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Notes on the Windermere Supergroup of the country between Kendal and the River Lune on 1: 25 000-scale sheets SD59 and SD69(W)

Geology and Landscapes Northern Britain Programme

Internal Report IR/06/081

BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPES NORTHERN BRITAIN PROGRAMME

INTERNAL REPORT IR/06/081

Notes on the Windermere Supergroup of the country between Kendal and the River Lune on 1: 25 000-scale sheets SD59 and SD69(W)

Part of 1:50 000 geological series sheet 39 (Kendal)

With appendices relating to NY40SE and SD49NE

N J Soper

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Foreword

This report is the published product of a study by Professor N J Soper. The report describes the bedrock geology of 1:10 000-scale sheets SD59 and the western part of SD69. These maps, which form part of the 1:50 000 geological series sheet 39 (Kendal), were surveyed geologically under NERC contract F60/94E/31A to the University of Sheffield. This report should be read in conjunction with the maps.

Two appendices are included in this report to record formally, modifications to adjacent maps that have been released and reported upon elsewhere. Appendix 1 describes changes to the stratigraphy and structure on 1:10 000 sheet NY40SE and is by N J Soper. Appendix 2 describes the remapping of the Bannisdale Syncline on 1:10 000 sheet SD49NE and is by B C Webb.

This work formed part of the Lake District Regional Geological Survey programme, led by Dr P Stone. The report has been edited by Dr D Millward.

Acknowledgements

The author thanks the local landowners and tenant farmers for access to their land.

Notes

The numbers enclosed in square brackets are National Grid references. Unless otherwise stated the references lie with the 100 km square SD.

Contents

Summary

This report describes the bedrock geology and structure of the country that lies between the valleys of the River Kent to the west and the River Lune to the east and thus lies between the Lake District and the Howgill Fells.

The bedrock stratigraphy is described in section 2. Approximately 2800 m of uppermost Windermere Supergroup rocks of Ludlow age are exposed in the region, belonging to the Coniston Group and succeeding Bannisdale and Kirkby Moor Formations. The Coniston Group is undivided in the area. The former ‘Underbarrow Formation’ has been abandoned as a lithostratigraphical division. The structure is described in section 3. The occurrences of minor intrusions in the area are described in section 4. The lamprophyre dykes are considered to have been emplaced over an extended period during Early Devonian times, whilst the microgranitic bodies (Shap Dyke-swarm) are coeval with the Shap Granite Pluton.

Also included are two appendices that update previous mapping on NY40SE and SD49NE. These document in particular changes to the interpretation of the stratigraphy and structure, consequent upon work completed during resurvey of 1: 10 000 sheets SD59 and SD69. Importantly this includes part of the axial region of the Bannisdale Syncline, the southern limb of which is largely faulted out.

1 Introduction

This report describes the stratigraphy and structure of Ludlow age sedimentary rocks of the Windermere Supergroup in the area between Kendal and Sedbergh in the south-east Lake District. The area is located between the valleys of the River Kent to the west and Lune to the east and thus lies between the Lake District and the Howgill Fells. High ground of Whinfell in the north-east of the area is underlain by turbidite sandstones of the Coniston Group and in the south (Docker, Lambrigg and Firbank fells) by subtidal sandstones of the Kirkby Moor Formation. Between the two, largely drift covered low ground drained by the River Mint is underlain by siltstone and mudstone of the Bannisdale Formation, best exposed in the north-west of the area on Potter Fell. The low ground also contains two poorly exposed outliers of unconformable Carboniferous (Dinantian) strata at Skelsmergh and Grayrigg but these rocks are not described herein.

The primary survey was undertaken in the 1860s. The first geological map of the area (1:10 560 Sheet 39, Kendal) was published in 1871, with an accompanying memoir (Aveline and Hughes 1872). The superficial deposits were subsequently resurveyed and revised editions of the map and memoir published in 1888. The biostratigraphy of the upper part of the Ludlow succession east of Kendal was described by Shaw (1971). The current 1:10 000 resurvey of the Lake District by BGS commenced in 1981 and the first map covered the Windermere Supergroup of Kentmere and Crook, immediately west of the present area, published on the 1:25 000 scale in 1986 and accompanied by a report (Lawrence et al., 1986). Technical reports are now available for the area to the north (Southern Shap Fells; Soper, 1999) and to the east (southern Howgill Fells; Woodcock and Rickards, 1999, 2006).

