silty sandstone and silty mudstone couplets, with loading of cross-laminated sandstone into the mudstone layers. Newton Fell and Lindale bypass.

C. Regularly layered silty sandstone from the Lindale bypass

D. Ice-smoothed crag face in banded siltstone

E. Calcareous nodular layer in banded siltstone

F. Fresh surfaces in banded siltstone, Lindale bypass.

G. Slightly weathered exposure of banded siltstone.

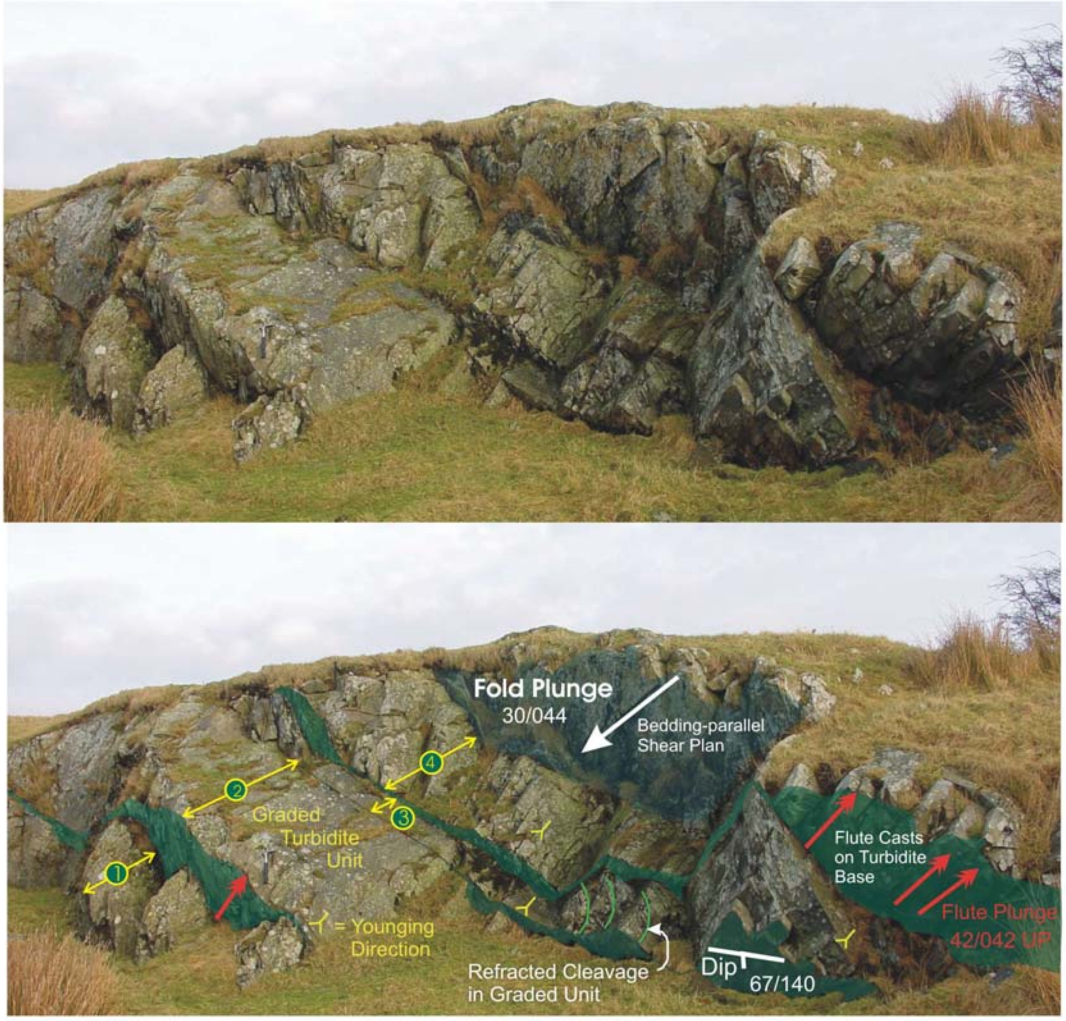

Plate 2. Turbidite sandstone unit within the Bannisdale Formation near the Height - Reservoir House track

Natural exposure [4036 8434] and annotated photograph showing measurements of bedding dip, fold plunge and flute axes used to re-orientate current data. Here the original direction of flow was 246°.

