University of Hull

# THE GEOLOGY OF THE BARBON AND MIDDLETON FELLS, NEAR KIRKBY LONSDALE, WESTMORLAND.

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in
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by

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# CONTENTS.

## SUMMARY

The results of stratigraphical, palaeontological, petrographical, and sedimentological investigations into the Silurian strata of the Barbon and Middleton Fells, east of the Lune Valley Westmorland, are described, and compared with strata of a similar age in other parts of the country.

A detailed stratigraphical succession has been erected for the first time, the strata having been sub-divided on a lithological basis into the Coniston Grits and Bannisdale Slates. Zoning of this succession by means of the graptolite faunas reveals that the *lundgreni*, *nilssoni-scanicus*, *leintwardinensis incipiens* and *leintwardinensis leintwardinensis* zones are present in the area. The *lundgreni* fauna which is indicative of the upper part of the Wenlock Series, is restricted almost entirely to the southern extremity of the area. The remainder of the strata fall within the Ludlow Series.

Statistical investigations into the petrography of the coarse sediments have shown that they may be classified as fine grained greywackes, which have been derived from the northern part of the Southern Uplands. Consideration of sedimentary structures and changes in thickness and grain size of the sediments in adjacent areas supports this conclusion. This indicates that there is little evidence in favour of the Lake District and Southern Uplands areas

of deposition being separated by a border land mass in Ludlovian times.

The coarse grained sediments are shown to have been brought into the area from the north-west, by comparatively vigorous turbidity currents. Finer grained sediments, however, are considered to represent deposition from low grade currents during quiescent periods which become more and more dominant in the higher parts of the succession. Pyritic films in these finer sediments suggest that deposition took place under anaerobic conditions.

Consideration of the structure has revealed that during the Caledonian orogeny the sediments were folded and faulted along WNW-ESE axes, to produce two large open synclines on which minor folding is superimposed. The effect of the later Hercynian orogeny was to introduce a set of N-S and NE-SW trending faults into the area, and to tilt the strata slightly to the north-west.

# ACKNOWLEDGEMENTS

The work described in this thesis was carried out during the tenure of a post-graduate studentship provided by the Department of Scientific and Industrial Research, (now the Scientific Research Council). The author would like to express his thanks to the Department, and also to Professor D. T. Donovan, the Head of the Department of Geology in the University of Hull, who has made available to the author the resources of the Department.

The author would also like to thank many research workers in the field of Silurian Geology in all parts of the world, who have provided offprints of their publications and much valuable advice. In particular thanks are due to Mr. J. H. McD. Whitaker, Dr. C. H. Holland, Dr. R. J. Bailey, Dr. P. G. Llewellyn, Dr. W. A. Cummins, and many other members of the Ludlow Research Group. Dr. R. B. Rickards formerly of the University of Hull Department of Geology, and now of the Sedgwick Museum Cambridge, kindly helped the author with the identification of graptolites, and provided valuable discussions on many other aspects of Silurian Geology. Dr. E. K. Walton of the University of Edinburgh Department of Geology, and Dr. P. T. Warren of the Geological Survey have also been of particular assistance in many ways, and have loaned the author thin sections of greywackes from the Southern Uplands, thus making direct comparison with this area possible. Dr. Walton also acted as a very generous host on the occasion of a visit to the Edinburgh Department. Thanks are also due to Mr. A. G. Brighton, curator of the Sedgwick Museum, Cambridge, for permission to examine the extensive collection of graptolites and other Silurian fossils.

Many members of the Geology Department at Hull University have given the author great help and encouragement. Dr. N. S. Angus helped with the identification of igneous rock fragments in the greywackes, and Mr. R. V. Dingle provided information on the Silurian inliers of the Midland Valley of Scotland. Thanks are also due to other members of staff and research students, especially Messrs. B. N. Fletcher, C. W. Claxton, R. C. Whatley and R. G. Clements for much valuable advice and criticism, and to members of the Technical Staff for help in photographic work.

The author's supervisors were Dr. J. W. Neale from 1962 to 1964, and Mr. L. F. Penny for the 1964-65 Session, when Dr. Neale was in the United States. To both of them the author would like to express his especial thanks. Dr. Neale has been a constant source of inspiration and help, not only in the laboratory but in the field also. During his present year in the United States he has never failed to keep in touch with the progress of the work. Mr. L. F. Penny has been of particular assistance during the present year; he has critically read the entire manuscript of the work, and has never failed to assist in any way.

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# CHAPTER 1

## INTRODUCTION

The Barbon and Middleton Fells form a distinctive triangular tract of country lying to the east of the Lune Valley northeast of the town of Kirkby Lonsdale, and extending in a northerly direction through the counties of Lancashire and Westmorland for some 9 miles, into the West Riding of Yorkshire, near Sedbergh, (See fig.1-1). The north eastern side of this triangle is about 4 miles wide, and follows the course of the River Dee, which flows in a north westerly direction to join the Rawthey and Lune at Middleton Bridge. From this point southwards, the broad, flat, faulted valley of the Lune forms the western boundary of the area, from which the Barbon and Middleton Fells rise steeply. The easterly extent of the region is marked by the deep faulted valleys of Barbondale, and Leck Beck, which joins the Lune to the south of Kirkby Lonsdale.

Within the area thus defined, lie a series of deeply dissected rolling fells, rising to a height of almost 2000 feet along their eastern edge, and which stand out in marked contrast to the surrounding more gently sloping Carboniferous country. Drainage is predominantly to the west, most of the streams rising close to the eastern limits of the area, and flowing down deep V-shaped valleys to join the River Lune. The drainage in the east from Barbondale is largely from the Carboniferous country to the southeast.

Evidence of glaciation is restricted to the major river valleys, which form the boundaries of the region, and to the lower reaches of the larger tributaries draining off the fells. The U-shape, overdeepening, and heavy drift deposits of Dentdale and the Lune Valley indicate the passage of major glaciers down these valleys during the Pleistocene. At the northern apex of the region, deep hollowing and grooving into softer bands of strata, are probably a result of the Dentdale ice being deflected to the south, against the hillside, by the much larger and more powerful glaciers moving from the north, down the Rawthey and Lune Valleys.

The strata of the Barbon and Middleton Fells are almost entirely of Silurian age, apart from a small inlier of Ordovician rocks at the northeastern edge of the area, and form the southeastern limit of the main Lake District outcrop. To the north, the Howgill Fells are formed of rocks of similar age. To the east, however, Carboniferous strata are down faulted against the Silurian by the Dent

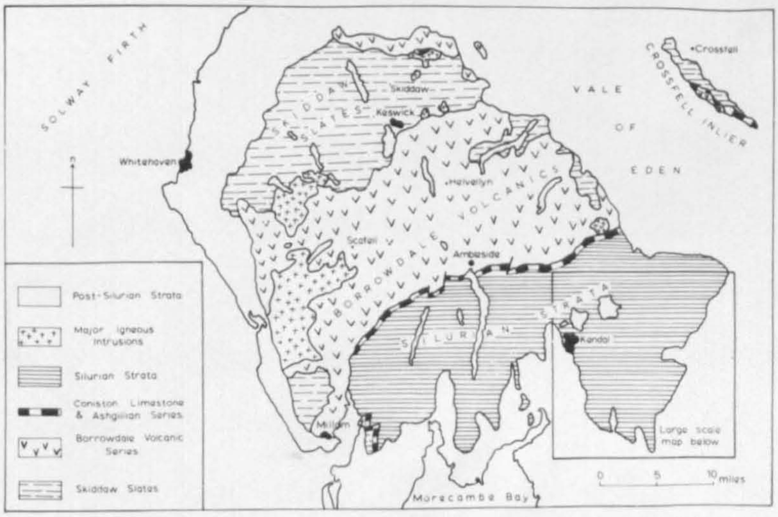



FIG. Showing the distribution of the pre-Carboniferous rocks of the Lake District and adjacent areas. (After H.M. Geol. Survey.)

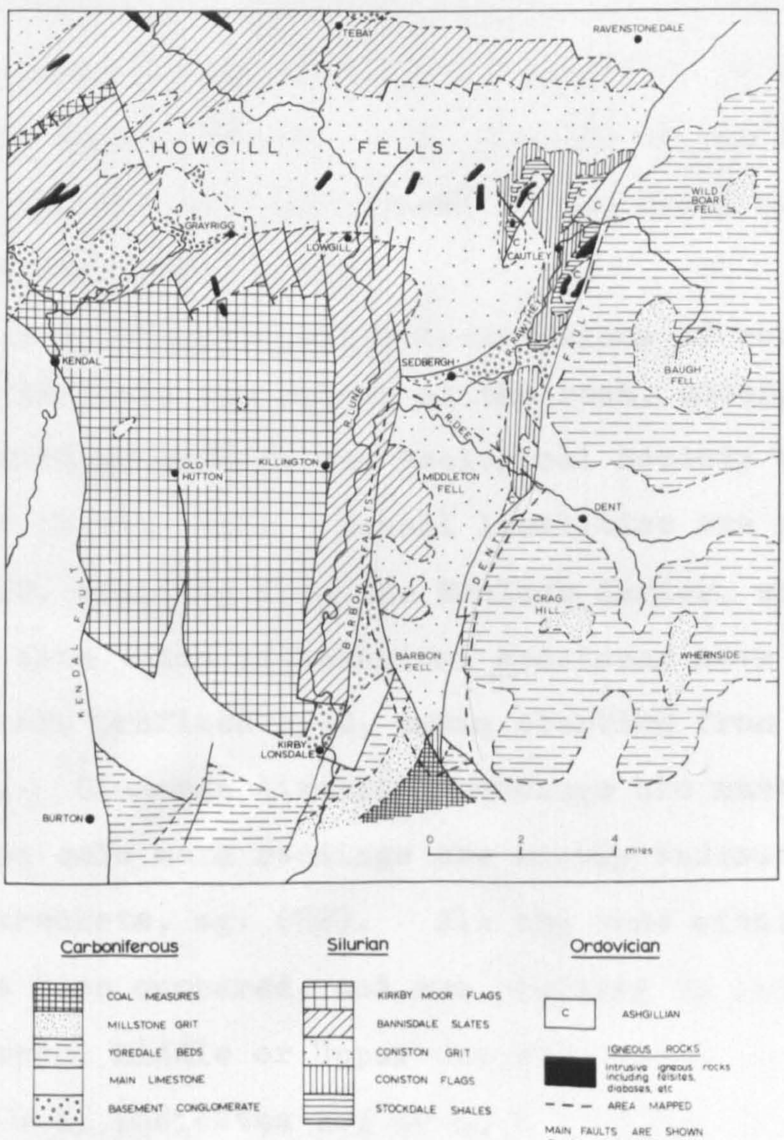



FIG. 1-1 The Geological setting of the Barbon and Middleton Fells. (After H.M. Geol. Survey.)

Fault, which thus forms a useful structural, as well as physical boundary to the region. Similarly, in the west, the Barbon Fault, which extends from north to south down the eastern side of the Lune Valley, marks both the physical and Geological extent of the region.

Text figure1·1 indicates the geographical and geological setting of the region, which is covered by the one inch Ordnance Survey Sheet number 89, Lancaster and Kendal, and by the following Ordnance Survey 6" Sheets:- SD 68, NW, NE, SW, SE; and SD 67, NW, NE. The geology of the area is covered by the one inch Geological Survey Sheet number 98 SE, (New Series Sheet 49), 1869.

Figures in brackets after descriptions of rock colours, eg., (N4), indicate the colour of the rock, according to the Munsell system as used in the Geological Society of America, Rock-Colour Chart, 1951. Fossil localities are numbered from F1 - 50, starting from the Wenlock Series, whereas localities from which lithological specimens have been collected, are prefixed by S, again starting from the Wenlockian. Cleavage direction readings are numbered from 1C, upwards, and sole mark readings are simply indicated by the figure in brackets, eg. (52). All the beds within the Ludlow Series have been numbered, and are prefixed by letters to indicate Lower, Middle or Upper Coniston Grits etc. For example, UCG 1, indicates bed or unit 1 of the Upper Coniston

Grits. Six figure grid references are given for all localities. Specimens now in the University of Hull collection are listed in the appendix, along with their catalogue and locality numbers.

# CHAPTER 2

## HISTORY OF PREVIOUS RESEARCH

Interest in the geology of the Lake District dates from at least the early part of the 19th century. As was to be expected, the very early workers, such as Otley (1820), were more concerned with establishing the major geological divisions of the region, rather than detailed work on particular areas. Descriptions of the Barbon and Middleton Fells are thus usually brief, and to gain some idea of the knowledge existing at this time, it is necessary to consider works which deal with adjacent areas, and with the Lake District as a whole. The Howgill Fells to the north, and of the same age, appear to have attracted rather more attention than the Middleton Fells. The descriptions of the Howgills indicate that the general succession was known at an early date.

The basic structure of the region was mentioned by Phillips (1828), and Sedgwick (1831). Phillips notes that " .... a great area of cleaved slate rocks, bounded by great dislocations ...." occurs in this area. The classic work of this period, however, was "The Geology of the Mountain Limestone District", also by Phillips, and first published in 1836, as Part II of "Illustrations of the Geology of Yorkshire". It is apparent from this work that a remarkable amount was known about the geology of the entire Pennine region, even at this time. The strata of the Howgill and Middleton Fells are briefly described, and it was noted that considerable variations in structure and texture occur. The Dent Fault in Barbondale was also mentioned, and was thought to have a throw of ".... one thousand, two thousand or more feet ...." (1836, p.104).

In 1839, Marshall, in his "Section from Shap Granite to Casterton Fell", recognised the similarities between the strata of Casterton Fell, at the southern end of the area, and that of the Blawith area near Coniston. He also noted that a WNW - ESE cleavage was developed in these rocks. The work of Sharp, in 1841-42, divided Marshall's "Blawith Slate" succession into three units, based on lithology, and was the first to note that these rocks could be correlated in part with the lower divisions of the Upper Silurian rocks of Denbighshire. The folding of the Silurian strata of Westmorland was considered to be a result of the "outburst" of the Shap Granite, although the principal N-S faults were recognised as being of much later date.

This threefold division of the Blawith Slate was further developed by Sedgwick, in his papers of 1845, 1846, and 1852 (see table 1), in which he also noted that the fossils of the Coniston or Brathay Flags were similar to those of the Lower Denbigh Flags, which in turn could be correlated with the Wenlock Shale. The Coniston Grits were found to be unfossiliferous, but could be compared with harder gritty bands in the Denbigh Flags. The uppermost division, now known as the Bannisdale Slates, was then termed the Ireleth Slates. In his 1846 paper, Sedgwick gave a general account of the stratigraphy and structure of the area extending from the Howgill Fells south through the Barbon and Middleton Fells, along with several useful sections showing the major folding and faulting. This paper also placed the Brathay Flags in the "Lower Silurian", along with the Llandeilo and Caradoc rocks, whereas the Coniston Grits and Ireleth Slates were considered to be of "Upper Silurian" age.

The first paper to deal specifically with the Barbon and Middleton Fells was by Hughes, and published in 1866. In this "Note on the Silurian rocks of Casterton Low Fell, Kirkby Lonsdale, Westmorland", the succession in the south of the area, from the Coniston Flags up through the Lower part of the Coniston Grits was described, along with a section illustrating the predominant north westerly dip in this region. The fauna of phacopid trilobites, brachiopods and graptolites confirmed the suggestion that these rocks were of the same age as the Denbighshire Grits. A further paper by Hughes in 1867 is significant in that it recognises that the Coniston Flags should be placed at the base of the "Upper Silurian", and should no longer be associated with the Coniston Limestone.

This early work formed a valuable basis for the work of the Geological Survey, whose Memoir on "The Geology of the Neighbourhood of Kirkby Lonsdale and Kendal" was published in 1872, under the authorship of Aveline, Hughes, and Tiddeman. All the strata in the Barbon and Middleton Fells were placed in either the Lower or Upper Silurian, as Lapworth's (1879) divisions of Cambrian, Ordovician and Silurian were not yet recognised. Thus the small Ordovician inlier in the north east of the area, was placed in the Lower Silurian. Table 1 shows the classification adopted by the Survey, which was basically that proposed by Sedgwick in 1845. Detailed descriptions of the succession were given, along with faunal lists and localities. The structure of the region also received considerable attention, and it was established that the area was folded and faulted predominantly along WNW-ESE axes. The major N-S trending disturbances forming the boundaries to the area were recognised as being of much later date, and a more accurate estimate of their downthrow, in the region of 5000 feet was made.

The Survey Memoir was the last work to deal specifically with the Barbon and Middleton Fells. Since then however, much work has been carried out on the Silurian strata of adjacent regions, and on its zonal classification. Much

Table 1.

Classifications of the Silurian rocks of the Lake District adopted by some of the principal workers.

<table>
<tr><th rowspan="2">Marshall 1839.</th><th colspan="2" rowspan="2">Sharp 1841–42<br>Sedgwick 1845-46</th><th colspan="2" rowspan="2">Aveline et al 1872</th><th colspan="3">Present Classification.</th></tr>
<tr><th>Divs.</th><th>Series</th><th></th></tr>
<tr><td rowspan="4">Blawith Slates</td><td rowspan="3">UPPER SILURIAN</td><td rowspan="2">Ireleth Slates</td><td rowspan="5">UPPER SILURIAN</td><td>Upper Ludlow</td><td>Kirkby Moor Flags</td><td rowspan="3">Ludlow</td><td rowspan="5">SILURIAN</td></tr>
<tr><td>Lower Ludlow</td><td>Bannis-<br>-dale Slates</td></tr>
<tr><td>Coniston Grits</td><td rowspan="2">Wenlock Rocks</td><td>Coniston Grits *</td></tr>
<tr><td rowspan="3">LOWER SILURIAN</td><td>Coniston Flags</td><td>Coniston Flags</td><td>Wenlock</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td>Stock-<br>-dale Shales</td><td>Stock-<br>-dale Shales</td><td>Llando-<br>-very</td></tr>
<tr><td>LOWER SILURIAN</td><td>Bala Beds</td><td>Ashgill Shales</td><td>Ashgill</td><td>ORDOVICIAN</td></tr>
</table>

Table 1.

*The Coldwell Beds are recognised at this level in some areas.

of this has a direct or indirect bearing on the area under consideration, and leads up to the present day classification, and so is considered here.

Aveline et al. (1872), Nicholson (1872), and Davies and Lees (1876), contributed information on unconformities and thicknesses of the strata, which have useful application to the Barbon and Middleton Fells. Marr (1878), in a paper on "Life Zones in the Silurian of the Lake District", split the Coniston Flags and Grits into zones, based on the Phacopid trilobite faunas, and thus proved that the Coniston Grits of Helm Knott, at the northern edge of the Middleton Fells, are equivalent in age to the Coldwell beds of the Lake District, which had not previously been recognised in this region. Bird (1881), briefly referred to the Howgill, and Barbon and Middleton Fells in his "Short Sketch of the Geology of Yorkshire" and Marr (1887), provided a very useful correlation between the Crummackdale area, and the standard Lake District succession.

In 1892, a significant step towards the present day classification of the Silurian was taken when Marr proposed a series of zones based on graptolites. Further papers by Marr (1913), and Marr and Fearnsides (1910), mentioned the Ordovician strata, but again concentrated largely on the Howgill Fells.

The classic paper by Watney and Welch (1911), on "The Zonal Classification of the Salopian Rocks of Cautley and

Ravenstonedale", proposed a series of zones based on graptolite faunal assemblages, and is largely the classification used today. They also considered that the upper limit of the Wenlock should be drawn at the top of the zone of Cyrtograptus lundgreni.

Marr (1916, 1921) and Kendal and Wroot (1924), again mentioned the area, but in works of much larger scope, and added little new knowledge. In 1927 however, Marr's paper on "The Deposition of the Later Silurian Rocks of the Lake District" considered the strata to have been laid down in a gulf, the margins of which underwent considerable oscillation, to produce coarse and fine sediments.

After the period of Marr, little was contributed towards the geology of the area, until the 1950's, apart from more general papers by Wager (1931), and McConnell (1939), dealing with structure and erosion. A paper by King and Wilcockson (1934), dealing essentially with the Lower Palaeozoic rocks of Horton-in-Ribblesdale, did however provide a very useful correlation table between the Horton-in-Ribblesdale area and the main Lake District outcrop.

The period from 1954 onwards however, marks the beginning of a decade in which intensive research has been carried out into all aspects of the Silurian strata of the Lake District. Wilson (1954) dealt with the stratigraphy and palaeontology of the Valentian rocks of Cautley, and

Mitchell (1956), reviewed the geological history of the Lake District. The work of Llewellyn (1960), on the Silurian rocks of Longsleddale, and Norman (1961), on the Silurian strata of the Blawith area, is of great importance to the present work, as these two authors were the first to deal specifically with the sedimentary petrology, depositional history and derivation of the Lake District Ludlovian rocks. They concluded that the Ludlovian sediments were derived from an area of Borrowdale Volcanic rocks, lying along the northern edge of the Lake District, and that deposition was carried out by turbidity currents flowing into a deep trough to the south.

Further work on the palaeontology of the region was carried o-ut by Ingham (1962), who described in detail the Ordovician inliers around Sedbergh and Dent, and erected several new stages within the Ashgillian, based on the trilobite faunas. Rickards (1963), dealt in detail with the Silurian graptolite faunas of the Howgill Fells, in which the work of Watney and Welch was revised and greatly extended. Another aspect of his work (1964), dealt with the origin and evolution of the graptolitic mudstones throughout the Silurian succession, which were considered to show a gradual change from extremely anaerobic bottom conditions in the Llandoverian mudstone, to a much more aerobic state by the time the Ludlovian strata is reached.

Recent work has thus established a modern zonal classification and depositional history for the Silurian strata in many parts of the Lake District and adjacent areas. The Barbon and Middleton Fells however, have been virtually untouched since the work of the Geological Survey in 1872, and thus the present work is intended to deal with the stratigraphy, structure and zonal classification of the strata in the light of present day knowledge. An important aspect of the work is the petrography, provenance and sedimentation of the strata, by which means a picture of the palaeogeography during the Ludlovian period in this, and adjacent areas has been built up. A comparison with the conclusions of Llewellyn (1960), and Norman (1961), has been made, with whom agreement is largely reached, except with regard to the provenance of the sediments. It is hoped that this work will prove useful in the understanding of the Silurian System as a whole, not only in the Lake District, but in other parts of the country also.

# CHAPTER 3

## THE STRATIGRAPHICAL SUCCESSION

### Introductory Statement

The stratigraphical succession within the Barbon and Middleton Fells consists almost entirely of rocks of Ludlovian age. The exceptions are,(i) a small area of Wenlockian Flagstones, in the vicinity of Leck Beck (647780), in the south of the area, and (ii) a small fault bounded inlier of Caradocian, Ashgillian, and Wenlockian beds, just to the west of the hamlet of Gawthrop (693874), at the northeastern extremity of the region.

The Ludlovian strata are split into two major divisions, the Coniston Grits - a series of fine grained "greywackes" and banded siltstones - and the Bannisdale Slates, consisting essentially of interbedded banded siltstones and unbanded mudstones. The area of outcrop of the more slaty upper part of the Bannisdale Slates is restricted to two synclinal valleys to the east of the Barbon Fault, in the central and north western part of the region. The remainder of the fells are made up of the various divisions of the Coniston Grits, and the Lower Bannisdale Slates - a transitional division between the grits and true slates.

In this chapter, a description of the succession and its lithologies is given, along with a discussion of variations in thickness. The Ordovician inlier in the Gawthrop area, however, is only briefly described, as it has recently been the subject of a detailed faunal and stratigraphical study by Ingham (1962), which is not yet published.

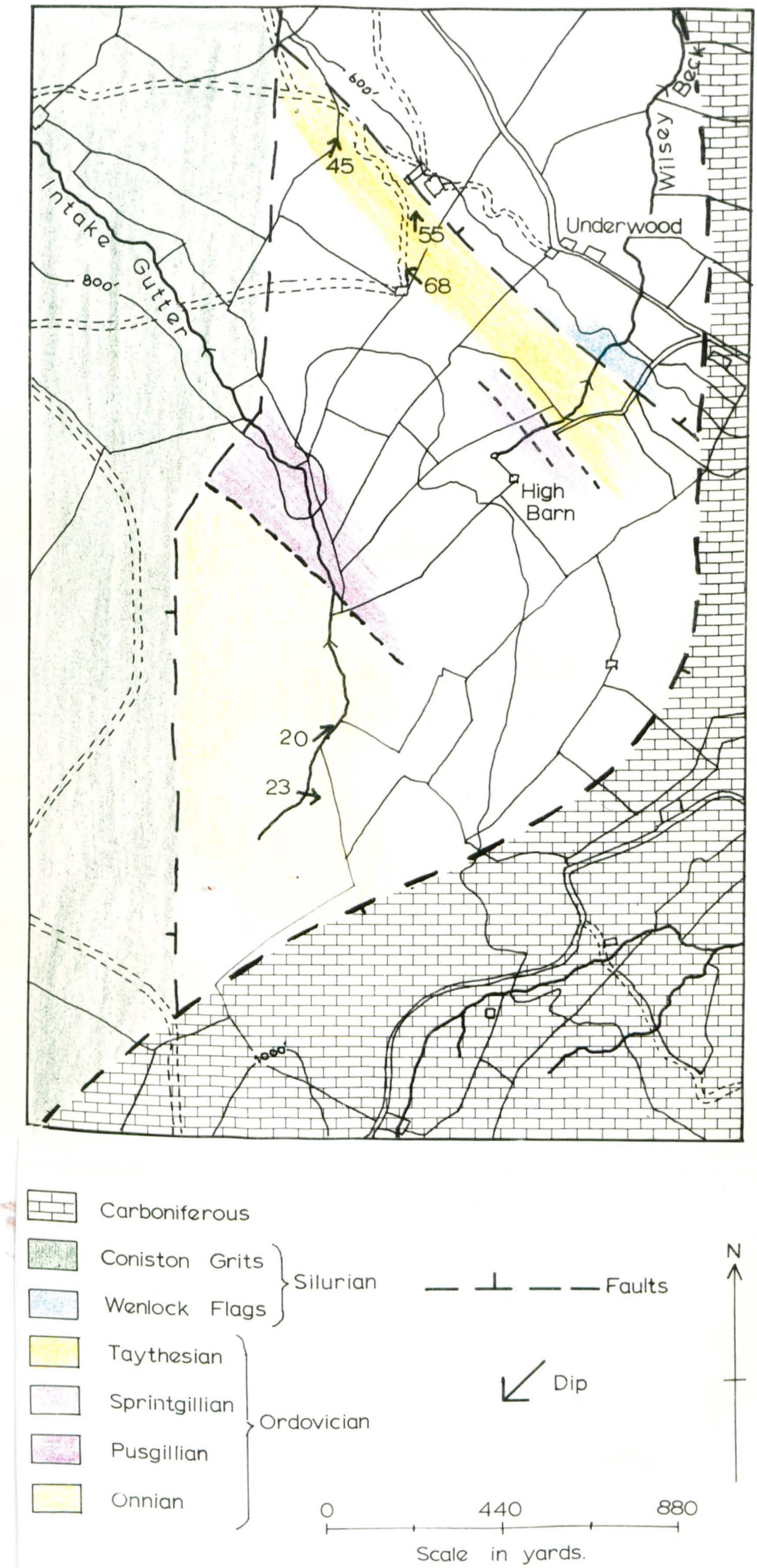
The concept of zoning in the Silurian is briefly summarised and precedes the description of the Silurian stratigraphy, in which fossiliferous horizons and the zoning of the strata are described and discussed.

(1) The Gawthrop Ordovician inlier

In the Survey Memoir of 1872, a brief description was given of the "Lower Silurian" Coniston limestone and shale in Helm Gill (687890), (on the northern side of Dentdale), along with a faunal list which indicated an abundance of brachiopods, phacopid trilobites, crinoids and corals. It was noted that similar rocks occurred on the south side of the valley, just to the west of Gawthrop, but the two exposed areas were not thought to be continuous across the Dent valley.

The Gawthrop inlier (See fig.3-1), is in fact very heavily covered with drift, and exposures are restricted to three small watercourses. About 90 feet of grey mudstones dipping gently to the north east are intermittently exposed

FIG. 3-1. The Gawthrop Ordovician Inlier.



in the small stream known as Intake Gutter (686871), at the southern end of the inlier. Between this stream and High Barn (688875), exposures are non-existent, but at the latter point, calcareous grits and mudstones, again dipping north east, are exposed, and yield a large brachiopod and trilobite fauna. Descending Wilsey Beck from High Barn, but rising up the succession, further exposures of fossiliferous calcareous mudstone occur, until the section is cut off by a north west trending fault, which brings down Wenlockian flagstones. Several hundred yards to the west, calcareous mudstone is again exposed in another small stream section.

The inlier thus shows an ascending succession from north to south. The work of Ingham (1962), on the trilobite faunas placed the southernmost exposure in the Onnian Stage of the Caradoc Series, whereas the exposures to the north of High Barn were placed in the Sprintgillian and Taythesian Stages of the Ashgill Series.

Although very poorly exposed, the boundaries of the inlier can almost certainly be deduced as faulted. In the east, the line of the Dent Fault is marked by a small scarp, and a marked change in the type of vegetation. Crags of Carboniferous limestone are exposed in this scarp, but nowhere is the actual fault plane seen. The exact western boundary of the inlier cannot be defined, but slight changes in topography and drainage, and the positions of adjacent small exposures of Ludlovian strata, and Ordovician shales, suggest that this junction is also faulted. A north-south trending fault is thus postulated as downthrowing Silurian grits against the Ordovician. The proposed line of this fault also links up easily with a similar trending fault on the north side of the valley, which again brings Coniston Grits against Ordovician shales and limestones. The north eastern extent of the inlier is easily defined by the north west trending fault seen in Wilsey Beck (688877). The fault brings down bluey grey (N4), banded Wenlock flagstones, and shows that the Gawthrop and Helm Gill inliers are not continuous across the drift covered Dent valley.

Due to the faulted relationship with the surrounding younger strata, no conclusion about the nature of the Ordovician-Silurian boundary can be drawn in this area, although in the Howgill Fells to the north, Rickards (1963 p.12) has described sections which show sedimentation to have been continuous from the Ashgill Shales, through into the basal Silurian beds.

## The Stratigraphical Succession (Continued)

### (2) The Silurian Strata

#### (a) The Zonal Classification

The zonal classification of the Silurian based on graptolite faunal assemblages, evolved mainly in the first half of this century, and is briefly summarised below.

One of the first workers to realise the value of fossils in the Silurian rocks of the Lake District was Adam Sedgwick who noted in his papers of 1845 and 1846, that the fossils of the Brathey Flags were similar to those in the Lower Denbigh Flags of North Wales, and were thus presumably of the same age. Similarly, the Survey Memoir (1872, p.13) proposed tentative correlations with the Welsh Borderland, based on the fossil content of the rocks. Marr (1878), erected a series of zones based on the Phacopid trilobite fauna, but later, (1892), zoned the strata by means of graptolites.

The first workers to attempt a detailed faunal study within the Silurian of the Lake District, however, were Watney and Welch, who proposed the following zones in 1911:-

| | | |
|---|---|---|
| Lower Ludlow | $D_2$ | Zone of <u>Monograptus leintwardinensis</u> Hopk. |
| | D1. | Zone of <u>Monograptus nilssoni</u> Barr. <u>Phacops obtusicaudatus</u> Bed. |
| Wenlock | C4. | Zone of <u>Cyrtograptus lundgreni</u> Tullb. |
| | C3. | Zone of <u>Cyrtograptus rigidus</u> Tullb. |
| | C2. | Zone of <u>Monograptus riccartonensis</u> Lapw. |
| | C1. | Zone of <u>Cyrtograptus murchisoni</u> Carr. |

This work, carried out on the Silurian rocks of Cautley and Ravenstonedale extended the work of Marr, and emphasised the need for the faunal assemblages of the strata as a whole to be considered before assigning it to a particular zone. The work of Elles and Wood (1901-18), on the graptolite faunas of the entire British Isles, resulted in the erection of a rather more comprehensive zonal scheme, of which the Wenlock and Ludlow zones were as follows:-

| | |
|---|---|
| Ludlow | Zone of _Monograptus leintwardinensis_ |
| | Zone of _Monograptus tumescens_ |
| | Zone of _Monograptus scanicus_ |
| | Zone of _Monograptus nilssoni_ |
| | Zone of _Monograptus vulgaris_ |
| Wenlock | Zone of _Cyrtograptus lundgreni_ |
| | Zone of _Cyrtograptus rigidus_ |
| | Zone of _Cyrtograptus linnarssoni_ |
| | Zone of _Cyrtograptus symmetricus_ |
| | Zone of _Monograptus riccartonensis_ |
| | Zone of _Cyrtograptus murchisoni_ |

These authors also emphasised the importance of the faunal assemblages, and stated, (Vol 2, p.515):-

> " .......... that a Graptolite zone is characterised by a special association of Graptolites, and that that form in this association which apparently combines restricted vertical range with wide horizontal distribution is most conveniently selected as the index of the zone".

The present day classification is still based largely on the work of Elles and Wood, although some of their zones can be proved only in a few restricted parts of Wales and the Welsh Borderland, whilst other zones can be sub-divided in some parts of the country.

The most recent zonal work in the Lake District has been carried out by Rickards (1964), in the Howgill Fells, and has resulted in the classifications of Watney and Welch, and Elles and Wood, being extended in some directions, but modified in others. (Dr. Rickards' zonal scheme is shown in table 2, along with those of Watney and Welch, and Elles and Wood). The lower zones of the Wenlock Series for example, were found to be capable of subdivision, whereas in the Ludlow Series, the zones of *Monograptus vulgaris* and *Monograptus tumescens* could not be proved, although Rickards considered that his Zone of *Monograptus leintwardinensis incipiens* was probably equivalent to the *Monograptus tumescens* Zone of Elles and Wood. In addition, the Zones of *Monograptus nilssoni* and *Monograptus scanicus* could not be separated, due to the characteristic faunal assemblages occurring together.

The Zonal classification of the Silurian can thus be seen to have evolved rapidly in the early part of this century, until the appearance of the monograph of British Graptolites by Elles and Wood. This work proved adequate for many years, and it is only now that modern workers are

<table>
<tr><th></th><th>ELLES AND WOOD.(1901-18.)<br>(British Isles.)</th><th>WATNEY AND WELCH.(1911)<br>(Howgill Fells.)</th><th>RICKARDS.(1963)<br>(Howgill Fells.)</th></tr>
<tr><td rowspan="5">LUDLOW SERIES</td><td>Zone of M. leintwardinensis.</td><td>M. leintwardinensis.</td><td>Zone of M. leintwardinensis.</td></tr>
<tr><td>Zone of M. tumescens.</td><td rowspan="3">P. nilssoni.</td><td>Zone of M. leintwardinensis incipiens.</td></tr>
<tr><td>Zone of M. scanicus.</td><td rowspan="3">Zone of P. nilssoni.-M. scanicus.</td></tr>
<tr><td>Zone of M. nilssoni.</td></tr>
<tr><td>Zone of M. vulgaris.</td><td>Phacops obtusicaudatus Bed.</td></tr>
<tr><td rowspan="9">WENLOCK SERIES</td><td>Zone of C. lundgreni.</td><td>Zone of C. lundgreni.</td><td>Zone of C. lundgreni.</td></tr>
<tr><td>Zone of C. rigidus.</td><td></td><td>Zone of C. ellesi.</td></tr>
<tr><td>Zone of C. linnarssoni.</td><td>Zone of C. rigidus.</td><td>Zone of C. rigidus.</td></tr>
<tr><td rowspan="2">Zone of C. symmetricus.</td><td rowspan="4">Zone of M. riccartonensis.</td><td>Zone of M. flexilis belophorus.</td></tr>
<tr><td rowspan="2">Zone of M. antennulatus.</td></tr>
<tr><td rowspan="2">Zone of M. riccartonensis.</td></tr>
<tr><td>Zone of M. riccartonensis.</td></tr>
<tr><td rowspan="2">Zone of C. murchisoni.</td><td rowspan="2">Zone of C. murchisoni.</td><td>Zone of C. murchisoni.</td></tr>
<tr><td>Zone of C. centrifugus.- C. insectus.</td></tr>
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Table. 2. The correlation of the graptolite Zones erected by Elles and Wood, Watney and Welch, and Rickards.

proposing that the zones should be refined in the light of recent discoveries. The early concept of zones based on an assemblage of fossils is still the principle by which this work is carried out.

In the present work on the Barbon and Middleton Fells, the work of Elles and Wood has been used in conjunction with that of Rickards. The zonal scheme proposed agrees largely with that of the latter author, due probably to the proximity of the two areas. The zoning of each division of the Wenlock and Ludlow Series is discussed in the following pages of this chapter, and summarised at the end.

(b) The Wenlockian Strata

There are no exposures of Llandovery strata within the Barbon and Middleton Fells, the nearest exposures being in the Rawthey valley to the north east of Sedbergh.

Wenlockian rocks however, are exposed in two parts of the region, in Leck Beck (647780) in the south, and to the north of the Gawthrop Ordovician inlier. Neither of these two sections are completely satisfactory, as they are both cut off by faults. The Leck Beck section however, passes through a great thickness of flagstones, and was first described by Hughes in 1866, who noted that the trilobite and graptolite faunas indicated that the strata were equivalent in age to the Denbigh Grits, and thus to the Wenlock Shales. The Survey Memoir (1872) came to a

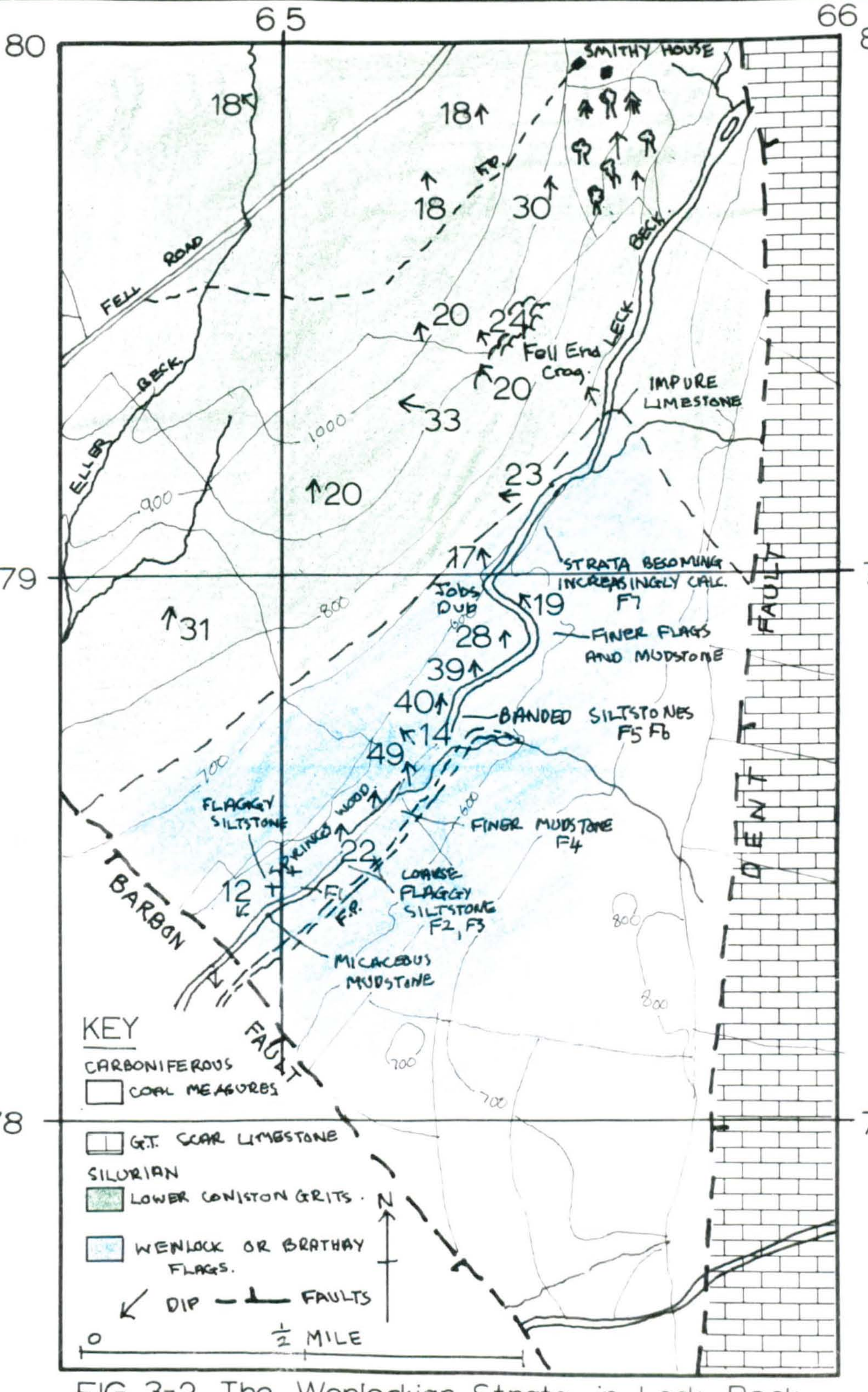



FIG. 3-2. The Wenlockian Strata in Leck Beck.

similar conclusion, but published only the following short faunal list:-

| | |
|---|---|
| Cardiola interrupta, | Sowerby. |
| Orthoceras primaevum, | Forbes. |
| Graptolithus priodon, | Bronn. |
| Graptolithus colonus, | Barrande. |

The occurrence of M. priodon is usually an indication of the lowest two Wenlockian zones, but the Survey have recorded this fossil from localities in other parts of the area which cannot possibly be anything other than uppermost Wenlockian. It would appear therefore that this is either a case of misidentification, or the graptolite has a much longer range than previously suspected. The fauna collected during the present work is certainly an Upper Wenlockian assemblage.

The section begins to the north east of the Barbon Fault (in Springs Wood, 648783), which brings down red Coal Measure Shales to the south west. The dip is at first gently to the south west, probably as a result of dragging in the vicinity of the fault, but thereafter becomes horizontal, before assuming a constant northerly direction which varies in amount between 20 and 50 degrees. The section is unfaulted, and thus measurement of the thickness is straightforward. (See fig.3-2). The lithology basically is a grey (N4), banded siltstone, often with a bluey tinge,

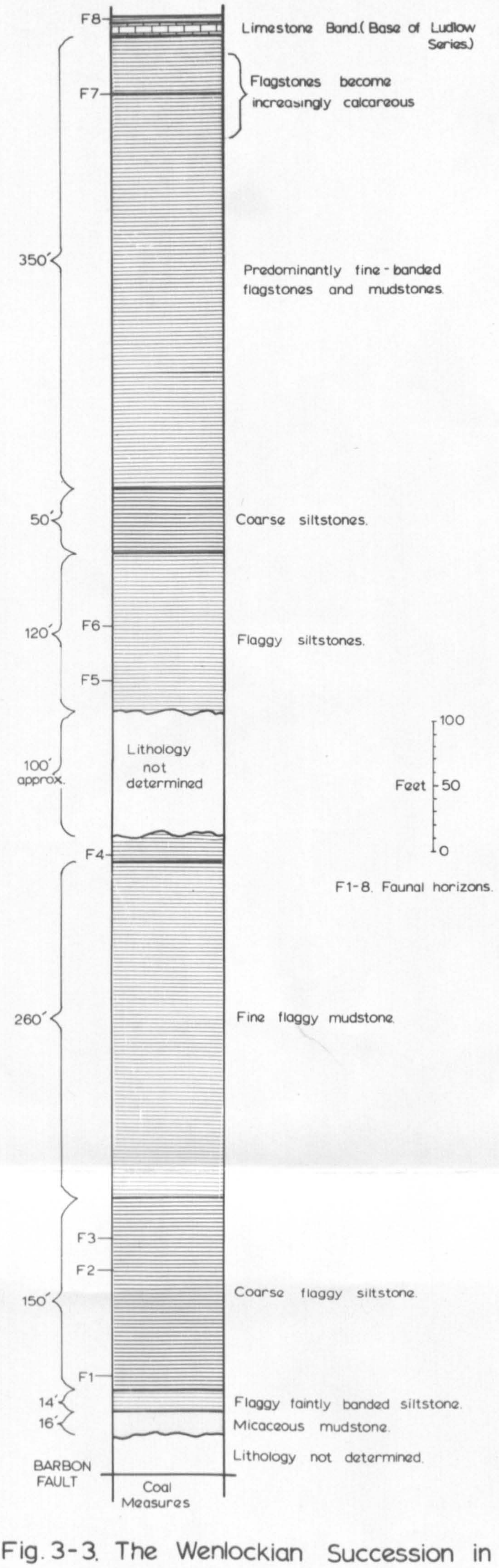



Fig. 3-3. The Wenlockian Succession in Leck Beck.

and the banding is fine enough to give rock surfaces a finely striated appearance. There are variations however within this lithology, which arise mainly as a result of slight changes in grain size, combined with changes in the density of the banding. Although useful for working this particular section, it is not suggested that these variations could be used to draw lithological correlations with Wenlockian rocks in other parts of the region. The banding itself results from the combination of micro-grading, and the deposition of black carbonaceous or pyrite laminae within the sediment. The origin, development and significance of this banding, however, is discussed in chapter .

Text figures 3-2 and 3-3 show the succession between the Barbon Fault and the basal Ludlovian beds. Immediately beyond the fault exposures occur only in the centre of the river, and it is thus not possible to examine them closely in order to determine the lithology. Above this are 16 feet of grey almost unbanded somewhat micaceous mudstones, followed by 14 feet of flaggy faintly banded siltstones. The junctions between these different lithologies are easily missed due to the overall change being slight, but with care it is possible to pin down exactly the point at which the change takes place. The first fossiliferous horizon (F1), occurs near the base of the succeeding 150 foot bed of coarser flaggy siltstone. Preservation is poor, the graptolites especially remaining only as pyrite films on the bedding planes. The following fauna has however been identified; F1:-

<u>Cyrtograptus lundgreni</u>, Tullberg.
<u>Monograptus flemingii</u>, Salter.
<u>Monoclimacis kingi</u>, MS, Rickards.
<u>Pristiograptus pseudodubius</u> (Boucek).
<u>Orthoceras sp</u>.

An identical fauna was obtained at two other horizons within this bed (F2, F3). It is of interest that fossils are restricted almost entirely to these somewhat coarser beds. In the succeeding 260 feet of finer flaggy mudstones for example, graptolites are almost completely absent, as are other fossils. The significance of this is discussed in the chapter dealing with the origin and evolution of this lithology. Above the unfossiliferous banded mudstones, the strata again becomes silty and yielded the following;- F4:-

<u>Cyrtograptus lundgreni</u> ? Tullberg.
<u>Monograptus flemingii</u> Salter.
<u>Pristiograptus pseudodubius</u> (Boucek).
<u>Gothograptus nassa</u> ? (Holm).
<u>Orthoceras sp</u>.

Exposures above this point are poor, and are permanently covered by water. It is estimated that about 100 feet of strata are passed over in this way, before fossiliferous banded siltstones, (F5, F6), approximately 120 feet thick are reached, passing up into fifty feet of somewhat coarser beds. Above this the lithology reverts to finer banded flags and mudstones, which are on the whole unfossiliferous, apart from several isolated coarser horizons. This lithology continues through the gorge at Jobs Dub (654788), but above this point becomes increasingly calcareous. The blueness of the flags becomes somewhat more apparent, due to the increase in calcium content, and the banding becomes somewhat intermittent. A few thin silty fossiliferous horizons remain however, (F7), and yield mainly Monograptus flemingii, a form typical of the Wenlockian.