2 Stratigraphy

Only the uppermost (Ludlow age) part of the Windermere Supergroup is exposed in the area covered by this report. The lithostratigraphical scheme introduced by Kneller et al. (1994) and adopted on 1:50 000 Geological Sheets 38 and 48 (Ambleside and Ulverston) requires some modification as the Ludlow strata are traced eastwards on to the Kendal sheet.

2.1 CONISTON GROUP (Ctg) – LUDLOW SERIES

Dominant lithology: turbidite sandstone beds in packets tens of metres thick.

Thickness: c. 1000 m exposed, base not seen.

The five-fold division of the Coniston Group recognised by Lawrence et al., 1986) in the Kentmere–Crook area cannot be sustained due to the eastward failure of the fine-grained Latrigg and Moorhowe formations in the southern Shap Fells (Soper, 1999), so that the three individual sandstone-dominated formations are not distinguishable and are grouped as ‘Ctg undivided’. The upper part of this sequence is exposed in the north-east of the present area, particularly on Grayrigg Pike [605 995] and the southern slopes of Whinfell to the west.

The greywacke sandstone is generally fine to medium grained with a muddy matrix, commonly showing delayed grading into thin silty mudstone tops. Bed thickness is commonly less than 1.0 m, but amalgamated beds up to 2.5 m are present, for example at [606 994]. Many beds show little internal structure, but parallel and wavy lamination, ripple cross-lamination and sporadic convolute lamination are present; recessively weathered calcareous nodules of diagenetic origin are locally common.

The greywackes are interpreted as the deposits of sandy turbiditic submarine fan systems. Erosional bottom structures indicate palaeoflow from the north-east. Examples are well exposed in Dillicar quarry [615 988] where there are groove casts with complex ‘ropy’ morphology and flute casts of arcuate shape.

Interbedded finer grained ‘slate’ packets are typically poorly exposed. They are dominated by Bannisdale-type banded siltstone–mudstone with minor intervals of laminated muddy siltstone of Brathay type. The Coniston Group passes up into the Bannisdale Formation by an increase in the proportion of these slate packets; the boundary is taken at a particular unit exposed at [609 975] which can be traced eastwards through the Howgill Fells.

2.2 BANNISDALE FORMATION (Bnd) – LUDLOW SERIES

Dominant lithologies: banded siltstone–mudstone couplets, turbidite sandstone.

Thickness: c.1400 m in east of area.

The Bannisdale Formation conformably overlies the Coniston Group and constitutes the second of the two major divisions of the Ludlow rocks in the Lake District and Howgill Fells. Its characteristic lithology consists of graded siltstone–mudstone couplets commonly a few centimetres thick, the ‘banded unit’ facies of Rickards (1967). Ripple cross-lamination and convolute lamination are commonly developed, particularly in the upper part of the sequence, together with calcareous nodules of diagenetic origin. This facies is thought to represent deposition from dilute turbidity flows, of smaller volume and perhaps greater frequency than those responsible for the sandstone. Thin units of hemipelagite continue to represent background sedimentation in the lower part of the formation. Turbidite sandstone beds are also commonly present in the lower part of the sequence and in the east of the present area these develop into mappable sandstone packets. A few records of erosional bottom structures from these sandstone beds, for example at [6086 9735] indicate palaeoflow from the north-east, as in the Coniston Group.

The thickness of the Bannisdale Formation is difficult to estimate because of minor folding, faulting and lack of marker horizons. An estimate of 1400 m was made in the vicinity of Lowgill [960 610] where both base and top are seen and there is little minor folding. This includes several sandstone packets towards the base. The outcrop widens substantially westwards in poorly exposed ground, towards the large tract occupied by the Bannisdale Formation in the adjacent Ambleside district. There, a thickness of more than 4 km was inferred by Kneller et al. (1994), which may be excessive. To the east, in the Howgill Fells where the top of the formation is not seen, Woodcock and Rickards estimated a thickness of 1.5 km.