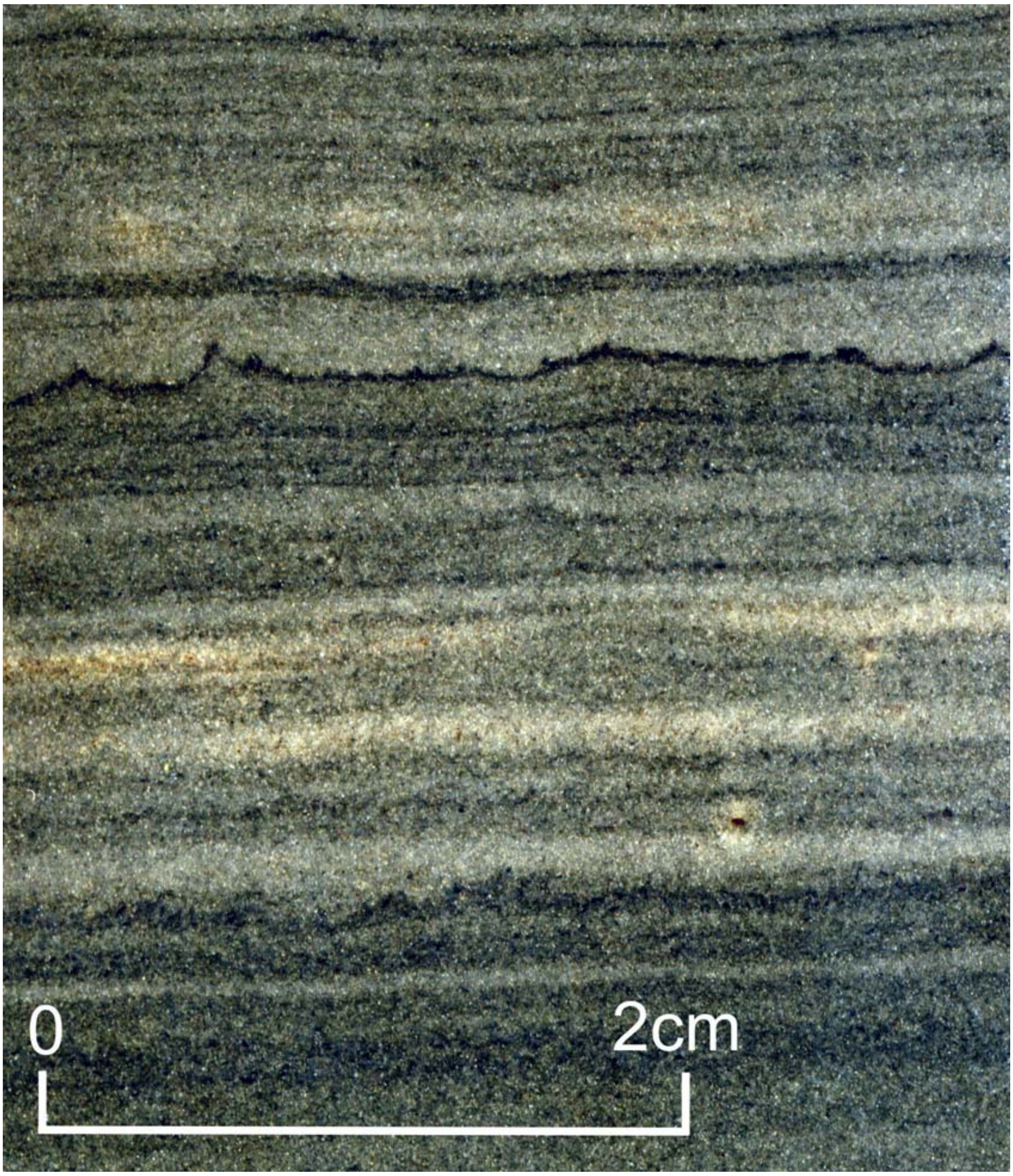

Plate 3. Detail of fine lamination in sandstone from the Kirkby Moor Formation at Millside

Magnified x4.