The Top of the Wenlock Series

As noted above, the calcium content of the Brathay or Coniston flags increases above the Jobs Dub gorge. This development continues until two thin impure limestone beds are formed. The lower bed has a thickness of 1 foot, and the upper 2 feet. In the banded siltstone immediately above the first limestone, the following fauna was obtained; F8:-

Monograptus colonus compactus, Wood
Monograptus varians, Wood
Monograptus chimaera, Barrande
Monograptus chimaera salweyi, (Lapworth)
Monograptus scanicus, Tullberg
Pristiograptus dubius, (Suess)
Pristiograptus nilssoni, (Barrande)

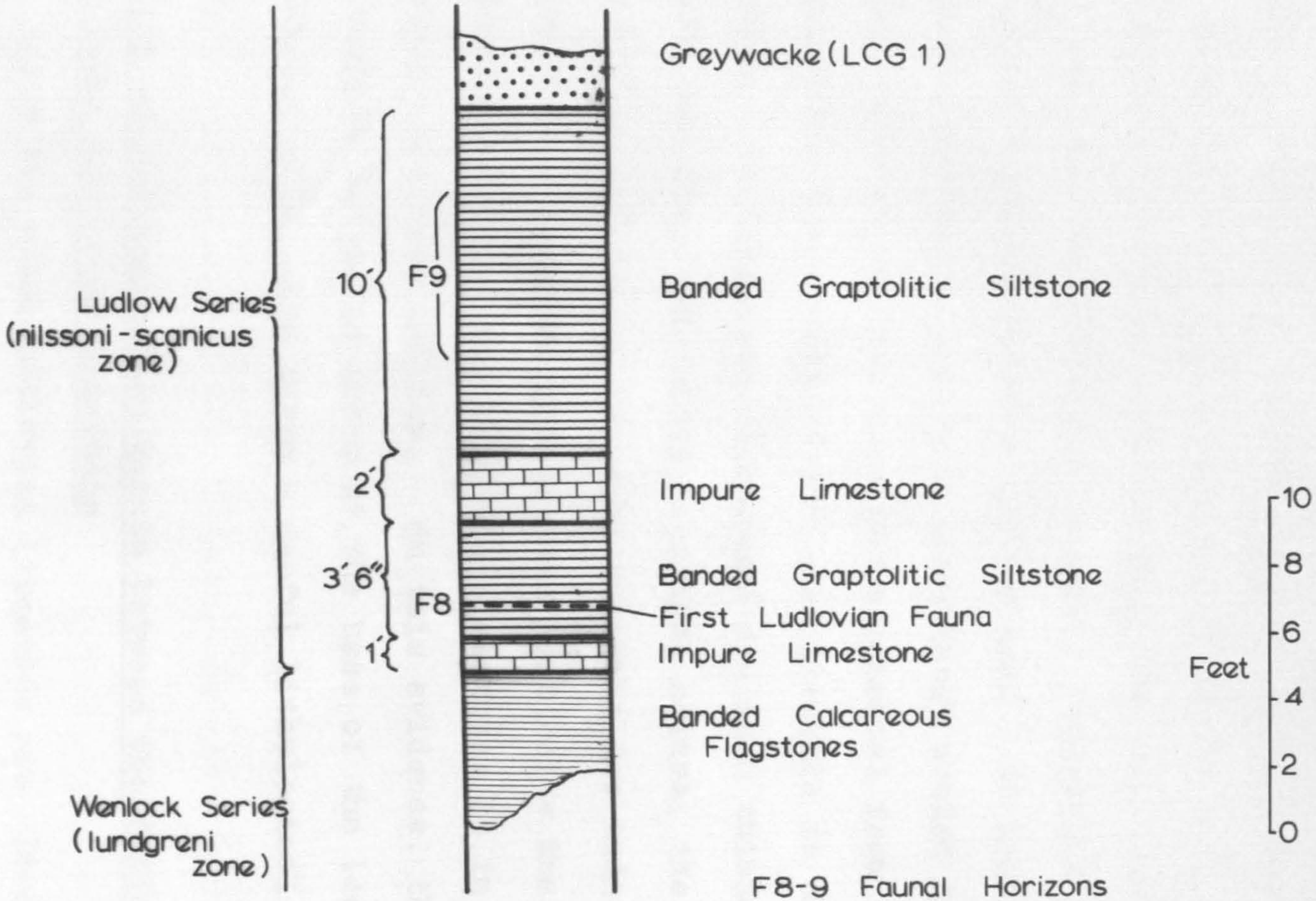



Fig. 3-4. The Wenlockian-Ludlovian junction in Leck Beck.

This fauna is typical of the Ludlovian nilssoni-scanicus Zone. In the Howgill Fells to the north, the base of the Ludlow Series is also marked by a bipartite limestone bed, the lower unit of which reaches a thickness of 9 feet, and the upper 12-18 feet. In the Howgills, the limestone is often exposed as a brown rottenstone, yielding a rich Phacopid trilobite fauna of Ludlow age. In Leck Beck, however, the only exposure is constantly eroded by the stream, thus preventing the rotted material from accumulating from which it would be possible to collect fossils. Although the limestones are much thinner here than in the Howgills, their bipartite nature, the occurrence of a nilssoni-scanicus fauna between the two beds, and the presence of Wenlockian graptolites just below the lower limestone, all indicate that the limestones do in fact represent the same horizon. On this evidence, the top of the Wenlock Series is drawn at the base of the lower limestone, which also forms a useful lithological marker band.

## Zoning of the Wenlockian Strata between the fault and the basal Ludlovian Limestone

Below the basal Ludlovian limestone are almost 1070 feet of Wenlockian strata, consisting essentially of grey (N4), banded flagstones in which slight lithological variations can be discerned. The fauna is not abundant, but the assemblage of:-

*Monograptus flemingii*, Salter

*Cyrtograptus lundgreni*, Tullberg

*Pristiograptus pseudodubius*, (Boucek)

*Monoclimacis kingi*, MS Rickards

*Gothograptus nassa*, (Holm), has been collected throughout the section. *C.lundgreni* appears to be more abundant in the lower part of the section, whilst *G. nassa* is extremely rare. This fauna is indicative of the *C.lundgreni* Zone of the Wenlockian, and compares closely with that obtained by Rickards in the Howgill Fells. The Leck Beck section however is thicker than the entire Wenlock Series in the Howgill Fells, which Rickards (1963), considered to have a total thickness of between 760 and 850 feet. In Leck Beck, the 1070 feet of strata are entirely within the *lundgreni* zone, of which the base is not seen, whereas in the Howgills, the *lundgreni* zone is only 300-400 feet. Rickards, however, found evidence of thickening towards the south, in almost all of the divisions of the Wenlock Series. The Leck Beck section suggests that this effect is very considerable, and implies a fairly sudden southward deepening of the geosynclinal trough. Further evidence in support of this deepening comes from the Ludlow Series, and from sedimentological studies, and is discussed in a later chapter.

## Other Exposures of Wenlockian Strata

The only other exposure of Wenlockian strata is, as was noted earlier, to the north of the faulted Ordivician inlier at Gawthrop. Here exposures are very poor. The few pyritised graptolite fragments obtained resemble M.flemingii, and thus suggest that the flags are at least in the upper half of the Wenlock Series. On Helms Knott (685895), on the northern side of Dentdale, Coniston Flags occur again, and here the relationship to the overlying Coniston Grits suggests that these also represent the upper part of the series.

## Conclusions

(a) Slight differences in grain size and the density of banding make it possible to divide the flagstones into a number of lithological units, which are of use in working the section.

(b) Fossils are almost entirely restricted to the coarser, more silty beds, and are poorly preserved as pyrite films.

(c) The faunal assemblages of M.flemingii, C.lundgreni, P.pseudodubius, Monoclimacis kingi MS Rickards, and G.nassa, are the same throughout the succession, and are indicative of the Zone of Cyrtograptus lundgreni.

(d) This zone of which the base is not seen has a total thickness of 1070 feet, which is more than double the thickness of the same zone in the Howgill Fells to the north.

(e) This thickening which begins in the southern part of the Howgill Fells suggests a sudden deepening of the geosynclinal trough, to the south, in which sediment accumulated. This is supported by sedimentological studies which are discussed in a later chapter.

(f) The Wenlockian-Ludlovian boundary can be established by a change in the faunal assemblage, but is also marked lithologically by the development of a thin limestone bed. There is however no evidence of a break in sedimentation, as the development of the limestone bed is preceded by a gradual increase in calcium content in the underlying Wenlockian sediments.

## (c) The Ludlovian Strata

Apart from the two small areas of Ordovician and Wenlockian strata, the Barbon and Middleton Fells, as previously mentioned, are formed entirely of rocks belonging to the Ludlow Series, i.e. The Coniston Grits and Bannisdale Slates.

Although the divisions of Wenlock and Ludlow Series have long been recognised, the boundary between the two, was for a long time drawn just above the base of the Bannisdale Slates. Thus Sedgwick (1845-46), and Aveline et al (1872), considered the Brathay Flags and Coniston Grits under the same heading of "Wenlock Rocks". The lower part of the Bannisdale Slates were also placed in the Wenlockian, and indeed the only Ludlovian rocks were the upper part of the Bannisdale Slates, described as of Lower Ludlow age, and the Kirkby Moor Flags, which were placed in the "Upper Ludlow". (See table 1).

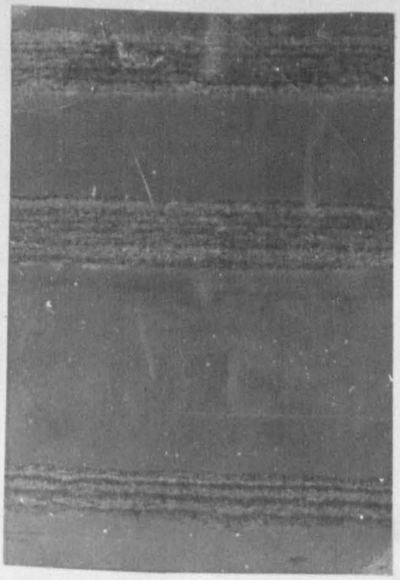
In 1911, however, Watney and Welch proposed that the upper limit of the Wenlockian should be taken at the top of the Zone of Cyrtograptus lundgreni, (which in this area is at the top of the Brathay Flags), and that the strata above all belonged to the Ludlow Series. In this work, which was carried out largely in the Howgill Fells, the emphasis was on the faunal content of the rocks, and the graptolite zones erected enabled correlations to be made with strata of equivalent age in the Welsh Borderland and Wales. Three lithological divisions of the Coniston Grits had previously been described by Dakyns (1891), in the Mallerstang Sheet Memoir, but these were not recognised by Watney and Welch, nor by Rickards (1963), who split the Coniston Grits into only two lithological divisions.

No work of this kind was carried out in the Barbon and Middleton Fells. In the following pages of this chapter, however, it is shown that the Coniston Grits can be divided into three lithological divisions, and split into a number of zones based on the graptolite faunas. The Bannisdale Slates are separated into two divisions.

The lower limit of the Ludlow Series is as previously described, taken at the base of the bipartite limestone bed in Leck Beck, below which a typical Wenlockian fauna is found. The top of the Series cannot be defined in this area, as the highest sections end in the middle of the Bannisdale Slates. The overlying Kirkby Moor Flags do occur on the western side of the Lune Valley however, but the junctions with the Bannisdale Slates are always faulted.

### (1) The Coniston Grits

The strata overlying the bipartite limestone in Leck Beck consist of a thick series of unfossiliferous grits separated at numerous horizons by thin beds of banded graptolitic siltstone. The Coldwell Beds, a flaggy division found at the base of the Ludlow Series in some areas, cannot be recognised in this region. The so called Coniston Grits are in fact predominantly rather fine grained grey (N5), muddy sandstones and coarse siltstones, which are considered to have been deposited by turbidity currents. They have been referred to as greywackes by previous authors. The term greywacke is used in the present work, but only loosely; true greywackes, i.e. coarse poorly sorted rocks containing many rock fragments, and set in a fine grained matrix, (Pettijohn 1957, pp. 301-305), are developed only



(A)

(B)


(C)

Fig. 3-5.

(A) The Banded Unit lithology

(B) The Graptolitic Siltstone lithology

(C) The Greywacke lithology

at isolated horizons in the succession. The banded graptolitic siltstones are finer grained than the grits, and darker grey (N4), when weathered, but still fall within the silt class. Weathered surfaces appear yellowish brown (10 YR6/2). The chief distinguishing feature of this lithology is the banding, which gives rock surfaces a finely striated appearance, similar to that seen in the Coniston Flags, and which has the same origin. As higher levels in the succession are reached, a third type of lithology becomes more predominant for a time. This can be described essentially, as consisting of interbedded laminae of banded siltstone, and unbanded mudstone, with a predominant grey colour (N4), and hereafter referred to as the banded unit lithology. The thicknesses of the alternating laminae are variable, but figure 3-5, in which the silt laminae are 7 mm. thick, and the mudstone 15-20 mm. in thickness, is fairly typical. The siltstone laminae are in many cases graptolitic. The upper part of the Bannisdale Slates are made up almost entirely of this lithology, but within the Coniston Grits, it is prevalent only in the middle of the Series. On this basis, the Coniston Grits may be split into three divisions as follows:-

| | | |
|---|---|---|
| Coniston Grits | Upper (Beds UCG 1-11) | Predominantly fine greywacke and thin graptolitic siltstone beds. |
| | Middle (Beds MCG 1-8) | Equal proportions of fine greywacke and banded units. |
| | Lower (Beds LCG 1-15) | Predominantly fine greywacke and thin graptolitic siltstone beds, with a coarser greywacke at the base. |

(The numbering of individual beds or units is shown on the text figures.)

(a) <u>The Lower Coniston Grits</u>.

The only complete section in the Lower Coniston Grits begins immediately above the basal Ludlow beds in Leck Beck, and continues in crag exposures and stream sections on the hillsides to the north west of the river, for almost a mile, to Brownthwaite Moss (647805), (Figure 3-6). Dips are constantly to the north or north west, at about 20 degrees in the river valley, decreasing to about 8 degrees in the upper part of the section. Another short and poorly exposed section occurs to the north of Leck Beck, in Gale Beck (656805). To the north of these localities, the Lower Coniston Grits are overlain by the Middle and Upper

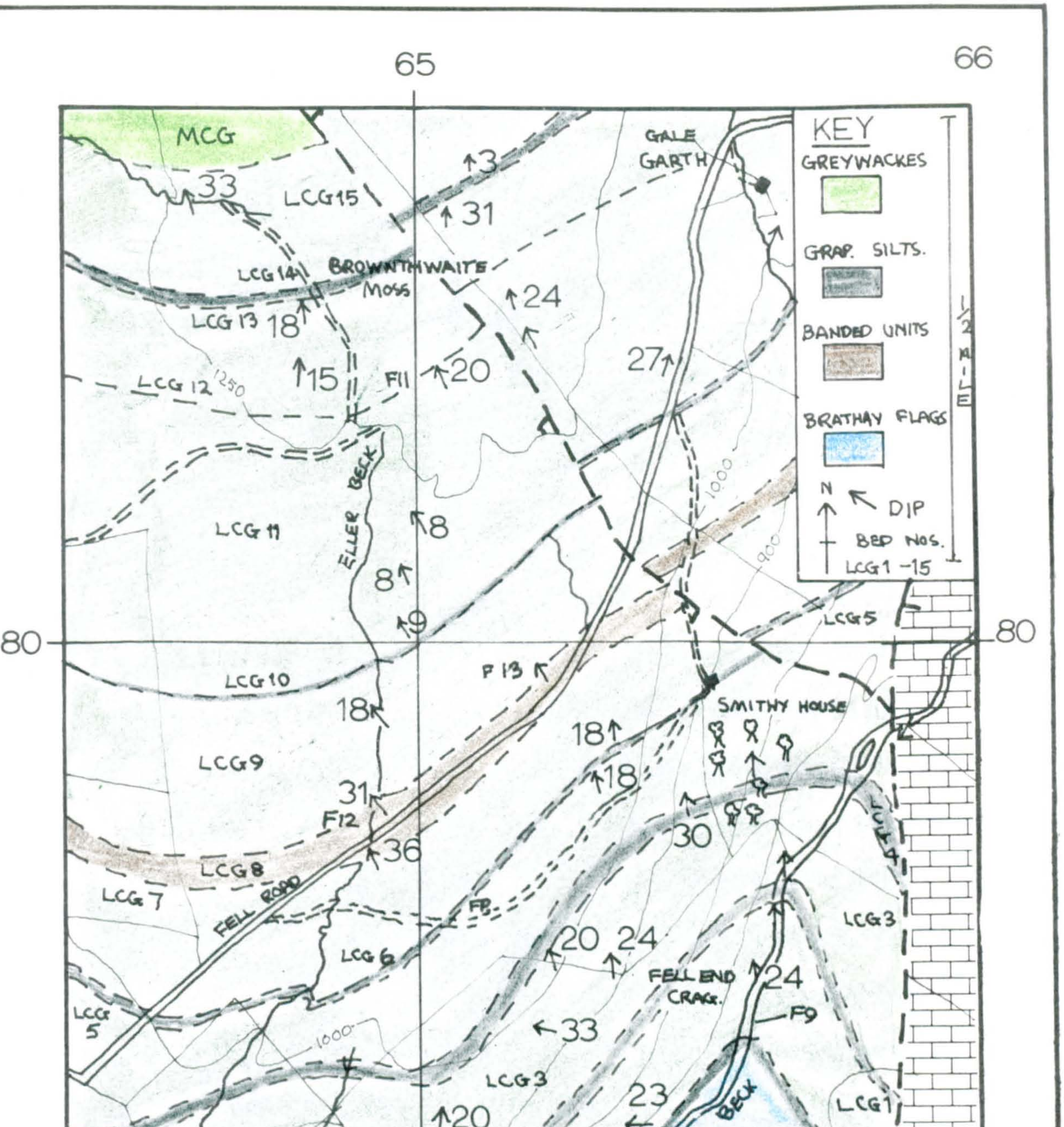



FIG. 3-6. The Lower Coniston Grits north-west of Leck Beck.

divisions of the Series, and are seen again only in Helms Knott, Dentdale (684896). The localities are shown in figure 3-7.

Above the limestone in Leck Beck are 10 feet of graptolitic siltstones (F9), which yield a fauna of:- Pristiograptus dubius, P.nilssoni, Monograptus chimaera c.f. salweyi, M. c.f. colonus, M.leintwardinensis incipiens, M.scanicus, Monoclimacis haupti, and Pterinea sp., typical of the nilssoni-scanicus Zone. This is followed by the first greywacke unit of the Coniston Grits, which is somewhat coarser than average. This bed (LCG1), has a thickness of 143 feet, and forms the steep sloping hillside up from the river bed. The bedding is massive, with flute markings on the undersides, where coarse sediment overlies the graded mudstone top of the preceding bed. Many other sedimentary structures and features are visible, but these are dealt with more fully in a succeeding chapter. At the top of this first greywacke unit is a marked break in slope, produced by a softer easily weathered banded graptolitic siltstone bed (LCG2), with a thickness of approximately 28 feet. This bed which produces rather badly drained ground is poorly exposed, and the thickness has to be largely estimated from a few small exposures scattered around the hillside. The graptolite fauna is poorly preserved (F10), but appears to be similar to that obtained from the under and overlying beds.

The second greywacke unit of 127 feet (Bed LCG3), is marked by a considerable steepening of the hillside, and is well exposed in crags running along the hill. This bed is somewhat finer than the preceding greywacke, and is more representative of the Coniston Grits as a whole. Grading is present in some of the beds, but is not always obvious. The mudstone tops to these beds usually grade very quickly down into the underlying grit, but sometimes have sharply defined lower limits, suggesting that the coarse sediment was deposited very quickly, with little or no grading. Flute and groove casts are again abundant, wherever coarse sediment overlies the mudstone top of the preceding bed. Above this unit is another poorly exposed bed of banded graptolitic siltstone, (LCG4), (F11), some 35 feet thick which contains largely M.leintwardinensis incipiens, and a few M.chimaera. The succeeding 100' greywacke unit (LCG5), is also somewhat poorly exposed, apart from a few crags, and is rather fine grained. In several places however, it contains large shale pellets, which would appear to have been derived from the destruction of pre-existing mudstone partings. The graptolitic siltstone above this (LCG6) is very thin (15') and poorly fossiliferous, and is again succeeded by a thick greywacke unit (LCG7), (105') containing calcareous nodules which weather brown. The top of this unit follows approximately the line of the Fell Road (647796), which crosses the area in a north easterly direction, in a shallow marshy depression.

On the north side of the road, the banded unit lithology is seen for the first time, (Bed LCG8). This is the only occurrence of this lithology in the Lower Coniston Grits, and the thickness of 86' is thin in comparison with the units in the Middle Coniston Grits and Bannisdale Slates. This particular unit, although displaying the alternating laminae of unbanded mudstone and banded siltstone at several horizons, is somewhat atypical, as it contains a large proportion of ordinary banded graptolitic siltstone. From an exposure in Eller Beck, just above the point at which it crosses the Fell Road (F12),(659797), and from a nearby road side quarry (F13), the following fauna was obtained:- Pristiograptus nilssoni, P.vicinus, Monograptus varians pumilis, M.chimaera salweyi, M.leintwardinensis incipiens, Pterinea subfolcata, Slava [Cardiola] interrupta, and Orthoceras sp. Shelly fossils are particularly abundant in the quarry exposure, and graptolites rare. It appears to be usually the case that wherever shelly fossils are common, graptolites are less abundant than normal.

Above the Fell Road, the banded unit is overlain by an extremely thick, rather fine grained greywacke unit, which at first appears to have an unbroken thickness of approximately 590', up to the summit of Brownthwaite Pike (647805). Closer examination however, reveals that the unit can in fact be split into three. The first part, (Bed LCG9), is well exposed in the upper part of Eller Beck, and in numerous crag exposures to the east of the stream. In one of these exposures 150 feet above the top of the banded unit, is a very thin development (8'), of very coarse banded siltstone, (Bed LCG10). This marks the top of the first division in this apparently very thick greywacke unit. The banding is very widely spaced, and appears to be a transition between greywacke, and the normal banded graptolitic siltstone. Its origin and significance however, is discussed in a later chapter. The second part of the greywacke unit, (Bed LCG11), has a thickness of 272 feet, and is again rather fine grained, and dips gently to the northwest at about 8 degrees. The upper limit of this greywacke is defined by a very thin development of banded graptolitic siltstone. The thickness of this siltstone, (Bed LCG12), is just over 1 foot, but it has yielded several specimens of M.leintwardinensis incipiens, and Slava [Cardiola] interrupta (F14). It is followed by the third part of the greywacke unit, (LCG13), which is 160 feet thick, and at the top of which is a somewhat thicker (20') development of graptolitic siltstone, (LCG14), yielding the following fauna (F15):- P.bohemicus, M.chimaera, M.leintwardinensis incipiens, Slava [Cardiola] interrupta, and Pterinea sp.

The greywacke above this, (LCG15), has a thickness of 260 feet, and forms the summit and northern slope of Brownthwaite Pike, and is somewhat coarser than the immediately preceding units. This unit is also exposed in the middle part of Grove Gill, Whelprigg (638813), half a mile to the north west, in a faulted strike Section. Two N-S trending faults bring down higher divisions of the Coniston Grits downstream of the greywacke, and make it impossible to check accurately the thickness measured on Brownthwaite Pike.

Above this greywacke is the first really thick development of the banded unit lithology typical of the Middle Coniston Grits, (Bed MCG1). The junction between the 260' greywacke unit, and the overlying banded unit is taken as the boundary between the Lower and Middle Coniston Grits.

The only other exposure of the Lower Coniston Grits is on Helms Knott (684896), along the north eastern edge of the area. Here, strata very low in the succession crop out. The relationships with the overlying divisions are faulted or poorly exposed, and it is thus not possible to define the upper limit of the division, or even to measure its approximate thickness. In 3 or 4 small exposures of graptolitic siltstone however, the following fauna has been obtained, (F16):- Monoclimacis haupti, P. c.f. wandalensis, P.bohemicus, P.dubius, P. nilssoni, M.colonus, M.chimaera chimaera, M. leintwardinensis incipiens, M. varians pumilis, M. roemeri, M.scanicus, Slava [Cardiola] interrupta, Pterinea subfolcata, and Orthoceras sp.

Lithologically, the Lower Coniston Grits may be summarised as consisting of a thick series of fine grained greywackes, separated at numerous horizons by thin beds of graptolitic siltstone, and having a total thickness of 1510 feet.

Zoning of the Lower Coniston Grits.

The graptolite fauna of the Lower Coniston Grits is as follows:-

M.varians pumilis Wood.
M. colonus (Barrande).
M. chimaera chimaera (Barrande).
M. chimaera salweyi Lapworth.
M. scanicus Tullberg.
M. leintwardinensis incipiens Wood.
M. roemeri (Barrande).
P. dubius (Suess).
P. nilssoni (Barrande).
P. bohemicus (Barrande).
P. vicinus (Perner).

This is very similar, with one notable exception, to that of the combined Zones of P.nilssoni and M.scanicus of Elles and Wood. It does not seem possible to separate these two Zones in this area. The occurrence of M.leintwardinensis incipiens in association with the nilssoni-scanicus fauna, appears to be a characteristic feature of this area, although according to Elles and Wood this form is restricted to the tumescens and leintwardinensis Zones. In addition, the more recently redescribed species of Monoclimacis haupti (Kuhne) and P. wandalensis (Watney and Welch), have been collected from the Lower Coniston Grits, and these also are typical of the nilssoni-scanicus Zone. Slava [Cardiola] interrupta, and Pterinea subfolcata are shelly fossils occurring throughout the Ludlow Series. There does not appear to be any marked change in the assemblages collected at different horizons within the Lower Coniston Grits, except that Monoclimacis hauptı and P. dubius have been found only at the very base of the Series in Leck Beck, and also on Helms Knott.

The exact stratigraphical position of the Helms Knott locality is difficult to place, owing to the poor state of exposure. The field relationships with adjacent exposures of Wenlock Flags however, suggest that it is almost at the base of the Ludlow Series. The similarity between the assemblage collected here, and that obtained from the siltstone immediately above the limestone in Leck Beck, tends to confirm this impression. On this evidence, Helms Knott is tentatively correlated with the base of the Ludlow Series in Leck Beck, as shown in figure 3-7.

The vulgaris Zone erected by Elles and Wood at the base of the Ludlow Series cannot be differentiated, as the faunal assemblages in Leck Beck change directly from those typical of the Wenlockian Cyrtograptus lundgreni Zone, to those characteristic of the nilssoni-scanicus Zone. All the 1510 feet of the Lower Coniston Grits are therefore placed in this Zone.

Comparison with the Howgill Fells.

In the Howgill Fells Rickards split the Coniston Grits into Lower and Upper only. His division of Lower Coniston Grits, however, of just over 1000 feet in thickness, compares closely with the Lower Coniston Grits division in the Barbon and Middleton Fells. The faunal assemblages are also very similar. The correlation between the two areas is

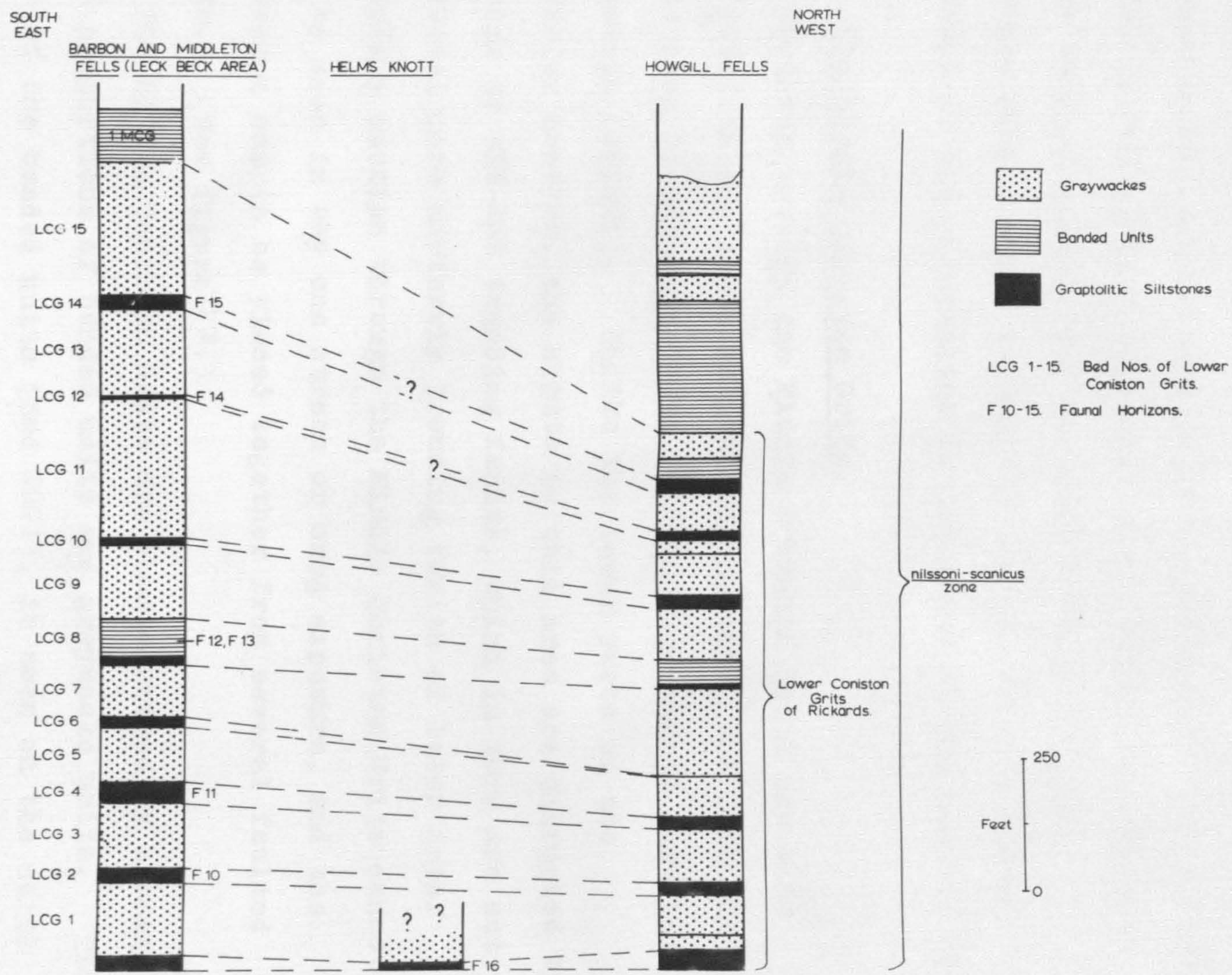


Fig. 3-7. The Correlation of the Lower Coniston Grits between the Barbon, Middleton and Howgill Fells.

summarised in figure 3-7.

The significant feature of the comparison of these two adjacent areas, is that the Lower Coniston Grits become much thicker to the south. This southward thickening was seen in the Wenlock Series, and its continuation into the Ludlovian adds further support to the theory of a marked deepening of the geosyncline to the south of the Howgill Fells.

(b) <u>The Middle Coniston Grits.</u>

Sections through the Middle Coniston Grits are also restricted to the southern part of the area, and form the ground from Brownthwaite Moss (650810) northwards down into Barbondale (645827). Unlike the lower parts of the succession however, the strata in this area are disrupted by a number of WNW-ESE trending faults, which in turn are cut by several more northerly trending faults of later date. A complete section through the Middle Coniston Grits cannot thus be seen in any one stream or crag exposure, and the succession has to be pieced together from several faulted blocks. (See figure 3-8.)

The Middle Coniston Grits are characterised by almost equal proportions of banded units and greywacke units. The first of the banded units (Bed MCG1), is seen on the north western side of Brownthwaite Moss, in a small tributary (643819), of Grove Gill, and also several hundred yards further to the north west in Grove Gill itself. The lithology is typically

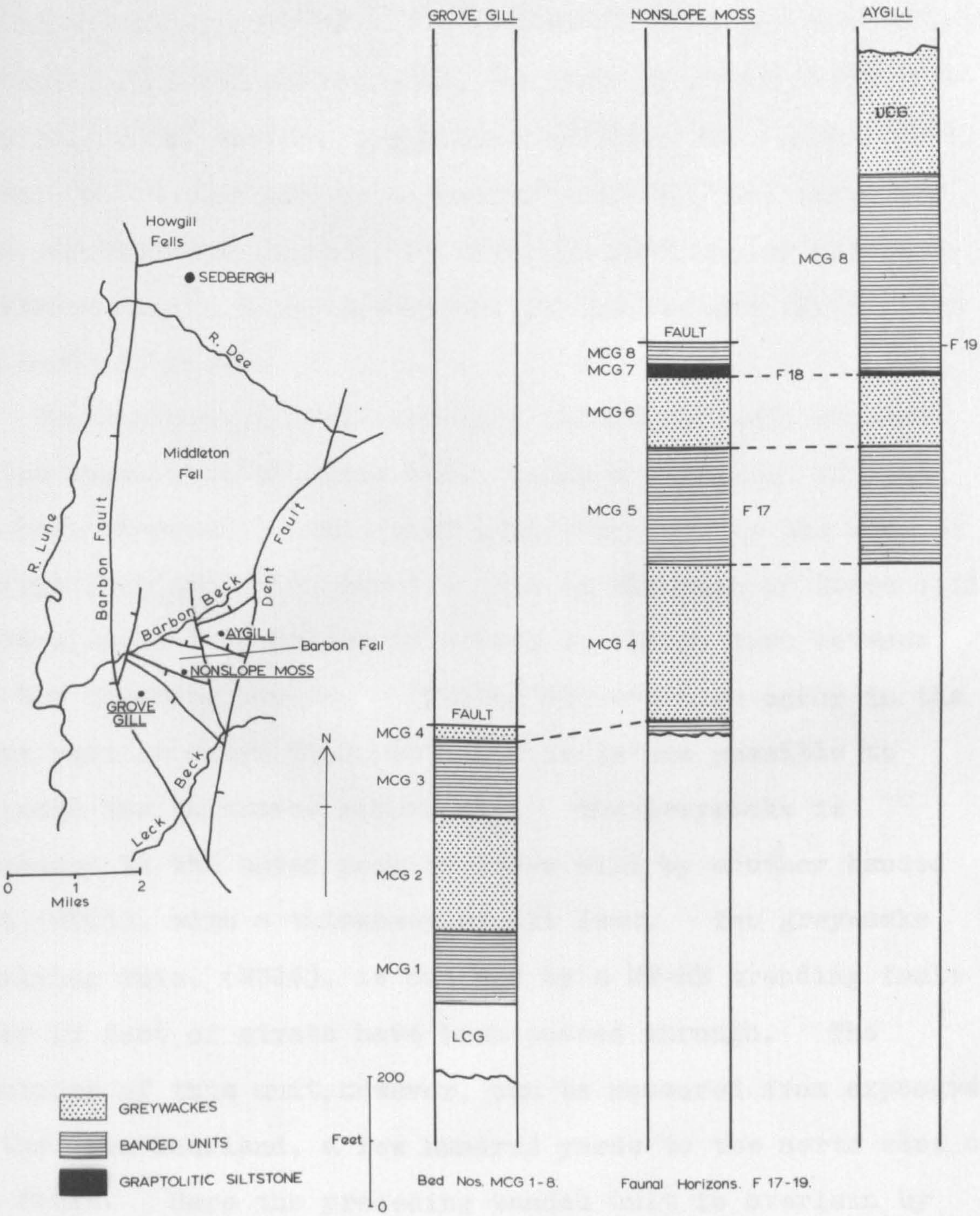



Fig. 3-8. Fault isolated sections through the Middle Coniston Grits.

one of alternating laminae of banded siltstone and unbanded mudstone, although in addition this unit contains a few thin beds of fine greywacke, a variation often found at the lower levels in the succession. Exposures of this unit are very poor and unfossiliferous, but from the position of adjacent greywacke units, a thickness for the banded unit of 110 feet has been estimated.

The succeeding greywacke unit (MCG2), is well exposed in the upper part of Grove Gill, where a thickness of 176' has been measured. This unit also crops out to the west of Bullpot Farm (662816), about a mile to the east of Grove Gill, where a similar thickness of strata is thrown down between two N-S trending faults. Faulted slivers also occur in the lower part of Grove Gill, but here it is not possible to estimate the thickness accurately. The greywacke is succeeded in the upper part of Grove Gill by another banded unit (MCG3), with a thickness of 121 feet. The greywacke overlying this, (MCG4), is cut off by a NW-SE trending fault after 15 feet of strata have been passed through. The remainder of this unit, however, can be measured from exposures on the open moorland, a few hundred yards to the north east of the fault. Here the preceding banded unit is overlain by 243 feet of fine grained micaceous greywacke, displaying prominent graded bedding and numerous sole markings.

The remainder of the Middle Coniston Grits succession is pieced together from adjacent fault bounded blocks of strata, (See figure 3-8), inwhich the 243' greywacke unit with its graded bedding and sole markings, forms a useful marker horizon. This distinctive unit is downthrown on the NE side of the NW trending fault on Nonslope Moss (649815), and is overlain by a banded unit which is well exposed in a series of crags dipping to the north east at 25 degrees. This unit, (Bed MCG5), which has a total thickness of 180' contains a rather higher proportion of banded graptolitic siltstone than normal, and yielded the following fauna; (F17):- M. chimaera salweyi, M. c.f. varians, M. leintwardinensis incipiens, P. bohemicus, Slava [Cardiola] interrupta, and Pterinea sp.

The base of the overlying greywacke unit, (MCG6), is exposed in the upper part of the crags, and is massively bedded with well developed mudstone tops to the graded beds. The remainder of this unit is very poorly exposed, but scattered outcrops of greywacke to the north of the crags, indicate that there is no change in lithology for a distance of a ¼ mile. Taking into account the dip, and slope of the ground, this leaves room for approximately 110 feet of strata. In the upper reaches of 3 small streams (653820), which rise to the north west of the crags, and flow down into Barbondale, this greywacke gives way to a thin bed of banded graptolitic siltstone, (MCG7), yielding poorly preserved M.leintwardinensis incipiens (F18), and overlain by a banded unit, (MCG8).

A few yards further downstream, the section is cut off

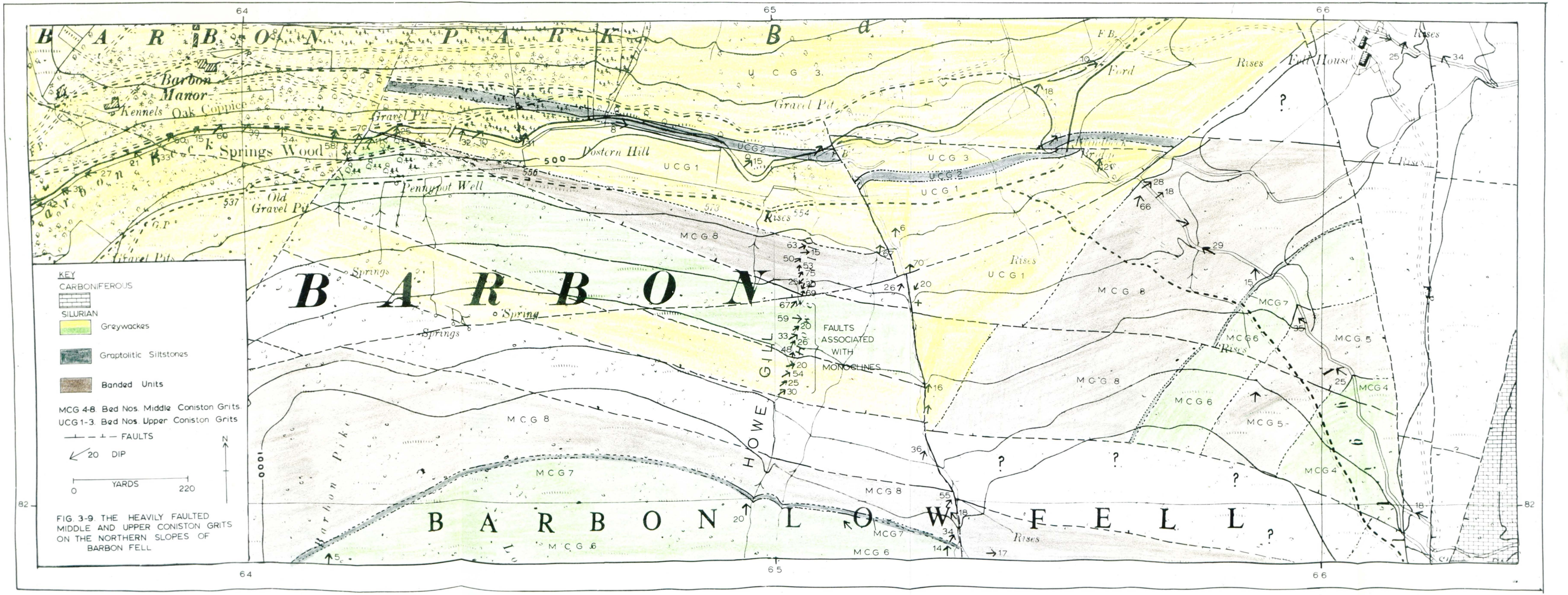



FIG. 3-9. THE HEAVILY FAULTED MIDDLE AND UPPER CONISTON GRITS ON THE NORTHERN SLOPES OF BARBON FELL

by the first of three closely spaced WNW trending faults, which in turn are cut by an ENE trending fracture. The section is badly shattered by these disturbances, and it is difficult to determine accurately, the stratigraphic level of any of the strata between here and the Barbondale road (650825) several hundred yards to the north. (See figure 31) Only a tentative interpretation of the stratigraphic horizons represented in this heavily faulted area, is shown on the 6" inset maps.

In Aygill (660823), however, ¾ of a mile to the north east, an ascending succession through the Middle Coniston Grits is seen, from the 180' banded unit, (MCG5), upwards, working downstream. Here, the banded unit, (MCG8), overlying the 110' greywacke has a total thickness of 300 feet. The lithology is rather coarser than normal, and thin bands of greywacke replace some of the banded siltstone laminae, towards the top of the unit. A fauna of M. leintwardinensis incipiens, M. chimaera, and M. varians, has been collected low down (F19), in this unit.

At the base of this section, the banded unit is overlain by a thick massive bedded greywacke which is cut by a NE trending fault. Adjacent stream sections indicate that the throw of this fault is small, and in the order of 50 feet to the north. Taking this into account, the greywacke would appear to have a thickness of approximately 200 feet. This agrees closely with the thickness of a similar unit measured in nearby Barbon Beck, which is also underlain by a banded unit. In Barbon Beck, this 200' greywacke is overlain by a thin bed of banded graptolitic siltstone, followed by a greywacke unit several hundred feet in thickness.

The strata below the 200' greywacke are characterised by alternating beds of greywackes and banded units, of approximately equal thickness. From this point upwards, the sedimentation appears to have reverted to the type characteristic of the Lower Coniston Grits. The change to dominantly coarse sedimentation is quite marked, and thus the upper limit of the Middle Coniston Grits is drawn at the top of the 300' banded unit, (Bed MCG8). This division of the series has a total thickness of 1240 feet, and is easily recognised in the field, especially when the graptolite fauna is also taken into consideration. Little variation in the thickness of beds from one stream section to another is seen, due to the very short distances involved.

The Zoning of the Middle Coniston Grits.

This division is poorly fossiliferous compared with the strata below, and where graptolites do occur, the preservation is usually bad. The fauna of the Middle Coniston Grits is as follows:-

M. chimaera salweyi Lapworth.
M. cf. varians Wood.
M. leintwardinensis incipiens Wood.

P. bohemicus (Barrande).
Slava [Cardiola] interrupta (Sowerby).
Pterinea sp.

This is much smaller than that obtained from the Lower

Coniston Grits, both in the number of species and individuals. M. leintwardinensis incipiens is undoubtedly the most common form, but its association with P. bohemicus, M. varians, and M. chimaera salweyi, indicates that the strata fall definitely within the nilssoni-scanicus Zone, even though the Zone fossils of P. nilssoni and M. scanicus have not been recorded. This restricted fauna again makes it impossible to differentiate between the nilssoni and scanicus Zones, as all the types recorded are common to both.

The comparative abundance of M. leintwardinensis incipiens so low in the succession, is again the only anomalous feature of the assemblage. It appears that its original restriction by Elles and Wood, to the leintwardinensis Zone, is only the case in certain parts of the country. Wood (1900, p.443), for example, described M. leintwardinensis incipiens from strata in the Long Mountain District, which would probably be equivalent to the tumescens Zone elsewhere. In the Barbon and Middleton Fells (and the Howgills according to Dr. Rickards), this species is the common fossil throughout the succession.

## Comparison with the Howgill Fells.

A middle division of the Coniston Grits was not recognised by Rickards in the Howgill Fells, as the development of the banded unit lithology is not as marked in this area. In the middle of the Coniston Grit Series

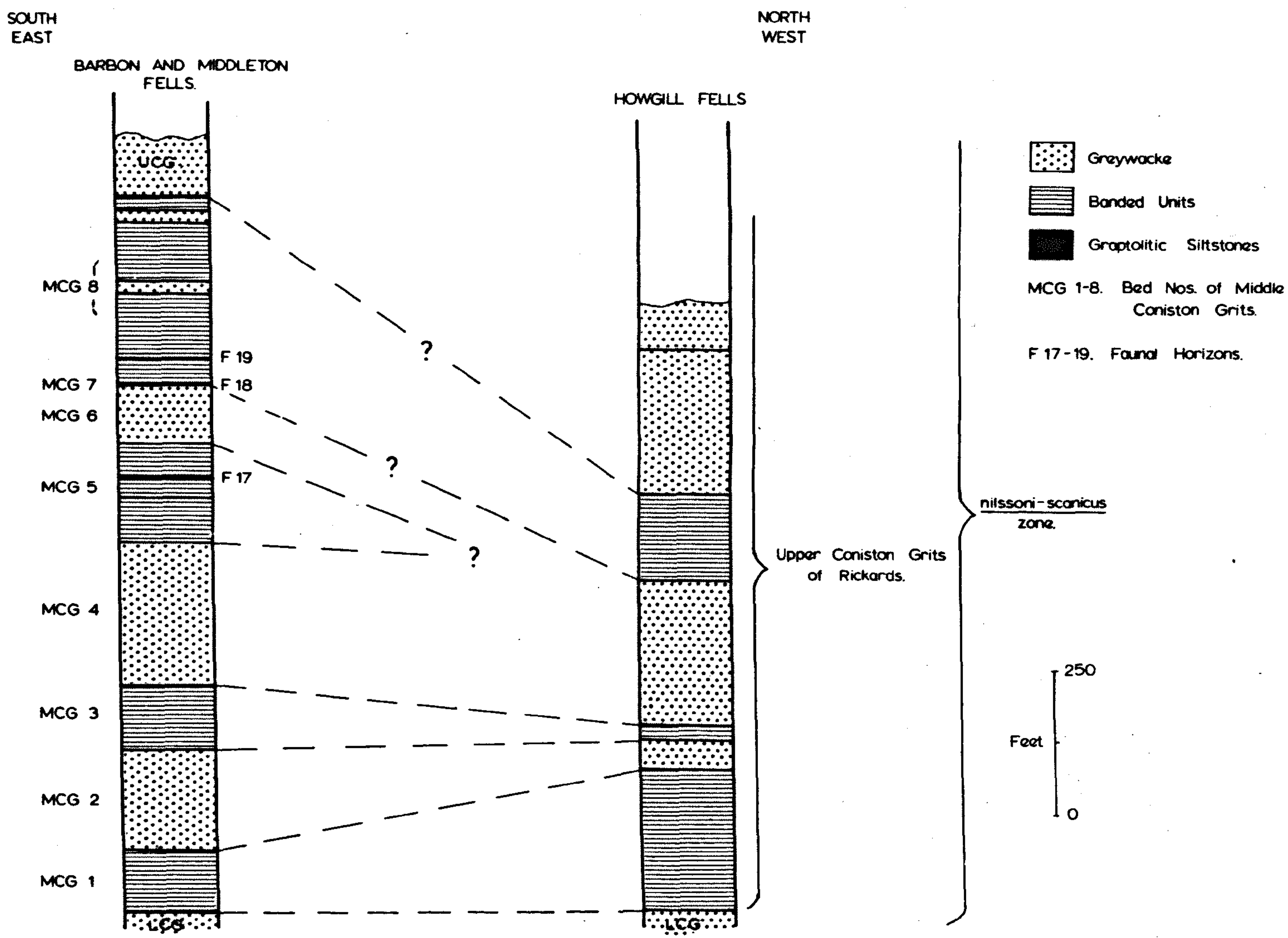



Fig. 3-10. The Correlation of the Middle Coniston Grits of the Barbon and Middleton Fells with the equivalent strata in the Howgill Fells.

in this area, however, are two thick banded units of 250 feet and 450 feet, separated by a greywacke unit containing another thin banded unit. The total thickness from the base of the 250' unit to the top of the 150' unit is almost 800 feet, which were placed by Rickards at the base of his Upper Coniston Grits division.