The top of the formation is taken at the incoming of thick sandstones of the Kirkby Moor Formation, a conformable and rapidly transitional boundary. In the Kendal area, Shaw (1971) defined a sequence of fine-grained strata with a shelly fauna between the Bannisdale and Kirkby Moor formations as the Underbarrow Formation, replacing the term ‘Passage Beds’ of Aveline and Hughes (1872). This biostratigraphically defined unit does not have a mappable lithological base – bioturbation and shelly lags occur well down in the Bannisdale Formation – so the Underbarrow Formation has been abandoned as a formal lithostratigraphical division.

2.3 KIRKBY MOOR FORMATION (KMF) – LUDLOW SERIES

Lithology: Thickly bedded sandstone, rather featureless or with convolute bedding; thin-bedded fine sandstone with hummocky and swaley bedding, siltstone.

Thickness: c. 430 m exposed, top not seen.

Detailed descriptions of the lithofacies present in the Kirkby Moor formation have been made by Shaw (1971) and King (1994), who recognised five facies associations within the Bannisdale and

Kirkby Moor formations. In the present area most outcrops represent King's association C, dominated by 'stratified sandstone with HCS' (hummocky cross-stratification). The typical lithology consists of thick-bedded (up to 2 m), medium to fine sandstone which is rather massive and devoid of internal structures apart from convolute-bedding (interpreted as a result of dewatering), sporadic channelised bedforms and shell lags. Convex-down convolute 'rolls' are commonly developed about a quarter of the way up from the base of thick beds; their axes tend to be aligned north-west–south-east. Thin sandstone beds with HCS and ripple cross-laminated siltstone units are present, and are probably under-represented in natural outcrops. King (1994) attributed the Kirkby Moor Formation to deposition in a storm-dominated shelf environment, representing an upward-shallowing sequence towards the end of Windermere Supergroup deposition.

On biostratigraphical grounds Shaw (1971) recognised a further sequence above the Kirkby Moor Formation, the Scout Hill Flags. The outcrop depicted on his map does not accord with the structural pattern established during the present resurvey. Lithologically the strata are indistinguishable from the Kirkby Moor Formation and accordingly, the Scout Hill Flags have been abandoned as a formal lithostratigraphical unit. Conversely, a fine-grained unit that crops out just south of the present area on The Helm [530 890] and was defined as the Helm Member by King (1994), does appear to represent a viable lithostratigraphical division comprising her facies association D. It does not extend into the present area.

Also to the south of the present area is Hills Quarry [5960 8803] which King (1994) suggested as a better type locality for the Underbarrow Formation. The lithology here is more distinctive than at Underbarrow. It consists of grey silty mudstone and pale, graded or cross-laminated siltstone, interbedded on a decimetre scale, and weakly bioturbated. It is not known where these beds lie within the Kirkby Moor Formation, or whether they extend into drift-covered ground at the southern margin of the present area. If during the resurvey of the Kirkby Lonsdale sheet it is decided to formalise this division, the name 'Underbarrow' should be avoided.

3 Structure

The Windermere Supergroup was deformed during the Acadian orogeny towards the end of Early Devonian time (Soper et al., 1987) which produced typical 'slate belt' structures – folding and cleavage developed under low anchizone conditions in the present area. Northerly trending faults are an equally important influence on the outcrop pattern.

3.1 REGIONAL FOLDS

The area lies to the south of the trace of the main regional scale fold in the Windermere Supergroup, the east-north-east–trending Bannisdale syncline, and is characterised by broad, open folding which is generally anticlinal in the Coniston Group in the north of the area, synclinal in the Kirkby Moor Formation to the south.

The northern anticlinal tract was called the Selside anticline by Moseley (1972), but it does not form the coherent regional trace depicted on his synoptic map, passing down-section to the west into 'noisy' minor folding typical of the Bannisdale Formation. The southern Benson Knott anticline is a well defined east-plunging fold on Benson Knott itself [550 940] with limb dips of 40°-50° but traced eastwards towards Lambrigg Fell [585 945] dips diminish and the fold loses coherence. To the south is a tract of open folding in the Kirkby Moor Formation, in which the first anticline brings up several inliers of Bannisdale Formation, incidentally not depicted on Shaw's biostratigraphical map (1971).