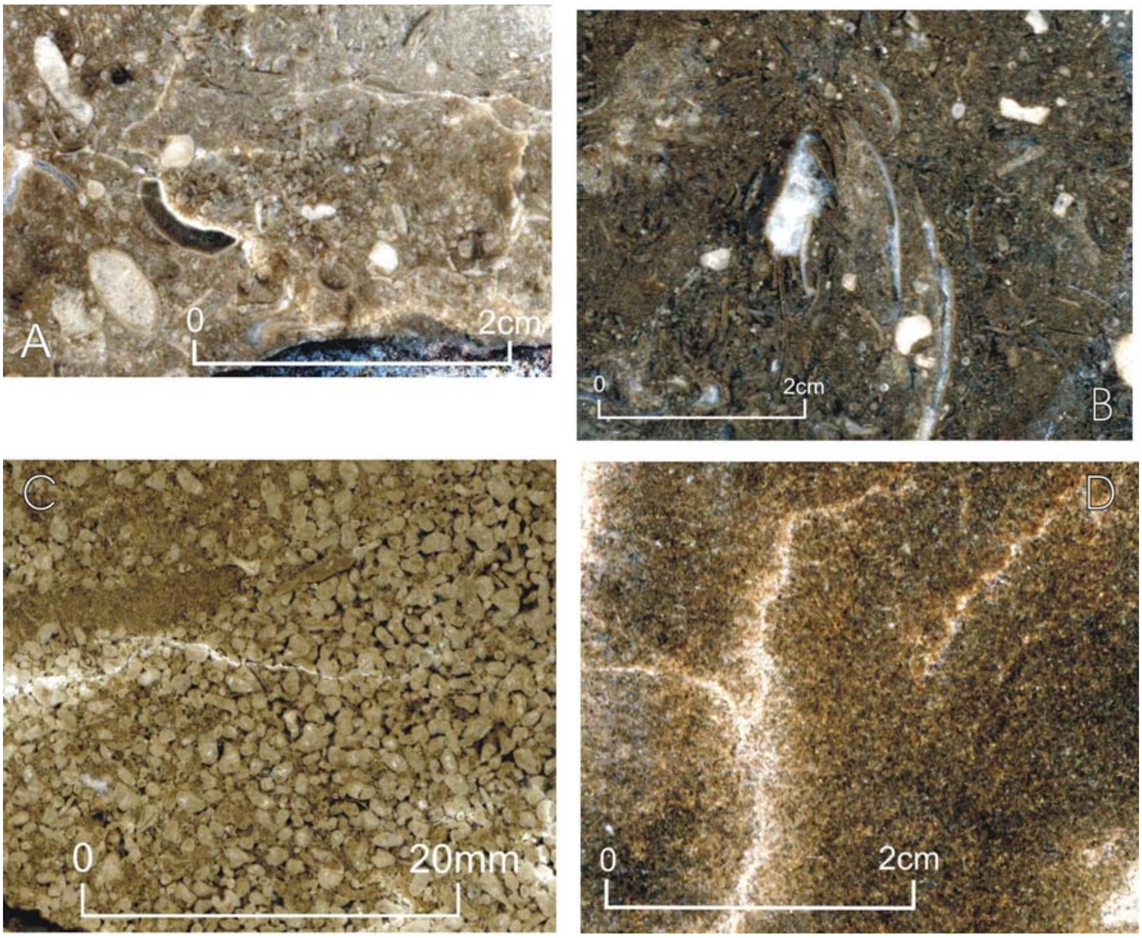

Plate 4. Photomicrographs of limestones from the Great Scar Limestone Group

A. Pale creamy grey medium-grained shelly grainstone. Park Limestone Formation. Summit of Yewbarrow [4342 8438].

B. Dark grey, fine-grained shelly packstone with crinoids. Dalton Formation, western crags of Yewbarrow [4323 8434].

C. Pale grey, coarse-grained peloidal grainstone. Red Hill Limestone Formation, above Holy Well, Witherslack [4308 8323].

D. Brown-grey, medium-grained dolomitised crystalline packstone. Martin Limestone Formation, north-west of Key Moss [4290 8445].