In the Barbon and Middleton Fells thick banded units are developed at approximately the same level in the succession. Here, as in the lower division of the Series, the thickness of strata in which this lithology is prevalent, is much greater than in the Howgills. The faunal assemblages however are similar, and so for these reasons, the first 800 feet of Rickards' Upper Coniston Grits have been correlated with the Middle Coniston Grits of the Barbon and Middleton Fells, as shown in figure 3-10. The amount of variation from one area to the other, is much more marked than in the Lower Coniston Grits, and thus correlations between individual units are only tentative.

Once again the strata thicken considerably to the south, indicating that the southward deepening of the geosyncline was a marked feature over a long period of time.

(c) The Upper Coniston Grits.

This division of the Coniston Grits has a much more widespread distribution throughout the area than the preceding divisions, and forms much of the lower ground along the south eastern and north eastern margins of the region. The best sections in the lower part of the division are exposed in Barbon Beck, just to the east of Barbon Park (652826), and on the hillside immediately to the north of the river. The higher parts of the succession are poorly exposed, but can be pieced together by working along the strike of the strata, up Barbondale, and from sections on Holme Fell (645905)? on the northwestern edge of the area. The upper part of this division is also seen in the numerous stream sections running into the Dent Valley, on the northeastern edge of the area. The value of these however, is very much reduced by a number of WNW trending faults, which in many cases make it impossible to determine the exact horizon. The widespread distribution of the strata also allows variations in thickness to be followed from the south to the north of the area.

The first greywacke unit of the Upper Coniston Grits, (Bed UCG1), is exposed in a strike section in Barbon Beck, between the two N-S trending faults (647828). It is fine grained and displays a high proportion of current lamination. Working upstream, higher and higher parts of the unit are gradually brought down to river level, by which means a total thickness of 204 feet has been measured, before graptolitic siltstone replaces the greywacke. Further upstream, intensive faulting brings down a higher division of the series, leaving only the upper part of the unit, and the overlying banded graptolitic siltstone exposed.

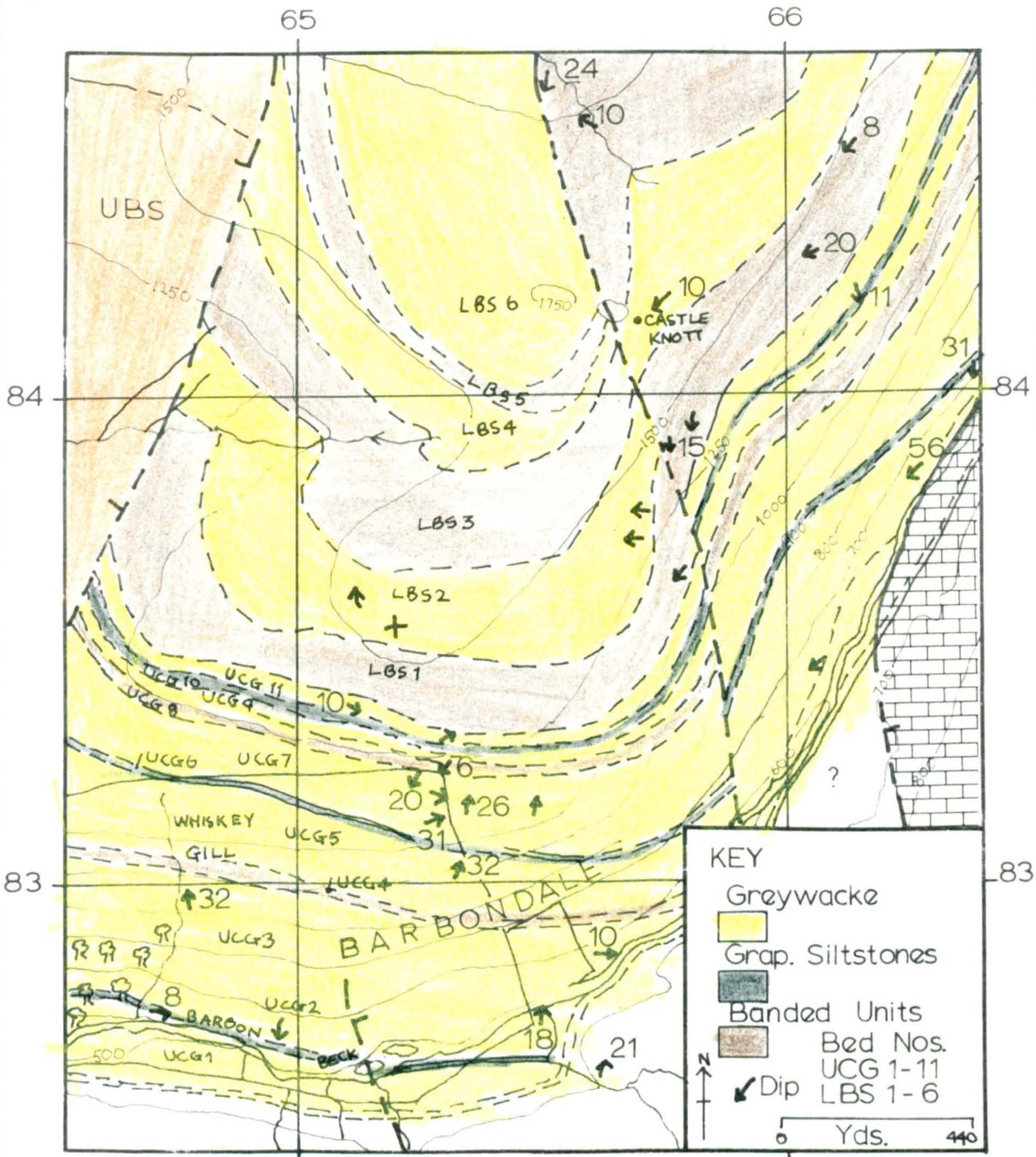



FIG. 3-11. Sketch of the Upper Coniston Grits and Lower Bannisdale Slates in the Whiskey Gill area.

The overlying banded siltstone, (Bed UCG2), is exposed in the northern bank of the river for several hundred yards to the west of the faulted area. It has a total thickness of 11 feet, and is poorly fossiliferous, but has yielded a few fragments of (F20):- P. bohemicus and M. varians pumilis. This siltstone can be traced for a short distance in the faulted strata further upstream, where it is overlain by a greywacke unit. This unit, (UCG3), is massively bedded with well developed mudstone partings. Grading is developed but is difficult to follow, owing to the overall fine grained nature of the strata. The unit can be traced in exposures upstream from Blindbeck Bridge (655827), where the dip is generally to the east or north east at fairly low angles. On the hillside above Barbon Park, the unit is again exposed in numerous small crags, where some rather coarser beds are developed. The total thickness of approximately 710 feet, makes this the thickest individual greywacke unit seen in the entire succession. Careful examination of all the exposures and sections along the strike of this bed reveal no intervening graptolitic siltstone or banded units.

Towards the top of Whiskey Gill, on the north eastern corner of Barbon Park (648829), the greywacke is overlain by an unfossiliferous banded unit (Bed UCG4), of 42 feet in thickness. Along the strike to the east, a similar thickness of strata is exposed in Barbon Beck, several hundred yards to the north east of Blindbeck Bridge.

The lower part of the overlying greywacke, (UCG5), is well exposed in Barbon Beck. Here, however, the strata is broken and contorted by an adjacent N-S trending fault. Dips are variable in direction over short distances, and it is thus difficult to measure accurately, the thickness exposed at this point. This unit does appear to have a considerable thickness, and by piecing together exposures along the strike from Whiskey Gill to Barbon Beck, an approximate thickness of 240 feet has been estimated. The succeeding banded graptolite siltstone, (UCG6), is exposed on the hillside several hundred yards to the east of Whiskey Gill. This horizon (F21), which is 23 feet in thickness has yielded a few specimens of M. varians, and numerous M. leintwardinensis incipiens. A similar fauna, with P. bohemicus in addition, was obtained from the same horizon (F22), on Holme Fell at the northwestern extremity of region. Here however, the siltstone is only 15 feet thick.

The greywacke above, (UCG7), is well exposed only at one point in the Whiskey Gill area. In overhanging crags numerous flute markings are developed. The dip of the strata however swings round from 31 degrees NE, to 46 degrees SW, in the space of a hundred yards, as a small NW trending syncline is crossed. This makes estimation of the thickness rather difficult, but along the strike, away from the fold, slight changes in topography indicate that the unit has a thickness of 250 feet. Along the north eastern edge of the region, a thick greywacke unit is exposed in the upper part of Haw Gill, Dentdale (682880). By working down from the higher parts of the succession, which are extremely well exposed in Combe Scars (677875) to the south, this greywacke fits in at the same horizon as that exposed to the east of Whiskey Gill. The thickness here can be measured accurately, and is 253 feet. This similarity probably results from these two localities being along the strike from one another, and at the same distance from the supposed source of the sediments. At right angles to the strike however, to the north west, on Holme Fell (645495), the unit decreases to 240 feet.

The greywacke is succeeded by a thin banded unit, (UCG8), which has a thickness of 66 feet in the Whiskey Gill area, 64 feet in Haw Gill, and 60 feet on Holme Fell. (See figure 3-12) The Whiskey Gill exposure, where weathered, has yielded, (F23):- M. varians pumilis, M. leintwardinensis incipiens, and P. bohemicus. The strata in the Holme Fell locality however are highly cleaved, and have yielded only fragmentary unidentifiable specimens. The Haw Gill exposure is unweathered, and has not yielded any graptolites.

The greywacke unit overlying,(UCG9), has a thickness of 50 feet in the Whiskey Gill area, approximately 50 feet to the south of Calf Top, Barbondale (668850), where it is poorly exposed, decreasing to 44 feet on Holme Fell. In all these localities it is rather thinly bedded, with well developed mudstone partings.

The succeeding graptolitic siltstone, (UCG10), is well exposed and richly fossiliferous in the following localities:- 600 yards SSE of Calf Top (668850), (F24); the middle part of Brackensgill, Dentdale (665890), (F25); the lower part of Ruddles Gill, Dentdale (662895), (F26); and in the old quarries on Holme Fell (645493), (F27). The unit decreases slightly in thickness from 25 feet in the Calf Top area, to 23 feet on Holme Fell, and at the top approaches a banded unit in its lithology. The fauna although abundant, consists entirely of M. leintwardinensis incipiens, apart from the Ruddles Gill locality (F26), where two specimens have been tentatively identified by Dr. Rickards as P. c.f. tumescens.

Although showing signs of grading into a banded unit towards the top, the graptolitic siltstone is suddenly replaced by a rather micaceous greywacke unit (UCG11), in all the above mentioned localities. The thickness of this is 59 feet at Calf Top and near Combe Scars, and 51 feet in Ruddles Gill. The upper part of the Holme Fell locality is unexposed, but there is room for 45 feet of strata between the top of the underlying graptolitic siltstone, and the succeeding banded unit.

In every part of the region, this greywacke unit is overlain by a great thickness of the banded unit lithology, which thus again becomes much more dominant. The top of the greywacke appears to mark the end of a dominantly

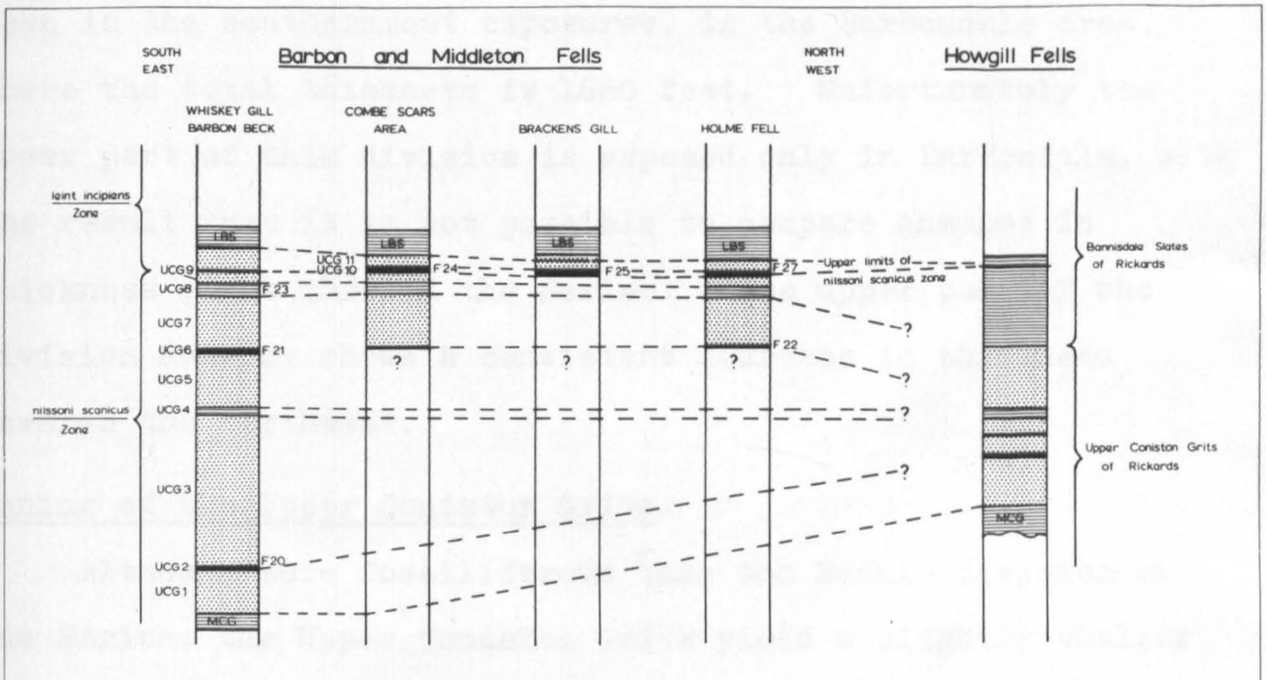



Fig. 3-12. Sections through the Upper Coniston Grits from South-east to North-west across the Barbon and Middleton Fells, and their correlation with the Howgill Fells.

arenaceous phase in the sedimentation. On lithological grounds, the upper limit to the Upper Coniston Grits is drawn at the top of this unit. The maximum thickness is seen in the southernmost exposures, in the Barbondale area, where the total thickness is 1680 feet. Unfortunately the lower part of this division is exposed only in Barbondale, with the result that it is not possible to compare changes in thickness right through the Series. The upper part of the division however shows a consistent decrease in thickness towards the northwest.

Zoning of the Upper Coniston Grits.

Although more fossiliferous than the Middle division of the Series, the Upper Coniston Grits yield a slightly smaller number of species. The Series up to and including the 66' banded unit, yields a fauna of M. varians pumilis, P. bohemicus, and M. leintwardinensis incipiens, again indicative of the nilssoni-scanicus Zone. Above this horizon however, the forms typical of the nilssoni-scanicus Zone are completely absent. Intensive collecting in four richly fossiliferous horizons at this level yielded only M. leintwardinensis incipiens, and a few doubtful specimens of P. tumescens.

On these grounds, the upper limit of the nilssoni-scanicus Zone is drawn at the top of the 50' greywacke unit. The strata above this level are considered to be equivalent to the leintwardinensis incipiens Zone in the Howgill Fells, which Dr. Rickards considers is probably equivalent to the tumescens

Zone of Elles and Wood.

Comparison with the Howgill Fells.

The uppermost 800 feet of the Coniston Grits in the Howgill Fells consist predominantly of thick greywacke units, with only a few thin beds of graptolitic siltstone and banded units. This indicates a return to predominantly coarse sedimentation, following the finer grained phase lower down in the series. This is similar to the position in the Barbon and Middleton Fells, where, however, the thickness at first appears to be double that seen in the Howgills. When the extent of the graptolite Zones is taken into consideration, however, it becomes apparent that coarse sedimentation carried on for a longer period in the south.

Deposition of sediments from turbidity currents is characteristically very variable over comparatively short distances, and this feature appears to become more predominant at these higher levels in the succession. The result is that the correlation of individual units in the two areas is difficult.

Consideration of the graptolite Zones shows that in the Howgill Fells, the corresponding strata fall well within the nilssoni-scanicus Zone. In the Barbon and Middleton Fells however, the uppermost 80 feet of strata extend into the P. tumescens or M. leintwardinensis incipiens Zone, which is represented by Bannisdale Slates in the Howgills. This suggests that either the nilssoni-scanicus fauna died out slightly earlier in the Barbon and Middleton Fells, or that the Bannisdale Slate lithology developed somewhat earlier in the Howgills. The latter explanation would appear to be more likely, as both the Survey Memoirs, and Rickards (1963), noted that the base of the Bannisdale Slates occurred at varying horizons, from one area to another. This would mean that much of the Upper Coniston Grits, are in fact really equivalent to the lower part of the Bannisdale Slates, in the Howgill Fells. A certain amount of coarse sedimentation continues in higher divisions of the leintwardinensis incipiens Zone, in the Barbon and Middleton Fells, and is described below.

Taking these factors into consideration, it appears that the 1680 feet of Upper Coniston Grits in this area, are equivalent to the uppermost 800 feet of the Upper Coniston Grits, and first 350 feet of the Bannisdale Slates, in the Howgill Fells. This correlation is summarised in figure 3-12, and shows that there is still a considerable thickening of strata to the south of the Howgill Fells.

## (2) The Bannisdale Slates.

In the Howgill Fells, the strata at this level in the Ludlow Series are formed almost entirely of the banded unit lithology. In the Barbon and Middleton Fells, however, (as mentioned above), coarse greywacke sedimentation continues to be rather more prevalent for a time. This gives rise to alternating beds of greywackes and banded units, in proportions similar to those seen in the Middle Coniston Grits. Only at a much higher level does the true Bannisdale Slate lithology become continuous. On this basis, the Bannisdale Slates in the Barbon and Middleton Fells have been split into two divisions as follows:-

| | | |
|---|---|---|
| Bannisdale Slates | Upper | Formed almost entirely of the banded unit lithology. |
| | Lower (Beds LBS 1-6) | Approximately equal proportions of greywackes and banded units. |

(a) <u>The Lower Bannisdale Slates.</u>

This lower division of the Bannisdale Slates has a widespread distribution throughout the eastern and northeastern parts of the area. It forms the higher slopes of the fells bordering Barbondale and the Dent Valley, and extends over and into the upper reaches of the western river valleys. Exposures are good, especially in the lower part of the division, allowing changes in the thickness of individual units to be compared from south east to north west.

The most southerly exposure of the first banded unit, (LBS1), is high up on the southern slopes of Castle Knott (658837). The typical banded unit lithology, with alternating laminae of banded siltstone and unbanded mudstone, is well developed, apart from a few thin greywacke beds in the middle. The grain size is somewhat finer than at lower levels in the succession, resulting in a much greater development of cleavage than previously seen. The unit is fossiliferous, but the graptolites occur only along very thin horizons in the banded siltstone, and not distributed throughout the bed. Two main fossiliferous horizons, one near the base (F28), and the other near the top of the unit (F29), yielded numerous M. leintwardinensis incipiens, along with s everal specimens of Slava [Cardiola] interrupta, and Orthoceras sp. The thickness of the unit in this locality is just under 200 feet. It is also exposed in numerous crag sections along the length of Barbondale, and can be followed easily across the 3 N-S trending faults which cut the hillside. A large number of specimens of M. leintwardinensis incipiens have been collected at several localities (F30-36), in this area. A perfect cliff section through the unit is seen at Combe Scars (677875), (See figure 13), where a thickness of 200 feet has been measured. A fauna restricted to M. leintwardinensis incipiens only, has also been collected at this locality (F37). Further to the northwest, along the southern slopes of Dentdale, the unit is exposed in a number of stream sections, and begins to thicken considerably, and in Brackensgill (665889), has reached a thickness of 276 feet. This is a remarkable increase in a distance of 1½ miles, and would at first appear to indicate that a mistake in the horizon has been made,

FIG. 3-13. The Lower Bannisdale Slates at Combe Scars, Dentdale. From the east (above) and the north (below)

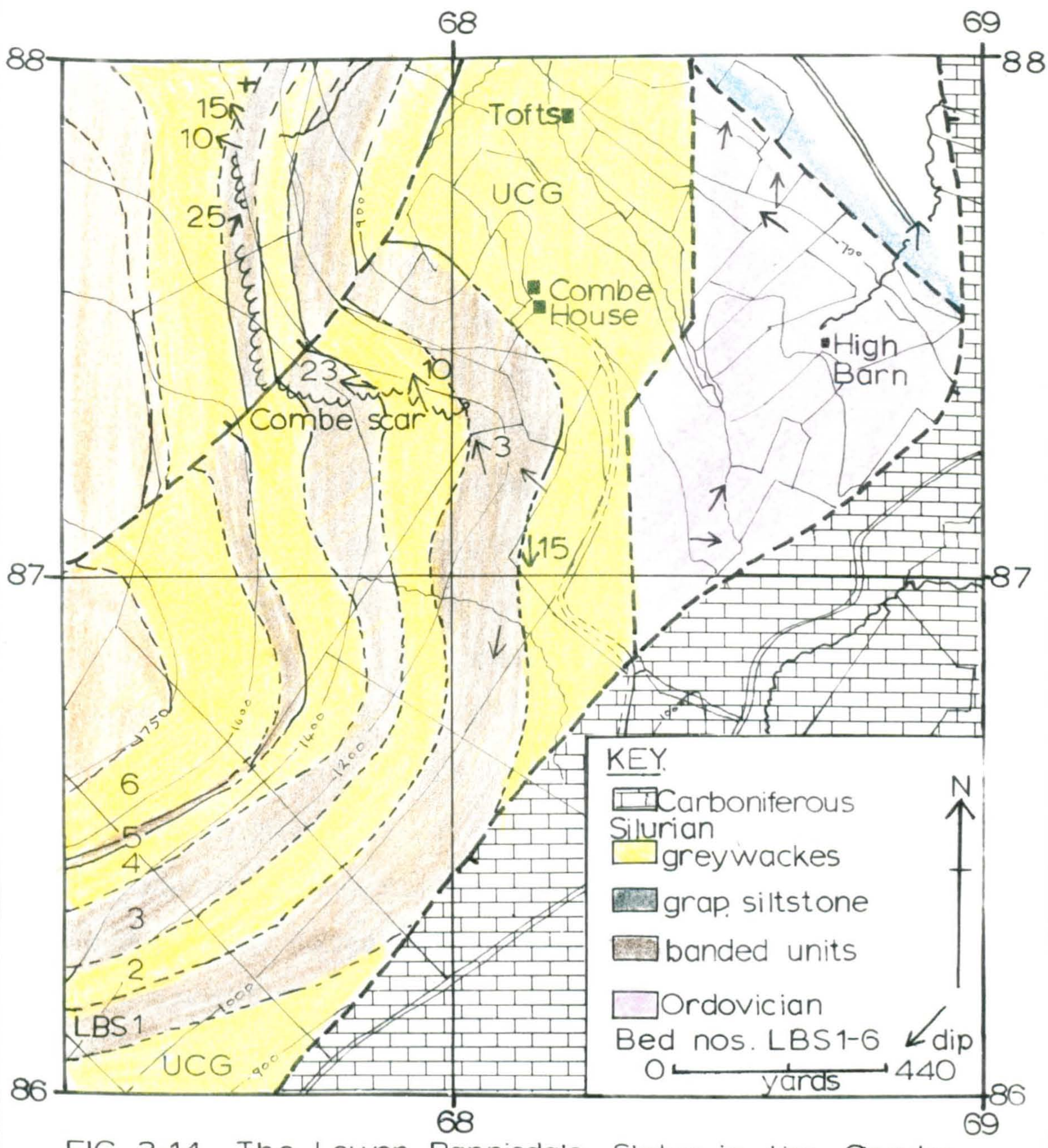



FIG. 3-14. The Lower Bannisdale Slates in the Combe Scars area.

perhaps due to unexposed faults. Exposures along the valley side from Combe Scars are very good, however, and the displacement of the unit by 3 N-S trending faults can be followed easily. There is no doubt that this is the same unit. On Holme Fell, a mile further to the north west, the unit reaches a thickness of 285 feet.

The succeeding greywacke, (LBS2), is massively bedded, with well developed mudstone partings, in which sole markings are abundant. The most southerly exposure is just to the southwest of Castle Knott (658837), where in almost horizontal strata, a thickness of 165 feet has been measured. This unit can also be traced northeastwards up Barbondale, and is well exposed in crag sections just below the summit of the fell. In Combe Scars (677875), there is a complete section through the unit, which at this point has a thickness of 168 feet. The greywacke is then followed easily down the southern side of Dentdale, across three faults, by a series of crag sections. In a few places exposures do become poor, but the scarp produced by the more resistant nature of the unit serves as a useful guide. Beyond Combe Scars the thickness decreases rapidly, until in Brackensgill, it has dropped to 120 feet. On Holme Fell however, it shows a marginal increase to 125 feet.

At the top of the greywacke there is a sharp junction with the overlying banded unit, (LBS3). Exposures are poor to the south west of Castle Knott, but in the upper reaches of Southdale Gill (655846), however, the unit crops out, and dips downstream. The dip, and the slope of the valley are similar, resulting in large bedding plane exposures. The lithology is rather more flaggy than usual, and within the unit there are several thin beds of greywacke, 2 to 3 feet thick. The stream section is cut off by a N-S trending fault, but scattered exposures on the north eastern side of the valley, leave room for approximately 170 feet of strata. The cleavage which is prevalent at this level in the succession destroys the graptolites, and as a result only a few poorly preserved specimens of M. leintwardinensis incipiens, Slava [Cardiola] interrupta, and Orthoceras sp. were obtained at 2 horizons (F38, F39). To the north, exposures are poor until Combe Scars are reached. Here, a complete section through the unit is exposed in the upper part of the cliff. The lithology is similar to Southdale Gill, with a few thin beds of greywacke. The degree of cleavage is much less however, and localities F40, and F41 have yielded large numbers of M. leintwardinensis incipiens. The thickness of the unit in Combe Scars is 163 feet, but working northwestwards, it increases rapidly, and in Brackensgill has reached 238 feet, and on Holme Fell, 245 feet. Once again the high degree of exposure ensures that this is the same unit, as seen in Combe Scars.

The succeeding greywacke, (Bed LBS4), is poorly exposed throughout the area, as it usually forms the poorly drained summit to the fells. Scattered exposures above Combe Scars reveal a rather fine grained thinly bedded greywacke, with a thickness of a pproximately 170 feet. Although the degree of exposure is poor, the greywacke forms a small but steep scarp at the summit of the fells. This can be traced to the northwest, and decreases in thickness to 130 feet above Brackensgill, and 88 feet on the summit of Holme Fell.

A banded unit, (LBS5), overlies the greywacke, but is not exposed on the slopes of Barbondale south of Combe Scars. A slackening in the hillslope at the level the unit could be expected to occur, however, suggests that at this locality its thickness is probably about 75 feet. To the northwest it is exposed intermittently in the upper parts of the rivers which drain west into the Lune Valley. In all these sections the strata dip downstream at a similar degree to the hillslope, making the thickness of the unit deceptive. Careful measurement in the upper part of Luge Gill (659879), directly south of Brackensgill, indicates a thickness of 85 feet. The strata here are highly cleaved, but yielded several good specimens of M. leintwardinensis incipiens, and P. cf.tumescens, along with the usual shelly forms of Orthoceras sp., and Slava [Cardiola] interrupta. On Holme Fell, the strata are again highly cleaved, and did not yield any fossils. Here the thickness has increased further to 100 feet.

This banded unit is followed by the last thick greywacke unit in the Ludlow Series, (Bed LBS6). The most southerly exposure of this unit is in Southdale Gill (652848), where, however, the section is cut off in the east and west by two N-S trending faults. The section exposed has a thickness of 180 feet. A total thickness of approximately 260 feet has been estimated by working up the hillsides from the underlying banded unit, which is exposed near Castle Knott, and in Northdale Gill (653854). A similar thickness has been estimated between the upper parts of Wrestle and Luge Gills (665865). Further to the northwest, the greywacke is well exposed in a tributary of Luge Gill, in a section dipping downstream. The lithology here is rather flaggy, and finer grained than normal, and the thickness has fallen to 180 feet. A mile further to the northwest, it has fallen still more to 135 feet.

Above this level, in all sections, the banded unit lithology becomes almost continuous, and coarse strata are restricted to beds of only 1 or 2 feet in thickness, within the finer sediment. The upper limit of the Lower Bannisdale Slates is thus drawn at the top of this last thick greywacke unit. The thickness of strata within this division varies from 1042 feet in the south east, on the hillsides above Barbondale, down to 978 feet on Holme Fell, in the northwest. This variation itself is not very great. The variation in individual units from north to south, however, is both marked and unusual. The greywacke units all thin very considerably to the northwest, whereas the banded units thicken to a certain extent in this direction.

Zoning of the Lower Bannisdale Slates.

The banded units within the Lower Bannisdale Slates are richly fossiliferous, but preservation is often bad, due to cleavage. The graptolite species are restricted entirely to *M. leintwardinensis incipiens*, and a few doubtful specimens of *P. tumescens*. The usual shelly types such as *Orthoceras sp.* and *Slava [Cardiola] interrupta*, also occur. This fauna is similar throughout the division, and is indicative of the *M. leintwardinensis incipiens* Zone of Rickards, (= *P. tumescens* Zone of Elles and Wood?), in which it is thus placed.

Comparison with the Howgill Fells.

In the Howgill Fells, the strata within the *M. leintwardinensis incipiens* Zone consist entirely of thick banded units, apart from a greywacke unit of 140 feet near the top of the Zone. In the south of the Barbon and Middleton Fells, however, coarse sediment is much more abundant, and forms over half of the succession. Moving northwestwards towards the Howgill Fells, the proportion of greywacke drops sharply, whereas the amount of the banded unit lithology increases, indicating a transition to the Howgill type of sedimentation.

In the Barbon and Middleton Fells, a thick greywacke unit marks the upper limit of the Lower Bannisdale Slates,

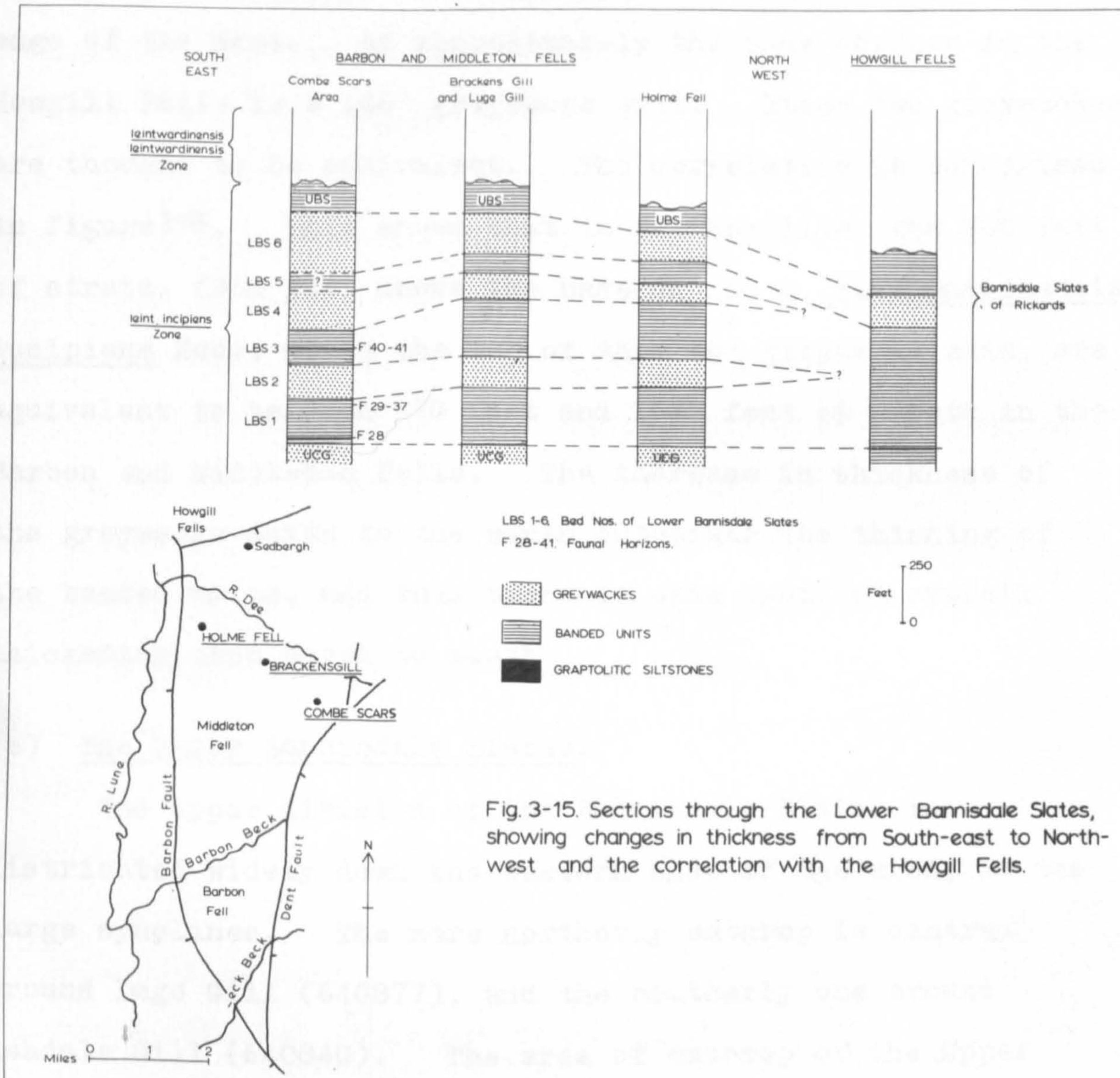



Fig. 3-15. Sections through the Lower Bannisdale Slates, showing changes in thickness from South-east to North-west and the correlation with the Howgill Fells.

and has a considerable thickness, even at the northwestern edge of the area. At approximately the same horizon in the Howgill Fells is a 140' greywacke unit. These two greywackes are thought to be equivalent. The correlation is summarised in figure 3-15. This shows that in the Howgills, the 700 feet of strata, from just above the base of the *M. leintwardinensis incipiens* Zone, up to the top of the 140' greywacke unit, are equivalent to between 978 feet and 1042 feet of strata in the Barbon and Middleton Fells. The increase in thickness of the greywacke units to the south outweighs the thinning of the banded units, and thus there is once again an overall thickening from north to south.

(b) The Upper Bannisdale Slates.

The upper division of the Bannisdale Slates is distributed widely down the western side of the area, in two large synclines. The more northerly outcrop is centred around Luge Gill (640877), and the southerly one around Ashdale Gill (640840). The area of outcrop of the Upper Bannisdale Slates is in fact similar to the Bannisdale Slates division shown on the Geological Survey map of 1869.

The extent of the areas occupied by these two outcrops, is defined easily on most sides, by faults, or by the underlying thick greywacke unit. Between the two areas of Bannisdale Slates however, exposures are very poor, apart from the Millhouse Beck section (640854). This section itself is rather problematical, as it is cut by faults, and isolated from all other exposures. No graptolites have been obtained from the section, but the banded unit exposed on the southern side of the stream has a thickness of 70 feet, and is under and overlain by well bedded greywacke units. This suggests that this may be the 75' banded unit near the top of the Lower Bannisdale Slates. The dip of the strata away from the E-W fault which runs down the valley, is to the north. Half a mile to the south, however, on the northern side of the Ashdale Gill outcrop of Bannisdale Slates, the dip is everywhere to the south. This indicates an anticlinal axis running through the unexposed ground between the two sections. When this is taken into account, the strata below the Bannisdale Slates fall into position, and the 70' banded unit comes in at the expected position in Millhouse Beck.

The problem of the succession to the north of Millhouse Beck cannot be solved as easily. The E-W fault downthrows to the south, but it is not possible to say precisely, by how much, as there is no means of defining the horizon of the few scattered outcrops of greywacke on its northern side. It has been assumed that these probably represent part of the 250' unit at the top of the Lower Bannisdale Slates. On this assumption, the southern limit of the Upper Bannisdale Slates has been drawn in tentatively.

The strata within the Upper Bannisdale Slates are extremely monotonous, and are formed entirely of the banded unit lithology. In the higher parts of the succession, however, the differentiation into alternating laminae of banded siltstone, and unbanded mudstone is less apparent. The strata become more uniformly fine grained, and the alternating laminae are more difficult to pick out.

Exposures are good, especially in the northern and larger of the two synclines, where the series is exposed in crags in addition to stream sections. The most complete section is followed by working southeastwards from the northern side of Holme Knott (646896), down into Ridding Beck (645892), and then following the stream down to Beckside Hall (634885). The first part of the section from north of Holme Knott is along the strike, but as this is up the hillside, it passes through approximately 350 feet of banded rocks. The strata appear to be poorly fossiliferous due to the cleavage, but 35 feet above the top of the underlying greywacke unit, a slightly more weathered horizon yielded several M. leintwardinensis incipiens, along with a large number of Pterinea sp. Just to the south of Holme Knott, however, 150 feet from the base of the series, a small number of M. leintwardinensis leintwardinensis, and M. leintwardinensis incipiens were obtained, (F44). Passing down from Holme Knott into the upper part of Ridding Beck, part of the succession is repeated, but working downstream a slowly ascending succession is passed through. The typical banded unit lithology continues, but appears to become very poorly fossiliferous. Exact thicknesses are difficult to estimate in this very long section, but approximately 450 feet from the base of the series, the highest fossiliferous horizon discovered in the Bannisdale Slates, (F45), yielded a few poorly preserved specimens of M. leintwardinensis leintwardinensis. Above this level, no fossils of any type have been collected.

Altogether, approximately 700 feet of the typical banded strata are passed through between Holme Knott, and the lower part of Ridding Beck. The section is cut off at the Barbon Fault, but the uppermost 170 feet of strata exposed become more uniformly fine grained and micaceous. The banding is still present, but is much more difficult to discern.

The top of the Upper Bannisdale Slates is not reached in this, or any of the other sections, due to the Barbon Fault cutting off the upper part, along the western edge of the area. The Holme Knott-Ridding Beck section, however, shows that the series has a thickness of at least 870 feet in this area.

In Luge Gill (637877), and Brow Gill (635868), further to the south, less complete sections are exposed, and are complicated by faulting. Both of these sections show the more typical banded unit lithology, and in their upper parts have yielded a few specimens of M. leintwardinensis leintwardinensis and M. leintwardinensis incipiens, (F46, F47). This indicates that they probably represent the middle part of the Upper Bannisdale Slates.

The area of Upper Bannisdale Slates around Ashdale Gill, is rather thinner. The stream itself runs almost along the axis of the fold, and thus forms a strike section. Exposures from the northern edge of the outcrop, down into Ashdale Gill, however, are good, and a maximum thickness of approximately 620 feet has been estimated. The banded unit lithology is extremely well developed, and, even in the higher parts of the succession, there is no suggestion of the more uniform fine grained lithology developing. Cleavage is very dominant, and almost at right angles to the bedding, but the strata do not form good slates. It has the effect, however, of destroying the fossils, as the bedding planes are fractured into irregular slivers.

On the south side of the syncline, 40 feet above the base of the division, at Eskholme Pike (639833), a banded siltstone horizon (F48), yielded a large number of fragmentary M. leintwardinensis incipiens, plus several shelly fragments. The stream section has not yielded fossils at all, even though a very careful search was made, and this suggests that it is probably just a little too high in the succession. Two adjacent localities, (F49, F50) in the crags on the northern side of the stream, however, which are about 400 feet from the base of the division, have yielded 4 poorly preserved specimens of M. leintwardinensis leintwardinensis and a few M. leintwardinensis incipiens.

The maximum thickness of the Upper Bannisdale Slates, in the Barbon and Middleton Fells, is never seen, as the upper parts of the succession are faulted out. The thickness, however, is at least 870 feet, and is seen in the more northerly of the two outcrops. The southern exposure has the appearance of being rather thinner, but this is due to the section being faulted out at a lower level in the succession. It is thus not possible to determine definitely, changes in thickness from north to south, in this division of the Ludlow Series, although there may in fact be a little thickening in this direction.

Zoning of the Upper Bannisdale Slates.

Both on Holme Fell, and in Ashdale Gill, the strata at 35 and 40 feet from the base of the division, yielded only M. leintwardinensis incipiens. This is identical to that collected from the underlying Lower Bannisdale Slates, and indicates that these lower beds also fall within the Zone of M. leintwardinensis incipiens. Above this level, the strata appear to be very poorly fossiliferous, and on Holme Fell the next graptolite horizon is some 115 feet above the M. leintwardinensis incipiens locality. Here however, this form occurs in association with M. leintwardinensis leintwardinensis. Similarly in Ashdale Gill, a large thickness of apparently barren strata is passed through, until some 400 feet from the base of the series, M. leintwardinensis incipiens, and M. leintwardinensis

leintwardinensis are recorded together. The upper part of the series appears to be completely unfossiliferous.

The leintwardinensis Zone as defined by Elles and Wood (1901-18), contained almost only M. leintwardinensis var. incipiens, and M. leintwardinensis. This is similar to the position in the Barbon and Middleton Fells. Thus the strata above the lowest locality on Holme Fell, which yields both of these forms, (i.e. 150 feet from the base of the division), are placed in the leintwardinensis Zone. In the Ashdale Gill area, the first record of M.leintwardinensis leintwardinensis, is rather higher. This suggests either a slight thickening of the strata from north to south, or that the strong cleavage has obscured the first occurrence of this species.

Figure 3-16 summarises the succession and zoning of the Upper Bannisdale Slates, and shows that although the lithological and zonal boundaries do not quite coincide, most of the Upper Bannisdale Slates fall within the leintwardinensis Zone.

Comparison with the Howgill Fells.

The Upper Bannisdale Slates in the Barbon and Middleton Fells, are correlated with the strata above the 140' greywacke unit, (in the middle of the Bannisdale Slates), in the Howgill Fells. The lithologies of thick banded units are identical in both areas. In the Howgills, only 440 feet of strata have been measured above the greywacke. Dr. Rickards

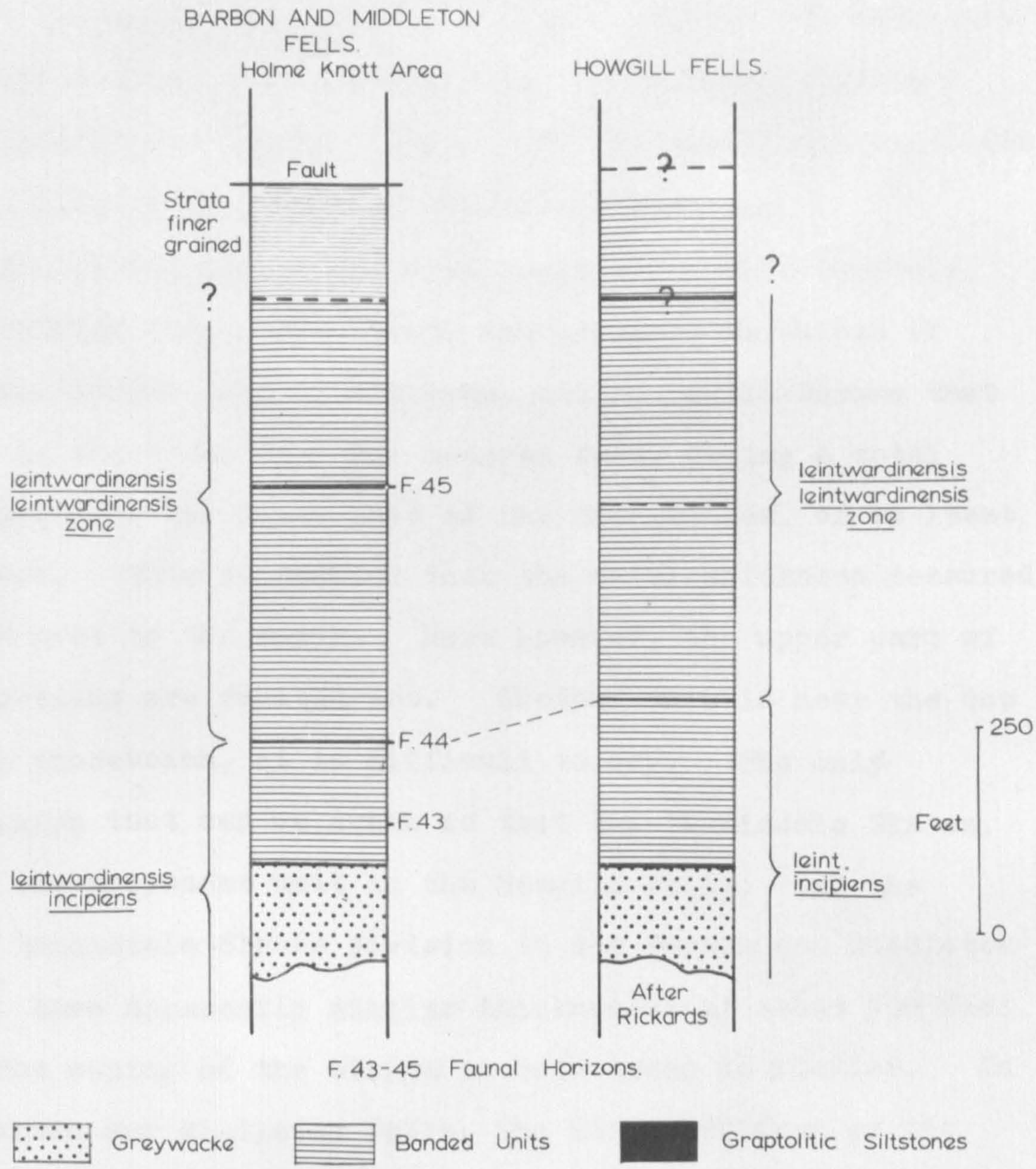



Fig. 3-16. Correlation of the Upper Bannisdale Slates with the equivalent horizons in the Howgill Fells.

indicates, however, that the thickness of strata to the top of the leintwardinensis Zone is probably about 700 feet, and that above this level there are further unfossiliferous divisions of Bannisdale Slates. In the Barbon and Middleton Fells, a total thickness of 870 feet, including unfossiliferous strata has been measured. Unfortunately, Dr. Rickards does not estimate the probable thickness of unfossiliferous beds in his area, but one would assume that it is in the order of a few hundred feet, giving a total thickness for the upper part of the Bannisdales, of at least 900 feet. This is greater than the total thickness measured in the area to the south. Here however, the upper part of the sections are faulted out. Whether this is near the top of the succession, it is difficult to say. The only conclusion that can be drawn is that the Bannisdale Slates, above the greywacke unit in the Howgill Fells; and the Upper Bannisdale Slates division in the Barbon and Middleton Fells, have apparently similar thicknesses of about 900 feet.

The zoning of the strata in both areas is similar. In the Barbon and Middleton Fells, the first 150 feet of the division, up to the first recorded occurrence of M. leintwardinensis leintwardinensis, are placed in the leintwardinensis incipiens Zone, and the remainder in the leintwardinensis Zone. The leintwardinensis Zone appears to come in at a slightly higher level in the Howgills, but this may be due to the poorly fossiliferous nature of the strata at this level.

The Ludlovian Strata - Conclusions.

(1) The Ludlow Series can be split on a lithological basis into the Coniston Grits below, and the Bannisdale Slates above.

(2) The Coniston Grits themselves are split into 3 lithological divisions, and the Bannisdale Slates into two. These divisions and their thicknesses are summarised in the table below:-

| | | | |
|---|---|---|---|
| Bannisdale Slates | Upper | 870' min. | Formed almost entirely of the banded unit lithology. |
| | Lower | 978' in the north<br>1042' in the south | Approximately equal proportions of greywacke units and banded units. Banded units form a larger proportion in the north of the area, and greywacke units a larger proportion in the south. |
| Coniston Grits | Upper | 1680' | Predominantly fine greywacke and thin graptolitic siltstone beds. |
| | Middle | 1240' | Equal proportions of fine greywackes and banded units. |
| | Lower | 1510' | Predominantly fine greywacke units, and thin banded graptolitic siltstone beds, with a coarser greywacke at the base. |

(3) There is a definite thickening of the strata from the north to the south of the area, which can be followed in the higher divisions of the Series.