3.2 CLEAVAGE

As is typical in the Windermere Supergroup, the style of the Acadian cleavage is related to lithology and ranges from crude anastomosing stress dissolution seams in sandstone to a penetrative grain shape fabric in mudstone. Additionally, in this area there is a relation between cleavage intensity and stratigraphical level – the strain diminishes upwards. In the Kirkby Moor Formation sandstone is typically uncleaved whereas the thin silty interbeds carry a low-angle spaced cleavage that evidently reflects a greater component of flexural strain than of regional shortening.

The cleavage trends slightly north of east in the northern part of the area, roughly east–west around Kendal and slightly south of east in the south-east of the area. The area thus represents a nexus between the Caledonoid trend typical of the Lake District and the east-south-east-trending structures of the Howgill Fells and Ribblesdale. Where fold traces can be defined accurately, the cleavage generally strikes clockwise at a small angle, which is typical of the Caledonoid tract, whereas in Ribblesdale the transection is at a very small, anticlockwise angle (Soper et al., 1987). This shows that the regional arcuate pattern defined by the fold traces does not quite coincide with that of the cleavage.

3.3 FAULTS

Faults with a generally northerly trend are widely developed in the Windermere Supergroup, and in the Ulverston area some of them have displacements of both post-Carboniferous and Acadian age (Soper, 1993). Moseley (1968), in his structural study of the Shap Fells, noted that the northerly faults often separate tracts with different fold patterns. He suggested that displacement on the faults accompanied the folding, partitioning the strain. The present resurvey has confirmed this observation (Soper, 1999). It is clear that the amount and sense of displacement vary along the fault plane, accommodating the flexural and ductile strains associated with the folding and cleavage. It was suggested that faults of this type represent basement fractures that were reactivated and propagated up into the Windermere Supergroup cover during the Acadian deformation. It is not known whether 'basement' in this sense refers to underlying Borrowdale Volcanic rocks, so that the faults might have been initiated as volcanotectonic fractures, or to the deep basement, the character of which unknown.

In the present area the northerly faults typically comprise discrete north-north-east and north-north-west-trending sets. Examples of both sets are exposed in Roan Head quarry [586 928] which is exploiting sandstone of the Kirkby Moor Formation for roadstone. The permanent east face of the quarry is composed of large fault planes, strike 012°, dip 66° to the west, with apparently normal (down-west) displacement and narrow (up to 250 mm) zones of fault breccia. A north-north-west-striking zone of hematised fault breccia more than 10 m thick dips to the north-east at 58°. It appears that both fault sets have the geometry of extensional faults, and thus if they were initiated by the propagation up into the Silurian cover of pre-existing basement fractures, this may have taken place during a period of extension. And since they were already present during the Acadian deformation, to which they are geometrically unrelated, this must have occurred post-Silurian, pre-Emsian.

The Early Devonian is now recognised as an important period of sinistral transtension in the North Atlantic Caledonides (Dewey and Strachan, 2003; Soper and Woodcock, 2003) and it is supposed that the north-north-east faults and perhaps the north-north-west set were formed then. They were thus ideally orientated for reactivation down-west during the period of extension that occurred in Permo-Triassic time and produced the east-dipping tilt blocks of Carboniferous strata that are characteristic of the southern Lake District. Most of the mapped north-north-east-trending faults show down to the west displacements of the stratigraphy, which are likely to comprise both Early Devonian and Permo-Triassic components. The most important faults stratigraphically, however, belong to the north-north-west set. These include the Firbank Fault which terminates the outcrop of the Kirkby Moor Formation to the east and the Kendal fault which forms the eastern boundary of the Underbarrow Carboniferous block.

New extensional faults were also initiated during the Permo-Triassic. The most obvious of these have curvilinear traces which are concave to the south-west and throw down in that direction, with Carboniferous rocks in the hanging wall. This is consistent with the generally north-east – south-west direction inferred for Permo-Triassic extension in the East Irish Sea area (Needham and Morgan, 1997). The best examples in the present area are the Grayrigg and Skelsmergh faults which form the north-eastern boundaries of the eponymous Carboniferous inliers. Such faults probably have a listric form, in contrast to the through-going geometry inferred for the northerly sets.

4 Minor intrusions

A number of pink microgranite or felsite dykes are exposed in the area and the presence of erratic blocks and fragments built into walls indicates the presence of others obscured by till. The main examples are listed below, with brief field notes.