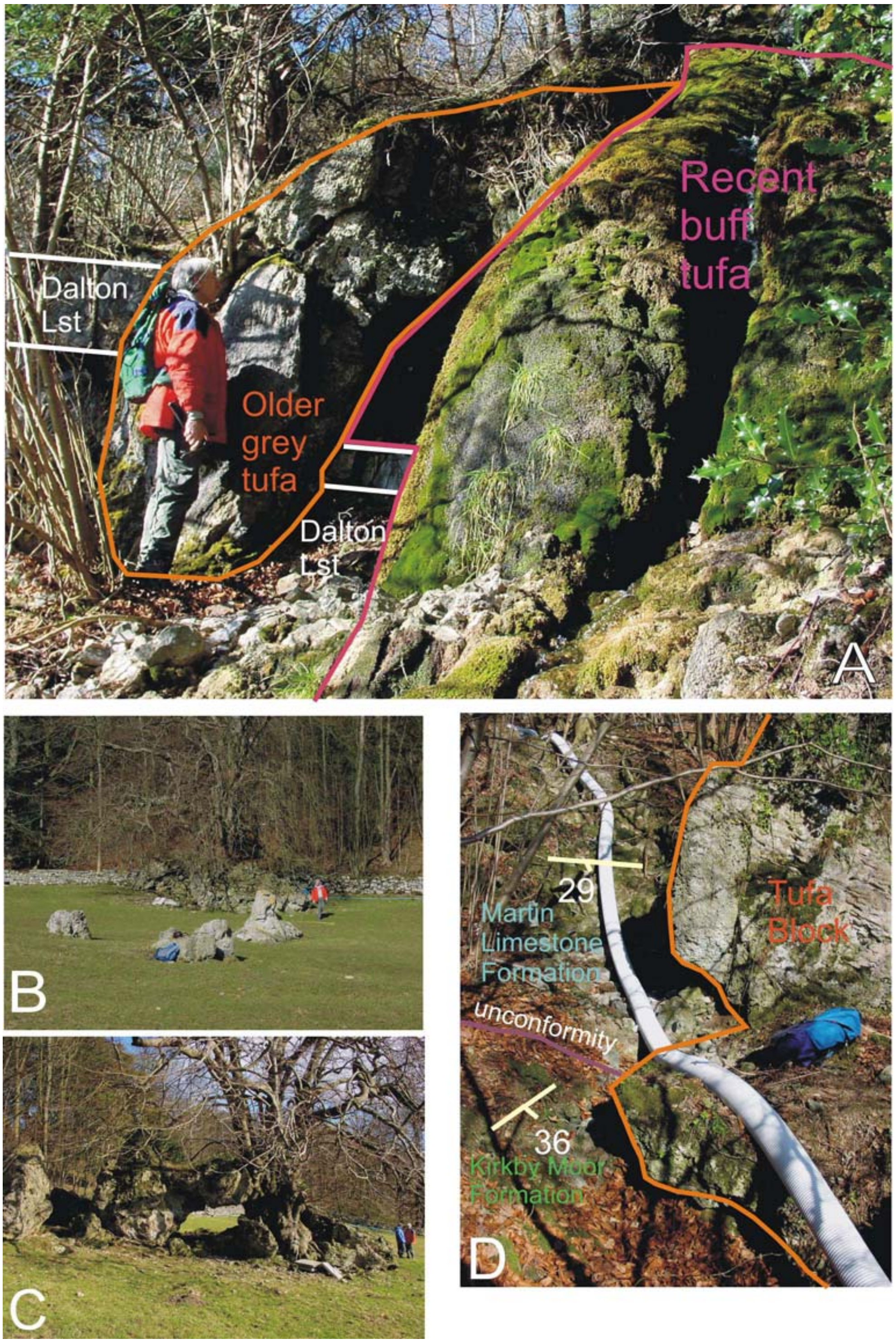

Plate 5. Whitbarrow Lodge Tufa Deposit

A. Tufa-filled cave in crag at 90 m OD

B, C. Tufa blocks spread across lower field at 15 m OD

D. Tufa block lying on unconformity at base of Carboniferous succession.