(4) Compared with the Howgill Fells, this thickening is even more marked. The 4500 feet of Ludlovian strata in the Howgills, are represented by approximately 6300 feet of strata in the Barbon and Middleton Fells.

(5) This suggests that the deepening of the geosyncline to the south, seen in the Wenlockian, is continued into the Ludlovian.

(6) The Ludlow Series is divisible into three Zones based on the graptolite faunas:-

(3) M. leintwardinensis.

(2) M. leintwardinensis incipiens (= Zone of P. tumescens ?

(1) P. nilssoni - M. scanicus.

The vulgaris Zone has not been recognised, and it is not possible to separate the nilssoni and scanicus Zones.

The succession, its zonation and correlation with the Howgill Fells is summarised in figure 3-17.

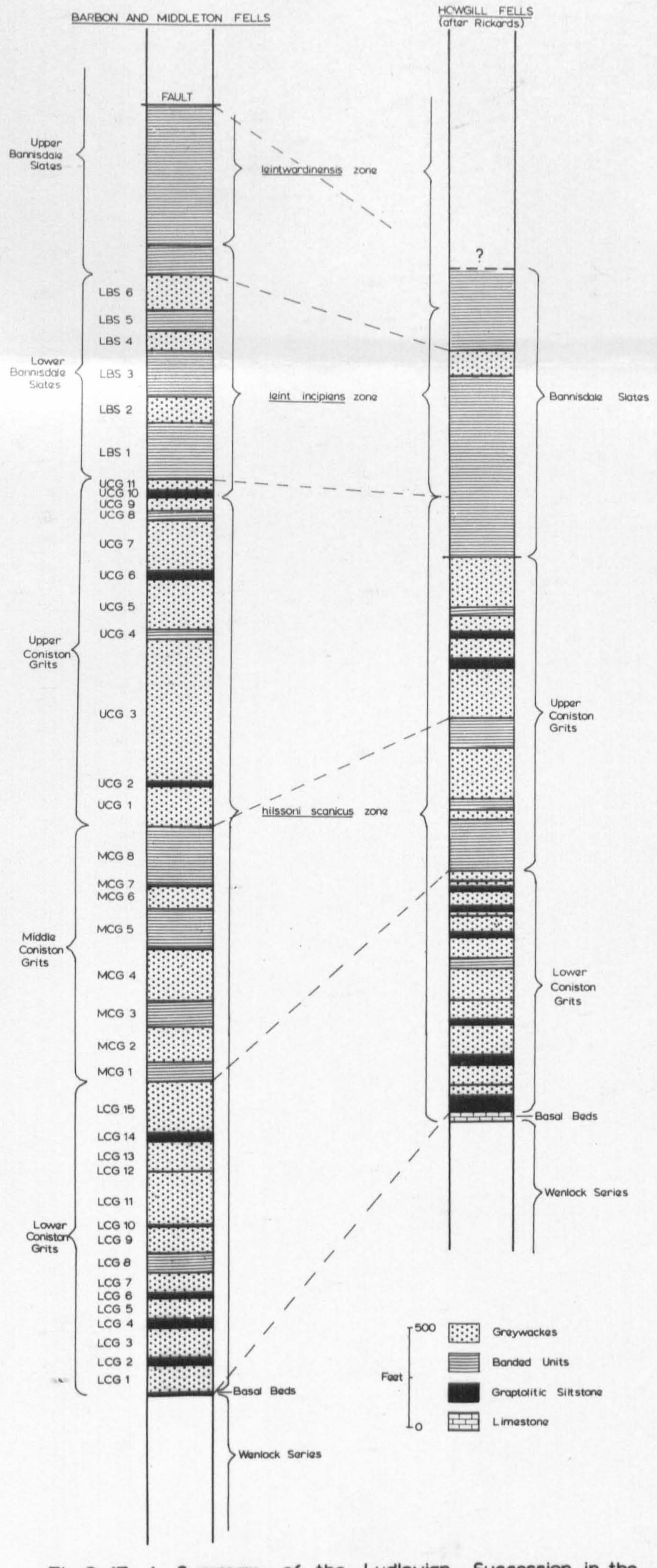
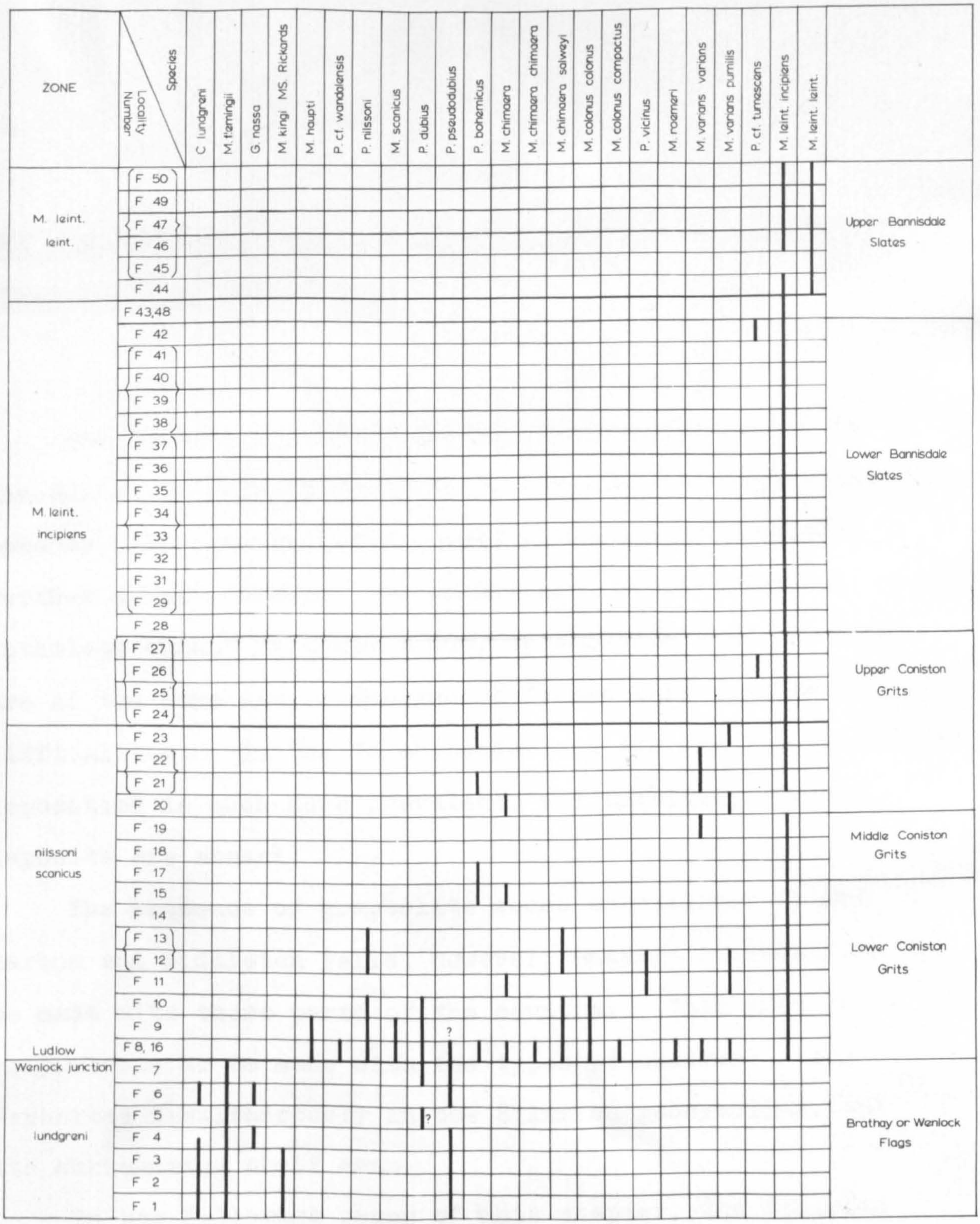



Fig. 3-17. A Summary of the Ludlovian Succession in the Barbon and Middleton Fells and its correlation with the Howgill Fells.




NB. Localities bracketed together occur within the same lithological unit and thus represent approximately the same horizon.

Fig. 3-18. Range chart of the graptolite species in the Silurian strata of the Barbon and Middleton Fells.

# CHAPTER 4

## THE CORRELATION OF THE BARBON AND MIDDLETON FELLS WITH OTHER PARTS OF THE COUNTRY.

The Silurian lithological succession established in the Barbon and Middleton Fells is of value in comparisons between this area and other parts of north-west England. Further afield however, the development of an identical lithology cannot be taken alone, as evidence that the strata are of the same age. Changes of facies also produce difficulties. In the Welsh Borderland for example, limestone deposition is much more prevalent, and turbidity current deposits are absent.

The sequence of graptolite zones established in the Barbon and Middleton Fells, however, enables correlations to be made with these parts of the country. This enables comparisons to be made with the types of sediment being deposited simultaneously in the Silurian geosyncline, and its surrounding shelf seas.

In the following pages of this chapter, the Silurian strata of the Barbon and Middleton Fells are compared with strata of the same age in other parts of the country. In addition, the Ludlovian greywackes are compared with the

Llandoverian and Wenlockian greywackes in the Southern Uplands, and the Wenlockian Denbigh Grits in North Wales. Although somewhat older than the Coniston Grits, the coarse sediments in these areas show the same sedimentary features and mode of deposition, and indicate that deposition from turbidity currents was a widespread feature throughout the Silurian. The close similarity between the Wenlockian greywackes of the Southern Uplands, and the Ludlovian greywackes of the Lake District, is discussed further in the subsequent chapters, on the petrography of the sediments.

(a) Comparison with the Lake District.

The Barbon and Middleton Fells form the southeastern margins of the main Lake District outcrop of Silurian strata, which thus extends for a distance of some 25 miles from east to west. As a result of the highly faulted nature of the strata, however, it is not possible to follow the various divisions continuously across the region. The Fells are thus compared with the standard Lake District succession, which is best seen in the Windermere area (Marr 1916), and also with the successions established by Llewellyn (1960), in the Longsleddale area, and Norman (1961), in the Blawith area.

The succession adopted by Marr, for the Ambleside-Windermere District is as follows:-

| | | | |
|---|---|---|---|
| | Kirkby Moor Flags | 1500' | Upper Ludlow |
| | Bannisdale Slates | 5000' | Lower Ludlow |
| | Coniston Grits / Sheerbate Flags / Coniston Grits | 4000' | Lower Ludlow |
| Upper Coniston Flags | Upper Coldwell Beds | 1500' | Lower Ludlow |
| Upper Coniston Flags | Middle Coldwell Beds | 400' | Lower Ludlow |
| Upper Coniston Flags | Lower Coldwell Beds | 400' | Lower Ludlow |
| | Lower Coniston Flags | 1000' | Wenlock |
| | Stockdale Shales | 250' | Llandovery |

The lithologies in this area are similar to those in the Barbon and Middleton Fells. Comparison of the thickness however, presents some difficulties. The Coldwell Beds - a division not recognised in the Barbon area - have a total thickness of approximately 2300 feet (according to Marr), and consist essentially of greyish flaggy siltstone and fine greywackes. The fauna obtained from them indicates a Ludlovian age. In the Barbon and Middleton Fells, however, the strata between the top of the Wenlock Series, and the base of the Bannisdale Slates, are all placed within the Coniston Grits, and have a thickness of 4400 feet. In the Ambleside area, the Coniston Grits reach only 4000 feet in thickness. Thus a correlation based on lithology alone, shows a slight thickening from northwest to southeast, whereas one based on the graptolite zones, shows a thinning from 6300 feet at Ambleside, to 4400 feet in the southeast.

Comparison with the Howgill Fells showed that even over short distances, changes in lithology occurred in strata of the same age. The Coldwell Beds of the Ambleside area are probably best considered as a continuation of somewhat finer sedimentation, at a time when coarser sediment was being deposited elsewhere. Thus there is in fact a reduction in thickness from northwest to southeast. Marr also recognised a flaggy somewhat more argillaceous division in the middle of the Coniston Grits - the Sheerbate Flags, - which it is proposed to correlate with the Middle Coniston Grits of the Barbon and Middleton Fells. (See figure 4-1.)

More recently, the work of Llewellyn (1960), and Norman (1961), has extended the classification proposed by Marr, to other parts of the Lake District. Llewellyn, in the Longsleddale area recognised all of Marr's divisions, and also found that the thicknesses were similar. Norman in the Blawith area, south of Coniston, also split the Ludlow Series into a similar number of lithological divisions, but gave them local names. Thus his Salthouse Mudstone Formation is equivalent to the Sheerbate Flags, and the Yewbank Sandstone Formation equals the Upper Coniston Grits and so on. In addition, he recognised a transition group - the Tottlebank Transition Formation - between the Upper Coniston Grits and Bannisdale Slates. This appears to be equivalent to the Lower Bannisdale Slates division of the Barbon and Middleton Fells. The total thickness of the

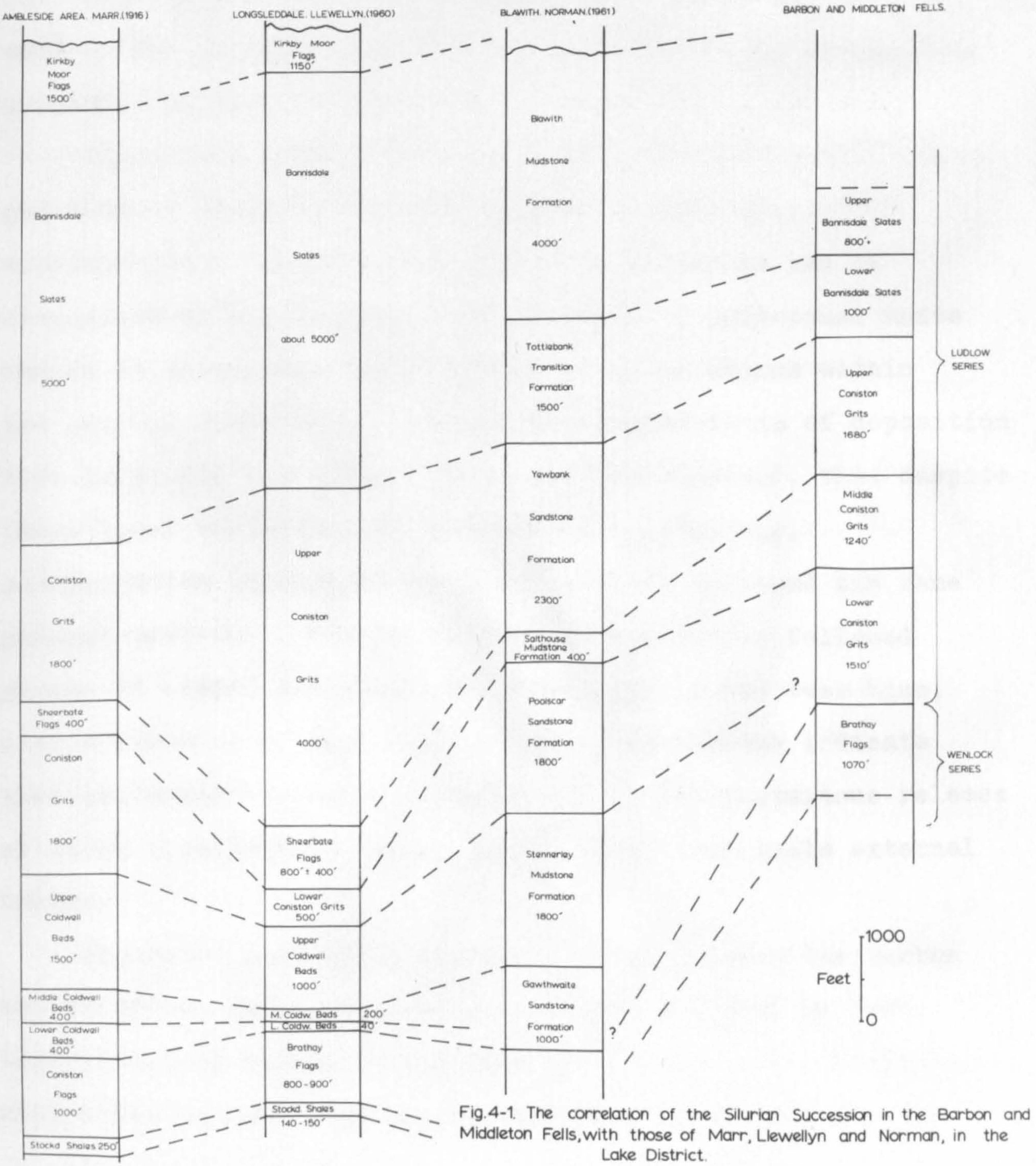



Fig. 4-1. The correlation of the Silurian Succession in the Barbon and Middleton Fells, with those of Marr, Llewellyn and Norman, in the Lake District.

Ludlow Series in his area appears to be somewhat thicker than in the Barbon Fells.

Neither of these two authors carried out detailed zonal work on the strata, as both considered the Series to be almost unfossiliferous.

Comparison between the Barbon and Middleton Fells, however, and these 3 areas of the Lake District, shows many close similarities. The broad lithological divisions can be recognised in all regions. Correlation of individual units cannot be attempted, owing to the local variations within the general succession - a feature characteristic of deposition from turbidity currents. It is apparent however, that despite these local variations in thickness and lithology, sedimentation throughout the Lake District followed the same general pattern. Periods of fine sedimentation followed phases of coarse deposition at approximately the same time, over a distance of 30 miles. This would perhaps indicate that sedimentation was controlled not by the fortuitous release of local turbidity currents, but by some large scale external factor.

Figure 4-1 summarises the correlation between the Barbon and Middleton Fells, and the successions proposed by Marr, Llewellyn, and Norman in the Lake District. The correlation with other parts of the country is shown in table 3 .

(b) <u>Comparison with the Horton-in-Ribblesdale area</u>.

Some 10 miles southeast of the Barbon and Middleton Fells, is the inlier of Lower Palaezoic rocks in the Horton-in-Ribblesdale and Austwick areas. In addition to Silurian rocks, Pre-Cambrian and Ordovician strata are exposed. Most of the Silurian succession falls within the Wenlockian, and the lithologies are again very similar to those seen in the main Lake District outcrop. King and Wilcockson (1934 p.28), give the following succession, and correlation with the Lake District:-

| | Zones | Horton-in-Ribblesdale | | Lake District |
|---|---|---|---|---|
| Lu | | Studfold Sandstone | 200'+ | Coniston Grits |
| | M.nilssoni | Horton Flags | 1300'-1400' | Coldwell Beds |
| W | C.lundgreni | Base of Horton Flags | | |
| | M.riccartonensis | Middle Austwick Grits and Flags | 7-800' | Brathay Flags |
| | C.murchisoni | Lower Austwick Grits and Flags | | |
| Ll. | | Shales and Limestones | | |

The succession ends in the Studfold Sandstone, (a fine greywacke very similar to the greywacke units in the Coniston Grits), after 200 feet of strata have been passed through. The underlying Horton Flags, with a total thickness of 1300-1400 feet, are placed almost entirely within the <u>nilssoni</u> Zone. The lithology is something of a transition between the Brathay Flags and the Coniston Grits, which King and Wilcockson equated with the Coldwell Beds. The <u>nilssoni</u> Zone thus has a thickness of at least 1500 feet, which would appear to be equivalent to the Lower Coniston Grits in the Barbon and Middleton Fells. This is only a very tentative correlation however, as the top of the succession is never seen, and the Series as a whole could in fact be much thinner in this area. The base of the Horton Flags, which are represented by the Moughton Whetstone, yield a fauna indicative of the Wenlockian C. lundgreni Zone. The exact thickness is not given by King and Wilcockson, but they indicate that it is a thin division. If this is so, the lundgreni Zone has thinned considerably from the southern end of the Barbon and Middleton Fells, where a thickness of just over 1000 feet was measured. This suggests that the Ludlow Series may also be much thinner in this area, and that the Horton Flags and Studfold Sandstone, may be equivalent to the entire Coniston Grit Series, and not just the lower division.

Even though changes in thickness prevent exact correlation with the Barbon and Middleton Fells, it is apparent that this area was affected by the same type of sedimentation, throughout the Silurian. There is the suggestion of a thinning of the strata in this area, which would indicate a shallowing of the trough. The significance of this however, is discussed in chapter 10, which deals with the palaeogeography of the region.

(c) Comparison with the Welsh Borderland and North Wales.

In the Welsh Borderland, the turbidite type of sedimentation is absent, and the succession is considered to be typical of deposition in a shelf sea, at the eastern margin of the Welsh geosyncline. Here, the Wenlock and Ludlow Series consist largely of calcareous shales and limestones. Graptolites vary considerably in their abundance, and are even absent from some of the beds, but are generally sufficient to allow correlation with the basin facies to the west. Recent work by Holland, Lawson and Walmsley (1963), in this area, has established a new classification of the Ludlovian strata, based on shelly faunal assemblages, and to a lesser extent on lithological characteristics. On the basis of the graptolite zones, most of which can be proved in this area, the Silurian strata of the Lake District, and the Barbon and Middleton Fells, are here correlated with those of the Welsh Borderland. This is shown in the composite correlation table (table 3 ), at the end of the chapter.

In the basin facies to the west of the Welsh Borderland, i.e. in Central and North Wales, graptolitic shales and greywackes predominate in the Wenlock and Ludlow Series. Greywackes are especially well developed in the west of the region, in a line running from Central Wales up to the North Wales coast. To the east, they give way largely to shales. The succession and its graptolite zones may be summarised as follows, (Boswell 1949, Cummins 1957, 1959):-

| Formation | Zone | Series |
|---|---|---|
| Lower Ludlow or Wilsonia Grits 1500'- 3000' | M. leintwardinensis | Ludlow |
| | M. tumescens | |
| | M. scanicus | |
| Nantglyn Flags 2000'-3000' | M. nilssoni | |
| | M. vulgaris | |
| | C. lundgreni | Wenlock |
| Denbigh Grits "several thousand" feet thick | C. rigidus | |
| | C. linnarssoni | |
| | C. symmetricus | |
| | M. riccartonensis | |
| | C. murchisoni | |

The lithology of the grits, especially the Lower Ludlow Grits, is very similar to the Coniston Grits. The Nantglyn Flags show a very close resemblance to the banded graptolitic siltstones, and the banded units, in the Coniston Grits and Bannisdale Slates. Although these sediments were derived from a different part of the country, (Cummins 1957 pp.442-443), and in part are older, the sequence of lithologies indicates that they were deposited under identical conditions to the Ludlovian rocks of the Lake District. Deposition from turbidity currents appears to have been a feature of sedimentation in the Silurian geosyncline(s) in many parts of the country. The correlation of the Barbon and Middleton Fells with the Welsh Borderland and North Wales is also shown in table 3 .

(d) <u>Comparison with Ireland</u>

Silurian strata occur widely in northeast and Central Ireland. In the Devilsbit Mountains of County Tipperary, south-west of Dublin, the strata exposed are typical of much of the Irish Silurian. The greywackes, siltstones, and laminated flagstones present in this area, were described by Cope (1955). Although he was not able to map the strata on a lithological basis, owing to the absence of good marker horizons, zoning of the strata by means of the graptolite faunas was carried out. This proved that much of the area was formed of Wenlockian rocks belonging to the C.lundgreni Zone, which has a thickness of at least 5000 feet. The Ludlow Series is approximately 3000 feet thick, 2500 feet of which Cope considered to be in the tumescens Zone, but which may in fact represent the nilssoni-scanicus Zone elsewhere. Approximately 50% of the succession is made up of grits and greywackes, and the other 50% of laminated flagstones, siltstones and mudstones. The laminated flagstones appear to be very similar to the banded graptolitic siltstones of the Barbon and Middleton Fells.

The lithologies in this area of Ireland thus show close similarities to the Barbon and Middleton Fells, indicating that the sediments were probably deposited under similar conditions. Deposition seems to have been more uniform in Central Ireland however, as the graptolite zoning shows coarse and fine sediment to be of almost equal importance, in both the Wenlock and Ludlow Series. The only change seen is a slight decrease in grain size in the higher parts of the Ludlow Series. This may perhaps be compared with the development of the Bannisdale Slate lithology in the Lake District, and shows that increasingly fine grained sedimentation, (although better developed in some areas than others), is a widespread feature of the later stages of the Silurian. Cope considered that the area had closer affinities to the Lake District than North Wales. The correlation may be summarised as follows:-

| Zones | Devilsbit Mountains, Eire. | Barbon and Middleton Fells. |
|---|---|---|
| leintwardinensis | ? ? | U.Bannisdale Slates 900' + |
| tumescens (=leint.incipiens?) | Greywackes and associated Flagstones & Siltstones becoming slightly | L.Bannisdale Slates 1000' approx.<br>Upper Coniston Grits 1680' |
| nilssoni-scanicus | finer towards the top of the succession 3000' | Middle Coniston Grits 1250'<br>Lower Coniston Grits 1500' |
| lundgreni | Greywackes and associated Flagstones & Siltstones 5000' | Brathay or Coniston Flags 1000' |

See also table 3 in which the correlation with other parts of the country is shown.

(e) Comparison with Scotland.

In the Southern Uplands, Silurian strata are restricted to the Llandovery and Wenlock Series. Ludlovian strata are absent, due either to non-deposition, or to later erosion. In the Midland Valley of Scotland however, Wenlockian, and possibly Ludlovian rocks are exposed in a series of inliers, along the southern margin of the Valley. These are:- Lesmahagow, the Hagshaw Hills, the Tinto District, and the Pentland Hills.

In all of these inliers, the Silurian strata consist of shales, siltstones and greywackes, similar to those of the Lake District. In many cases it is difficult to prove the exact age of these sediments, as except for the Pentland Hills, and Tinto District, graptolites are absent, (Lamont 1952, Rolfe 1961). The eurypterid and fish fauna however, is considered to be indicative of a Wenlock and possibly Ludlow age. At the top of the succession in the Lesmahagow inlier, there is a transition through green and yellow beds, into red mudstones and sandstones yielding a typical Downtonian fauna. The faunas of this area have perhaps closer affinities to the Devonian, but the lithologies and sedimentary structures compare with the Silurian strata of the Lake District. Thus it may be concluded that sedimentation was probably of the same type, deposition having taken place from turbidity currents. The position of these inliers is given further consideration in chapter 10, dealing with the palaeogeography of the Silurian.

In the Southern Uplands, as mentioned above, only Llandoverian and Wenlockian strata occur. The Llandovery rocks have been described by Walton (1955), who considered that the predominantly medium, and coarse grained greywackes, were derived from a land area to the north-west.

The Wenlockian strata of the Hawick area are also of the greywacke type. Although the graptolite faunas show these rocks to be older than the Coniston Grits, comparisons with the Lake District, based on lithology and sedimentary structures, show many similarities, indicating that deposition took place from turbidity currents. The Wenlockian strata of this area are of great importance in the discussion of the petrography and provenance of the Coniston Grits, in the following chapters. For this reason the succession described by Warren (1964), is given below.

| Divisions | Lithologies | Zones |
|---|---|---|
| Caddroun Burn (Upper) Beds (Lower) | Greywackes, siltstones and Graptolitic Shales 5000' | *C. lundgreni*, *C. rigidus* (Upper); *C. linnarssoni*, *C. symmetricus* (Lower) |
| Penchrise Burn Beds | Greywackes, siltstones and graptolitic shales 1500' | *M. riccartonensis* |
| Shankend Beds | Greywackes, mudstones and graptolitic shales 2000' | *M. riccartonensis* / *C. murchisoni* |
| Stobs Castle Beds | Greywackes, mudstones, red mudstones and graptolitic shales 4500' | *C. murchisoni* |
| Hawick Rocks | Flaggy greywackes and red mudstones, shales 12000' | Wenlock? (No fossils) |

This shows that (apart from the Hawick Rocks, whose position is uncertain), there are 13000 feet of Wenlockian strata in this area. The infilling effect of such a thickness of sediment, and its significance in the Silurian palaeogeography, is considered in chapter 10 . The only direct correlation possible between this area and the Barbon and Middleton Fells, is between the Upper Caddroun Burn Beds, and the Brathay Flags, which both fall within the C. lundgreni Zone. This correlation which shows a contrast between coarse sedimentation in the Southern Uplands, and fine sedimentation in the Lake District, is summarised in table 3 .

## Conclusions.

Correlation of the Silurian strata of the Barbon and Middleton Fells with other parts of the country, by means of the graptolite zones, shows many close similarities. The lithological types of the same age, developed in the Lake District, Horton-in-Ribblesdale, North Wales, Central Ireland, and the Midland Valley of Scotland, are almost identical. The sediments deposited in these areas are, in some cases, derived from different land masses, but the similarity of the rock types produced, indicates that the manner of deposition must have been similar. Only in the Welsh Borderland is there any contrast, where the calcareous sediments are considered to indicate deposition in shallower water. The remainder of the Silurian strata are considered to have been deposited from turbidity currents, which were thus an extremely widespread feature of Silurian sedimentation.

In the Southern Uplands, the development of coarse sedimentation in the Llandovery and Wenlock Series, at a time when fine sediment was being deposited in the nearby Lake District, is important from the palaeogeographical aspect. This is considered further in chapter 10.

Table 3 summarises the correlation of the Wenlockian and Ludlovian strata in the areas considered above.

| System | Series | Graptolite Zones (Rickards 1963 and this study.) | Barbon and Middleton Fells: Present Study | Howgill Fells: Rickards (1963) | Lake District: Marr(1916) Llewellyn(1960)Norman (1961) | Welsh Borderland: Holland et al (1963) | North Wales: Boswell(1949) Cummins (1957, 1959) | Central Ireland: Cope (1955) | Southern Uplands: Warren(1963) | Graptolite Zones (Elles and Wood 1901-18.) |
|---|---|---|---|---|---|---|---|---|---|---|
| SILURIAN | LUDLOVIAN | | | | Kirkby Moor Flags | Whitcliffe Beds | Lower Ludlow or Wilsonia Grits | | | |
| | | M. leintwardinensis leintwardinensis | Upper Bannisdale Slates | Bannisdale Slates | Bannisdale Slates | Leintwardine Beds | | | | M. leintwardinensis |
| | | M. leint. incipiens | Lower Bannisdale Slates | | Lower part = Tottlebank Transition Formation of Norman | Bringewood Beds | | Greywackes, Flagstones and Siltstones | | M. tumescens |
| | | | | | | Upper Elton Beds | | | | |
| | | P. nilssoni - -M. scanicus | Upper Coniston Grits | Upper Coniston Grits | Upper Coniston Grits = Yewbank Sandstone Formation of Norman | Lower and Middle Elton Beds | Nantglyn Flags | | | M. scanicus |
| | | | Middle Coniston Grits | | Sheerbate Flags =Salthouse Mudstone Formation of Norman | | | | | M. nilssoni |
| | | | Lower Coniston Grits | Lower Coniston Grits | Lower Coniston Grits = Poolscar Sandstone Formation of Norman; Middle & Upper Coldwell Beds | | | | | M. vulgaris |
| | Wenlockian | C. lundgreni | Brathay Flags | Wenlock Series Stage 4 | Lower Coldwell Beds | Wenlock Limestone | | Greywackes,Flagstones,etc | Caddroun Burn Beds | C. lundgreni |
| | | C. ellesi | | | Brathay Flags | | Denbigh Grits | | | C. rigidus |
| | | C. rigidus | | Wenlock Series Stage 3 | | | | | | C. linnarssoni |
| | | M. flexilis belophorus | | | | | | | | C. symmetricus |
| | | M. antennulatus | | | | | | | | |
| | | M. riccartonensis | | Wenlock Series Stage 2 | | | | | Penchrise Burn Beds | M. riccartonenis |
| | | | | | | | | | Shankend Beds | |
| | | C. murchisoni | | | | | | | Stobs Castle Beds | C. murchisoni |
| | | C. centrifugus | | Wenlock Series Stage 1 | | | | | | |
| | | -C. insectus | | | | | | | | |
| | Llandoverian | | | Stockdale Shales | Stockdale Shales | | | | | |

Table 3. The correlation of Silurian strata between North-west England, North Wales, Ireland and Scotland.

# CHAPTER 5

## THE PETROGRAPHY OF THE COARSE GRAINED SEDIMENTS

### (1) Introductory Statement

In Chapter 3, page 31 , the main lithological types present in the Barbon and Middleton Fells were briefly mentioned, before the description of the Stratigraphical Succession. These are the greywackes, banded graptolitic siltstones, banded units, and, in addition, the mudstone partings to the graded greywacke beds. In this chapter, the petrography of the greywackes is described in detail. The other finer sediments are considered together in chapter 7 .

### (2) The Definition and History of the term "Greywacke"

The term 'greywacke' has long been a source of confusion, so much so in fact, that many authors have advocated the abandonment of the term. Originally, the word GRAUWACKE was coined by Werner to describe a group of dark, rather coarse grained rocks, derived essentially from the breakdown of basic igneous material, (Boswell, 1960, p.154). This word was imported and anglicised by Jameson (1808), in order to give a name to some of the British Lower Palaeozoic rocks, which were poorly sorted and contained a variety of dark coloured constituents. In many cases the word appeared to be used in a stratigraphical, rather than petrological sense, and many of these greywackes had little resemblance to the German types from which the word was borrowed.

In 1936, the American Committee on Sedimentation proposed the following definition:- "A sandstone composed of 33% or more of easily destroyed minerals and rock fragments derived by rapid disintegration of basic igneous rocks, slates and dark coloured rocks. It may or may not be intensely indurated or metamorphosed". This definition was still rather vague, and further confusion has arisen. In some cases there has been a tendency to define greywackes merely from the fact that they contain graded bedding, or sole markings. Boswell (1960), however, considers that greywackes should be defined from the following criteria:-

(1) Grain size ranging through conglomerate and breccia to sandstone.

(2) Poor sorting of the grains, with much fine matrix.

(3) A remarkable variety of rock and mineral fragments.

(4) Shape of the grains predominantly angular to sub-angular.

This is similar to the definition proposed by Pettijohn (1957), which may be summarised as a coarse poorly sorted rock containing many rock fragments, and set in a fine grained matrix. A further paper by Pettijohn (1960), on the definition of the term, points out that Mattiat (1960), who worked on the Kulm greywackes of the Harz Mountains, where the term was first used 160 years ago, defines the average greywacke as having the following composition:-

| | |
|---|---|
| Quartz | 27% |
| Felspar | 19% |
| Interstitial Material | 21% |
| Rock Fragments | 30% |
| Heavy Minerals | 2% |
| Rare Minerals | 1% |

As will be shown in the following descriptions, the Coniston Grits, especially in terms of grain size, are, with only a few exceptions, somewhat atypical of the above definitions. The percentage of rock fragments and felspar is also smaller, and the proportion of quartz greater. There is, however, no other simple term which gives an indication of the general nature of the Coniston Grits in the field. For this reason the word greywacke is used as a general descriptive term. Although the word is used somewhat loosely, it is also useful in that it retains the terminology used by previous authors to describe these rocks. The exact classification of the Coniston Grits in terms of mineralogy, and the origin of the matrix - whether primary or secondary, - is discussed later in this chapter, after the description of the constituent minerals.

(3) <u>The Petrography of the greywacke units in the Coniston Grits and Bannisdale Slates</u>.

The petrographical descriptions of the greywackes following, are based on the modal analysis of 26 thin sections.

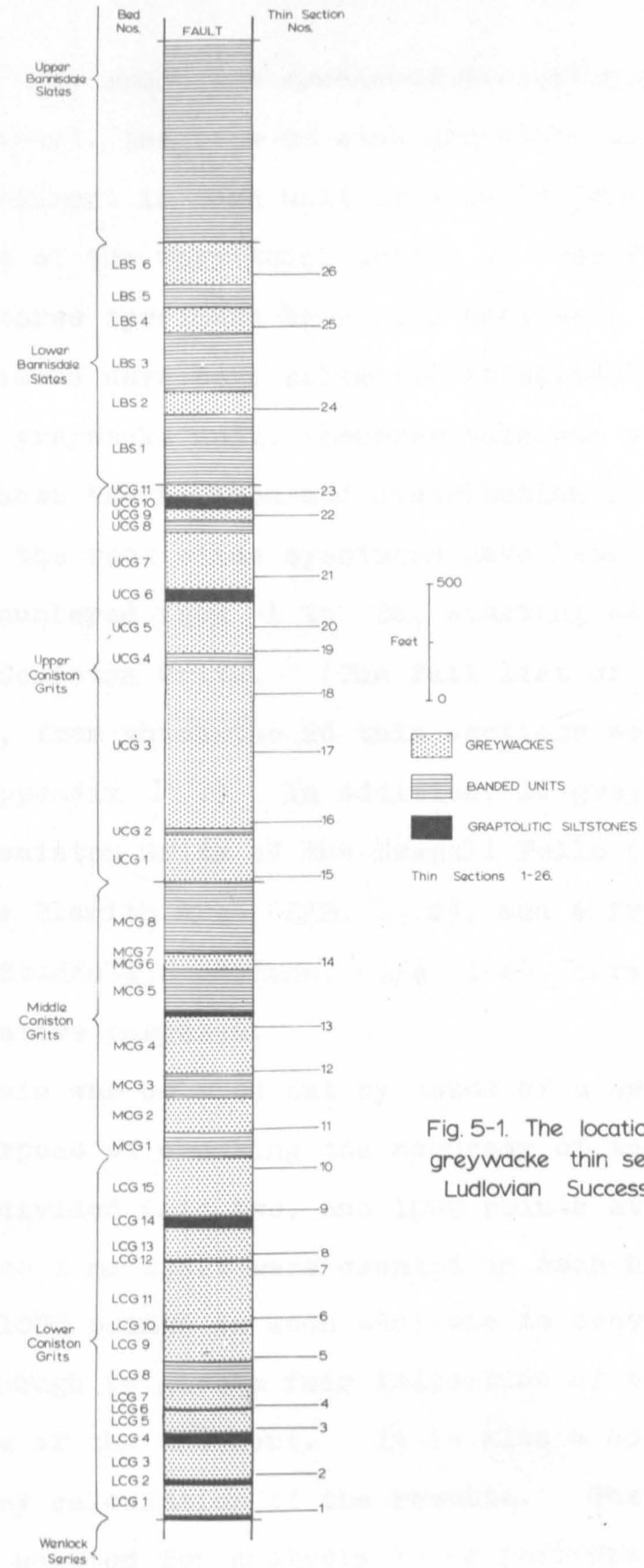



Fig. 5-1. The location of the 26 greywacke thin sections in the Ludlovian Succession.

These have been made from specimens collected at, (or as near to as possible), the base of each greywacke unit, as the coarsest sediment in each unit is usually found at this level. In the case of the very thick units, of over 200 feet, two and sometimes three specimens have been analysed. The second and third specimens have been collected at suitably coarse horizons within the greywacke unit, wherever this was possible. Figure 5-1 shows the horizon and distribution of the localities from which the rock slide specimens have been collected, and which are numbered from 1 to 26, starting at the base of the Lower Coniston Grits. (The full list of the 125 sampling localities, from which the 26 thin sections were selected, is shown in Appendix I .) In addition, 12 greywacke specimens from the Coniston Grits of the Howgill Fells (S/H. 1-12), 10 from the Blawith area (S/B. 1-10), and 4 from the Horton Flags and Studfold Sandstone, (S/A. 1-4), have been analysed for comparative purposes.

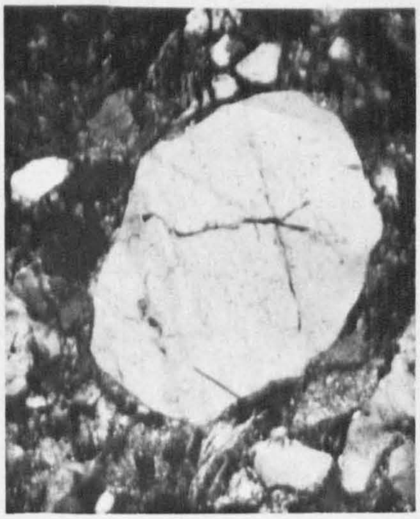
Analysis was carried out by means of a Swift Point Counter. For the purpose of checking the accuracy of the results, each slide was divided into two, and 1000 points at 1/6 mm intervals, in traverses 1 mm apart were counted in each half. The figure of 1000 points in each analysis is considered to be adequate enough to give a fair indication of the true composition of the sediment. It is also a convenient number for the easy calculation of the results. The grouping of components adopted for analysis is as follows:- Quartz,

TABLE 4 . The mean percentages of the important constituent minerals in the 26 greywackes analysed from the Barbon and Middleton Fells.

| | % Quartz | % Felspar | % Rock Fragments | % Carbonate | % Matrix incl Mica | % Others |
|---|---|---|---|---|---|---|
| 26 Analyses | 47.5 | 10.7 | 5.7 | 6.7 | 28.6 | 0.8 |

Felspar includes k-felspar and plagioclase, "others" includes heavy and opaque minerals. See text for full description.

(A)



(B)

(C)

FIG. 5-2. Quartz Grains. All Crossed Nicols, ×50.

(A) Slide No. 2.

(B) Slide No. 14.

(C) Slide No. 18.

orthoclase, plagioclase, heavy and opaque minerals, rock fragments, and matrix, which is sub-divided into muscovite, chlorite-sericite, and carbonate. The results and accuracy of the analyses are summarised in table 4, and are calculated to only 1 decimal place, to avoid giving a false impression of the accuracy. The full analysis of each thin section is shown in Appendix III A, along with re-analyses of some specimens, in order to check the statistical significance of the results.

The composition of the sediments varies little throughout the succession. Rock fragments in appreciable quantity, however, are found only in the coarser sediments low down in the Series. In the Howgill Fells, a thin development of coarse greywacke, known as the Winder Grit, is also found near the top of Rickard's division of Upper Coniston Grits. It is these coarse rocks which are of value in deducing the provenance of the sediments, and on which attention has been concentrated. As the mineralogy shows little change throughout the succession, the petrography is considered as a whole, except for the descriptions of the rock fragments, which are based on the coarser specimens.

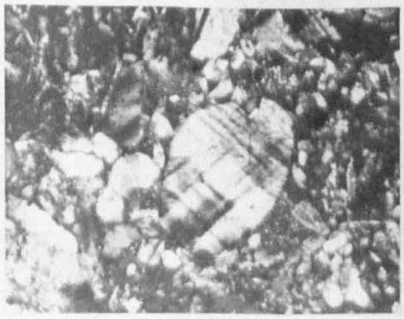
(a) Quartz (See figure 5-2)

This is the most abundant mineral. The percentage varies from 25% in the coarser sediments which contain a high proportion of rock fragments, up to about 58% in the silts, where rock fragments are few. Inclusions in quartz are common, and it is rare to find completely clear grains.

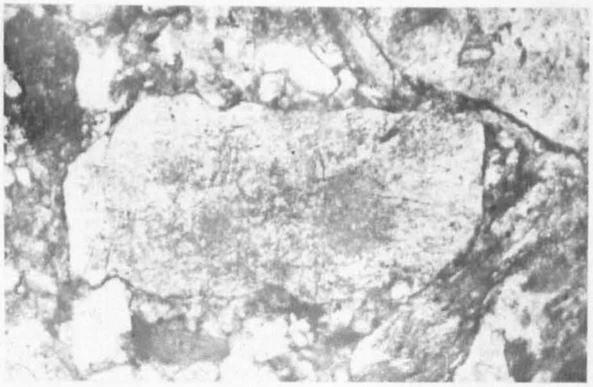
(A)

(B)

(C)



(D)



(E)

FIG. 5-3. Felspar Grains. All Crossed Nicols, × 50

(A) Oligoclase fragment. Slide No. 1
(B) Albite fragment. Slide No. 1
(C) Orthoclase fragment. Slide No. 9
(D) Microcline fragment. Slide No. 3
(E) Altered orthoclase fragment. Slide No. 15

The most common included minerals are zircon, apatite, tourmaline and rutile. The most abundant type of quartz grains are those containing lines of minute unidentifiable fragments, giving the mineral a finely peppered appearance. The shape of the grains is generally irregular, but roughly equi-dimensional, although a number of grains with a marked longitudinal outline also occur. Many of the latter show undulose extinction, which may perhaps indicate a metamorphic origin, but as Blatt and Christie (1963), point out, this is of very limited value in determining the origin of quartz. Another variety of elongated grain extinguishes in distinct patches, showing the grains to be made up of several crystals with varying optical orientations. These are considered to represent vein quartz. Mackie (1896), Gilligan (1919) and Bokman (1952), described how the inclusions and shape of the grains could be used to distinguish other varieties of quartz. These methods indicate that much of the quartz is of igneous origin.

(b) Felspar

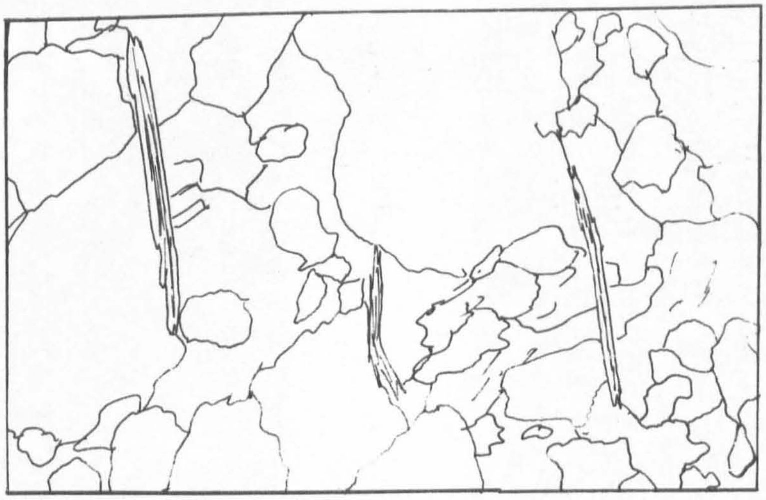
Felspar is common, and can form up to 16% of the rock, though generally around the 10% level. Orthoclase is by far the most abundant variety, (see figure 5-3), and is generally sericitised or kaolinised to a greater or lesser degree. Replacement of orthoclase by calcite is common. Microcline occurs throughout the stratigraphic succession (see figure 5-3), but is very rare, each thin section containing usually only one or two grains. Plagioclase is rare compared with orthoclase, and is usually less than 1% of the rock. The composition is generally in the oligoclase range, although a few grains of more sodic and calcic composition do occur.

(c) Micas

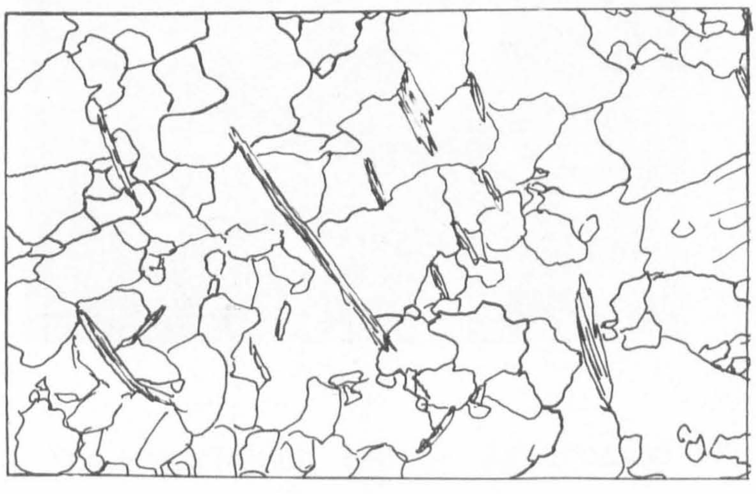
Muscovite, which is included in the matrix in table , is abundant in the fine sediments (see figure 5-4), where it may form up to 20% of the rock. In the coarse greywackes, however, it is less than 3%. The length of the muscovite flakes is extremely variable, but there appear to be two main types, some are long and thin, and others short and thick. Many of the long thin micas are bent by post depositional compression, which indicates that at least some of the mica has a detrital origin. By comparison, biotite is very rare, each thin section containing perhaps only 3 or 4 flakes. It is apparent, however, that some has been bleached or reduced to chlorite by secondary alteration. Chlorites form much of the interstitial matrix in the sediments, but are also found rarely as larger bladed flakes of penninite, probably of secondary origin.