[5123 9885] Pink microgranite dyke, greater than 9 m thick, strike 055°, close to crest of anticline in Bannisdale Formation.

[5145 9895] Same dyke, strike 062°, occupies core of anticline and can be traced for 50 m, terminating to east and west.

[5057 9854] Small exposure of ?same dyke, offset to left by north-north-west fault.

[5775 9860] In Whinhowe Beck. Large (c. 50 by 30 m) mass of quartz-feldspar porphyritic felsite in footwall of Grayrigg fault. Intruded into Coniston Group but margins obscure. Association with post-Carboniferous fault appears to be fortuitous. Two smaller masses immediately upstream.

[5818 0000] Small outcrop of porphyritic felsite within Coniston Group.

[5995 9919] 2 m thick flow banded felsite in Coniston Group, contact strikes 128°, dip 60° to north-east.

[6150 9926] Rotten felsite exposed for 75 m in gill, within Coniston Group but margins obscure.

[6077 9757] c. 10 m thick felsite with muscovite, weakly cleaved, intruded at top of Coniston Group, trend unclear.

It is thought that these dykes belong to the Shap Swarm. As they are traced towards the intrusion to the north of the present area on NY50, some examples carry smaller versions of the K-feldspar megacrysts characteristic of the Shap Granite Pluton. They are thus of late Lower Devonian age, which ties in with their structural relationships, essentially later than the folding but affected by a late increment of the cleavage (Soper and Kneller, 1990).

One lamprophyric dyke has been recorded in Kirkby Moor Formation at [5578 9399] as ‘rotten mica trap’. The location of a lamprophyre from the area analysed by Macdonald et al. (1985) [557 957], on Docker Fell appears to be in a railway cutting and was not examined.

Appendix 1 Amendments to NY40SE (Kentmere)

The 'Kentmere–Crook' phase of mapping (Lawrence et al., 1986) finished at easting 49 and NY40SE was drawn up as a part standard. The ground to the east of 49 was mapped in June 1995 by N J Soper and the standard completed by BGS in 1998. Survey of the axial region of the Bannisdale syncline on NY50 indicated that revision of the base of the Kirkby Moor Formation and the structure of the syncline as depicted on Kentmere–Crook were required. N J Soper remapped the synclinal termination of Kirkby Moor Formation on Brunt Knott on NY40SE in June 1999 and amended the standard in June 2003. B C Webb revised the syncline on SD49NE and drafted a new standard in 2003 (see his report in Appendix 2).

STRATIGRAPHY

In the Kendal area Shaw (1971) defined a sequence of fine-grained strata with a shelly fauna as the Underbarrow Formation, between the Bannisdale and Kirkby Moor formations, replacing the term 'Passage Beds' of Aveline and Hughes (1872). Lawrence et al. were unable to verify Shaw's Bannisdale–Underbarrow boundary and chose a higher level for the base of their Underbarrow Formation, which at outcrop, for example on Knott Hill [475 925], appears to consist of bioturbated Bannisdale facies. The only lithological boundary that can be widely recognised in this part of the succession in the Kendal area is the passage from Bannisdale 'banded facies' to subtidal sandstone of the Kirkby Moor Formation. Because its base cannot be defined lithologically (bioturbation and shelly lags occur sporadically well down into the Bannisdale Formation), the Underbarrow Formation has been abandoned as a lithostratigraphical unit. Lithologies in the narrow strip of Underbarrow Formation depicted by Lawrence et al. round the closure of the Bannisdale syncline on Brunt Knott appear to be typical Bannisdale 'banded' facies.

Mapping of the Kirkby Moor Formation in the core of the syncline on NY50 revealed a fine-grained interval at the base that represents a passage from typical 'banded facies' Bannisdale Formation to thick bedded subtidal sandstone of the Kirkby Moor Formation. This was designated KMF' on the standard for NY50SW. It consists of 0 to 100 m of laminated fine sandstone with hummocky cross-stratification and swaley bedding, quite distinct from 'Underbarrow' lithofacies. Remapping of the synclinal termination on Brunt Knott revealed 14 to c. 200 m of this facies. Member status has not been proposed for this unit and it is suggested that it should not be shown separately from Kirkby Moor Formation on the 1:50 000 map.

STRUCTURE

The closure of the Bannisdale syncline as depicted on Kentmere–Crook is fairly symmetrical with steep south-south-east dips in Kirkby Moor Formation rocks on the north limb and steep north-north-west dips on the south limb. Mapping of the structure on NY50 showed a different pattern, with steeply inclined Kirkby Moor Formation on the north limb faulted against Bannisdale Formation on the south limb. This asymmetrical structure means that along much of the fold trace there are no exposed Kirkby Moor Formation strata defining the south limb (see cross-sections, Technical Report WA/99/35, fig. 8).

Remapping of Brunt Knott on NY40 revealed a similar pattern: steep north-north-west dips depicted as south limb are inverted and young south. The map has been amended accordingly. This failure to recognise inverted strata also means that many of the minor folds in Bannisdale shown on NY40SE are likely to be spurious, particularly those with steeply opposed dips.

Appendix 2 Notes on the remapping of the Bannisdale Syncline on sheet SD49NE, by B Webb, May 2003

The original survey of this area, at the six-inch scale, was by W T Aveline in 1867–69. The western half of this sheet was last remapped at the 1:10,000 scale by B Webb (SW quadrant) and D J Lawrence (NW quadrant) in 1983. The eastern half of the sheet, along with that of the sheet to the north (NY40SE) was remapped at the 1:10,000 scale by N J Soper in 1995–99.

The Bannisdale Syncline trends east-north-east across the north-west quadrant of SD49NE and the south-east quadrant of NY40SE. The Kirkby Moor Formation crops out in the core of this structure. Lawrence considered both limbs of the fold to be present on SD49NE, with the Kirkby Moor Formation outcrop surrounded by a narrow outcrop of the Underbarrow Formation, which he considered to be present between the Kirkby Moor Formation and the underlying Bannisdale Formation. Soper found that the north-dipping Kirkby Moor strata mapped at the southern limb of the Bannisdale Syncline on Brunt Knott [NY 483 001] were, in fact, inverted and belong to the north limb. The southern limb is apparently faulted out and inverted Kirkby Moor Formation juxtaposed with Bannisdale Formation. Although he recognised a thin-bedded division at the base of the former, he considered that this could not be equated with the Underbarrow Formation. Disparities, therefore, existed between the two sheets.

Remapping at the 1:10,000 scale, within the north-west quadrant of SD49NE, was undertaken by B Webb in 2002. The aim was to re-examine the structure of the Bannisdale Syncline, and map the outcrop of the thin-bedded facies of the Kirkby Moor Formation, as defined by Soper.

LITHOSTRATIGRAPHIC BOUNDARIES

North of the Bannisdale Syncline, the Bannisdale Formation comprises bluish grey silty mudstone with pale grey siltstone laminae less than 2 mm thick. At outcrop, it has a massive appearance. The upwards transition into the basal, thin-bedded unit of the Kirkby Moor Formation, is well displayed just above the road along the eastern flank of Hugill Fell [462 997]. Over a distance of only 2–3 m, the pale grey siltstone laminae thicken to over 10 mm, and the rock takes on a distinctive flaggy appearance. This is taken as the base of the Kirkby Moor Formation. Above the base, siltstone beds continue to thicken and coarsen. The thin-bedded basal unit is defined as that part in which siltstone and fine sandstone beds ranged from 10 to 150 mm thick, producing a distinctive flaggy appearance at outcrop. It is approximately 50 m thick, and is designated KMF' on the map.

Above the thin-bedded facies, the Kirkby Moor Formation comprises sandstone and silty sandstone beds up to 2.0 m thick. Swaley cross-bedding and dewatering structures are locally present. Some of the finer grained units are rather massive and structureless, and are probably slumped. The beds appear to lack lateral continuity, but this may be the result of later minor faulting. The thickness of this part of the Kirkby Moor Formation is difficult to assess accurately, because of minor folding and faulting. It would appear to be from 250 to 300 m think.

On Hughill Fell, the thin-bedded facies can be traced west and south, round the northern limb, and into the core of the Bannisdale Syncline [456 990], where they are overlain, quite abruptly, by massive sandstone, with beds up to over 1 m thick, some showing dewatering structures.