(d) Heavy Minerals

Heavy Minerals are seen only occasionally in thin sections, only 3 or 4 grains being seen in each modal analysis. The most common types are zircon, garnet apatite and the opaque minerals, which consist largely of pyrite, magnetite, ilmenite and leucoxene. Complete heavy mineral analyses carried out



(A)



(B)

Fig. 5-4. Sketch of muscovite flakes, X 40
(A) Lower Coniston Grits.
(B) Middle Coniston Grits.

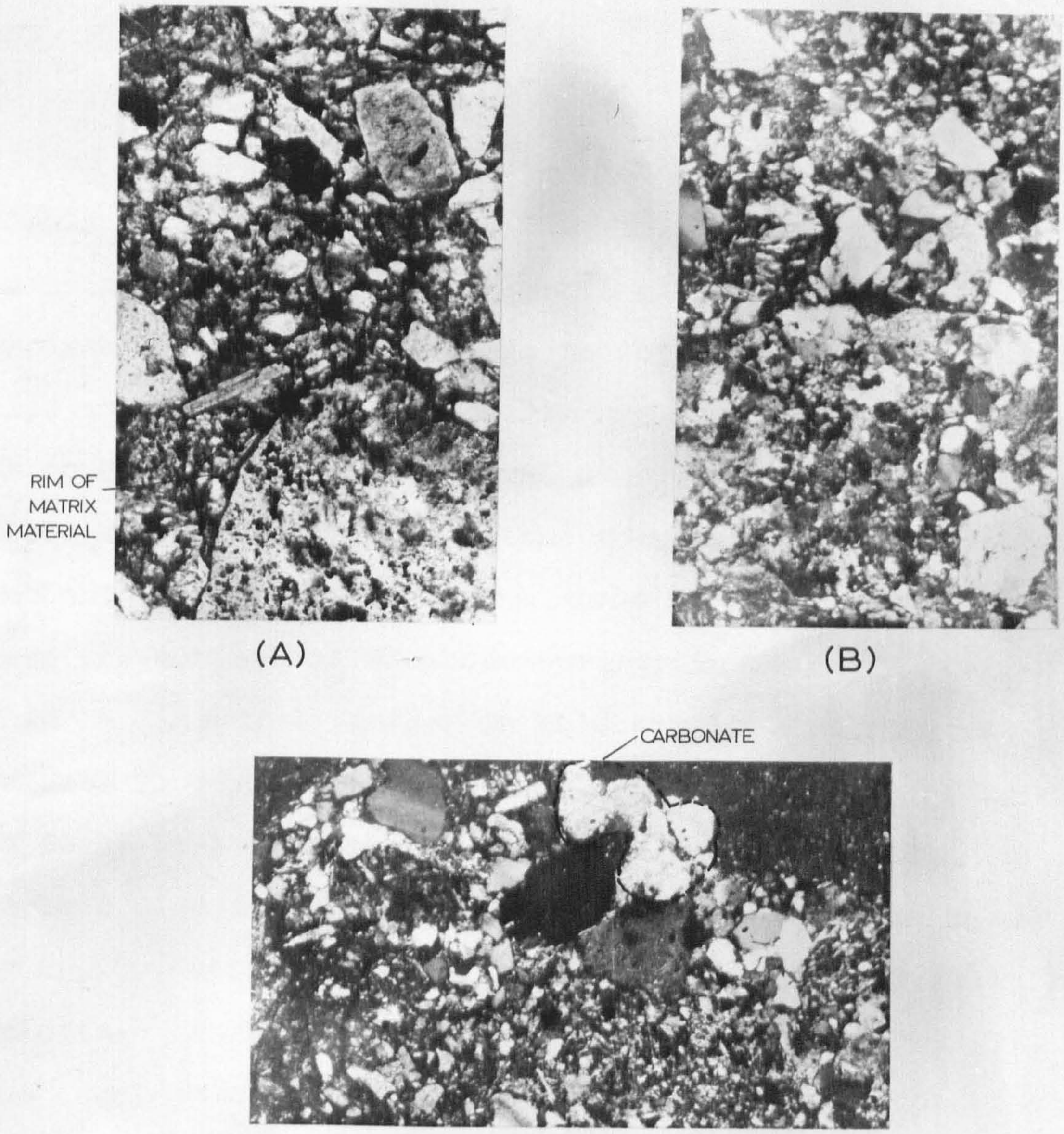



FIG. 5-5. The interstitial Matrix. All crossed Nicols, X35
(A) Rim of chloritic material around a chert fragment.
(B) The general "muddy" nature of the greywackes.
(C) Carbonate, a common constituent of the matrix.
All from the Lower and Middle Coniston Grits.

by bromoform separations are described below, paragraph 3g.

(e) Matrix, (See figure 5-5.)

Including mica and carbonate, the matrix forms about 35% of the rock. Apart from these minerals it is made up of highly altered felspathic fragments, along with chlorite sericite, and much unidentifiable clayey material. Silica is intergrown with the matrix to form a hard non-porous rock. Also included within the matrix are finely divided fragments of quartz, and other unaltered minerals with a grain size of 0.004 mm or less. Some of the matrix is thus depositional. The origin of the matrix as a whole in greywackes has, however, been the subject of much controversy in recent years, and this is discussed further in this chapter, on page 102. Calcite is very common, especially in the finer rocks, where it forms an important proportion of the matrix, and can replace almost every mineral in the rock. Dolomite may also occur, but cannot be distinguished with certainty from the calcite. Much of the carbonate is of secondary origin, but the development of thin limestone beds at certain horizons, as for example at the base of the Coniston Grits, suggests that some of the calcite is probably primary.

(f) Rock Fragments

Rock fragments in appreciable quantity are restricted to the beds with a mean grain size of over 0.05 mm, (see chapter 6 ). The percentage rises with increasing grain size, to a maximum

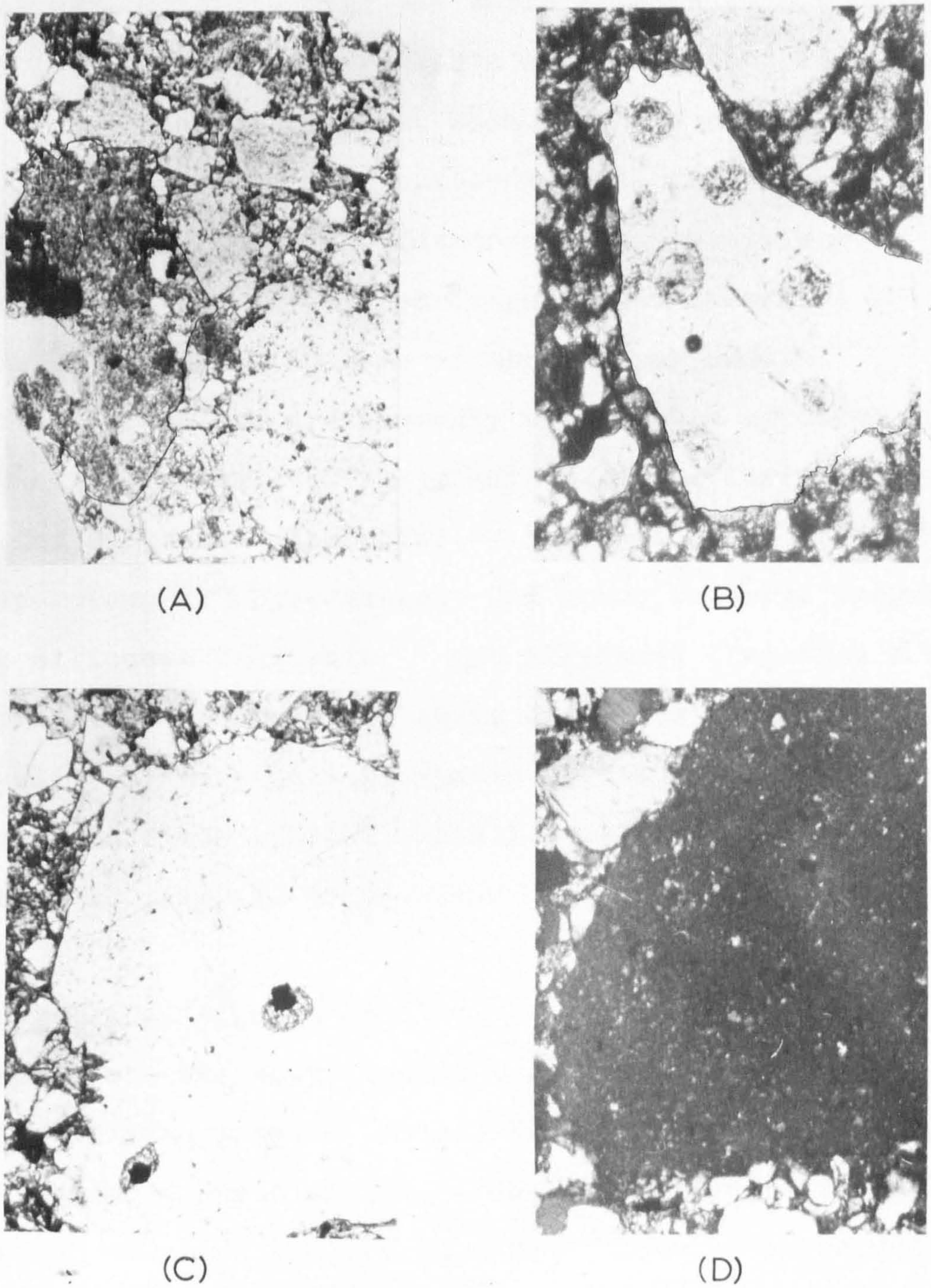



FIG. 5-6. Chert fragments from the Winder Grit.
(A),(B),(C), with Radiolarian remains ×50, plane polarised light.
(D) Chert fragment under crossed nicols × 50.

of about 46%, although over the whole succession the average is only 5.7%. Volcanic fragments are by far the most abundant, and include spilite, soda trachyte and rhyolite. Plutonic igneous rocks are represented sparingly by granite and granophyre fragments. Metamorphic fragments are extremely rare, but occasional fragments of quartzite and mica schist are found in some of the coarser beds. Sedimentary fragments are commonly represented by chert and siltstone. Fragments of shale and siltstone derived from within the sediments also occur. The rock types occur in the proportions of approximately 50% basic volcanic fragments, and 50% siliceous fragments. The siliceous fragments are made up of approximately 60% chert and siltstone, and 40% rhyolite. Only an approximate figure can be given, as the chert and finer grained varieties of rhyolite are easily confused, and thus the proportions may vary slightly either way.

(i) Cherts (See figure 5-6)

Cherts are the most important sedimentary fragments, and are very fine grained, almost cryptocrystalline and dark coloured under crossed nicols. Occasional fragments contain radiolarian remains, usually in a poor state of preservation, but in some the central capsules can be distinguished (see figure 5-6). These fragments are important in deducing the provenance of the sediments, as some of the forms compare closely with those described by Hinde (1890), from the

Scottish Ordovician.

(ii) Siltstones (See figure 5-7)

Calcareous siltstone fragments are common in the coarser grained sediments, in addition to indigenous fragments of shale and fine greywacke.

(iii) Spilites (See figure 5-8)

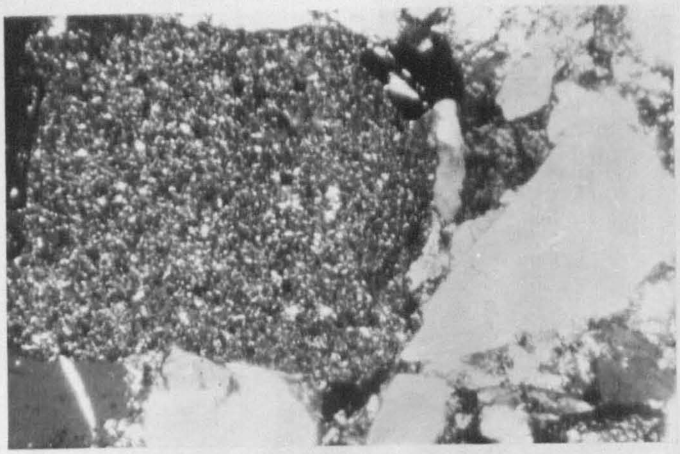
Spilite fragments are the most important basic volcanic group. Two main varieties can be distinguished, one in which the albite laths show a spherulitic texture, and the other in which the felspar is flow orientated. The interstitial ground mass is formed largely of chlorite and magnetite. The fragments are usually large in size, (up to 2 mm across), and are angular and elongate in outline.

(iv) Soda-trachytes (See figure 5-9)

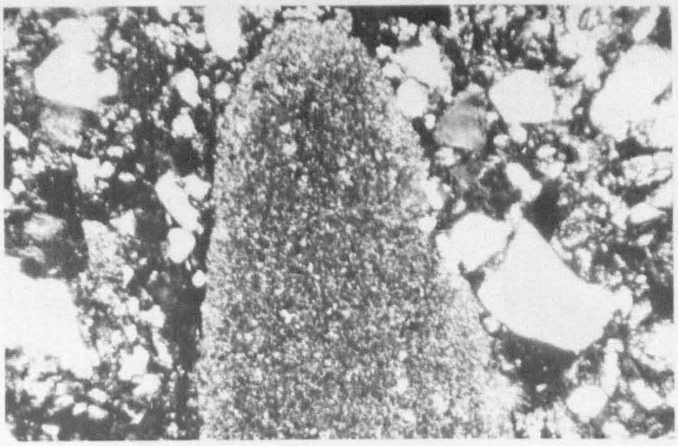
Soda-trachytes are also common, and are made up of phenocrysts of sanidine and albite set in a fine grained chloritic ground mass. Some fragments with a similar texture to the soda-trachyte contain plagioclase with a rather higher calcium content, in the andesine range, and these are referred to as andesites. They are not common, however, and such fragments are much more variable in size, and generally have a somewhat square or equi-dimensional outline.

(v) Granites and Granophyres (See figure 5-10)

Acid igneous rocks are also represented in the Coniston Grits. Coarse grained material is, however, rare, and is usually restricted in each slide to one or two fragments of

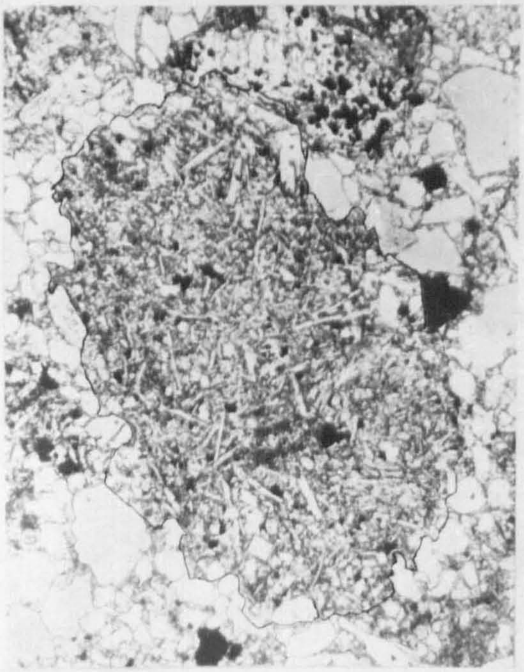


(A)



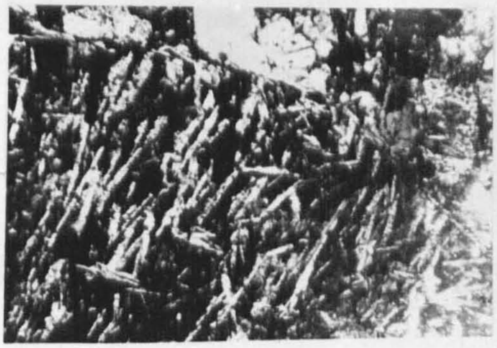
(B)

FIG. 5-7. Siltstone fragments. Crossed Nicols ×40
(A) From the Winder Grit.
(B) From the Lower Coniston Grits. Slide 1.



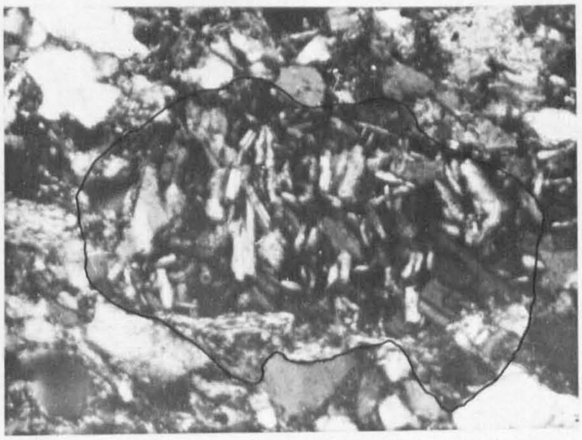
(A)

(B)

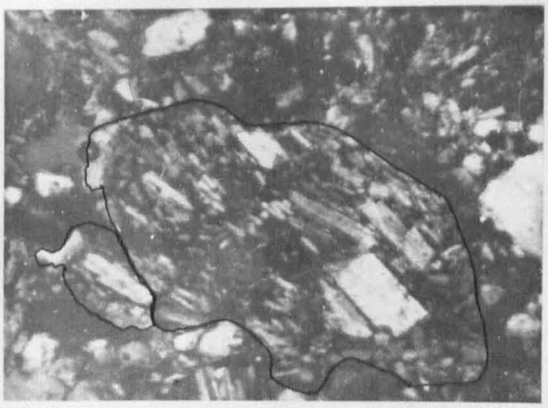


(C)

FIG. 5-8. Spilite fragments from the Coniston Grits.
(A) ×50 Plane Polarised light, Winder Grit.
(B) ×50 Crossed Nicols, " " .
(C) ×30 Plane Polarised light, 1st. greywacke L. Con. Grits.



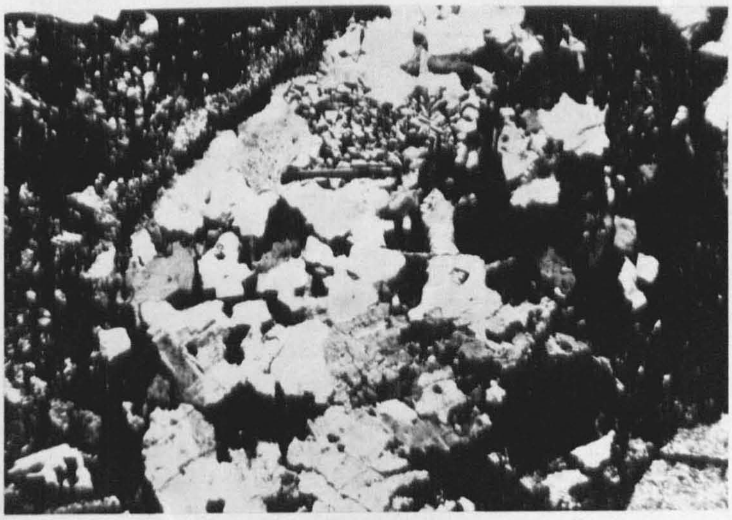
(A)



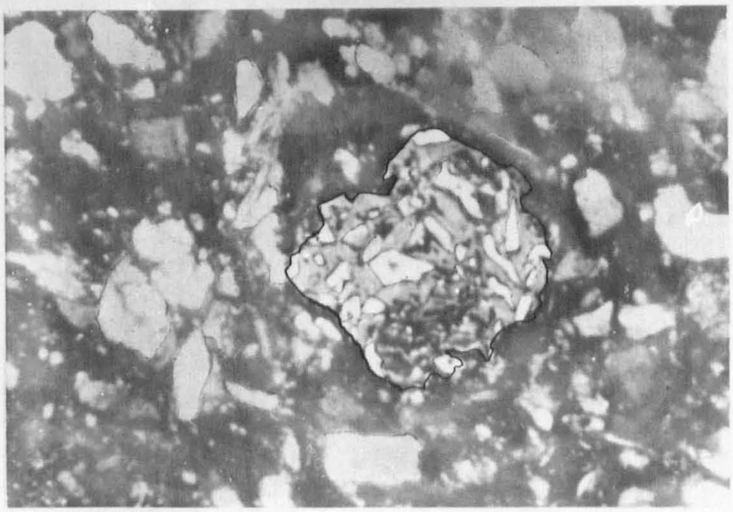
(B)

Fig.5-9. (A) Soda trachyte fragment from the Winder Grit. Crossed nicols, x 50

(B) Soda trachyte fragment from the Lower Coniston Grits displaying marked porphyritic and trachytic textures.
Slide No.1, crossed nicols, x 50



(A)



(B)

Fig. 5-10.(A) Granitic fragment, Winder Grit, × 40

(B) Granophyre fragment. L Coniston Grits, Slide 2. × 50 intergrown quartz and orthoclase, forming a granophyric texture.

(vi) Rhyolites (See figure 5-11)

Rhyolites on the other hand are quite abundant, and usually pinkish in colour, and form a series ranging from cryptocrystalline up to microgranitic. The rhyolite lavas are coarsely crystalline and contain quartz, orthoclase, and minute plagioclase crystals, along with sericite formed from the alteration of orthoclase. Ferro-magnesian minerals are almost absent. At the fine grained end of the series are devitrified glassy fragments derived from the ground mass of the rhyolites. They are typically composed of a mosaic felsitic ground mass, and grade into the coarser varieties. The glasses often contain pools and micro-veins of quartz. The very fine grained dark coloured types are easily confused with the chert fragments, some of which also contain pools of quartz. Careful examination however, shows that most of the glasses can be distinguished by the minute laths of plagioclase which they contain.

(vii) Metamorphic Fragments (See figure 5-12)

The very rare metamorphic fragments include several elongated pieces of brown mica-schist, rich in garnet, chlorite and quartz. These appear to be restricted mainly to the coarsest beds, where a fine grained variety of quartzite, in which the individual grains are completely welded together, also occurs sparingly.

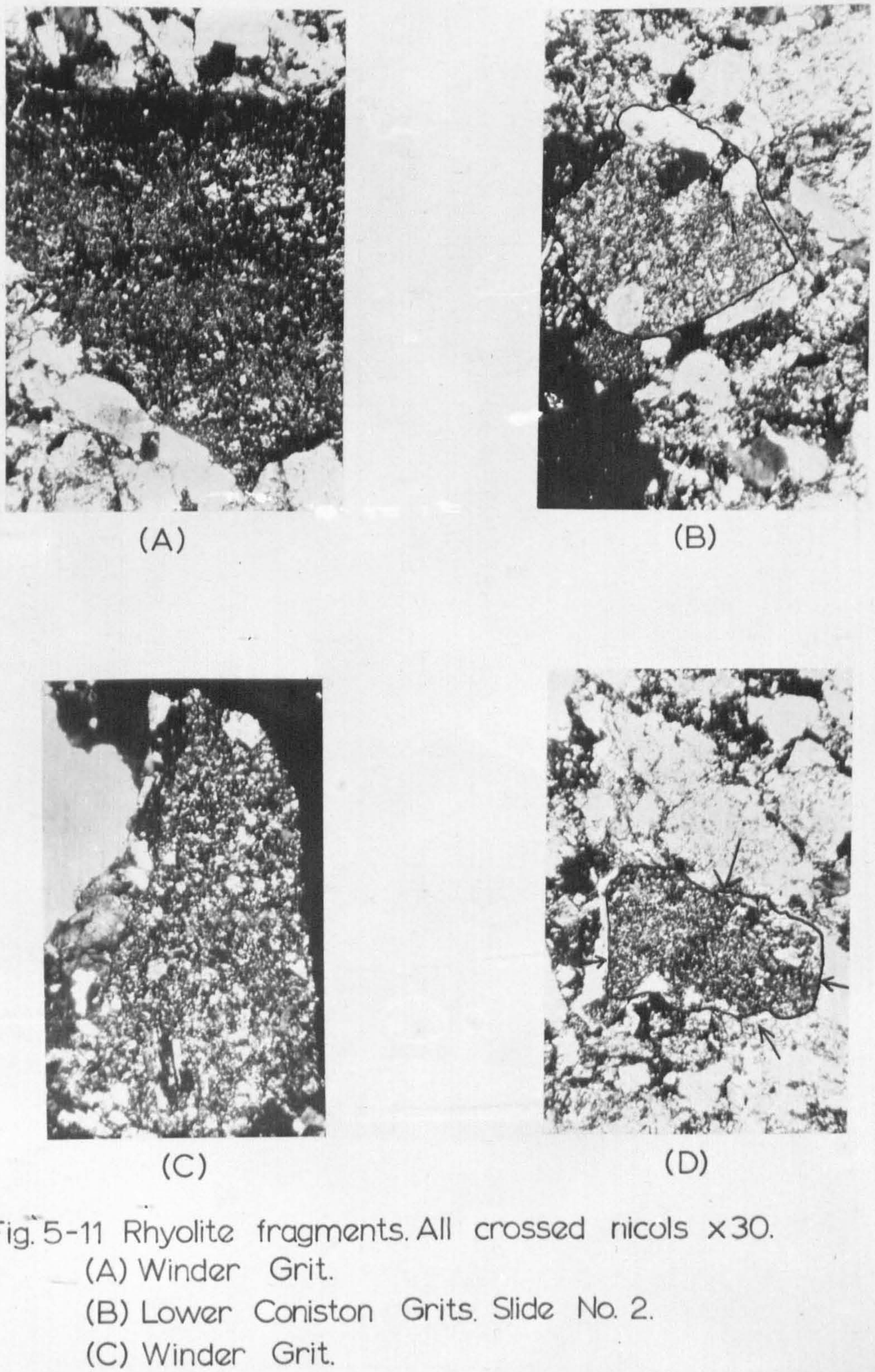
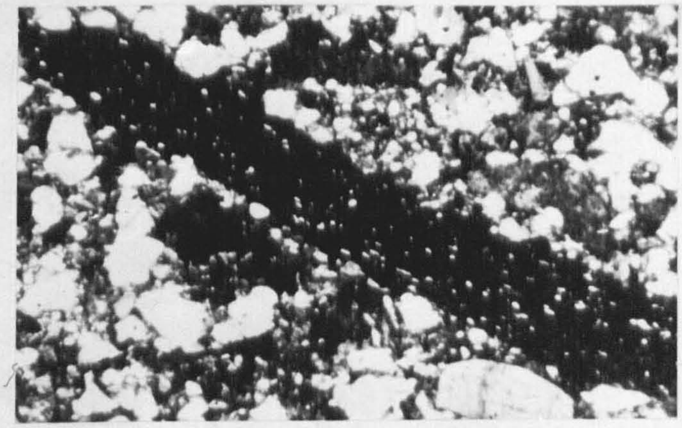
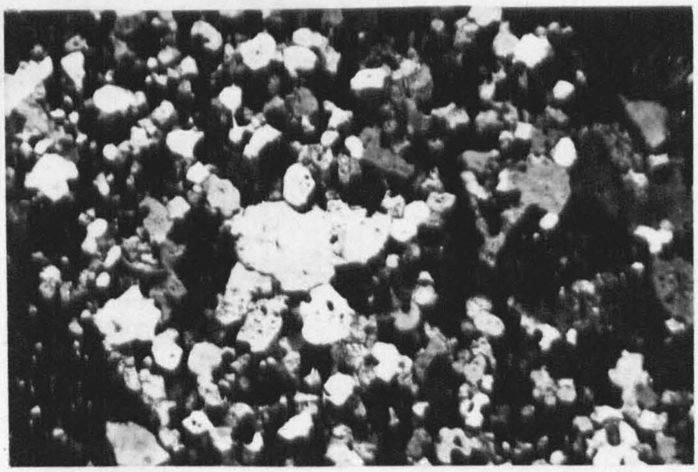



Fig. 5-11 Rhyolite fragments. All crossed nicols ×30.
(A) Winder Grit.
(B) Lower Coniston Grits. Slide No. 2.
(C) Winder Grit.
(D) Lower Coniston Grits. Slide No. 1.



(A)



(B)

Fig. 5-12.(A) Schist fragment, crossed nicols, ×40.
(B) Quartzite fragment, crossed nicols, ×40.
from the Winder Grit.

(g) Heavy Mineral Separations (See also paragraph 3d, page 94 )

The heavy minerals have been examined only qualitatively. Originally it was hoped to carry out a quantitative study, with a separation on every lithological unit throughout the succession. Difficulties however, in the crushing of the specimens, and the clearing of the grains after separation, seriously delayed the work. The heavy mineral analysis has thus been restricted to 15 separations spaced over the entire succession. Warren (1964, personal communication), suggests that a survey of this kind is probably quite adequate, as quantitative heavy mineral analyses carried out by him in the Southern Uplands, provided very little additional information over preliminary qualitative surveys. The crushing techniques which have to be used on greywackes, also introduce inaccuracies which would tend to reduce the value of quantitative analyses. Soft minerals for example may be destroyed.

The technique used in the present work was largely that described by Doeglas (1940). Specimens of about 500 gms. in weight were crushed to pass through a 60 mesh sieve, sieving the sample frequently to avoid undue crushing. (Due to the silicified nature of the rock, disintegration techniques proved useless.) The fraction held on a 120 mesh sieve was treated with warm 25% hydrochloric acid. After washing, the sample was panned to remove the excess of light fragments, and then placed in a separating funnel with bromoform (S.G. 2.89). The heavy minerals obtained, which represented between ½% and 1% of the original rock by weight, were then dried and mounted in Canada balsam. The results which are summarised in Appendix IV , revealed no significant change in the heavy mineralogy throughout the succession.

Apatite, zircon, rutile, garnet, biotite, tourmaline, and opaque iron minerals were obtained from almost all of the samples. (See figure 5-13.) Of the non-opaque minerals, pinkish zircons and garnets are the most abundant. Tourmaline is rare. Opaque minerals are very common, and consist largely of pyrite, magnetite, ilmenite and leucoxene.

(i) Zircon

Two varieties of zircon have been recognised. The first and most common type consists of purple, rounded or spherical grains, which are usually clear. The second type is colourless or pink, and generally angular or sub-hedral in outline. This type is often clouded by minute opaque inclusions, which cannot be positively identified.

(ii) Apatite

This mineral occurs usually as small rounded grains which are often corroded around the edges, and which display cleavage partings on some of the faces. Corrosion is probably due to the treatment with acid during processing.

(iii) Rutile

Rutile is fairly common, and occurs in small rounded to angular grains which vary in colour from yellowish to dusky red. These may in fact represent two types, as the yellow grains are more frequently angular in outline, whereas the red grains are often rounded.

(iv) Garnet

Garnet is common, and some of the grains reach a size of ½ mm across. The grains are usually pink in colour, but some solourless and yellowish varieties have been observed. A rounded or corroded outline with replacement by calcite is the most common appearance of this mineral.

(v) Biotite

Most of the separations contain numerous flakes of biotite. The mineral is usually deep brown in colour, but is often colourless around the edges, or replaced by chlorite. Some flakes of white mica have also been observed, and have probably been brought down by a slight increase in Specific Gravity, caused by impurities within the mineral.

(vi) Tourmaline

Tourmaline is rare, but occurs usually as bluey green or yellowish euhedral grains. In some cases minute needle like inclusions with a parallel arrangement are developed within the grains.

(vii) Opaque Minerals

(a) Pyrite

This is the most common opaque mineral, and occurs usually as small cubic grains with a yellowish lustre under

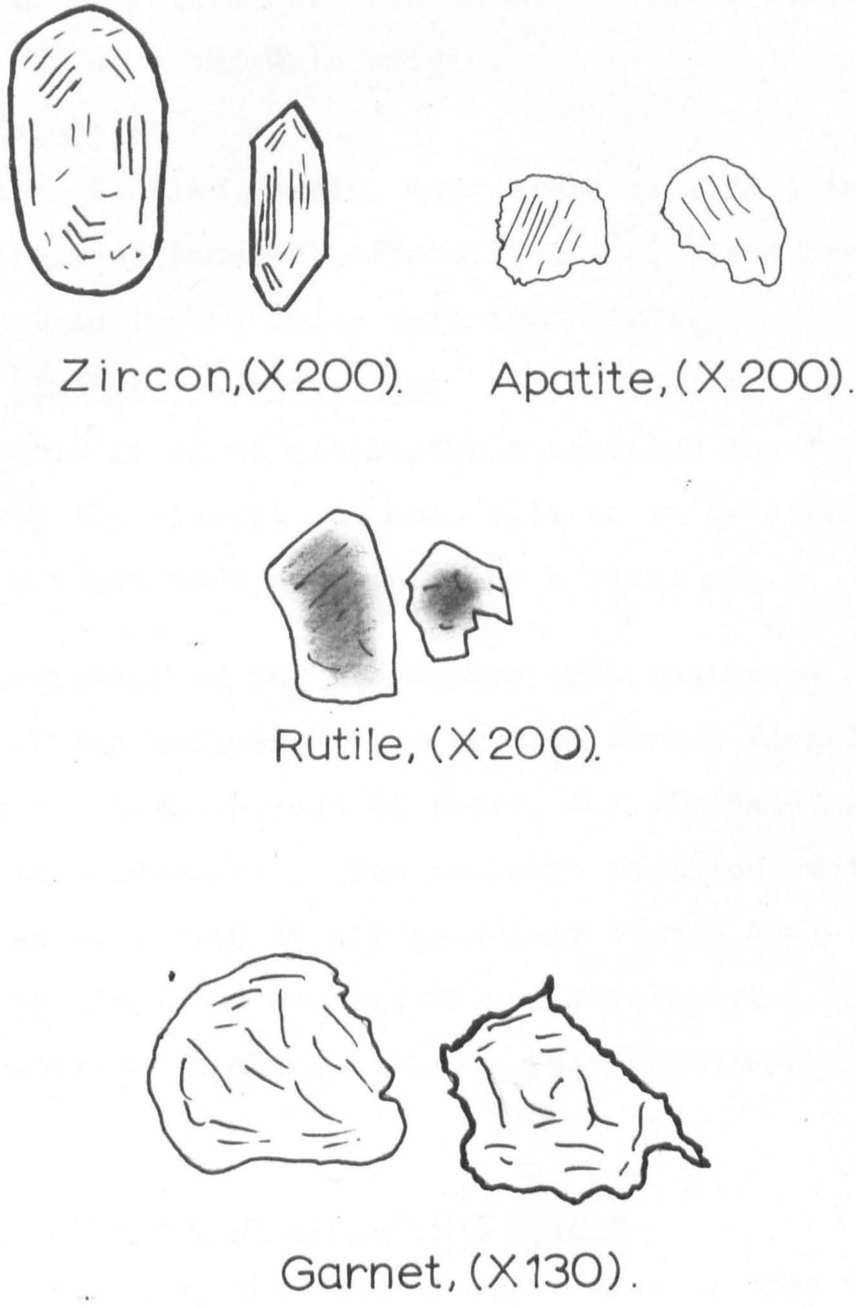



FIG. 5-13. Some of the more common Heavy Minerals.

reflected light. Rounded spherulitic aggregate also occur, and appear to be rather more common in the finer sediments. It is probably of authigenic origin.

(b) Magnetite

Magnetite is also common, and occurs as both irregular grains, and almost euhedral crystals, all of which display a black metallic lustre under reflected light.

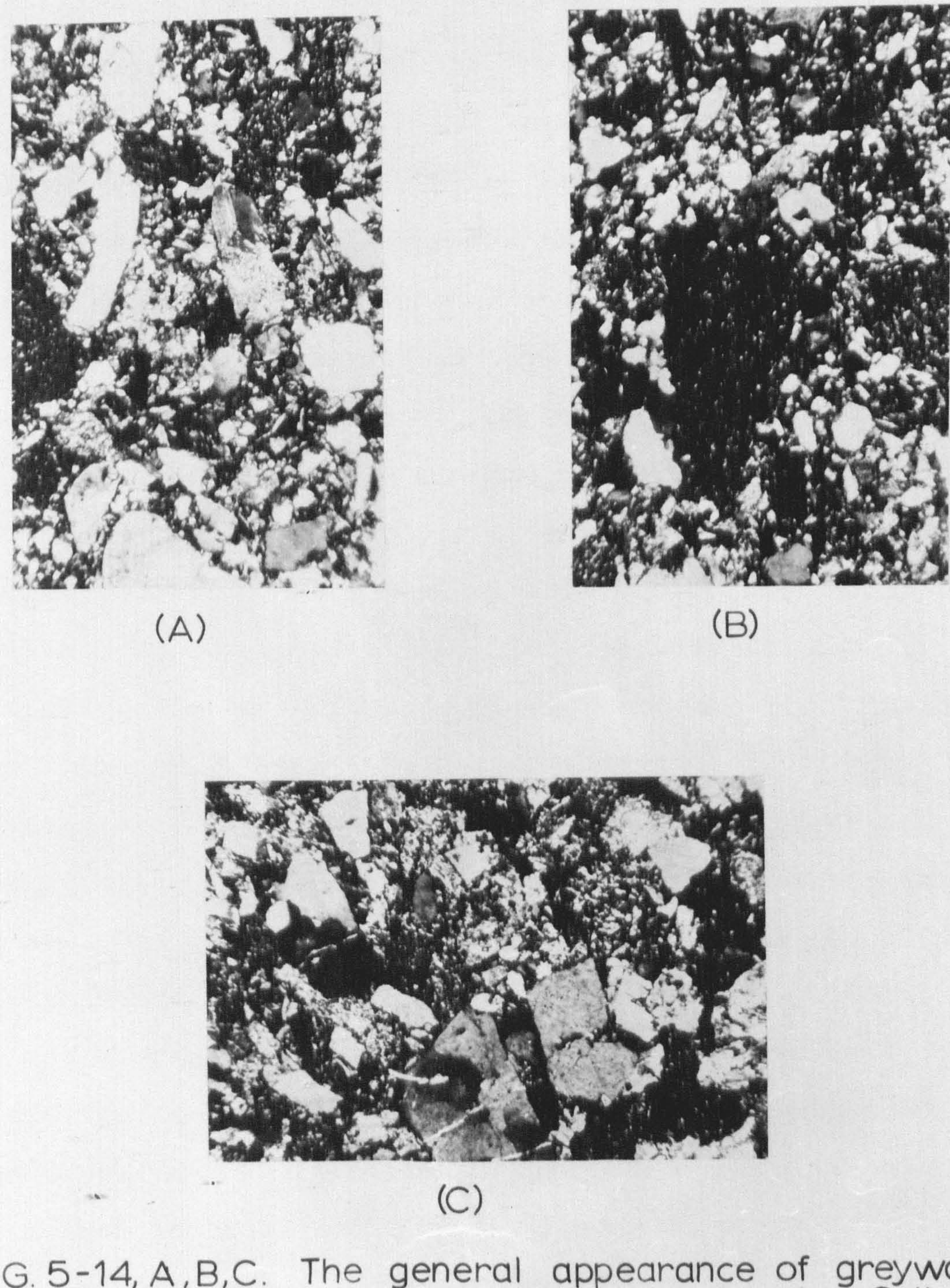
(c) Ilmenite and leucoxene

Unaltered ilmenite displaying a brownish lustre is rare. In most cases the mineral has been altered to leucoxene, and thus shows a brown core surrounded by a white rim.

The mineralogy of the greywackes thus indicates derivation of the sediments from an area formed largely of volcanic rocks, in which beds of chert, and plutonic igneous intrusions also occurred. The probable position of this land mass, as indicated by the petrology of the rock fragments, is discussed on page 115, of this chapter, and also in chapter 10, dealing with the palaeogeography of the region.

## (4) The Texture and Origin of the Matrix

Figure 5-14 shows the general appearance of thin sections of greywacke units in the Coniston Grits and Bannisdale Slates. In the coarser grained units, the size of individual grains is very variable, (See chapter 6 ), and the grains themselves are surrounded by a matrix of fine



(A) (B) (C)

FIG. 5-14, A, B, C. The general appearance of greywacke thin sections from the Lower Coniston Grits.(X30.)

grained and altered material. The finer grained sediments are somewhat more uniform in size, but the matrix in which the grains are set, is still apparent. The grains are angular to sub-angular in shape, and often display corroded edges and replacement by calcite, sericite or chlorite.

Many authors have considered that the matrix is an original depositional feature of the greywackes, and is indeed an essential feature of this type of deposition. Bailey (1930), concluded that greywackes represent the intermittent delivery of a mixture of grit, sand and mud onto the sea floor, thus implying that the matrix is original. Boswell, also in 1930, showed experimentally that silt and clay could be deposited along with sand, but using an electrolyte such as salt as a flocculating agent. Whether or not this would work in the sea, where the salts were extremely dilute, was very much open to doubt. Woodland (1938) after studying the greywackes of the Cambrian Harlech dome, also came out in favour of a detrital origin for the clay. Although Boswell (op cit), had suggested a means by which sand and clay could be deposited together, no really satisfactory explanation had been given. Greywackes were still considered to represent deposition in shallow water.

Kuenen and Migliorini (1950), however, suggested that greywackes were deposited by turbidity currents. These were described as currents of water carrying a mixture of sand silt and clay in suspension, and which because of their greater density, are able to flow under clear water, and deposit sediment rapidly in the deeper parts of the oceans, far from land. These authors considered that this theory explained the muddy matrix of greywackes, and also their extremely widespread occurrence. This view was shared by Pettijohn (1950, p.169), in which he states that:- "Greywackes are marked by a primary mud matrix, and are graded by reason of their deposition from turbidity currents".

In 1951, however, Ericson et al., found that samples of sand obtained from the deeper parts of the ocean, and from submarine canyons were well sorted. More so even than some of the samples obtained from adjacent continental shelves.

Cummins (1962), considers that experimental greywackes produced by Kuenen were atypical in that when poorly sorted they were not graded, and when they were graded they were well sorted. He did not, in fact, produce a poorly sorted and graded sediment, and thus did not prove the matrix to be primary. Cummins also shows that greywackes are abundant only in the Palaeozoic geosynclines. Turbidite deposits from Mesozoic and Tertiary geosynclines consist largely of ordinary well sorted sands, containing a high proportion of felspar and other unstable minerals. The conclusion is that the so called muddy matrix of greywackes is in fact of secondary origin, and is produced by slow post-depositional alteration of unstable minerals such as felspar, and the ferro-magnesian minerals in the rock fragments.

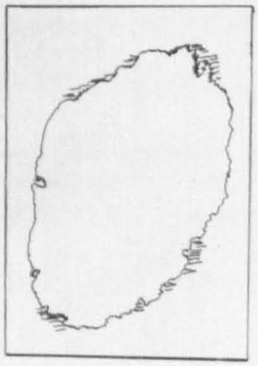
The matrix is usually defined as consisting largely of chlorite, sericite, clay minerals, carbonate and finely divided quartz and felspar. Difficulties arise at this point, however, as the grain size below which quartz and felspar are included in the matrix, varies from one author to another. Cummins (1962, p.57, figure 2), for example, includes all grains of less than 0.05 mm within the matrix, whereas Walton (1955, p.339), and Warren (1962, p.229), consider that only grains below 0.02 mm, should be placed in the matrix. In the present work, matrix is considered to include chlorite, sericite, mica, carbonate, and grains of quartz and felspar of less than 0.004 mm in diameter. Whatever size limits are placed on the definition of matrix, however, it should be possible to say whether or not it is of primary or secondary origin, and whether or not the finely divided quartz and felspar has been corroded to this size by secondary alteration.

Examination of the texture of the greywacke units within the Coniston Grits, as described on page 95, shows that much of the material classified as "matrix", must in fact be of secondary origin. The grains of quartz and felspar with corroded edges replaced by chlorite, sericite and calcite, have obviously been altered after deposition, (see figure 5-15). The finely fretted nature of many grains could not have survived transport, even in the comparatively abrasion free medium of a turbidity current. Many large felspar fragments are sericitised or kaolinised to such a degree, as to be

(A)

(B)

(C)



(D)

Fig. 5-15.(A),(B),(C), Sericitised and altered felspars.
×50, Crossed Nicols.
(A) Slide No. 2.
(B) Slide No. 1.
(C) Slide No. 3.
(D) Corroded quartz grain ×50, Winder Grit.

almost indistinguishable from the surrounding matrix, and could not have withstood transport in this condition.

On the other hand, the Coniston Grits contain much finely divided, fresh, completely unaltered quartz and felspar, the grain sizes of which are fine enough (less than 0.004 mm), to be classified as matrix. Also, some of the clayey material does not appear to be associated with the alteration of any quartz, felspar or rock fragment grains. This fine material has apparently been deposited along with the coarse grained fraction, and has not been produced by secondary alteration. Thus some of the matrix is in fact primary in origin. It is concluded that the original sediments were deposited as fairly clean sands, with only a comparatively small proportion of muddy or clayey material. The grain size within the coarser fraction, however, was variable between coarse sand and very fine silt. Later diagenetic changes resulted in the corrosion and alteration of the more unstable minerals, especially the felspars and rock fragments, along with the primary mud, to give the coarse fraction the appearance of having been deposited along with a large amount of clay. Silicification also probably took place at this stage to give the sediments their present durable nature. The origin of the matrix in this case is thus partly primary, but is augmented to a large extent by later alteration and recrystallisation.

## (5) The Classification of the Greywackes, based on Mineralogy

The definition of the so called average greywacke was discussed briefly at the beginning of this chapter. This showed that no really satisfactory definition exists, and that the composition ranges widely. "Average" greywackes have been described by Edwards (1947 a,b), Krynine (1948), Helmbold (1952), Pettijohn (1957), and Mattiat (1960). These are plotted on the triangular diagram (figure 5-16b), which shows that none of them falls near the centre of the field. This is itself a reflection of the loose definition, and indicates that there is probably no such thing as an average greywacke. The constituents are split into three groups. Felspar and the basic rock fragments form one co-ordinate, and quartz and siliceous fragments the second. The third co-ordinate under the heading of matrix includes chlorite, sericite, muscovite, carbonate and the accessory minerals. This grouping is usually satisfactory, as greywackes rich in basic rock fragments normally contain a fairly high proportion of felspar. Similarly, rocks rich in siliceous fragments usually also contain a good deal of quartz. The definition of matrix is rather vague, however, especially with regard to grain size, and it often includes anything which does not fit easily into the other groups. The greywackes described by Edwards (1947a,b), and Helmbold (1952), may be used as an example of the use of this type of classification. Both of them are rich in basic material and felspar, but poor in

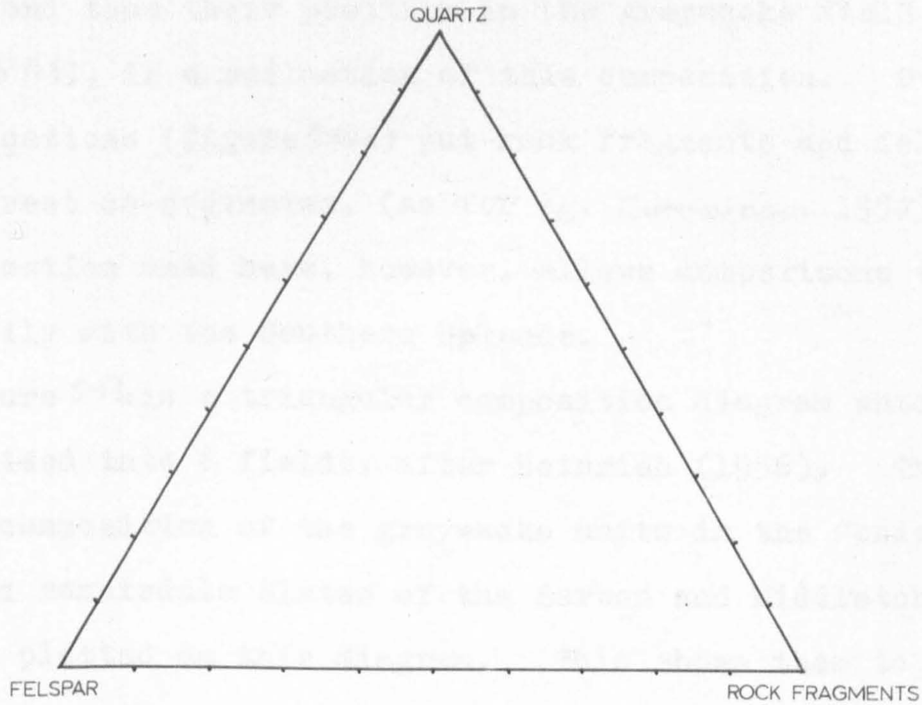



FIG. 5-16(A). The Composition diagram used by Cummins(1957).

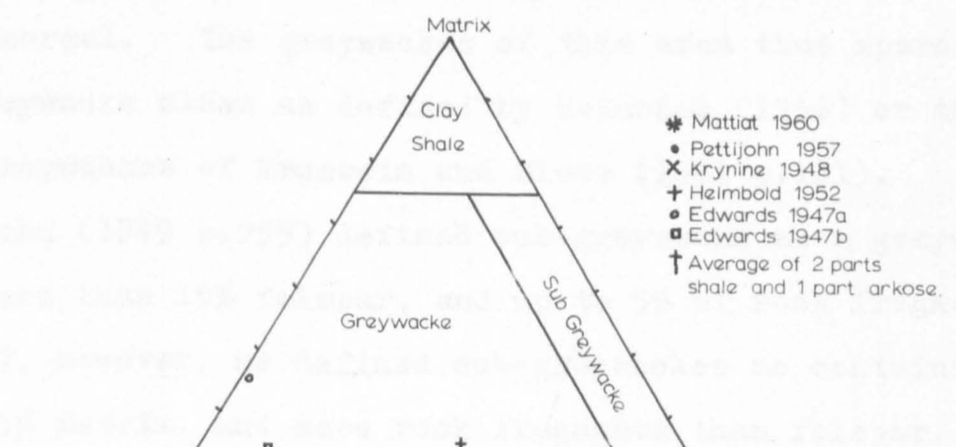



Fig.5-16 (B). The Composition diagram used in the present work (after Heinrich and Pettijohn). The mean composition analysed by a number of authors are plotted on the diagram.

quartz, and thus their position in the greywacke field (figure 5-16b), is a reflection of this composition. Other classifications (figure 5-16a) put rock fragments and felspar on different co-ordinates, (as for eg. Cummins., 1957). The classification used here, however, allows comparisons to be made easily with the Southern Uplands.

Figure 5-17a is a triangular composition diagram which has been divided into 6 fields, after Heinrich (1956). The mean mineral composition of the greywacke units in the Coniston Grits and Bannisdale Slates of the Barbon and Middleton Fells, has been plotted on this diagram. This shows them to be rich in quartz and siliceous material, but relatively poor in felspar and basic fragments. The proportion of matrix is about normal. The greywackes of this area thus approach the sub-greywacke class as defined by Heinrich (1956) or the low rank greywackes of Krumbein and Sloss (1951 p.121). Pettijohn (1949 p.255) defined sub-greywacke as a greywacke with less than 15% felspar, and up to 5% of rock fragments. In 1957, however, he defined sub-greywackes as containing less than 15% matrix, and more rock fragments than felspar. The 1949 definition appears to be more appropriate, and fits the composition of some of the greywacke units perfectly. The results obtained from the individual analyses (26 in number), have also been plotted separately on figure 5-17b. This shows that there is little variation in composition throughout the succession. The results fall almost on the boundary between

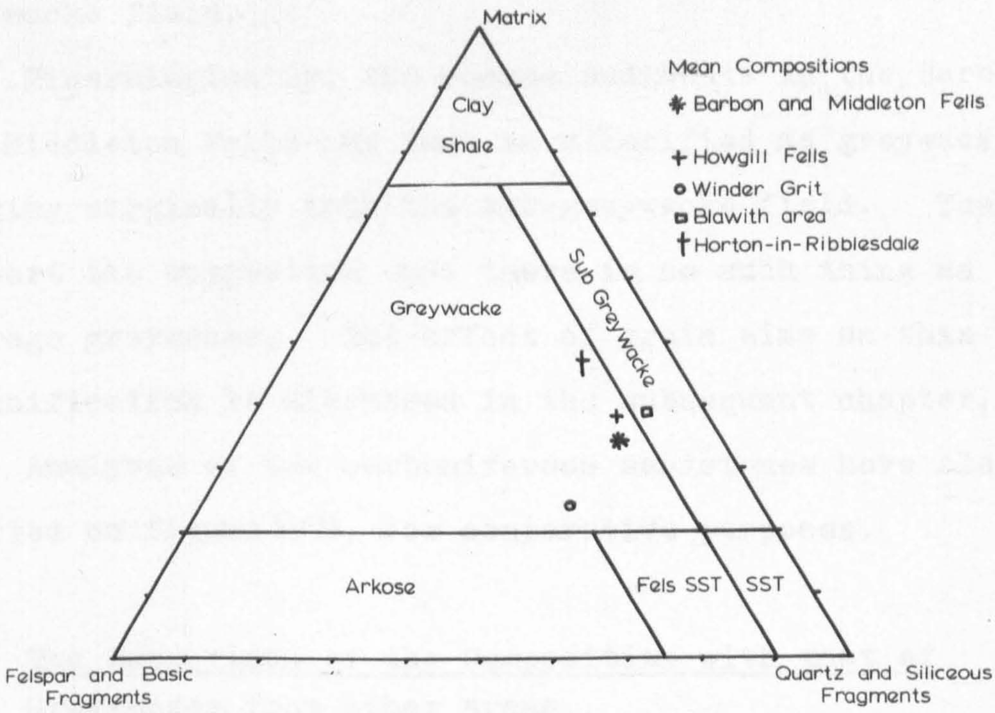



FIG.5-17(a). The mean mineralogical composition of greywackes analysed from the Barbon and Middleton Fells and other parts of N.W. England.

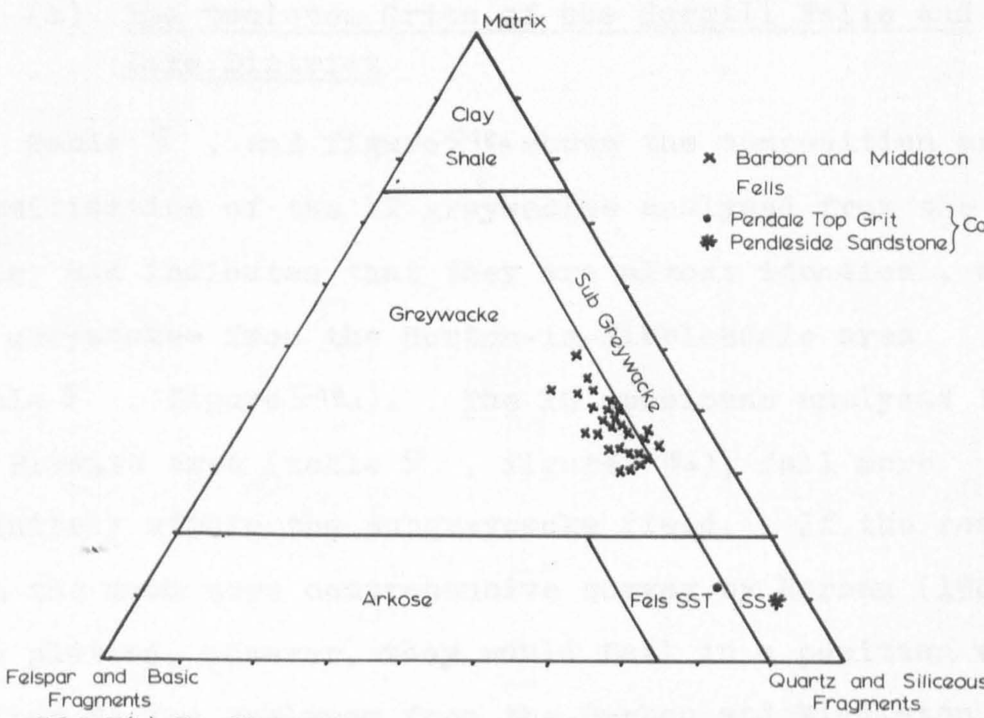



FIG.5-17(b) The 26 individual analyses from the Barbon and Middleton Fells. Two Carboniferous sandstones have also been plotted on the diagram for comparative purposes.

the two classes, although the majority are just within the greywacke field.

Mineralogically, the coarse sediments in the Barbon and Middleton Fells may thus be classified as greywackes, ranging marginally into the sub-greywacke field. They support the suggestion that there is no such thing as an average greywacke. The effect of grain size on this classification is discussed in the subsequent chapter.

Analyses of two carboniferous sandstones have also been plotted on figure 5-17b, for comparative purposes.

## (6) The Comparison of the Composition with that of Greywackes from other areas

### (a) The Coniston Grits of the Howgill Fells and Lake District

Table 5 , and figure 5-18a shows the composition and classification of the 12 greywackes analysed from the Howgill Fells, and indicates that they are almost identical, as are the greywackes from the Horton-in-Ribblesdale area (table 5 , figure 5-18a). The 10 specimens analysed from the Blawith area (table 5 , figure 5-18a), fall more definitely within the subgreywacke field. If the results from the much more comprehensive survey by Norman (1961), were plotted, however, they would fall in a position very similar to the analyses from the Barbon and Middleton, and Howgill Fells. The specimens analysed in the present work,

TABLE 5 . The mean percentages of the important constituent minerals in greywackes from other parts of north-west England, and the Wenlockian greywackes (U.Caddroun Burn Beds) of the Hawick area.

| Area and no. of Analyses | % Quartz | % Felspar | % Rock Fragments | % Carbonate | % Matrix incl Mica | % Others |
|---|---|---|---|---|---|---|
| Howgill Fells (12) | 47.3 | 9.8 | 3.2 | 7.5 | 31.8 | 0.4 |
| Howgill Fells, Winder Grit(3) | 31.4 | 7.5 | 36.5 | 5.1 | 19.0 | 0.5 |
| Blawith Area (10) | 52.9 | 6.2 | 0.6 | 8.2 | 31.6 | 0.5 |
| Horton-in-Ribblesdale(4) | 41.1 | 11.5 | 0.4 | 10.1 | 36.2 | 0.7 |
| Hawick area (after Warren 1963). | 21.6 | 6.0 | 27.5 | 13.6 | 30.2 | - |

Felspar includes k-felspar and plagioclase, "others" includes heavy and opaque minerals. See text for full description.

from this area, may thus be somewhat atypical. The 3 specimens of the Winder Grit which have been analysed, (table 5 ), however, differ quite markedly from the remainder of the Coniston Grits. Figure 5-18 shows that they fall further towards the felspar and basic rich side of the field. This is considered to be an effect of grain size, and is discussed in chapter 6 .

Apart from the Winder Grit, the Coniston Grits thus have a similar composition and texture throughout north-west England. These similarities, in addition to providing further evidence that the type of sedimentation was the same throughout this area, also indicate that the sediments were derived from the same or a very similar source.

(b) <u>The Silurian Greywackes of the Hawick area</u>

The Wenlockian strata of the Hawick area, which were analysed by Warren (1963), cover the field occupied by the Coniston Grits, as shown in figure 5-18b, but also extend much further towards both the clay rich, and quartz rich ends of the diagram. This reflects the higher proportion of rock fragments (especially siliceous varieties), due to the predominantly larger grain size, and the greater percentage of matrix. The percentage of matrix appears higher, due to some extent, to it including grains of up to 0.02 mm, compared with 0.004 in the present work.

A large number of Warren's thin sections from the Hawick area have been studied for comparative purposes. Apart from

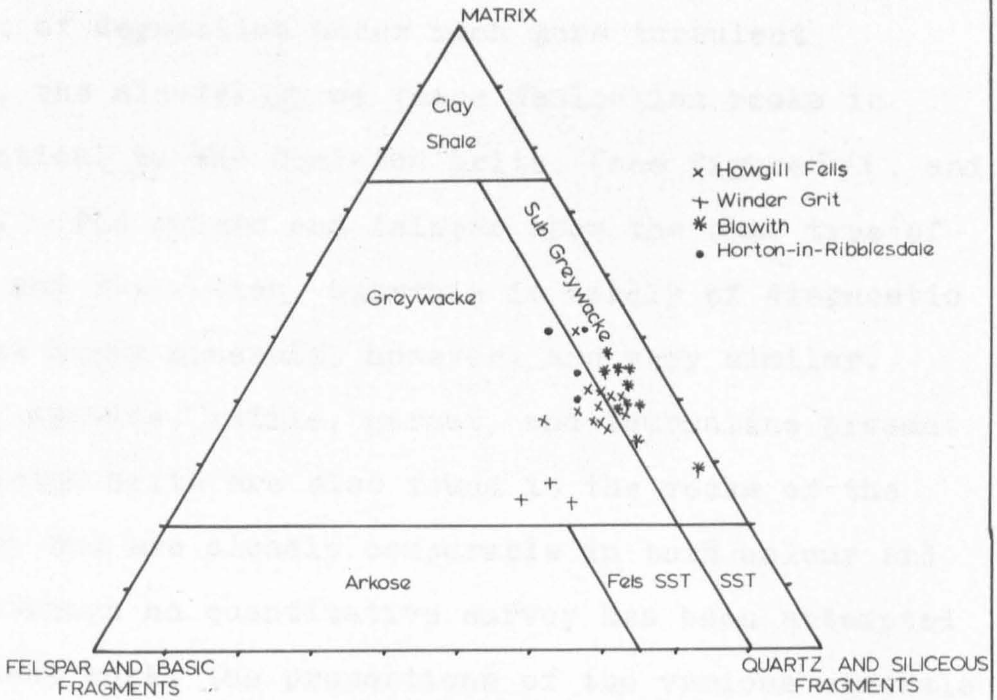



FIG. 5-18(a). The individual analyses from the Howgill Fells, Blawith and Horton-in-Ribblesdale areas.

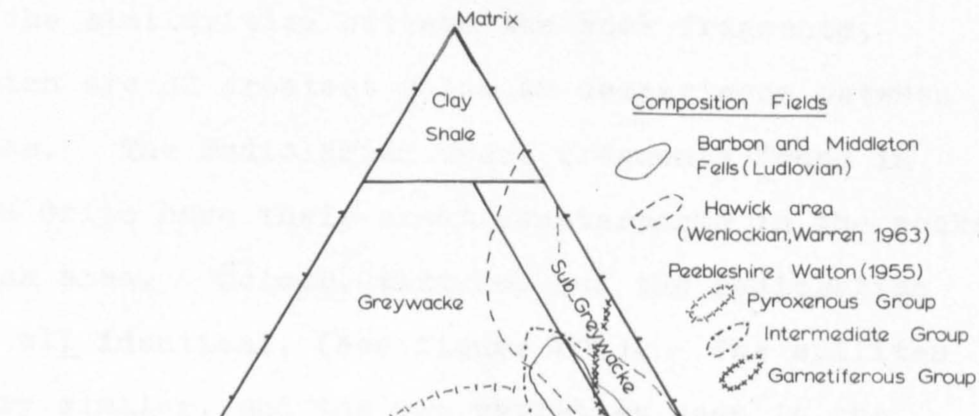
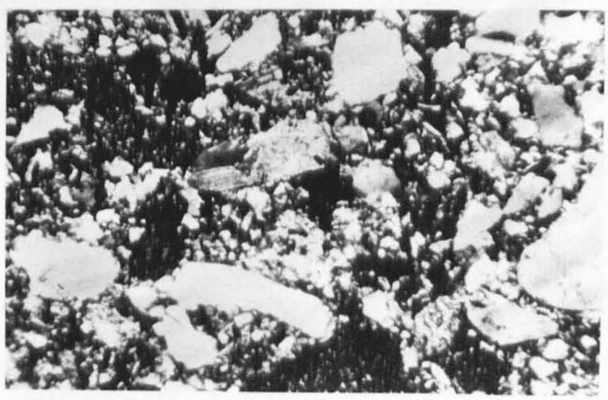



FIG. 5-18.(b). Comparison of the composition of the greywackes of the Barbon and Middleton Fells with the Llandoverian and Wenlockian greywackes from the Southern Uplands.

the wider quantitative range in the composition, which may be a result of deposition under much more turbulent conditions, the mineralogy of these Wenlockian rocks is almost identical to the Coniston Grits, (see figure 5-19, and table 5). The quartz and felspar show the same type of inclusions and alteration, but this is hardly of diagnostic value. The heavy minerals, however, are very similar. The zircon, apatite, rutile, garnet, and tourmaline present in the Coniston Grits are also found in the rocks of the Hawick area, and are closely comparable in both colour and shape. Although no quantitative survey has been attempted in the present work, the proportions of the various minerals would also appear to be similar.

It is the similarities between the rock fragments, however, which are of greatest value in comparisons between the two areas. The radiolarian chert fragments found in the Coniston Grits have their exact counterparts in the rocks of the Hawick area. Colour, texture, and the radiolarian remains are all identical, (see figure 5-19). The spilites too, are very similar, and the two varieties seen in the Coniston Grits are also found in the Hawick greywackes. Soda-trachyte and granophyre fragments are also found in the greywackes from both areas. The series of rhyolite fragments which range from cryptocrystalline to micrograntic are abundant in both areas. Similar metamorphic rock fragments also occur sparingly in the two areas. The nature of the

(A)



(B)

Fig. 5-19. Comparison of the Wenlockian greywackes of the Hawick area (A), with the Lower Coniston Grits (B). Crossed nicols, x30 matrix is of less diagnostic value, as the present work differs from that of Warren in the grain size limits placed on its definition. Even so, it appears to form a higher proportion of the Hawick greywackes. Mineralogically, however, it is comparable. Calcite forms an appreciable part of the rock in both areas.

### (7) The Source of the Sediments

These close similarities suggest that the Coniston Grits, and the Wenlockian greywackes of the Hawick area have been derived from similar sources, although at different times.

Recent work in the Lake District, however, by Llewellyn (1960) and Norman (1961), suggested that the Coniston Grits were derived from an area of Borrowdale Volcanics lying along the northern edge of the Lake District. Llewellyn also studied thin sections of the Winder Grit from the Howgill Fells, and found that the rock fragments in this bed were identical with those from the Coniston Grits of the Lake District.

Although the Coniston Grits are so similar to the Hawick greywackes, and were thus probably derived from the same source, detailed comparisons have also been carried out with rock slides of the Borrowdale Volcanic Series. These were obtained from the Harker collection of the Sedgwick Museum, Cambridge. This revealed that there are textural similarities between the Borrowdale Volcanic andesites, and the soda trachyte fragments of the Coniston Grits. The felspar fragments in the former, however, are all somewhat richer in calcium, being andesive rather than albite or oligoclase. Nothing closely comparable with the spilite fragments was found in any of the Harker collection of Borrowdale Volcanic material. The rhyolite fragments, however, do compare more closely, but their fine grain size, and the generally similar appearance of rhyolites wherever they occur, very much reduces their value as a means of tracing the source rocks. Another feature of the Borrowdale Volcanics is their wider range and higher proportion of mafic minerals, in contrast to the very little pyroxene or amphibole found in even the freshest rock fragments from the Coniston Grits.

The provenance of the Hawick greywackes can be traced to the north-west, to an area of Ordovician rocks in the northern belt of the Southern Uplands. This area is formed partly of the alkali rich Ballantrae Volcanic Series, together with radiolarian cherts. A study of the Harker collection of Girvan and Ballantrae material, shows that there are close similarities both in mineralogy and texture, between the spilites and soda trachytes, and the rock fragments in the Coniston Grits and Hawick greywackes.

This points strongly towards a Southern Uplands origin of the Ludlovian sediments. Further evidence is provided by the radiolarian chert fragments, and occasional fragments of schist, which are not known to occur in the Lake District at all. The schist fragments may in fact be derived from the Highlands. Garnets occur only sparingly in the Borrowdale Volcanic Series, thus their abundance, but the absence of kyanite in the heavy mineral assemblage, suggests that metamorphic strata, but only of the lower grades, were also being eroded at this time. The few granite and granophyre fragments, and the relative abundance of orthoclase compared to plagioclase, indicates that the land mass also contained granitic bodies. These probably provided the source for many of the heavy minerals such as zircon and apatite, (Mackie 1929).

Walton (1955) considered that the Llandovery greywackes in the Southern Uplands were also derived from an area of Ordovician rocks. Although there are mineralogical similarities, these rocks contain considerable amounts of pyroxene and amphibole. The source therefore, may have been from a different part of this land mass.

Further evidence for a Southern Uplands source for the sediments is provided by the palaeocurrent directions, which are discussed in chapter 8 .

It is therefore concluded that the Coniston Grits of the Barbon and Middleton Fells, were derived from a land mass on the northern edge of the Southern Uplands, (see chapter 10 , on the palaeogeography), and not from the Borrowdale Volcanic Series as previously thought.

General Conclusions

(i) The mineralogy of the greywacke units indicates that the sediments were derived from an area of volcanic rocks, which also contained beds of radiolarian chert, and some plutonic acid igneous bodies.

(ii) The mineralogy compares closely with the Wenlockian greywackes of the Hawick area, which Warren considers to have been derived from Ordovician rocks in the Northern Belt of the Southern Uplands. A comparison with rock slides of the Ballantrae Volcanic Series confirms this theory.

Comparisons with slides of Borrowdale Volcanic rocks, indicate that there is no real evidence to support the suggestion of Llewellyn and Norman, that the sediments were derived from the Borrowdale Volcanic Series.

(iii) The mineralogy and texture of the Silurian greywackes throughout north-west England is very similar, suggesting that they were deposited under comparable conditions, and derived from a similar source.

(iv) The plotting of the composition on a triangular diagram reveals that the sediments fall on the edge of the greywacke field, towards the sub-greywacke class, (in the sense of Pettijohn 1949, and Heinrich, 1956).

(v) The matrix is seen to replace and corrode the large mineral grains, and is thus considered to be largely a product of secondary alteration. Some unaltered finely divided quartz and felspar, along with clay, which does not appear to have been produced by alteration, indicates, however, that some of the matrix may be primary.

# CHAPTER 6

## THE GRAIN SIZE AND ROUNDNESS ANALYSIS OF THE COARSE SEDIMENTS

### (1) Grain Size Analysis

#### (a) Introduction and Method

The measurement of the grain size of sediments, whether unconsolidated or indurated presents many difficulties with regard to the accuracy of the results. Papers dealing with the methods, interpretation, and statistical presentation of the results are numerous. Among the more important works are those by Krumbein (1935, 1940,-1, 1955), Twenhofel and Tyler (1941), Chayes (1950), Inman (1952), Rosenfield et al (1953), Cadigan (1954), Pettijohn (1957), Grender (1961) and Milner (1962).

But when, as in the present study, the rocks are indurated, and ordinary thin section techniques have to be used, difficulties arise. The greatest disadvantage is the sectioning effect, which results in the grain size of the sediment appearing smaller than it actually is, as the plane of the section does not necessarily pass through the centres of the grains. Methods of overcoming this have been suggested by Krumbein (1935), and Chayes (1950). Krumbein considered that if the apparent mean grain diameter was multiplied by .4$\pi$ or 1.27, a result approaching the true value would be obtained. Rosenfield et al (1953), however, in a paper dealing with the comparison of sieve and thin section techniques, conclude that there is no generally applicable correction factor. The multiplication of the results by .4 for example, gives a true figure only in the case of perfectly spherical sediments.

The actual method of measuring grain size varies considerably. In some cases the maximum and minimum diameters are measured, (Twenhofel and Tyler (1941)), and the mean diameter calculated from the two results. Other authors have considered that measurement of the largest diameter apparent in the grain is adequate, (Rosenfield et al (1953, p.120), Cummins (1957), and Norman (1961)). Cope (1955) estimated the mean diameter by measuring the distance along a straight line which passes through the grain from surface to surface. This did not necessarily have to be the maximum diameter. The frequency of observation was then plotted against their values, and the apex of each curve was taken as the mean grain sample diameter. Warren (1963), estimated the average grain size by dividing the length of a slide traverse by the number of fragments in that traverse, excluding the matrix.

In the present work, grain size analysis has been carried out in order to estimate the degree of sorting within the sediment, and the effect of grain size on composition. For this purpose, the method used by Cummins and Norman has been adopted, in which the largest apparent diameter of each grain is measured. No correction has been made for the "sectioning effect", partly in view of the difficulties described by Rosenfield et al, but also because the uncorrected results allow direct comparison with Norman's grain size analyses. The importance of the "sectioning effect" is realised, however, and is allowed for in the discussions of the significance of the results.

The longest diameter of 200 grains in each of the 26 thin sections, ( 1-26), described on page 90 have been measured by use of an ocular micrometer, each division of which is equivalent to 0.02mm at a magnification of X50, and 0.005mm at a magnification of X200. Measurement was carried out at ½ mm intervals in traverses 1mm apart, on a Swift Point Counter. To avoid bias in the results which would result from the measurement of the long diameters of mica and chlorite flakes, only granular fragments were measured. In addition, the 12 greywacke specimens from the Howgill Fells, (S/H 1-12), the 10 from the Blawith area (S/B 1-10), and the 4 from the Horton area (S/A 1-4), have been measured for comparative purposes. The grains measured were split into 3 size classes based on the work of Wentworth (1935), Allen (1936), and Twenhofel (1937), on the American Committee on Sedimentation. These are as follows:-

$>$ 0.062mm diameter = Sand

0.004-0.062mm diameter = Silt

$<$ 0.004mm diameter = Clay

In the analyses, no accurate measurements smaller than 0.004mm could be made. Thus, all clay grains have been assumed to be of this size. The effect of this on the mean grain size of the sediment, however, is negligible.

(b) <u>The Mean Grain Size of the Sediments</u>

(i) <u>In the Barbon and Middleton Fells</u>

The coarsest sediments are of fine sand grade, with a mean grain size of up to 0.170mm. The majority of specimens analysed, however, fall into the silt class, with mean grain sizes ranging from 0.035mm, up to 0.060mm. The size of individual grains varies widely, even in the finer sediments, from little larger than mud grade, up to grains 0.250mm in size, (See Appendix V ). The coarser beds at the base of the succession contain numerous grains larger than 1.50mm in size, thus illustrating the poorly sorted nature of the sediments. Apart from these coarse beds low in the Series, there is no significant change in the grain size of the greywacke beds throughout the succession. The mean values obtained from the 26 analyses are summarised in table below. The full analyses and accuracy of the results are shown in Appendix VA. The overall uncorrected mean grain size of 0.059mm illustrates the predominant fine grained nature of the Coniston Grits, in the Barbon and Middleton Fells. Even after allowing for the "sectioning effect", the sediments still fall around the borderline between silt and fine sand.

| Mean Size of Sand Grains | % of Sand Grains | Mean Size of Silt Grains | % of Silt Grains | % of Clay Grade | Mean of Sand Sil and Clay |
|---|---|---|---|---|---|
| 0.109mm | 32.8% | 0.036mm | 54.2% | 13.0% | 0.059mm |

Table 6 . The mean grain size of the greywackes, based on 26 analyses, (uncorrected for the "sectioning effect").

(ii) Comparison with Adjacent Areas

The mean (uncorrected) values obtained from the specimens analysed from the Howgill Fells, and Blawith and Horton-in-Ribblesdale areas, are summarised in table 7 , below:-

| Area | Mean Size of Sand Grains | % of Sand Grains | Mean Size of Silt Grains | % of Silt Grains | % of Clay Grade | Mean Size of Sand Silt and Clay |
|---|---|---|---|---|---|---|
| Howgills(12) | 0.122mm | 47.6% | 0.040mm | 34.6% | 17.8% | 0.074mm |
| Winder Grit(3) | 0.378mm | 58.8% | 0.037mm | 22.7% | 18.5% | 0.253mm |
| Blawith (10) | 0.101mm | 34.1% | 0.040mm | 46.4% | 19.5% | 0.054mm |
| Horton in R. (4) | 0.106mm | 28.8% | 0.035mm | 49.4% | 21.8% | 0.049mm |

Table 7 .

Full analyses for each thin section are shown in Appendix VB-E. The specimens from the Blawith and Horton-in-Ribblesdale areas are almost identical to the Barbon and Middleton Fells. (The Blawith analyses agree closely with those of Norman). The mean grain sizes of the sand and silt fractions show only minor differences. The greywackes from the Barbon and Middleton Fells, however, contain a rather smaller proportion of clay grade material. The significance of this is discussed below. The general similarities in the mean grain sizes of the sand and silt fractions, suggest that the strength of the turbidity currents, and conditions of deposition were almost uniform over a wide part of northwestern England. Grain size analyses thus support the conclusions drawn in previous chapters.

The 12 specimens analysed from the Howgill Fells, however, are all somewhat coarser. The mean grain size of both the sand and silt fractions is greater. Here again the percentage of clay is somewhat higher. The Winder Grit is an extreme development of this coarser sedimentation, with a mean grain size of 0.253mm, although it is only the sand fraction which is coarser. The mean grain size of the silt fraction, of 0.037mm, is only slightly greater than that of the greywackes from the Barbon and Middleton Fells and thus shows that this grit is much more poorly sorted. The predominantly coarser grain size in the Howgill Fells indicates that rather more turbulent conditions existed in this area, allowing only the coarser sediment to be deposited. Evidence in support of this theory is seen in the giant flute casts developed at some horizons in the area. These are very much larger than anything seen in the Barbon and Middleton Fells, and could only have been formed by extremely strong turbidity currents.

The description of the stratigraphical succession showed that there is a considerable thickening of the strata from north to south, and that this is considered to result from a deepening of the geosynclinal trough in this direction. The evidence of strong turbidity currents in the Howgill Fells supports this theory, and suggests that there may have been a considerable steepening of the sea floor in this area. Currents would flow rapidly down the slope, only the coarser grades of sediment being deposited, and would spread out and lose strength in the flatter bottomed areas to the south, where the finer greywackes were deposited. Higher in the succession, however, greywackes are more predominant in the Barbon and Middleton Fells, and finer sediment in the Howgill Fells. This is considered to result from palaeogeographical changes, and is discussed in chapter 10.

(c) <u>The Percentage of Sand, Silt and Clay</u>.

(i) <u>In the Barbon and Middleton Fells</u>

The percentages of sand, silt and clay vary widely through the succession, (see App. VA). The percentage of sand ranges from 17% to 66%. Silt ranges from 25% to 70%, and clay from 8% to 20%. The percentage of clay is less than the percentage of matrix obtained in the mineralogical analyses, as mica and chlorite flakes have not been measured. Over the entire succession the greywackes contain a mean of 32.8% sand grade sediment, 54.2% silt, and 13.0% clay or matrix. This again illustrates the predominantly silty nature of the sediments, even if the "sectioning effect" is allowed for.

The triangular diagram (figure 6-1a), is drawn with sand (0.062mm +), silt (0.004mm to 0.062mm), and clay (< 0.004mm), as the 3 co-ordinates. The plotting of the grain size distribution on this diagram shows the sediments to be poorly sorted, or immature (Folk 1951), especially when compared with the two Carboniferous sandstones which are also plotted on the diagram. The main disadvantage of this type of representation, however, is that it gives no indication at all of the mean size of the sand fraction, but only its lower limit.

(ii) Comparison with Adjacent areas.

Figure 6-1b shows the analyses carried out on the greywackes from other areas. In the Howgill Fells, the sediments are also poorly sorted, slightly more so in fact than the Barbon and Middleton greywackes, but show less variation through the succession. The specimens from the Blawith and Horton-in-Ribblesdale areas show much closer similarities to the greywackes of the Barbon and Middleton Fells, the proportions of the 3 constituents varying widely. They do, however, contain a higher proportion of clay, and are thus rather more poorly sorted.

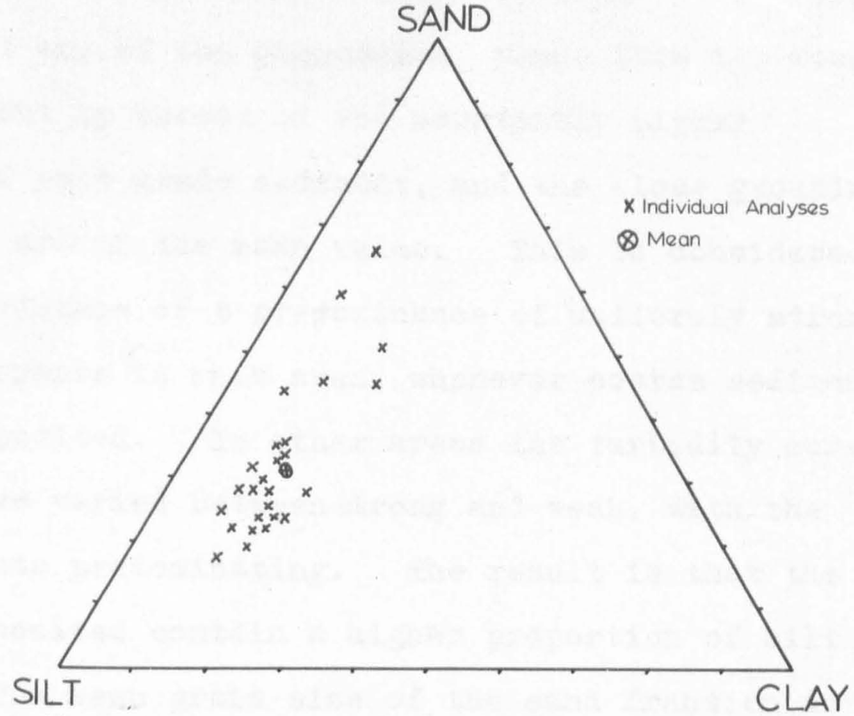


FIG.6-1(a). The Proportions of Sand, Silt and Clay in the greywackes of the Barbon and Middleton Fells.

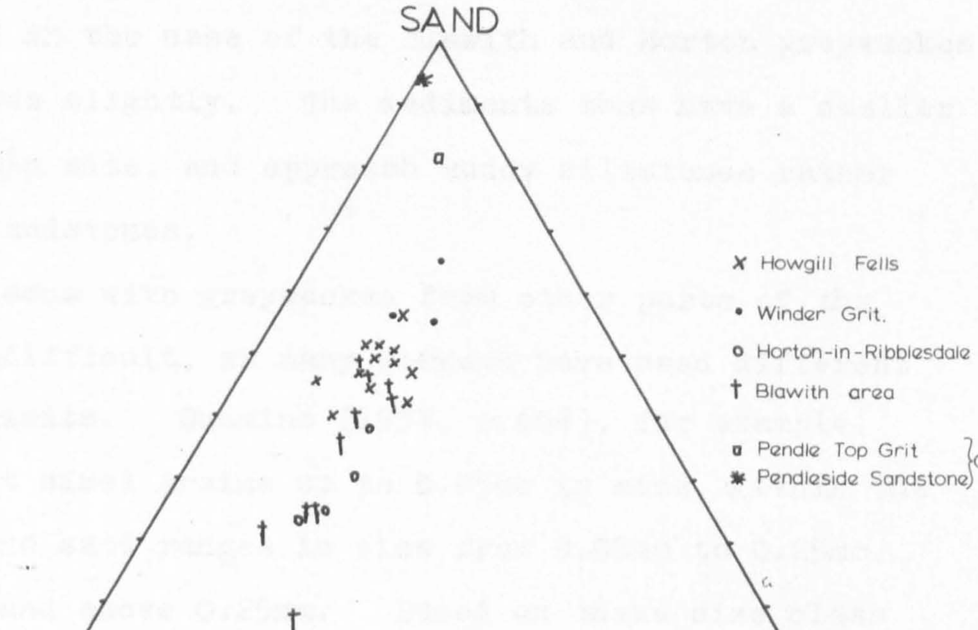


FIG. 6-1(b). The proportions of Sand, Silt and Clay in the greywackes of the Howgill Fells, Blawith and Horton-in-Ribblesdale areas. Two Carboniferous sandstones have been plotted on the diagram for comparative purposes.

Although there are only slight differences in the degree of sorting of any of the greywackes, those from the Howgill Fells stand out by reason of the constantly higher proportion of sand grade sediment, and the close grouping of the analyses around the mean value. This is considered to be further evidence of a predominance of uniformly strong turbidity currents in this area, whenever coarse sediment was being deposited. In other areas the turbidity currents appear to have varied between strong and weak, with the weaker currents predominating. The result is that the sediments deposited contain a higher proportion of silt grade sediment. The mean grain size of the sand fraction is also lower. The proportion of clay remains at a similar level, however, and in the case of the Blawith and Horton greywackes even increases slightly. The sediments thus have a smaller range in grain size, and approach muddy siltstones rather than muddy sandstones.

Comparisons with greywackes from other parts of the country are difficult, as many workers have used different size class limits. Cummins (1957, p.436), for example, includes silt sized grains up to 0.05mm in size, within the matrix. Fine sand ranges in size from 0.05mm to 0.25mm, and coarse sand above 0.25mm. Based on these size class limits, the Denbigh Grits appear to contain almost equal proportions of the 3 classes, and are thus very poorly sorted. The texture of the Denbigh Grits appears to be more comparable

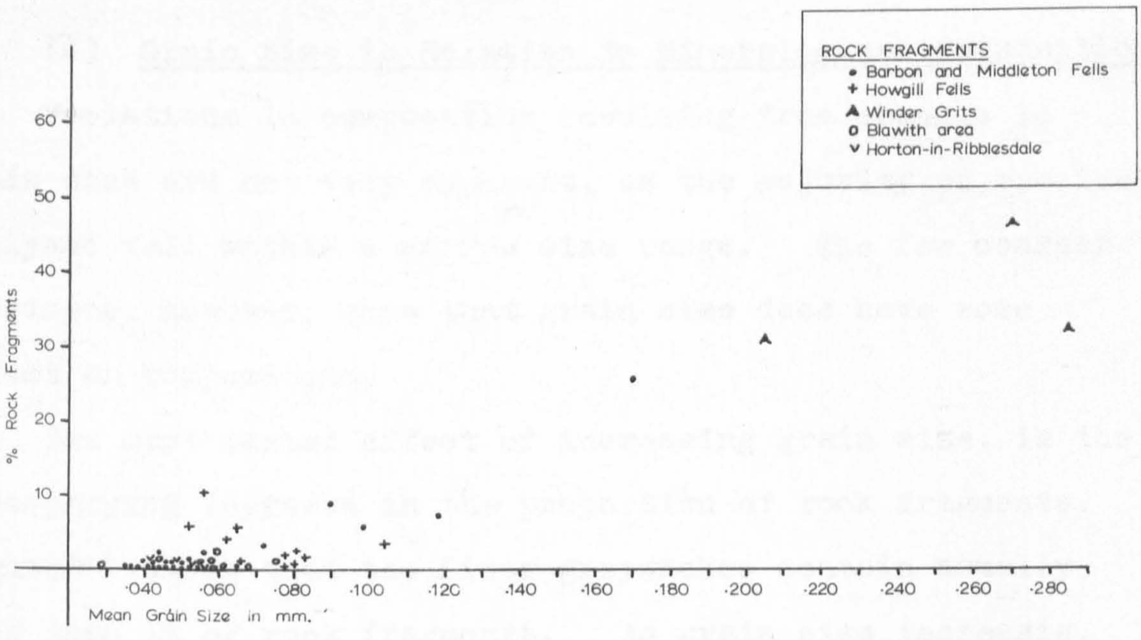



FIG. 6-2a. The relationship between grain size and the % of rock fragments in the greywackes.

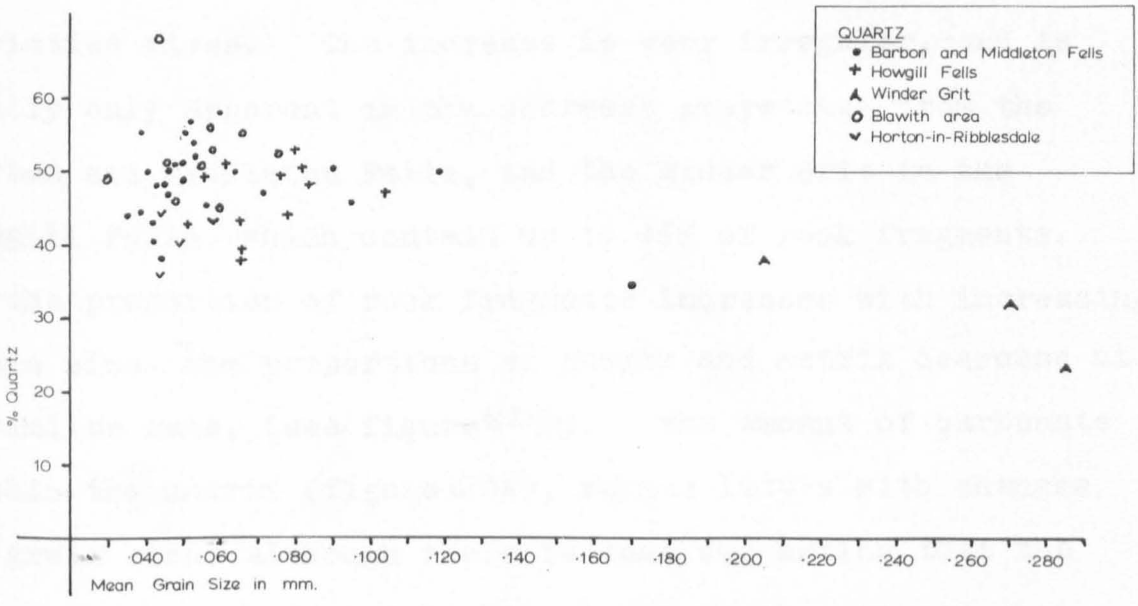



FIG. 6-2b. The relationship between grain size and the % of quartz in the greywackes.

with the Winder Grit rather than the remainder of the Coniston Grits.

(d) Grain Size in Relation to Mineralogical Composition.

Variations in composition resulting from changes in grain size are not very apparent, as the majority of specimens analysed fall within a narrow size range. The few coarser specimens, however, show that grain size does have some effect on composition.

The most marked effect of increasing grain size, is the accompanying increase in the proportion of rock fragments. Figure 6-2a shows that the finer greywackes contain usually less than 1% of rock fragments. As grain size increases, however, the proportion of rock fragments, especially acidic varieties rises. The increase is very irregular, and is really only apparent in the coarsest greywackes from the Barbon and Middleton Fells, and the Winder Grit in the Howgill Fells, which contain up to 46% of rock fragments. As the proportion of rock fragments increases with increasing grain size, the proportions of quartz and matrix decrease at a similar rate, (see figure 6-2b,3a). The amount of carbonate within the matrix (figure 6-3b), varies little with changes in grain size, although there is some suggestion that the percentage may be only slightly lower in the coarser greywackes. Further analyses of coarse greywackes are needed, however, before this trend can be confirmed. If this tendency is real, it suggests that the breakdown of rock

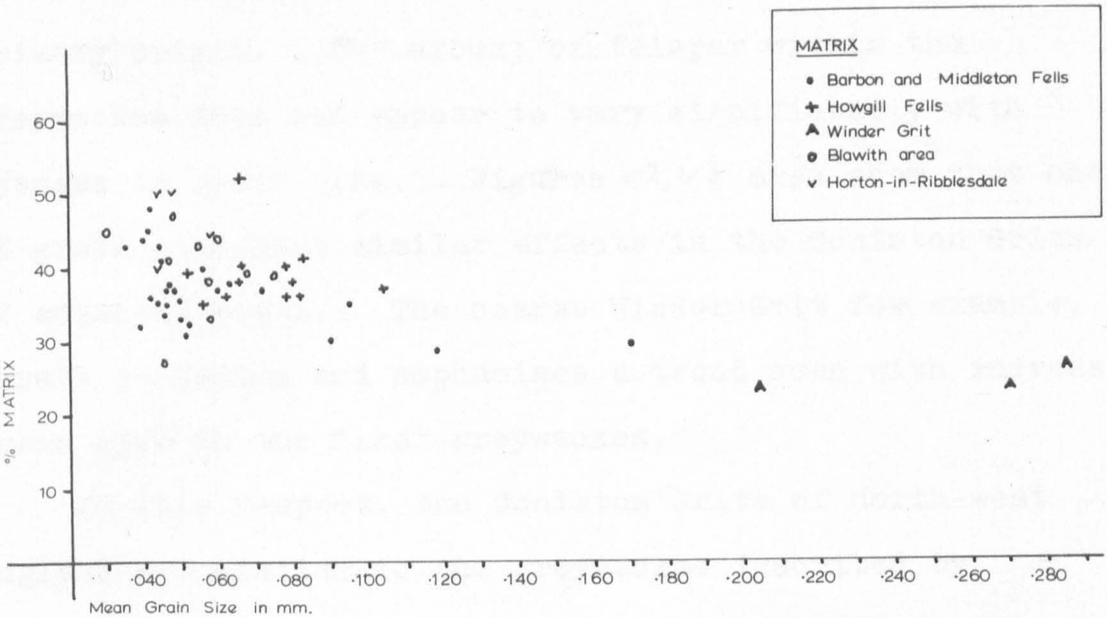



FIG. 6-3(a). The relationship between grain size and the % of matrix in the greywackes.

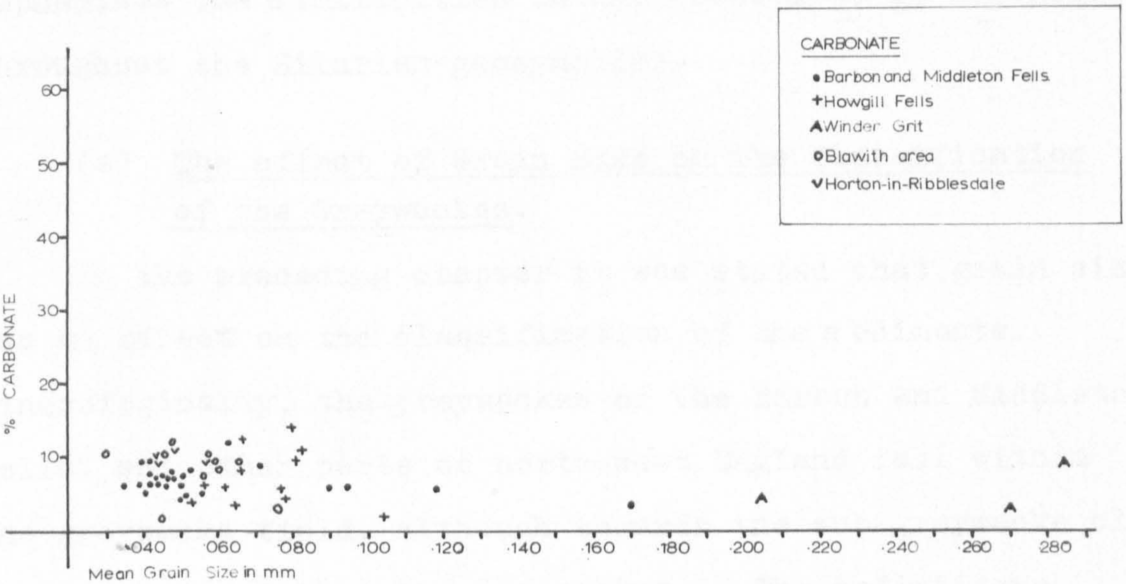



FIG. 6-3 (b). The relationship between grain size and the % of carbonate in the greywackes.

fragments leads largely to the production of finely divided quartz and chloritic material, and only a small amount of calcite. The remainder of the calcite may therefore be of primary origin. The amount of felspar within the greywackes does not appear to vary significantly with changes in grain size. Figures 6-2, 6-3 also show that changes of grain size have similar effects in the Coniston Grits of adjacent areas. The coarse Winder Grit for example, merely continues and emphasises a trend seen with increasing grain size in the finer greywackes.

In this respect, the Coniston Grits of north-west England are similar to the greywackes described by Cope (1955), Cummins (1957), and Warren (1963). This again emphasises the similarities in the conditions of deposition throughout the Silurian geosyncline.

(e) <u>The effect of Grain Size on the Classification of the Greywackes</u>.