Eastwards, along the southern limb of the syncline, the thin-bedded facies cannot be identified with any certainty, and some of the thicker sandstone beds also seem to be missing. Across the crest of the hill [461 900], exposure is sporadic. Exposures assigned by Lawrence to the Underbarrow Formation do, locally, contain sandstone beds up to 150 mm, interbedded with laminated, silty mudstone. They are not, however, regularly interbedded, and do not produce a flaggy appearance. Similar sandstone beds are common within undisputed Bannisdale Formation to the south, reaching a maximum thickness of 1.5 m in Reston Scar [460 986]. It seems more reasonable to equate Lawrence's Underbarrow Formation, here, with the Bannisdale Formation rather than the thin-bedded Kirkby Moor Formation.

From SD 463 991 eastwards to the valley bottom, the thin-bedded facies is noticeably absent. Massive siltstone beds, up to 1 m thick, interbedded with thinner sandstones, dip moderately to steeply north, and form a prominent feature along the southern edge of the Kirkby Moor Formation outcrop. Less than 20 m south, massive, dark, silty mudstone with some paler laminae is commonly exposed. Lawrence mapped much of these as Underbarrow Formation, but there appears to be no difference between them and undisputed Bannisdale Formation 80 m farther south. They are quite unlike the thin-bedded Kirkby Moor Formation unit seen on the northern limb. Across the Kent valley, north-east of Scroggs Farm [472 995], sporadic, small exposures adjacent to the Bannisdale Formation/Kirkby Moor Formation boundary, were mapped as Underbarrow Formation by Lawrence. The more southerly of these are of silty mudstone in which the bedding is obscure, and they cannot really be distinguished from the Bannisdale Formation. The more northerly exposures do contain thin siltstone and sandstone beds, giving them a flaggy appearance, but dip more steeply northwards than the cleavage. This indicates that they must young southwards, away from the undisputed Kirkby Moor Formation outcrop to the north, and be faulted against the older Bannisdale Formation to the south.

STRUCTURE OF THE BANNISDALE SYNCLINE

The closure of the syncline can only be identified near the western termination of the Kirkby Moor Formation outcrop. Here, although quite tight, the fold shows a concentric style, with a plunge of about 20^{o} to the east-north-east. The axial trace can be followed with certainty only for some 400 m, to SD 460 991. Over this distance, the southern limb maintains a constant outcrop width of about 100 m, whilst the northern limb widens to around 200 m. This would be consistent with the cutting out of some of the sandstone succession on the southern limb, but may also be the result of minor folding on the northern limb. Farther east, the southern limb becomes more attenuated. At SD 466 992, massive siltstone and sandstone beds close to the junction with the Bannisdale Formation show evidence of shearing with a sense of downthrow to the north, and on the east side of the Kent valley the limb is absent.

Mapping indicates similar faulting out of the southern limb of a minor syncline around SD 458 994, and an outcrop scale example is visible at SD 4560 9926. This latter lies within the Bannisdale Formation outcrop close to the junction with the thin-bedded Kirkby Moor Formation. It exposes a hanging wall cut-off resting on a footwall flat to its north. It is now steeply overturned towards the south, but effectively indicates northerly directed thrusting. The main syncline is thus interpreted as a footwall cut-off associated with northerly directed thrusting concurrent with regional folding.

MINOR FOLDS WITHIN THE BANNISDALE FORMATION

Within the Bannisdale Formation outcrop north of the Bannisdale Syncline, the present edition of NY40SE and the earlier edition of SD49NE depict numerous tight minor folds. Steep southerly dips predominate in this area, but steep northerly dips are locally present and, on SD49NE, appear to have been taken as evidence of opposing fold limbs without reference to vergence. Local overturning of the beds to give steep northerly dips, is common in this area and can be confirmed by cleavage/bedding relationships showing consistent northerly vergence. Erroneous fold traces have been removed from the redrafted SD49NE, but will remain on NY40SE, where they have not been checked. In view of this, any tight minor folds depicted on that map should be treated with suspicion.

The problem does not arise south of the Bannisdale Syncline, where the Bannisdale Formation includes sandstone beds and thus fold closures, younging evidence and cleavage relationships are consequently clearer.

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