In the preceding chapter it was stated that grain size has an effect on the classification of the sediments. Mineralogically, the greywackes of the Barbon and Middleton Fells, and other parts of north-west England fall within the greywacke field, although towards the sub-greywacke class. In this respect they are greywackes. The definitions proposed by Pettijohn (1957), and Boswell (1960), however, point out that one criterion of a greywacke is that it is coarse grained, with grains ranging through sandstone and breccia to conglomerate, (in contrast to Folk 1954). Thus in this respect, the only greywacke in the region which satisfies this part of the definition, is the Winder Grit. Even this bed is at the fine grained end of the scale. The remainder of the Coniston Grits, although having the composition, and to a certain extent, the poor sorting of a greywacke, do not have the necessary coarseness. They are in fact of siltstone or fine sandstone grade, and may be compared with the greywacke siltstones described by Warren (1963), from the Hawick area.

The fine grain size also has the effect of placing the sediments towards the subgreywacke side of the greywacke field, as increasing grain size leads up to the Winder Grit, which satisfies to a larger extent the criteria proposed by Boswell and Pettijohn. The majority of the Coniston Grits may therefore be classified as greywacke-siltstones, or fine sandstones, ranging marginally into the sub-greywacke field.

## (2) Estimation of Grain Roundness.

### (a) Introduction and Method.

Estimation of the degree of roundness, or the angularity of the edges and corners of the grains (which is not to be confused with the sphericity), involves considerable difficulties. Krumbein (1941), described geometrical methods of estimation, which, however, are complex and very slow in use. The time taken to obtain the more accurate results given by this method would not be justified, as in the present work, only a general idea of the roundness of the sediments is required. The other commonly used method of determining roundness, is by visual estimation. The fragments are compared with a chart of grains of varying degrees of roundness, each of which is given a certain numerical value. The biggest disadvantage of this method is that the observer may not be consistent in his determination of individual grains.

Rittenhouse (1943), devised a chart which combined roundness and sphericity. The large number of subdivisions within this chart, however, would probably result in many inaccuracies in estimation, and would be of little additional value. Powers (1953), introduced a rather simpler roundness scale, inwhich the grains were divided into 6 degrees of angularity, ranging from "very angular", to "well rounded". Each division was further sub-divided, depending on whether or not the grains had a high or low sphericity. Pettijohn (1957), proposed a roundness scale in which the grains were split into only 5 divisions, ranging from "angular" to "well rounded".

In the present work, Powers' roundness scale has been used, and the roundness of the grains in each division was considered to be the value of the mid-point given by Powers. One hundred grains were estimated in each of the 26 thin sections ( 1-26), described on page 90 , at a magnification of either X300 or X65, depending on the grain size. Only the roundness of the granular constituents such as quartz, felspar and rock fragments was estimated, as flaky minerals such as mica would bias the results. In addition, the roundness of the specimens from the Howgills, Blawith, and Horton-in-Ribblesdale areas has been estimated for comparative purposes.

(b) The Roundness and its significance

(i) In the Barbon and Middleton Fells

The estimations carried out on the 26 thin sections from this area show that the mean roundness lies just within the sub-angular class in almost every case. This is summarised in table 8 below:-

| Limits of Class | .12 – .17 | .17 – .25 | .25 – .35 | .35 – .49 | .49 – .70 | .70 – 1.00 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Mid Point | .14 Very Ang. | .21 Ang | .30 Sub Ang | .41 Sub Rnded | .59 Rnded | .86 Well Rnded | % High Sph. | % Low Sph. | Mean Round -ness |
| Mean of 26 Analyses | 8% | 38% | 47% | 7% | - | - | 57.6 | 42.4 | 0.26 |

Ang. = Angular
Rnded = Rounded
Sph. = Sphericity

Table 8 .

(The individual estimations are shown in Appendix VI ).
Angularity does not appear to be related to grain size. Figure for example shows that the roundness value for sediments of varying grain sizes is distributed fairly evenly

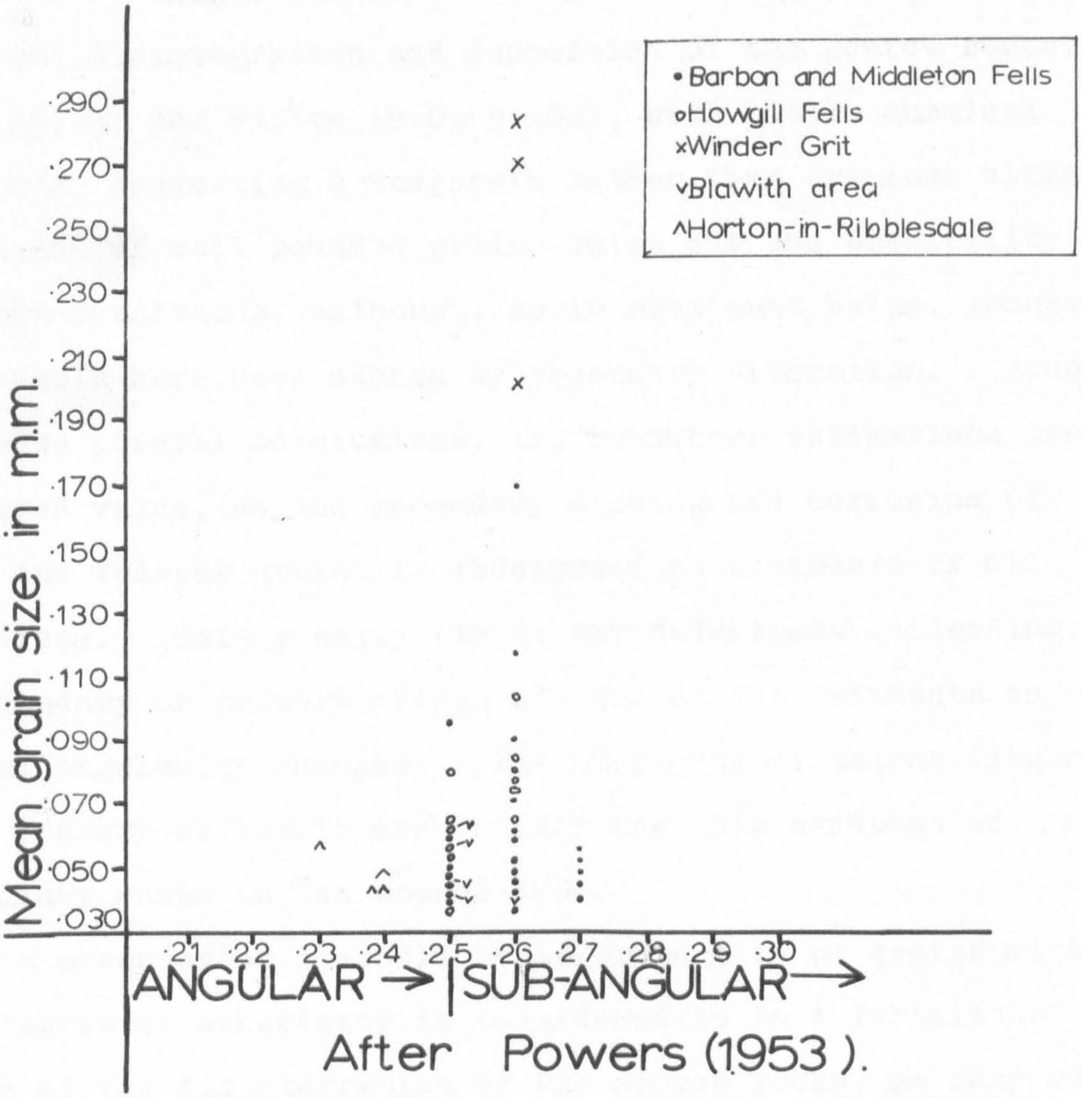



FIG. 6-4. The relationship between grain size and roundness.

on either side of the mean value of 0.26. Grains of high sphericity are slightly more common than elongated fragments in sediments of all grain sizes.

The sub-angular nature of the grains indicates rapid mechanical disintegration and deposition of the source rocks, (c.f. Bassett and Walton 1960, p.102), with little chemical weathering, suggesting a temperate rather than tropical climate. The absence of well rounded grains rules out the possibility of desert conditions, although, as is mentioned below, rounded grains could have been etched by secondary alteration. Apart from these general conclusions, the roundness estimations are of limited value, as the secondary etching and corrosion of quartz and felspar grains is widespread on sediments of all grain sizes. This greatly limits any deductions concerning the secondary or primary origin of some of the sediments in terms of angularity changes. The chert and siltstone fragments in the coarser sediments are in fact the only evidence of sedimentary rocks in the source area.

The presence of a considerable proportion of grains with a low degree of sphericity is considered to be a fortuitous feature of the disintegration of the source rocks, as many of them have identical optical properties to the more spherical fragments. A small number of the elongated quartz grains which show undulose extinction may possibly be of metamorphic origin, but as mentioned previously, this feature is of very limited value (Blatt and Christie 1963).

(ii) Comparison with adjacent areas

The mean values obtained from the specimens analysed from the Howgill Fells, and the Blawith and Horton-in-Ribblesdale areas, are shown in table 9 below. (The full analyses are shown in Appendix VI).

| Limits of Class | .12 | .17 | .25 | .35 | .49 | .70 | 1.00 | | |
|---|---|---|---|---|---|---|---|---|---|
| Mid Point | .14 | .21 | .30 | .41 | .59 | .86 | | | |
| | Very Ang. | Ang | Sub Ang | Sub Rnded | Rnded | Well Rnded | % High Sph. | % Low | Mean Round -ness |
| Howgills (12) | 8.4% | 36.0% | 52.0% | 3.6% | - | - | 51% | 49% | 0.25 |
| Howgills Winder G. (3) | 10 % | 35.0% | 47.0% | 8.0% | - | - | 44% | 56% | 0.26 |
| Blawith area (10) | 9.6% | 40.0% | 45.0% | 5.4% | - | - | 52% | 48% | 0.25 |
| Horton-in-R. (4) | 16.5% | 39.0% | 43.5% | 1.0% | - | - | 52% | 48% | 0.24 |

Ang. = Angular
Rnded = Rounded
Sph. = Sphericity

Table 9 .

The specimens from all these areas show close similarities to the greywackes of the Barbon and Middleton Fells. The only difference is a slightly higher proportion of grains within the "very angular" class. This is not thought to be of any significance. The proportions of high and low sphericity grains are also very similar, apart from the coarse Winder Grit, where elongated grains are more abundant. No significance is attached to this feature, however, as the optical properties of these elongated grains are identical to other more spherical fragments, and their breakdown would probably yield a number of smaller grains of high sphericity.

These similarities once again indicate that conditions of deposition were almost identical over wide areas of north-west England. The general sub-angular nature of the sediments suggests that mechanical disintegration of the source rocks was widespread, followed by a rapid phase of deposition, and then transport and ré-deposition by turbidity currents. The period of transport was too short to allow the grains to become rounded, and thus according to Folk (1951), the sediments are immature.

## General Conclusions

(1) The greywackes of the Barbon and Middleton Fells fall predominantly within the coarse silt to fine sand grade. Only at one or two isolated horizons were coarse sandstone or grit grade sediments deposited.

(2) In the Howgill Fells to the north, the mean grain size of the sediments is somewhat coarser. This, combined with the presence of giant flute casts suggests more turbulent conditions, perhaps brought about by a steepening of the sea floor in this area.

(3) The sediments contain appreciable quantities of sand, silt and clay together, and are thus poorly sorted. Variations in the degree of sorting between the Barbon and Middleton Fells and adjacent areas, are considered to be a result of variations in the strength of the turbidity currents.

(4) The composition of the greywackes is affected by changes in grain size. An increase in grain size results in a rise in the percentage of rock fragments, and a fall in the percentage of quartz and matrix.

(5) The definition of the term greywacke states that these rocks are coarse grained. In this respect the Silurian greywackes of north-western England are, with a few exceptions, atypical, even though the composition satisfies the mineralogical criterion. The Coniston Grits do in fact appear to compare closely with the greywacke siltstones described by Warren (1963), from the Hawick area.

(6) The predominantly sub-angular nature of the sediments indicates rapid mechanical disintegration of the source rocks, followed by a short phase of transport and deposition by turbidity currents.

# CHAPTER 7

## THE FINE GRAINED SEDIMENTS

### Introduction

The coarse sediments described in the previous two chapters indicate that strong turbidity currents flowed into the area during much of Ludlovian time. This is not the complete picture, however, as finer grained sediments form an appreciable part of the succession, especially in the Wenlockian and upper part of the Ludlow Series. These fine sediments, as previously mentioned in Chapter 5, have been sub-divided into the following types:-

(a) The banded graptolitic siltstone.

(b) The banded units.

(c) The mudstone partings to the graded greywacke beds.

(d) The impure limestones.

In this chapter, the petrography and origin of these fine sediments is described, followed by a discussion of their relationships to the coarser greywackes. Owing to the fine grain size, accurate modal analyses have not been possible, but the mean grain size is in every case, less than 0.030mm.

## (a) The Banded Graptolitic Siltstones

This lithology is basically a grey (N4), banded siltstone, the banding of which is fine enough to give rock surfaces a finely striated appearance, (see figure 3-5). Weathered surfaces, especially in the Ludlow Series, appear yellowish brown (10YR6/2). This is the only lithology in which fossils are preserved. It is common throughout the Silurian succession. It has been described from the Llandovery Series by Rickards (1963), and is predominant in the Wenlock Series. In the Ludlovian, however, it occurs as relatively thin bands in a generally coarse grained succession. There is a slight increase in the grain size of the lithology between the Wenlock and Ludlow Series, but this is not usually discernible in hand specimens. This change, although only slight, is of significance, as it reflects a trend in the Silurian sedimentation and conditions of deposition as a whole, and is discussed more fully in chapter 7, dealing with the conditions of deposition.

### (i) The Mineralogical Composition

Twenty five thin sections of the graptolitic siltstone (S/G/1-25), cut at right angles to the bedding, have been examined, including at least one from each horizon at which the lithology occurs. In addition, a number of sections cut parallel to the bedding have been studied, in order to determine the origin of the dark banding. The composition, like that of the coarser greywackes appears to vary little throughout the succession, and is thus described as a whole.

Quartz is by far the most abundant mineral and occurs in corroded angular to sub-angular grains. The overall fine grained and altered nature of the sediments, however, makes it difficult to distinguish the different varieties.

Felspar is also present, but only in small amounts. Orthoclase is the most abundant type, and is usually highly sericitised or kaolinised. Microcline has not been observed, but a few grains probably do occur. A few grains of plagioclase have also been observed. The fine grain size of the sediment, however, prevents positive identification of the variety.

Some muscovite is present, and occurs as thin flakes arranged parallel or sub-parallel to the bedding. It differs from the abundant sericite by its larger size, and post-depositional bending. The heavy minerals include magnetite and abundant pyrite.

No rock fragments are present in any of the siltstone specimens. This is considered to be a reflection of grain size, however, as rock fragments become increasingly rare in the finer greywackes.

The matrix is abundant, very much more so than in the greywackes, and is composed largely of sericite, chlorite, carbonate and much unidentifiable clayey material. The

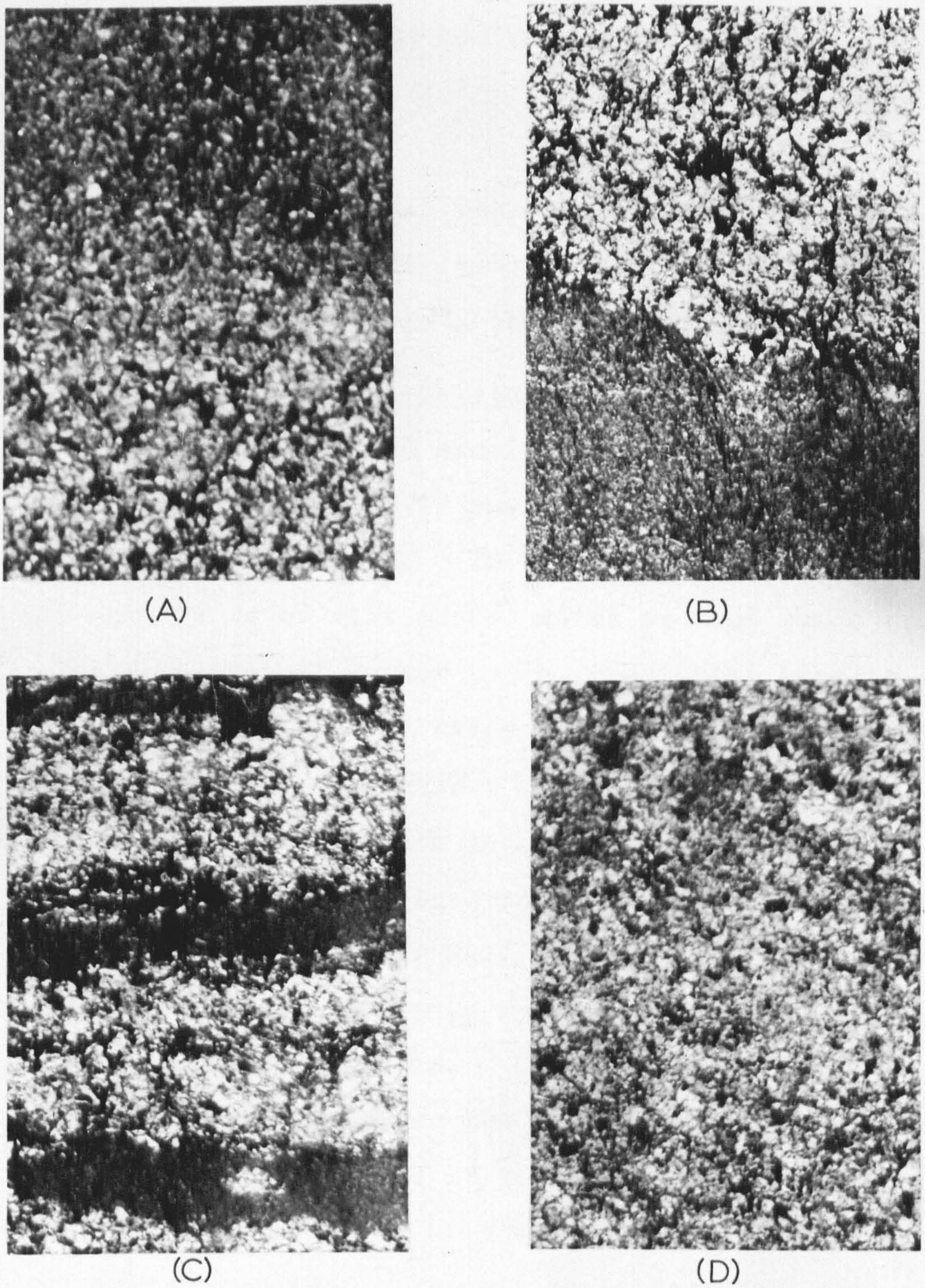



Fig. 7-1. Thin sections of the graptolitic siltstones.
(A) Siltstone lamina grading into mudstone.
(B)(C) Sharply defined alternating silt and mudstone laminae with sole structures (B)
(D) Ungraded Siltstone.
All ×60, unpolarised light.

sericite unlike the muscovite has a random orientation, indicating growth after deposition. The quantity of carbonate is variable.

The mineralogy thus shows many similarities to the finer greywackes, and indeed, it is shown below that the graptolitic siltstones do in fact grade into the fine greywackes.

(ii) <u>The texture and its Origin</u>

As was noted above, hand specimens of the siltstones have a very finely laminated or banded appearance, lighter and darker bands alternating. In thin section, the lighter bands are seen to be of silt grade, which in many cases grade up into the fine grained darker bands, consisting largely of chlorite, sericite and clayey material, (see fig.7-1a). In other cases, (fig.7-1b), there is a sharp junction between the coarse and fine bands, with no grading at all. In a third variety, clay material is altogether absent, the rock being made up entirely of fine silt. In these cases, the dark banding is produced entirely by carbonaceous or pyritic films which are described below. The thickness of the individual laminae in the first two varieties ranges between a ½ and 1mm. The graptolitic siltstones thus show on a micro-scale, all the features of the large scale grading seen in the coarser greywackes. Indeed, these features are reproduced to such an extent, that where a silt lamina overlies the graded clay top to the preceding lamina, sole markings on a micro-scale are often produced, (see figure 7-1).

These features have been described by Kuenen (1953), from coarse greywackes, and he considers them to be a result of deposition from turbidity currents. The fine grain size, small scale graded bedding, and general unsorted texture, suggest that the deposition in this case, however, was achieved by means of slow moving low density turbidity currents, similar to those described by Smith et al (1960), from lake deposits. The mud fraction of each graded lamina may have been partly deposited from suspension over a longer period of time (cf. Kuenen 1951). Cummins (1959), Llewellyn (1963, personal communication), Warren (1963), and Rickards (1964), arrive at similar conclusions.

The similarity of the mineralogy to that of the greywackes, suggests derivation from a similar source. In the absence of palaeocurrent indicators, this is assumed to be, like the greywackes, from the north-west. Carozzi (1957), describes how greywackes can be traced laterally into finer grained sediments, but which still retain the textural features of the coarse sediments. The graptolitic siltstones of the Barbon and Middleton Fells, and adjacent areas, may thus be the lateral equivalents of coarse greywackes. The other possibility is that they represent periods of widespread quieter deposition, when the agents producing large scale turbidity currents were quiescent. It is probable that both factors operated together, as some of the graptolitic siltstone beds can be traced over wide areas, whereas others cannot be traced even for the short distance between the Barbon and Middleton and Howgill Fells.

The graptolitic siltstones thus represent deposition from slow moving low density turbidity currents, which carried only fine grained sediment, but which still produced on a small scale, all the depositional features of a normal turbidity current. These may have originated as low density currents, or may be the lateral equivalents of the high density types.

Superimposed on this micro-grading are very thin irregular films and lenses of opaque material. Rickards (1964) referred to this as carbonaceous material, although he did recognise that some of it was probably formed of pyrites. Under reflected light, much of the banding gives a yellowish metallic lustre, and would thus appear to be largely pyrites. Carbonaceous material does also occur, but the present work indicates that it is not as prevalent as previously supposed. Carbon analyses carried out for Rickards showed in fact, a slightly smaller percentage of carbon in the siltstones than in the greywackes. It is therefore proposed in this work, to refer to these as pyritic films.

This banding is often found at the top or within the finer grained part of the graded laminae. It is by no means restricted to the fine grained material, however. Where it occurs within the silty part of the lamina, it has the

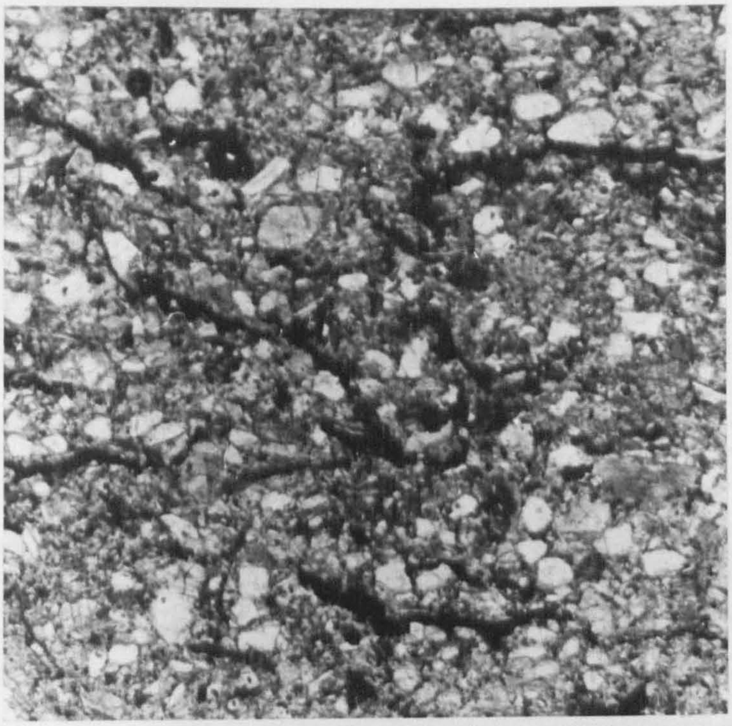


Fig. 7-2. Contorted pyritic films. (black) in a coarse graptolitic siltstone from the Lower Coniston Grits.

X 60 unpolarised light.

appearance of lenses of opaque material wrapped around the mineral grains, (see figure 7-2). (In sections cut parallel to the bedding, the pyritic film has a patchy appearance, due to its contorted nature). It would thus appear to be independent of grain size. This independence suggests that the agents which produced them were completely independent of the clastic sedimentation. There is thus no reason to suppose that the films were deposited only in times of fine or quiet sedimentation. During rapid coarse sedimentation, the original carbonaceous material would be overwhelmed and dispersed, (as would any graptolites). Also, as is discussed in chapter 9, conditions of deposition were probably more aerobic during the turbulent coarse sedimentation, and thus the carbonaceous material and iron compounds would also tend to be oxidised, rather than reduced to pyrites. Evidence that the films were deposited during periods of coarse deposition, is seen in a specimen from the Fell Road section of the Lower Coniston Grits, (Bed LCG 10). This bed has been classified as a graptolitic siltstone only by reason of its dark banding, and its fineness in comparison to the under and overlying greywackes. As figure 7-3 shows, this bed could easily be taken for a fine greywacke, but for the presence of the pyritic films.

The pyritic films and lenses have been proved to be independent of the silt and mudstone sedimentation, and thus their origin must be sought for elsewhere. Although the


Fig. 7-3. Pyritic films developed in fine greywacke, indicating a transition from greywacke to graptolitic siltstone. (Bed LCG 10, L. Con. Grits.)

so called carbonaceous material has been shown to be largely pyrites, its origin is still probably organic, and has been produced by the breakdown of organic material and iron compounds by bacteria under anaerobic bottom conditions, similar to those described by Wills (1922), and Zobell (1942). The carbonaceous material which is present probably represents the unaltered remains of this organic matter. Rickards (1964) considered this "carbonaceous" material to have been produced from algae, which lived in the surface waters, and the death of which was possibly an annual feature, thus producing annual films in the sediment. A second possibility was that the films were produced by periodic influxes of algae into the area, but which was not necessarily an annual feature. This would hardly produce the very regular banding seen in the siltstones, however. Jones (1954), Cummins (1959) and Llewellyn (1960) considered that the "carbonaceous" banding probably arose from the reworking of the mud immediately after deposition by worms, and that the banding was in fact compressed faecal pellets. Figure 7-4, however, shows that the effect of worms is to destroy the banding, which is in accordance with the work of Moor and Scruton (1957). This showed that the progressive activity of worms in recent sediments produces a series of stages between completely undisturbed banding and a completely homogenous mudstone. The possibility of the pyritic films being of secondary origin can be discounted, by the discovery of an orthoceras

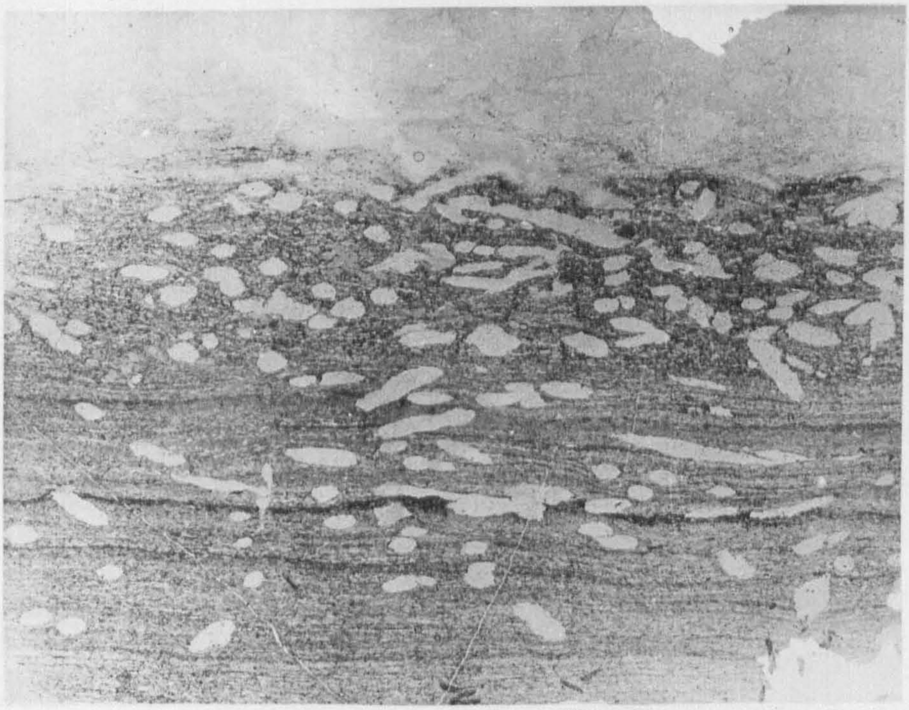


Fig. 7-4. The destruction of the dark banding in mudstone by the action of burrowing worms. For full explanation see text.
(×2, unpolarised light.)

embedded in the siltstone. The shell has fallen on to the unconsolidated sediment and sunk in to a depth of 14mm, depressing all the laminae around it, as shown in figure 7-5. Later sediment has been deposited evenly around the projecting portion of the shell. The depression of the laminae by this shell almost certainly indicates that they are a primary depositional feature. The shell also provides further evidence of quiet conditions of deposition, as strong turbidity currents flowing against the projecting part would have dislodged it. The first possibility mentioned by Rickards, that the films are an annual feature produced by the death of algae, thus seems the most plausible explanation. Furthermore, recent evidence of this type of sedimentation has been provided by Archangelsky (1927), who has shown that the periodic sedimentation of mud rich in organic matter, in the Black Sea, is dependent on the death of the plankton every winter.

As the pyritic films thus appear to be of an annual origin, the possibility arises of using them to deduce the period of time taken to deposit each bed of graptolitic siltstone. Rickards (1964, p.438), implies that Marr (1927), and Cope (1955), used this method to date banded siltstones. These workers, however, did not count the pyritic films, but the alternating silt and mudstone laminae. These they considered to represent dry and wet seasons, and thus one siltstone and one mudstone lamina accounted for one year's

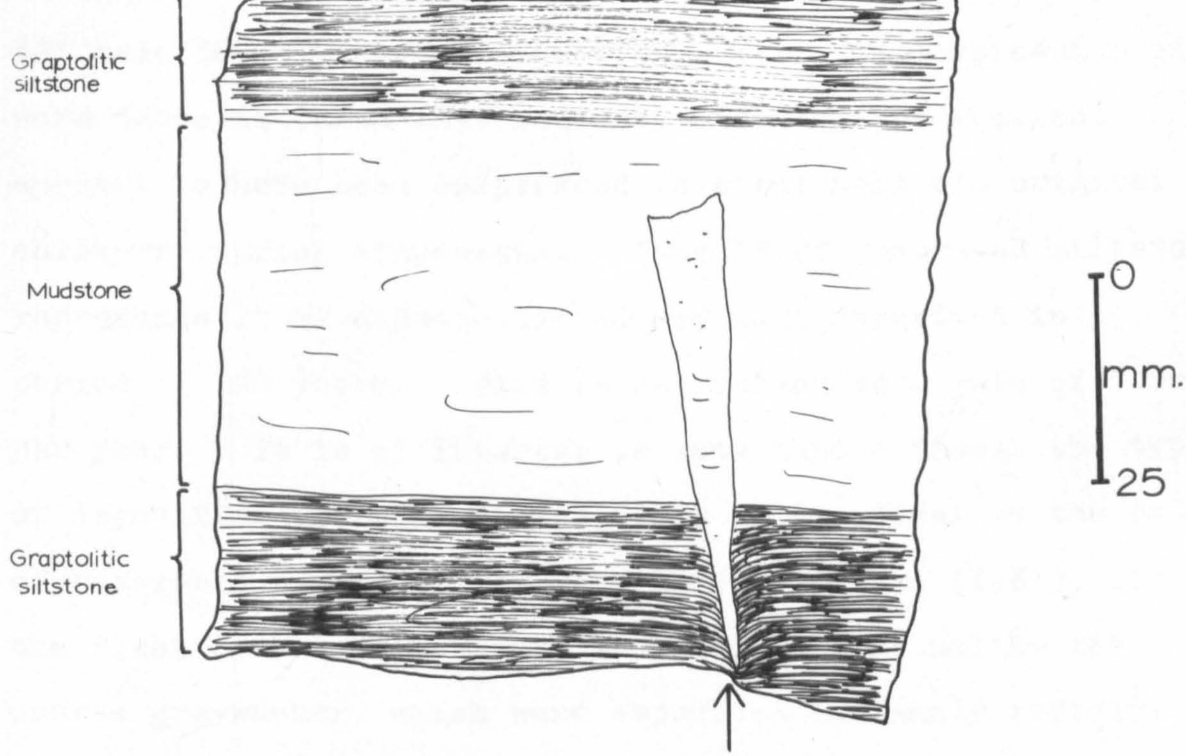



FIG. 7-5. Sketch of the depression of graptolitic siltstone laminae by an orthoceratid.

deposition. As was shown on page 141, however, the deposition of the sediment can no longer be considered to be a climatic feature. Counting of the pyritic bands reveals that their density is variable. Accurate counting is extremely difficult, however, as the bands are very much contorted, and lens into one another, but a figure in the order of 100 bands per inch has been estimated for some horizons. This implies that 1 inch of siltstone is equivalent to 100 years, and a 30' bed, 36000 years of deposition. If the compression of worm tubes is taken into account, however, the sediment appears to have been compressed to about half its original thickness during diagenesis. Thus 1" of indurated siltstone represents 2" of unconsolidated sediment deposited in a period of 100 years. This is equivalent to a rate of 0.5mm per year. It is of interest to note that although the types of deposition probably differ, this is identical to the rate of anaerobic sedimentation described by Dunham (1961), from the Black Sea. This figure is plausible, as unlike the coarse greywackes, which were deposited extremely rapidly, the graptolitic siltstones have been shown to be the result of comparatively slow deposition, by low grade turbidity currents, perhaps partly during periods of general quiescence, when the currents were small and intermittent. There are so many unknowns and possible sources of inaccuracy in this method, however, that it is not proposed to extend these estimations further.

The opaque pyritic films which are preserved only in the graptolitic siltstones, are thus considered to represent the remains of organic matter, with which graptolites may possibly have been associated. The evidence suggests that these films are of an annual origin, but are not consistent and regular enough to be used for accurate dating. Their absence in the coarse greywackes probably results from the extremely rapid and turbulent deposition completely overwhelming and oxidising the minute amounts of organic matter. This also accounts for the absence of graptolites in the greywackes.

(iii) <u>The occurrence of this Lithology in other areas.</u>

The graptolitic siltstones have been described under various names from different parts of the Lake District by Marr (1927), Llewellyn (1960), Norman (1961) and others. In addition, Rickards (1963, 1964), described in detail, the occurrence and origin of this lithology in the Howgill Fells. Examination of a number of thin sections from these areas show the lithology to be identical with that described from the Barbon and Middleton Fells. The graptolitic siltstones thus indicate that conditions of deposition were similar over wide areas of north-western England. This lithology has also been described by Cope (1955), from Central Ireland, by Cummins (1959), from North Wales, and by Warren (1963), from the Southern Uplands. Thus the siltstones were not restricted to the Lake District area of deposition, but indicate that low grade turbidity currents were a widespread means of sedimentation throughout the Silurian geosyncline. This evidence is discussed further in chapter 9 , dealing with the conditions of deposition as a whole.

(b) The Banded Units

(i) The Mineralogy and Texture

This lithology, as described in chapter 3, page 31 , consists essentially of interbedded laminae of banded graptolitic siltstone, and unbanded mudstone, with a predominant grey colour (N4). It is restricted entirely to the Ludlow Series, and is predominant in the Bannisdale Slates, where it forms almost the entire succession. It also occurs widely in the Lower Bannisdale Slates and Middle Coniston Grits, and at a few thinner horizons in the Lower and Upper Coniston Grits. In the Lower Coniston Grits, the graptolitic siltstone laminae are thicker than the unbanded mudstone (fig. 7-6a). Rising through the succession, however, the siltstone laminae become progressively thinner, and the mudstone laminae thicker, until in the Bannisdale Slates its typical development is seen (fig. 7-6b), in which the silt laminae are usually about 7mm thick, and the mudstones 15-20mm in thickness. The alternating laminae give rock faces a characteristic banded and sometimes flaggy appearance,

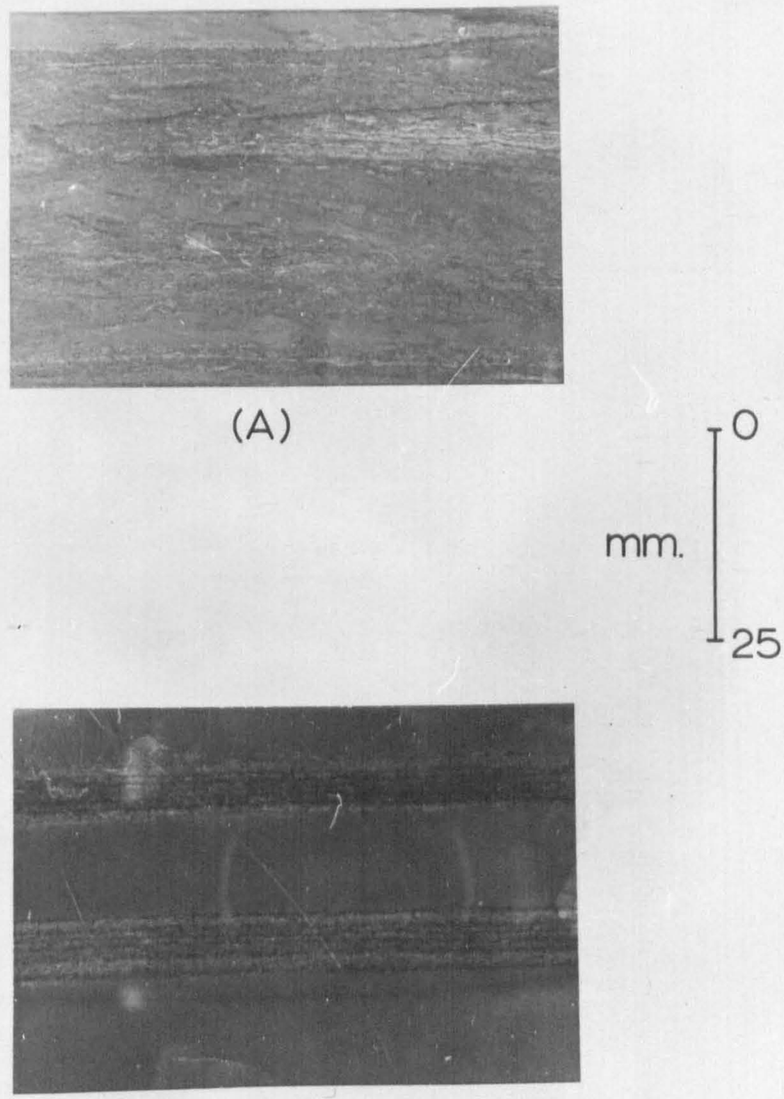



Fig. 7-6. (A) Banded Unit from the Lower Coniston Grits.
(B) Banded Unit from the Lower Bannisdale Slates.

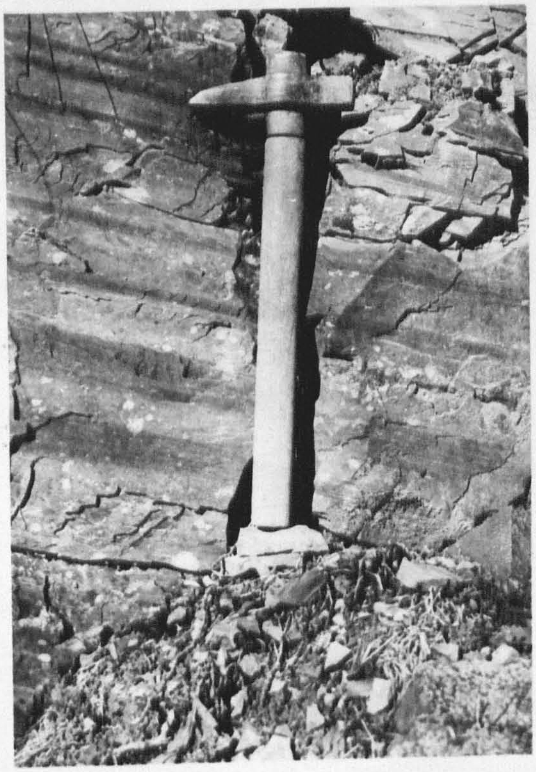


FIG. 7-7 The characteristic appearance of the Banded Unit lithology.

especially where selective weathering has occurred; hence the name banded units, (figure 7-7 ).

Examination of 20 thin sections of the banded unit lithology shows that the mineralogy of the siltstone laminae is identical to that of the normal graptolitic siltstones described above. The micro-grading, pyritic films, and general texture are also similar, indicating that the coarse laminae at least, originated by deposition from low grade turbidity currents. The mudstone laminae, are made up of finely divided chlorite and clayey material. They compare closely with the fine tops to the micro-graded units in the siltstone beds, and appear to be a development of them.

(ii) <u>The Origin of the Banded Units</u>

Rickards (1964), considered that the mudstone laminae were produced as a result of the reworking of banded graptolitic siltstone by burrowing worms, in the manner described by Moor and Scruton (1957), the end product of which is a homogeneous sediment. The pyritic banding is undoubtedly destroyed by the action of worms as shown in figure 7-4, but only when it occurs in fine mudstone. In the siltstone laminae, the worms appear to be only partly able to destroy the banding, the result being a mixed mottled sediment in which fragments of the pyritic film can still be seen. The mudstone tops to the siltstone laminae are considered to reflect the final deposition from a dying turbidity current, or perhaps even deposition from the muddy suspension left after the passage of the current. The distinct mudstone laminae found within the banded units are a further development of this type of sedimentation, and reflect the increasing dominance of quiescent conditions, in which turbidity currents were only of intermittent importance. The absence of the opaque pyritic films within the mudstone laminae does not mean that they were not deposited, or formed. As shown above, worms are able to destroy these films, but only when they are deposited within fine mud. Thus, it is considered that the films were originally deposited along with the mud as carbonaceous matter, but were in the majority of cases, quickly and completely destroyed by the action of worms, before pyrites could be formed, leaving a fine unbanded mudstone. Slow deposition would allow this process to take place easily and completely. Pyritic films are found within the mudstone tops of the graded siltstone laminae, however, but in this case, the mud bands are probably too thin and closely associated with the siltstone for the worms to be able to destroy them. The progressive development of this lithology through the succession is discussed further in the chapter dealing with the conditions of deposition as a whole.

The banded units, like the graptolitic siltstones also occur in the Howgill Fells, and the Lake District, and Cummins (1959), has described this lithology from the

Nantglyn Flags of Denbighshire. This is again evidence of widespread similarities in the conditions of deposition.

(c) The Mudstone Partings to the Greywacke Beds.

These are extremely fine grained dark grey mudstones (N3-4), occurring usually as the graded top to individual coarse greywacke beds. In other cases, there is a sharp junction between the mudstone and underlying greywacke. The mudstone bands, which rarely exceed 6 inches in thickness, are thus part of the greywacke sequence, but are considered here in view of their fine grain size.

In thin section, the mudstone as expected, is seen to be formed of clay minerals with a similar appearance to the mudstone laminae in the banded units. The origin of the mud is obviously from the fine grained tails of the high density turbidity currents which deposited the greywackes. The lack of structure or evidence of organic remains, however, suggests that unlike the mudstones in the banded units, these muds were deposited rapidly. So rapidly in fact, that carbonaceous material would be completely overwhelmed and scattered through the entire thickness of the bed. It would thus be a poor source of food supply for burrowing worms, and in any case, the succeeding coarse sediment was probably deposited before organic activity had fully developed. This lithology also, is common in other areas of greywacke sedimentation.

(d) <u>The Impure Limestones.</u>

In the Barbon and Middleton Fells, limestones are restricted to the bipartite bed at the base of the Ludlow Series. The limestone is exceedingly impure, and contains a high proportion of clayey and silty material. In the Howgill Fells, it is found weathered to a brown rottenstone in several localities, in which trilobites are abundant. Its deposition indicates the development of s omewhat clearer water conditions for a short time after the muddy and silty Wenlockian sedimentation, and before the coarse grained turbulent Ludlovian sedimentation. The abundance of shelly fossils in this limestone in the Howgill Fells (Rickards 1963), is an indication that the water became comparatively oxygenated, after the anaerobic conditions of the earlier part of the Silurian. This is a gain evidence of the gradual change in conditions of deposition, and is considered further in chapter 9 .

<u>General Conclusions</u>

(1) The graptolitic siltstones are formed largely of very thin alternating laminae of silt and mudstone, many of which exhibit grading on a microscopic scale. Only in this lithology are fossils preserved.

(2) The mineralogy and texture suggests a similar source and mode of deposition to the coarser greywackes. The fine grain size, however, is indicative of weaker

turbidity currents. It is thus concluded that the graptolitic siltstones represent deposition from low density turbidity currents, which carried only fine sediment. These may have originated as low density currents, or may be the lateral equivalents of the high density type.

(3) Superimposed on this micro-grading are thin contorted films of pyrites, which probably originated as carbonaceous material. These films are independent of the normal sedimentation, but are definitely primary, and may thus be of an annual origin.

(4) It is possible to use these pyritic films, assuming that they are of an annual origin, to deduce the rate of sedimentation. A plausible answer of 2 inches of unconsolidated sediment in 100 years is obtained, and if true, is further evidence that the sediments were deposited largely in quiescent periods when the currents were small and intermittent. There are so many unknown factors, however, that the estimations have not been extended further.

(5) The banded units consist essentially of alternations of graptolitic siltstone lithology, with unbanded mudstone laminae, which slowly increase in thickness as the higher parts of the succession are reached.

This lithology is considered to represent increasingly quiescent conditions of deposition.

(6) Originally, carbonaceous or pyritic material was probably present in the mudstone laminae, but its absence in the consolidated sediment is thought to result from the fine grain size allowing the sediment to be easily reworked by burrowing worms. In the coarser silts, the films are at the most, only partially destroyed, indicating that the worms could only operate effectively in fine sediment.

(7) The mudstone partings to the coarse greywacke beds, however, are thought to represent comparatively rapid deposition from the tail of a high density turbidity current.

(8) The impure limestones at the base of the Ludlow Series represent a temporary phase of somewhat more aerated water conditions.

(9) All these lithologies are common in Silurian strata in other parts of the country, and thus indicate widespread similarities in the conditions of deposition.

# CHAPTER 8

# SEDIMENTARY STRUCTURES

## (a) Introduction

The description and discussion of the mineralogy of the greywackes in chapter 5 indicated that the coarse sediments at least, appeared to have been derived from an area formed largely of volcanic rocks and beds of chert. Rocks of this type are common in the northern belt of the Southern Uplands, and fragments of them are found in some of the Silurian greywackes of southern Scotland. It was thus concluded that the Coniston Grits of the Barbon and Middleton Fells, and the Lake District, were derived from these rocks, and deposited by turbidity currents which flowed into the area from the north-west. In this chapter, the evidence from sedimentary structures is examined to see if it is possible to confirm this theory. In this respect, flute markings which act as current indicators, provide valuable evidence.

The structures of all types are most abundant in the coarse greywackes, but also occur commonly on a microscopic scale in the graptolitic siltstones. In the mudstone tops of the greywacke beds, however, the only structures are the flute markings scoured by the succeeding turbidity current.

(b) Depositional Structures

Depositional structures include graded bedding, current bedding, laminated bedding and the preferred orientation of the individual grains. The structures are abundant in almost all areas of turbidity current deposition, and have attracted a good deal of attention, especially in recent years. Among the more important works on the subject are those by Kuenen (1938, 1953), Kuenen and Migliorini (1950), Ksiazkiewicz (1954), Walton (1956), Cummins (1957, 1959), Wood and Smith (1959), Sanders (1960), Bouma (1962), and Lombard (1963). In the following pages, the structures described by these authors, and their mode of origin, are compared with similar features from the Barbon and Middleton Fells.

(i) Graded Bedding

Normal graded bedding, characterised by a continuous upward decrease in grain size, is not usually obvious in the coarse greywacke units, due to the overall change in grain size from bottom to top of each bed being only slight. A series of thin sections from different parts of the bed, however, show a slight but continuous decrease in grain size upwards. The coarser greywackes low down in the Coniston Grits of the Barbon and Middleton Fells, and the Winder Grit of the Howgill Fells, however, show grading to a rather greater extent, as the overall decrease in grain size through the beds is much greater. One notable feature of graded bedding, is that the degree of sorting of the sediment is affected to only a limited extent. Thus even though the beds grade from coarse to fine, there is still a wide range of individual grain sizes at any one horizon, except in the finest mudstones. Graded bedding of the normal type is much more apparent, however, in the graptolitic siltstones. Thin sections of this lithology, as described in chapter 7, contain numerous individual laminae which grade from silt up into fine mudstone over a thickness of ½ to 1mm (see figure 7-1a).

Delayed grading (Walton 1956), is much more common and noticeable throughout the Coniston Grits. In this type the grain size of the greywacke bed remains constant through almost the entire thickness of the bed, which may vary from 3 to 10 feet. The last 15-30cm of the bed, however, show a rapid grading up into fine grained mudstone, which separates the bed from the succeeding coarse greywacke. Although common at all horizons in the Coniston Grits, this type is particularly well developed low down in the Lower Coniston Grits, on the hillsides north of Leck Beck (647780). This type of grading is not seen in the graptolitic siltstones owing to the extreme thinness of the individual laminae.

Multiple and reversed grading (Kuenen 1953, fig 1D, Walton 1956), are common particularly in the thinly bedded greywacke units of the Middle Coniston Grits and Lower

Bannisdale Slates. Individual consecutive beds grade from coarse to fine through a thickness of 10-15cm. Sometimes each lamina can be distinguished by a definite fine grained top which forms a bedding plane. In many cases, however, laminae 30-40cm in thickness begin to grade into fine sediment, and then show a reversal to coarse grained sediment, without a distinctive junction. Sometimes this reversal of the grading is very sudden, taking place in 4 or 5mm, and at other times is much more gradual. Superimposed on this type of grading, there is sometimes an overall grading through the entire unit, from coarse to fine, similar to that described by Wood and Smith (1958). Overall grading is also common in the thick greywacke units of the Lower and Upper Coniston Grits. Individual beds show normal or delayed grading, but through the unit as a whole, which may have a thickness of 200 feet, there is a definite overall decrease in grain size upwards.

(ii) <u>The significance of the Graded Bedding</u>

The graded greywackes of the Barbon and Middleton Fells show almost all of the features described by Kuenen (1953,fig.1), which were considered by him to be indicative of deposition from turbidity currents in deep water at a long distance from the source. Variations in the type of graded bedding can thus be taken to reflect variations in the type and strength of these turbidity currents.

Normal graded bedding indicates the passage of a current which is slowly losing speed and strength. The powerful nose of the current carries a concentration of the coarser grade sediments, and thus the base of the graded bed contains a high proportion of coarse material, along with silt and mud. The succeeding parts of the current become progressively weaker, and are thus unable to carry, or have already deposited the largest grains. Finally, the weak tail is able to carry only silt and mud sized sediment, which is deposited at a slower rate. Thus the current leaves behind a bed of sediment grading from coarse into fine, but which is poorly sorted, as at any one horizon there is a wide range in the size of individual grains. As described above, normal grading is fairly common in the Barbon and Middleton Fells, especially on a microscopic scale in the graptolitic siltstones. Its comparatively poor development in the greywackes indicates perhaps, that the speed of the currents was fairly constant in this area, and that much of the finest sediment passed over in suspension to be deposited elsewhere. The abundance of this type of grading in the graptolitic siltstones, however, reflects deposition from numerous low grade currents. These may represent the dying tails of high density currents which had deposited their coarse sediment elsewhere (as mentioned in chapter 7), or may have been small features throughout their existence.

The delayed grading which is well developed in the Lower Coniston Grits, is considered by Kuenen (1953 p.1050) to represent deposition from a turbidity current with a uniform long continued supply. The deposition from this type of current would be expected to be widespread. This is confirmed by the correlations described in chapter 3, which show that individual units of the Lower Coniston Grits in the Barbon and Middleton Fells, have almost their exact equivalents in the Howgill Fells.

The multiple and reversed grading, common in the Middle Coniston Grits and Lower Bannisdale Slates, is considered by Kuenen to be indicative of deposition from successive pulses and tongues of the same turbidity current. The overall grading through units of this type suggests that this is in fact the case. The sediments deposited from currents of this type would be expected to show rather more variation over comparatively short distances. Comparisons between the Barbon and Middleton and Howgill Fells show this to be the case.

The graded bedding of the Barbon and Middleton Fells thus shows that the turbidity currents which flowed into the area were variable in nature. The deposition of the coarser sediments appears to have been carried out largely by comparatively long, continuous, and uniform currents, resulting in delayed grading, and poorly developed normal grading. At other times, however, the currents appear to have flowed in a series of pulses or waves, resulting in multiple and reversed grading. The finer grained sediment was deposited from weak currents which may have been the lateral equivalents of the above types, or, as described in chapter 7, may represent periods of general quiescence.

(iii) Current and Laminated Bedding

Current Bedding is extremely rare in the Barbon and Middleton Fells, and is restricted to some of the thinly bedded fine greywackes in the Upper Coniston Grits. It is never developed on a scale large enough to be measured accurately. General estimations from a few localities in Millhouse Beck, one of the few sections where current bedding is exposed, indicate the passage of currents from north-west to south-east. The current bedding appears to infill small irregularities in the earlier sediments, similar to those described by Kuenen (1953, p.1051). These irregularities have probably been produced by locally concentrated turbulence within the currents, the development of which could possibly lead to fluting.

Laminated Bedding (see figure 8-1) is rather more abundant, but again only in the upper part of the fine silty greywackes. Thin sections reveal that the laminae are made up of alternations of coarse and fine material, 1-5mm in thickness, some of which are graded. This laminated bedding does in fact resemble the graptolitic siltstones on a somewhat larger scale, except that the pyritic banding is usually absent. In Millhouse Beck, however, examples of this structure containing pyritic films have been discovered. The

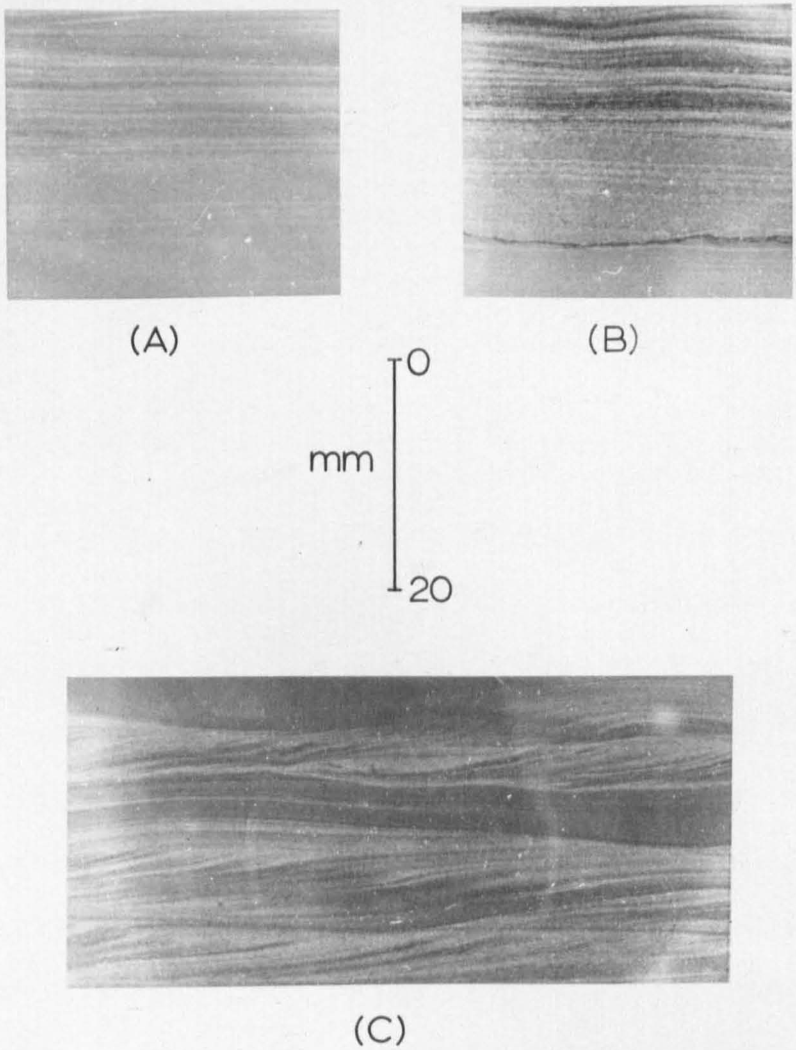



Fig. 8-1. (A) Laminated bedding in very fine greywacke.

(B) Laminated bedding emphasised by pyritic films.

(C) Combination of current and laminated bedding.

All specimens from Millhouse Beck locality.

restriction of this laminated bedding to the finest greywackes, and the similarity of its texture to the graptolitic siltstones suggests that it has been formed by an almost identical means. This could be small low grade turbidity currents, the lateral equivalents of a fluctuating large current which was producing multiple grading in coarse greywackes elsewhere. In most cases, however, the grain size and rate of deposition have been too great to allow preservation of the pyritic films. The development of this lithology towards the top of the finer greywackes shows beyond doubt that there is a transition between the greywackes and graptolitic siltstones. In normal circumstances this is not seen due to the sharp junction between these two lithologies.

Developing from this planar lamination is asymmetrical lamination, from which is developed convoluted bedding. This association is well developed in several localities, but notably Millhouse Beck, where the laminated and rippled bedding is highly convoluted. It is especially apparent in this section because of the pyritic banding, (figure 8-2), which serves to emphasize the convolutions. This structure has been described by Kuenen (1953, pp. 1056-58), and Williams (1960), and is considered to be a result of deposition on top of slurried rippled sediment. The weight of the overlying sediment contorts and emphasizes irregularities in the surface of deposition, which Sanders(1960),

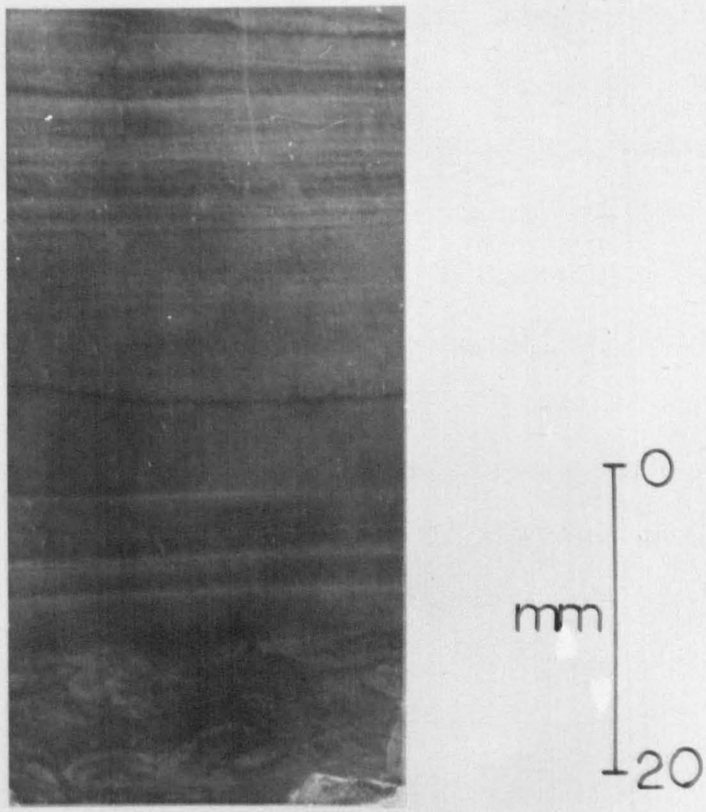



FIG. 8-2. Convoluted bedding overlain by laminated bedding.

considers must be present initially and from which the convolutions are developed. (See also Potter and Pettijohn 1963 p.152.) The marked convoluted nature of the specimens from the Barbon and Middleton Fells, suggests that the sediment was in an extremely slurried state, and almost flowed under the weight of the overlying sediment, rather than form well defined load structures. The formation of load structures, however, is discussed in more detail later in this chapter.

Another depositional feature of the greywackes is the preferred orientation of mineral grains. This shows the sediments to have been deposited by currents, and not by settling (cf Dapples and Rominger 1945), and is brought about by the deposition of grains with their long axes parallel to the current direction, in which position there is least resistance to the current. The long flakes of detrital mica illustrate this orientation extremely well, but it is also apparent to a certain extent with quartz and felspar grains and rock fragments.

The small scale depositional structures indicate that localised turbulence and variation produced features which are superimposed on the overall large scale grading. The laminated bedding represents on a rather larger scale, the type of structures seen in the graptolitic siltstones, but which was formed in a much shorter time.

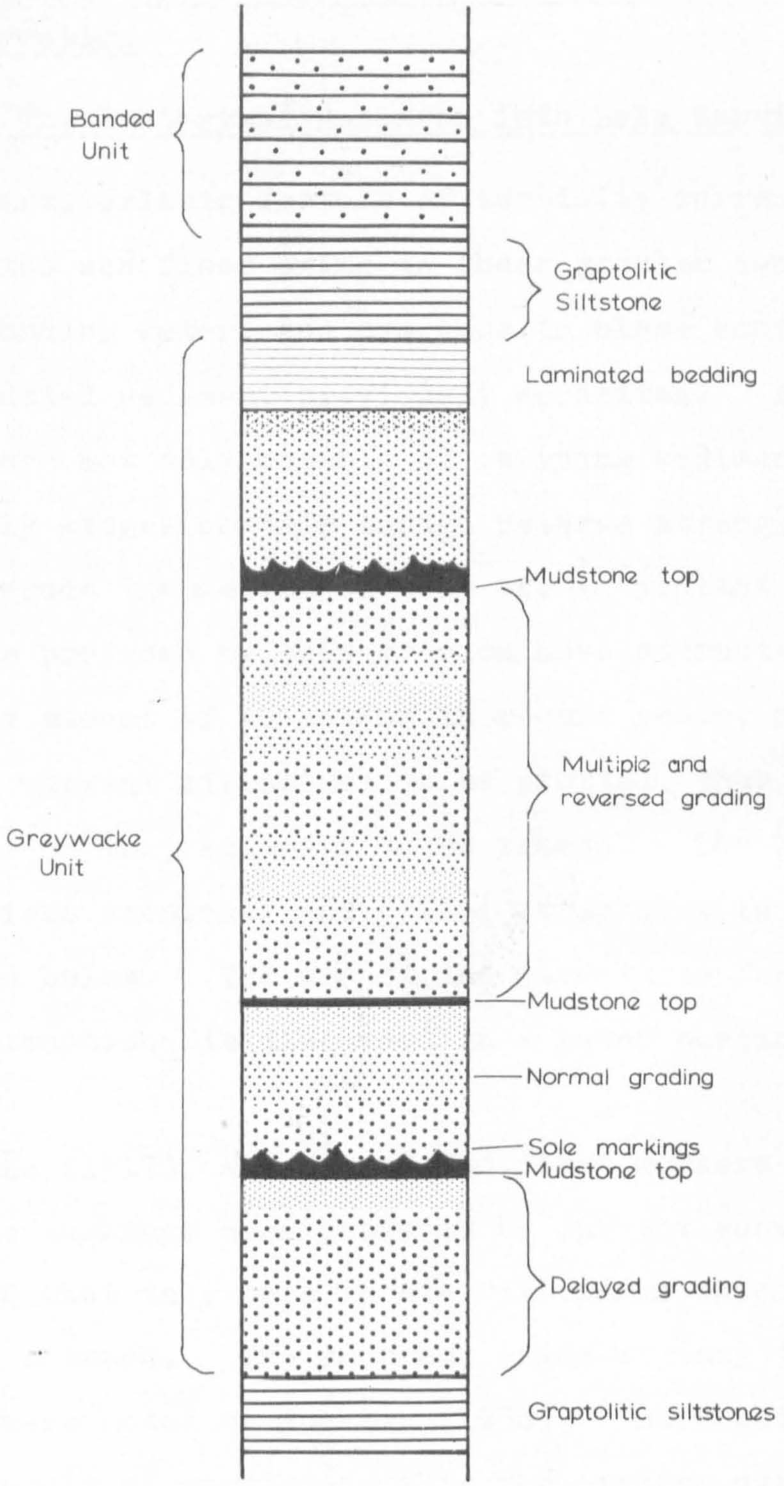



Fig. 8-3. The normal sequence of lithologies within the Ludlow Series.

## (c) Structures due to Erosion and Pre-consolidation Deformation

### (i) The History of Research into Sole Markings

A characteristic feature of turbidity currents is that they hug the sea floor owing to their greater density than the surrounding water, and are thus in close contact with the unconsolidated sediment previously deposited. Powerful currents are not only capable of carrying sediment, but in their early stages contain enough reserve strength to actively erode the sediments they are in contact with. The structures produced by this erosion have attracted a tremendous amount of attention in recent years, as they allow the current directions to be plotted, thus enabling the source of the sediments to be traced. The history of research into erosional and allied structures is briefly summarised below. The use of the structures for plotting current directions is discussed in a later section of this chapter.

Clarke (1917), was one of the first workers to recognise that flute markings were produced by current scour, but he considered that they were lobate rill marks which had been eroded on a beach. The undercut edges of many flute markings were noted by Rucklin (1938). He considered them to be a result of vortices within the eroding currents. This may be partly true, but in many cases is considered to be due to later loading of the unconsolidated sediment. As recently as 1950, flow markings were still being considered in terms of beach erosion. Rich, for example, suggested that some flute markings resemble the gouging developed around a stone on a beach. Kuenen (1953), however, finally proved beyond all doubt that these structures were a result of erosion and infilling by turbidity currents. Polished sections through large flute moulds showed that the largest grains had collected at the bottom of the structure, and that the grains became progressively finer upwards. This grading combined with undistorted current laminations, suggested that the sediment had been deposited from a turbidity current as an infilling of a pre-existing erosional structure. The term flute was proposed by Crowell (1955). He also considered that the turbulent eddies which produce flute markings were influenced by the earth's rotation, so that structures produced in the northern hemisphere were deflected slightly to the right (Coriolis Force). The deviation thus produced should be allowed for, according to Crowell, in plotting current directions. According to Ten Haaf (in Kuenen 1957), however, there is no definite evidence that this deviation takes place.

By 1955, flute and associated markings were generally accepted as being produced by eroding turbidity currents, and thus more recent work has tended to concentrate on the detailed aspects and significance of their formation. Dzulynski and

Radomski (1955), investigated the relationship between the erosion of the structures and their subsequent infilling, and came to the conclusion that they were eroded by one current, and infilled not by later stages of the same one, but by the following current. This theory is not accepted by Kuenen (1957), however, as there is no evidence of infilling of the structures by fine pelagic sediment between one turbidity current and the next. Also, the undercut edges of some flutes are original, and could not have survived unless infilled immediately. Work on the interpretation of flow markings, and their differentiation from structures produced by the loading of water saturated sediment, was carried out by Prentice (1956), and Kelling and Walton (1957). These authors showed that it is possible to distinguish flute moulds from load moulds, and loaded flute moulds by the distortion and cutting of the laminae within the structure. A paper by Kuenen and Prentice (1957), also dealt with this relationship between flute moulds and post-depositional loading. A slightly different aspect was dealt with by Smith (1957), who described directional grooves produced by the propelling of graptolites through mud by an incoming mud flow.

One of the most valuable papers dealing with sole markings was also published in 1957, by Kuenen. In this paper previous work is reviewed and many different types of flute markings are described. The sole markings were classified in terms of their mode of origin, (cf. Vassoevitch 1953), but it was emphasized that they are not necessarily restricted to turbidity current deposits. Further short papers dealing in detail with certain aspects of this work were published by Crowell (1958), Glaessner (1958), and Kuenen and Ten Haaf (1958). Yet another aspect of flute formation was described by Hsu (1959) whose work on the pre-alpine flysch showed that sole markings were much more common in poorly graded turbidity current deposits.

Further varieties of sole markings were described by Craig and Walton (1962), from the Southern Uplands, including a whole series of structures described as "tool marks", and which are produced by the movement of fossils or large grains across mud surfaces in varying manners. An important aspect of this paper was the clarification of the terms cast and mould with regard to sedimentary structures. These authors proposed that the term "mark" should be used to refer to the original structure on the upper surface of the fine grained bed. The term "mould" should be used in reference to the coarse grained infilling of the structure. The use of the term "cast" is wrong. These suggestions have been adopted in the present work, and hereafter "flute mould" refers to the structures developed on the under surface of the infilling coarse beds, usually referred to as "flute casts".

That sole markings really are produced by swirling eddies within turbidity currents, or by the dragging of fossil fragments across the surface of the mud, was proved by

Dzulynski and Walton (1963). In a series of experiments, turbidity currents made up of a suspension of plaster-of-paris in water, were made to flow over a soft "mud" surface formed of china clay or soft gelatine. The turbulent flow could be observed through the perspex sides of a small sedimentation tank, and from below when clear gelatine "mud" was used. Swirling eddies of these turbidity currents could actually be seen to erode and flute the "mud", and the flute moulds produced could be removed after the plaster-of-paris had set. Almost all of the sedimentary structures found preserved in greywackes could be produced by varying the rates of current flow, or by allowing the underlying mud varying lengths of time to settle. (The present writer has re-produced some of these structures in similar experiments). The varying types of structure were produced in 4 zones outwards, starting with flute markings near the source, and passing through furrows and ridges to smooth surfaces at a distance from the source. These experiments, although only qualitative, have resulted in the modification of Vassoevitch's (1953), classification, which was based on the time of origin of the structure. The revised classification is used in the present work, and is as follows:-

Pre-depositional {
- Obstacle scours
- Flute Marks
- Longitudinal Furrows — Tool Marks
- Dendritic Ridges

Frondescent Marks

Post-depositional {
- Flowage Structures
- Load Structures

} Syn- -depositional (Flute Marks to Load Structures)

(ii) <u>The Sole Markings of the Barbon and Middleton Fells</u>

Of the many different types of sole markings listed by Dzulynski and Walton, in their classification, only flute moulds, tool marks or groove moulds, and load structures are found in the Barbon and Middleton Fells. The significance of this in view of the conclusions reached from the experimental sole markings described above, is discussed later.

<u>Flute Moulds</u>

These structures are common throughout the Coniston Grits and Lower Bannisdale Slates and consist of long bulbous structures, the nose of which forms the upcurrent end. Downcurrent from the nose, the structure flares out into the surrounding bedding plane (see figure 8-4). They are found preserved on the basal bedding plane of coarse greywacke beds, where the coarse sediment directly overlies the mudstone top of the preceding bed. They are in fact restricted to this position in the sedimentation sequence, and are never found

FIG. 8-4a. Unloaded Flute Moulds, Millhouse Beck.

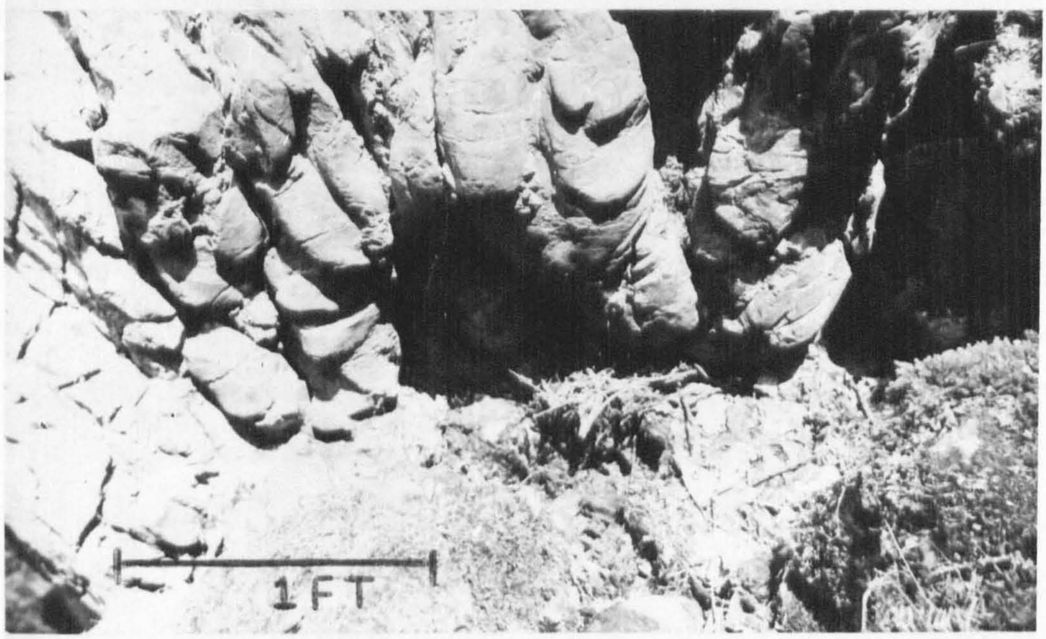



FIG. 8-4b. Loaded Flute Moulds, Millhouse Beck.

within coarse or fine sediments alone. The flutes appear to be equally common throughout the succession. No definite conclusions can be drawn in this respect, however, as exposure of the structures usually results from a fortuitous combination of dip and topography. Wherever conditions of exposure are suitable, flute moulds can usually be found. Localities in which the markings are absent are nearly always unsuitably exposed, i.e. there are no overhanging crags which show the basal bedding planes. The ideal type of exposure is well developed in the Leck Beck area, and in Millhouse Beck, (figure 8-4b), where dozens of the markings have been recorded.

The flute moulds are usually arranged in poorly developed rows or diagonal rows, (figure 8-5), similar to those illustrated by Kuenen (1957 p.237, figs. 4 and 5). A small vortex is commonly developed at the nose or upcurrent end of the structures. The size of the flute moulds throughout the succession is remarkably constant over the entire area. The length of the individual structures is rarely greater or less than 8-10 cms., and the width usually 3-4 cm., just behind the nose, widening gradually towards the tail. The greatest depth, at the nose of the mould, varies between 7 and 12 mm., but is often somewhat greater if post-depositional loading has taken place. Figure 8-4 shows the typical appearance and dimensions of the flute moulds from the Barbon and Middleton Fells.

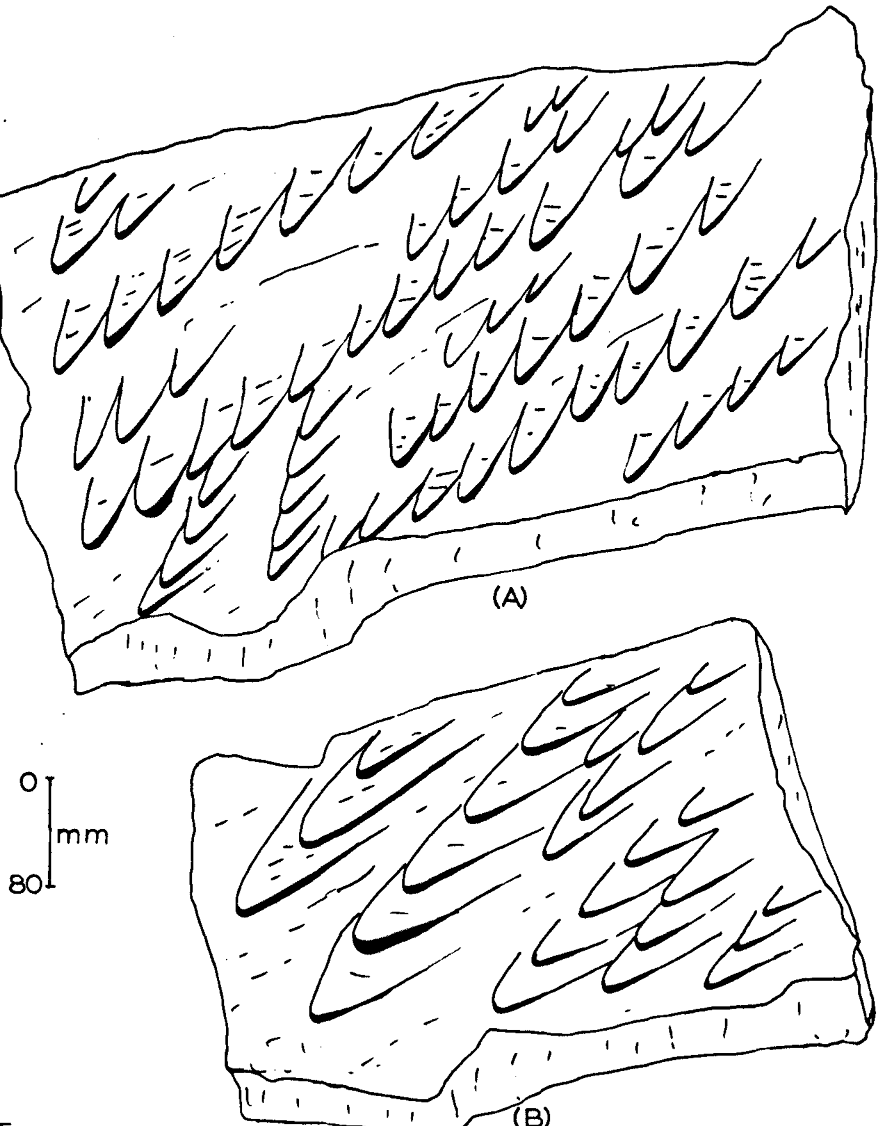



FIG. 8-5.
(A). Flute moulds developed in diagonal rows.
(B). Flute moulds in normal rows.

Groove Moulds

These structures are much rarer, and consist of parallel sided ridges usually 1-2 cm. in width, and 5-6 mm. in depth, cutting across the exposed bedding plane for a distance of 20 cm. or so. Several examples usually occur, however, in each good exposure of flute moulds. They are particularly well developed in the Lower Coniston Grits above Leck Beck, where several bedding planes contain only groove moulds. The stronger turbidity currents which appear to have been developed at this level probably account for the greater abundance of these structures at this horizon. The relationship between the strength of the current and the type of structure produced, and its significance, is mentioned below. In several localities, grooves cutting each other diagonally have been observed (figure 8-6), and indicate the passage of fragments across the mud surface in slightly varying directions. This is probably a result of small eddies producing very localised and slight variations within the general current direction. The greywackes in which the groove moulds are formed often contain large shale pellets, and it is probably these which have cut the grooves.

Load Moulds, and Loaded Flute and Groove Moulds

The deposition of sand on top of an uneven surface of soft, wet, unconsolidated mud, can result in the downwarping of the sand into the mud, as sand is much the denser of the two types of sediment (cf. Hamilton and Menard 1956). The

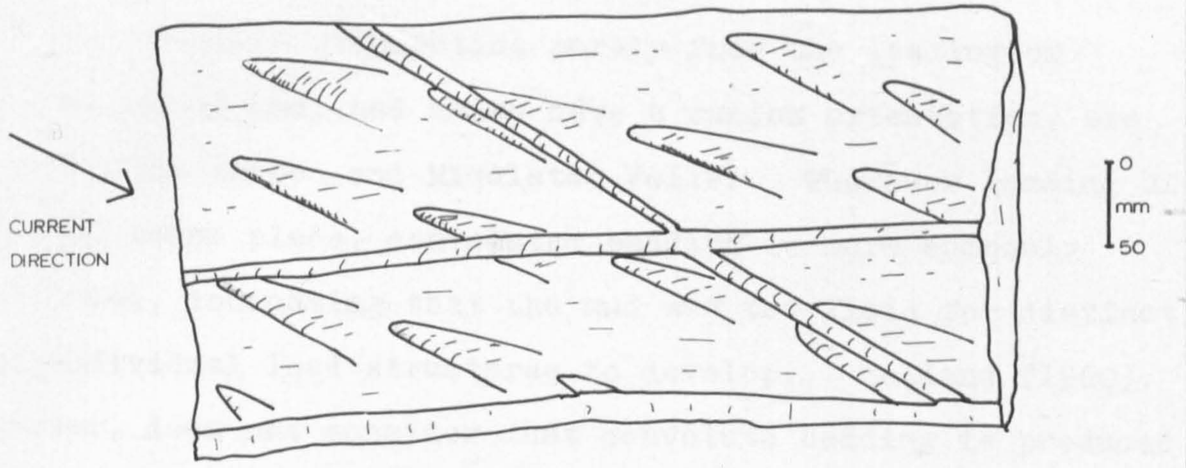



FIG. 8-6. Sketch of the underside of a greywacke bed with groove moulds cutting across flute moulds in two directions.

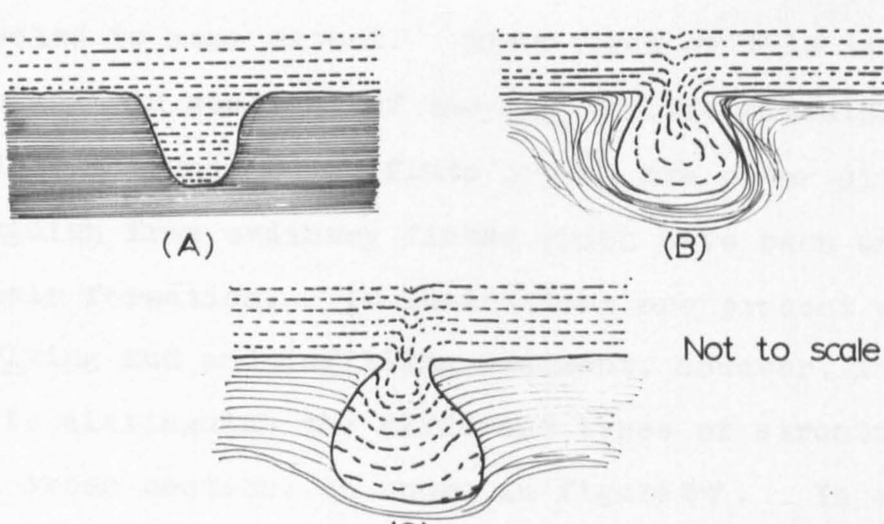



FIG. 8-7: Cross sections of :-
(A). Flute mould.
(B). Load mould.
(C). Loaded flute mould.

resulting structures in the coarse sand are known as load moulds.

Load moulds originating purely from the loading of oversaturated mud, and which have a random orientation, are rare in the Barbon and Middleton Fells. Wherever loading of mud has taken place, convoluted bedding is more commonly developed, indicating that the mud was too fluid for distinct and individual load structures to develop. Holland (1960), however, does not consider that convolute bedding is produced by loading, but that it forms within the sediment itself at the time of deposition. The loading of flute structures before consolidation of the sediment is, however, very common (cf. figure 8-4b), the majority of flute moulds having been affected to some extent. Structures of this type are also seen in thin sections of the graptolitic siltstone.

Load moulds and loaded flute moulds are often difficult to distinguish from ordinary flutes which have been undercut during their formation. If laminations are present within the underlying mud and infilling sediment, however, it is possible to distinguish the different types of structure easily in cross section, as shown in figure 8-7. In a normal flute mould, the laminations in the underlying mud are cut across and are undistorted. The laminae in the coarse sediment infilling the flute are also undisturbed. In an ordinary load mould, the laminae in the underlying mud are contorted, but have not been cut through, and the laminae in the overlying sand are also much contorted. In a loaded flute or groove mould, however, the laminae in the underlying mud have been both cut across and deformed. The overlying sand, as in ordinary load moulds is also contorted, but many of the laminae are cut off at the edge of the structure, showing them to have been deposited initially within the flute. In an ordinary load mould, the laminae in the overlying sand are pressed down into the mud from above, and are thus not cut off at the edges.

Other pre-consolidation deformities include worm burrows and tubes. These structures were described in chapter 7, in the discussion of the origin of the Banded Unit lithology.

(iii) Comparison with the Sole Markings of the Howgill Fells

A survey of the sole markings developed in the Coniston Grits of the Howgill Fells has also been made for comparative purposes. In that area, flute and groove moulds are even more abundant throughout the succession than in the Barbon and Middleton Fells. The flutes are of the same type, and occur in rows and diagonal rows. A significant feature of the structures in this area, however, is their size. Throughout the succession they are larger, and at some horizons (figure 8-8), giant loaded flute moulds, approximately 60 cms. long and 30 cms. wide are developed. These are far larger than anything the writer has seen in the Barbon and Middleton Fells, or indeed in any other part of the country.

FIG. 8-8a.

Giant Flute Moulds from the Howgill Fells.

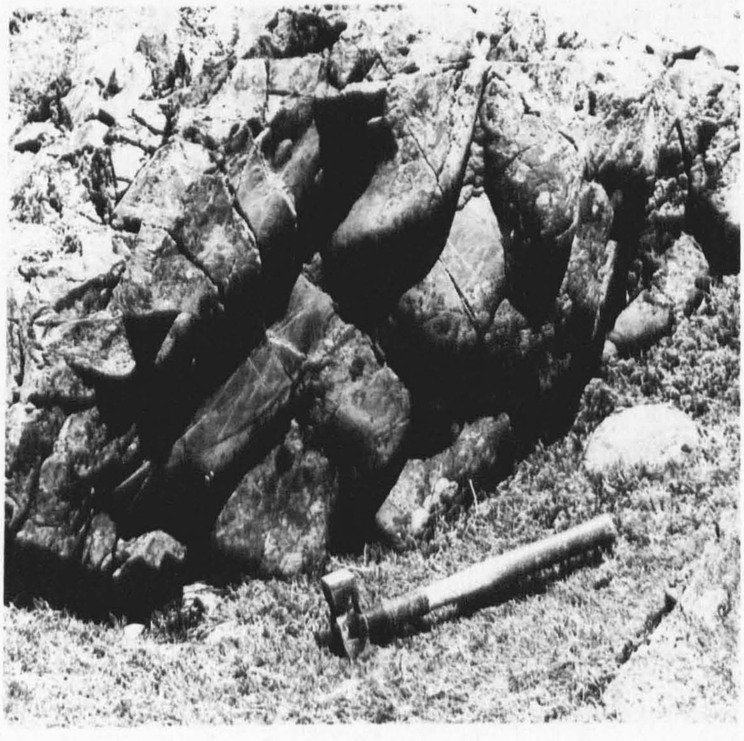


FIG. 8-8b.

Such structures could only have been produced by strong extremely turbulent scouring currents. This general increase in size and abundance of the structures, combined with the coarser nature of the sediments, is considered to be evidence of much stronger turbidity currents in the Howgills. Its significance is considered below.

(iv) The Significance of the Sole Markings

Apart from their value in indicating current directions, which is discussed in the subsequent section of this chapter, the sole markings also give some indication of the type of currents prevailing in the area. Throughout the Barbon and Middleton Fells, the size, type and abundance of flute moulds shows very little variation. This is an indication that the strength and types of turbidity currents crossing the area varied little through the entire succession. Grain size analyses described in chapter 6 also showed little variation, and this was considered to be indicative of uniform conditions throughout a large part of the Ludlow Series in this area. The sole markings thus provide additional support to this theory.

In the Howgill Fells, however, the giant proportions of the flute moulds indicate much more turbulent conditions, perhaps resulting from a steeper geosynclinal slope. This theory of stronger currents finds support in the grain size analyses carried out on greywackes from this area, which showed the sediments to be somewhat coarser than those from the Barbon and Middleton Fells.

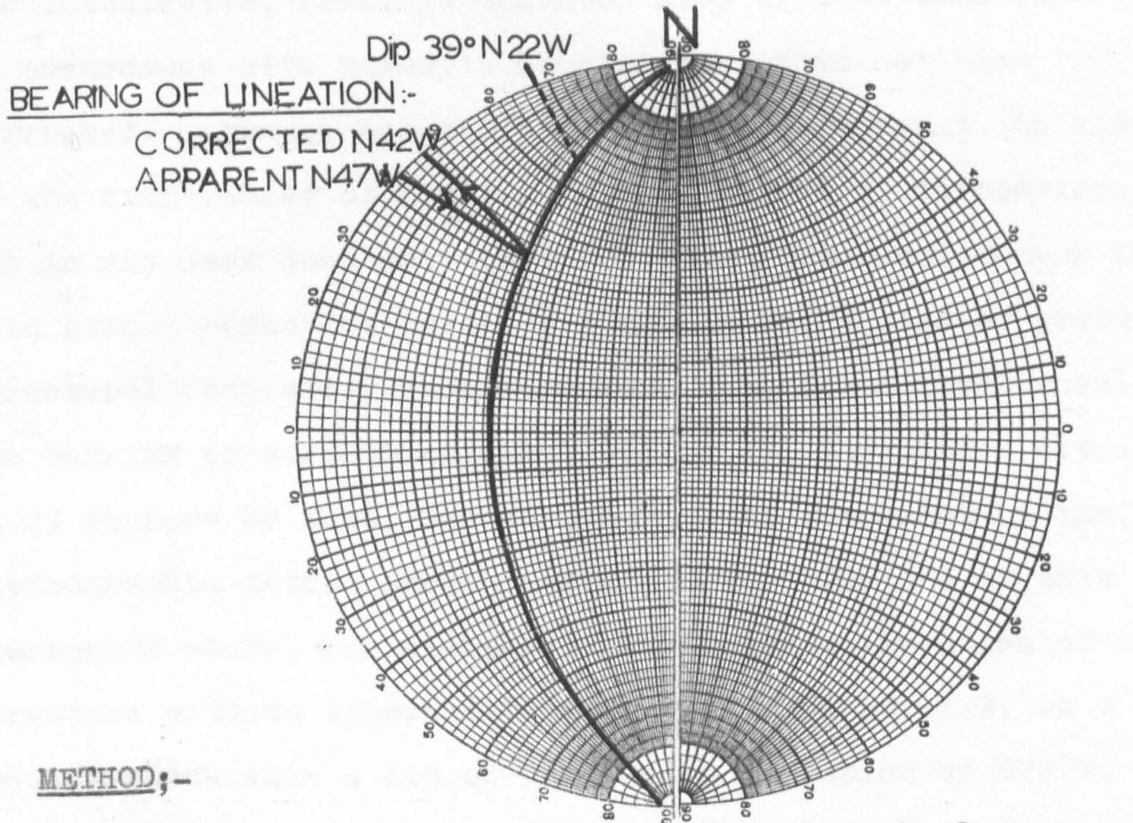
It is concluded that strong turbidity currents flowed down a comparatively steep slope in the area of the Howgill Fells, scouring large flute markings and depositing comparatively coarse sediment. In the Barbon and Middleton Fells to the south, conditions of deposition were rather quieter. The turbidity currents were weaker, and were capable only of scouring comparatively small flutes, and carrying and depositing finer sediment. The absence of the finer structures such as dendritic ridges and frondescent marks, considered by Dzulynski and Walton (1963), to be formed at a good distance from the source, indicates, however, that the currents were still reasonably strong. The conditions of deposition as a whole are considered in further detail in chapter 9, after the current directions have been considered below.

### (v) The Recording of Current Directions from the Flute Moulds

The greatest value of sole markings is in their use as palaeocurrent indicators. Flute moulds are particularly valuable in this respect, as the nose of the structure points upcurrent, and thus indicates the direction of movement. Groove moulds are also useful, but current movement could have taken place in either direction along their length. They are of greater value, however, when in association with flute moulds.

The effect of post depositional folding on the bearing of the lineation has long been realised. Cloos (1938), for example, devised a mechanical method of returning lineations to their correct orientation from readings taken in folded plunging strata. A similar method was devised by Ten Haaf (1959, in Bouma 1962, p.25). Most workers, however, have preferred mathematical or stereographic methods of correction. Wood and Smith (1958), corrected flute readings taken on the Aberystwyth Grits on the assumption that only one period of folding had occurred. The original orientation of the sole markings is then given by the formula 90 degrees-B+a, where B is the angle between the lineation and the dip direction, and "a" is the direction of strike in degrees east of north. In this method there are two possible positions of the lineation 180 degrees apart, but simple inspection gives the correct value. This method does not take the amount of dip into account, however, and is therefore only of use in areas of very gentle folding. Phillips (1954), described simple stereographic methods of correcting the lineations, in which the effect of plunge could also be taken into account. Plunge was also taken into consideration by Norman (1960). The effect of dip was first removed by a similar method to that used by Wood and Smith. A correction factor based on the proportion of plunge within the apparent dip was then added to the result, from a previously prepared chart. This method assumes that the folds are perfect geometrical surfaces, and that the plunge has been attained by rotation about a horizontal axis at right angles to the fold axis. Also that no distortion of the bedding planes or rotation of the fault blocks has taken place. Ramsey (1961), however, points out that other factors have to be taken into consideration. For example, it cannot always be assumed that the plunge was acquired by rotation about a horizontal axis at right angles to the fold axis. Serious errors can result if this factor is ignored. The type of folding has also to be taken into account, as the effect of shear folding on the orientation of sedimentary structures is quite different from that of normal flexural folding. The problem of types of plunge, and stereographical methods of removing it was further discussed by Potter and Pettijohn (1963, p.259), and Cummins (1964).

All the methods described above differ in detail, and it appears that unless the geometry of the folds is known perfectly, greater inaccuracies can be introduced than existed originally. Ramsey (1961 p.97), states that the effect of dips of less than 25 degrees on the lineations is so small, that it can be ignored in areas of flexural folding. In any case, the variable nature of turbidity currents means that the exact direction of the currents can never be really accurately determined. The stereographic correction of readings taken on very low dips would in fact give a false sense of accuracy to the results, and would amount to not more than 3 degrees.




METHOD;-

(1). Plot north and measure off dip direction in degrees east or west of north.
(2). Rotate dip direction down to east-west and measure inwards the amount of dip.
(3). Draw in the Great Circle.
(4). Return to north.
(5). Measure off the lineation east or west of north.
(6). Bring this down to east-west and mark the point at which it intersects the Great Circle.
(7). Rotate the dip direction to east-west and mark off new direction of lineation along the small circle.
(8). Rotate to north and read off the new correct bearing of the lineation.

FIG. 8-9. Stereographic method for removing the effect of dip on the bearing of sole markings.

As flexural folding predominates in the Barbon and Middleton Fells, readings taken on dips of less than 25 degrees, in accordance with Ramsey's conclusions, have not been corrected. Plunge has not been taken into account, in view of the differences of opinion in the methods of correction, but in any case does not appear to be an important factor in this area. (The few readings taken in localities of great structural complexity have been left out of the final results.) The bearing of structures developed on bedding planes dipping at 25 degrees or more, however, have been corrected by the stereographic method shown in figure 8-9. The use of this stereogram shows, for example, that the true lineation of a structure with an apparent bearing of N 47 degrees W, on a bedding plane with a dip of $36^{o}$, and a direction of $N22^{o}W$, is in fact $N42^{o}W$.

During the course of the field work, the directions of all sole markings were recorded, apart from a few occurring in structurally complex localities. Altogether some 220 readings were made. Only one reading was usually taken on each bedding plane, as at any one horizon all the structures normally had the same orientation. If groove moulds occurred on the same bedding plane, however, these were recorded separately, as it was found that their orientation often differed slightly from that of the surrounding flute moulds.

(vi) The Significance of the Results

The 220 readings taken on flute moulds and associated structures, and corrected where necessary, are shown in

Appendix VIII. These structures show a range of current diredtions between N5°E, and N100°W, as shown in figure 8-10a. There is, however, no significant variation throughout the succession (see figure 8-10b), the majority occurring between 30° and 40° W of N, and thus indicating that the sediments originated from a land mass lying to the north-west of the area of deposition.

In the Howgill Fells, Rickards also found that the currents originated predominantly from the north-west, or west-north-west, except at the base of the Ludlow Series, where they appear to have originated from the south-west. The same method of correcting the results was used throughout the area. Thus it is unlikely that this is a result of the wrong correction factor being used, unless localities in which the Lower Coniston Grits are exposed have some unique structural peculiarities. It appears more likely that the southwesterly direction is accounted for by a localised change in the current directions, brought about perhaps by a local peculiarity in the geosyncline (see chapter 9). In the Lake District, Llewellyn (1960), and Norman (1961), also found that the currents originated from the north-west. Norman, however, discovered a secondary northeasterly direction, which he thought was a result of flow along the length of the trough.

Current directions throughout northwestern England thus appear to have been predominantly from the north-west, (see figure 8-11), suggesting the existence of a land mass in this

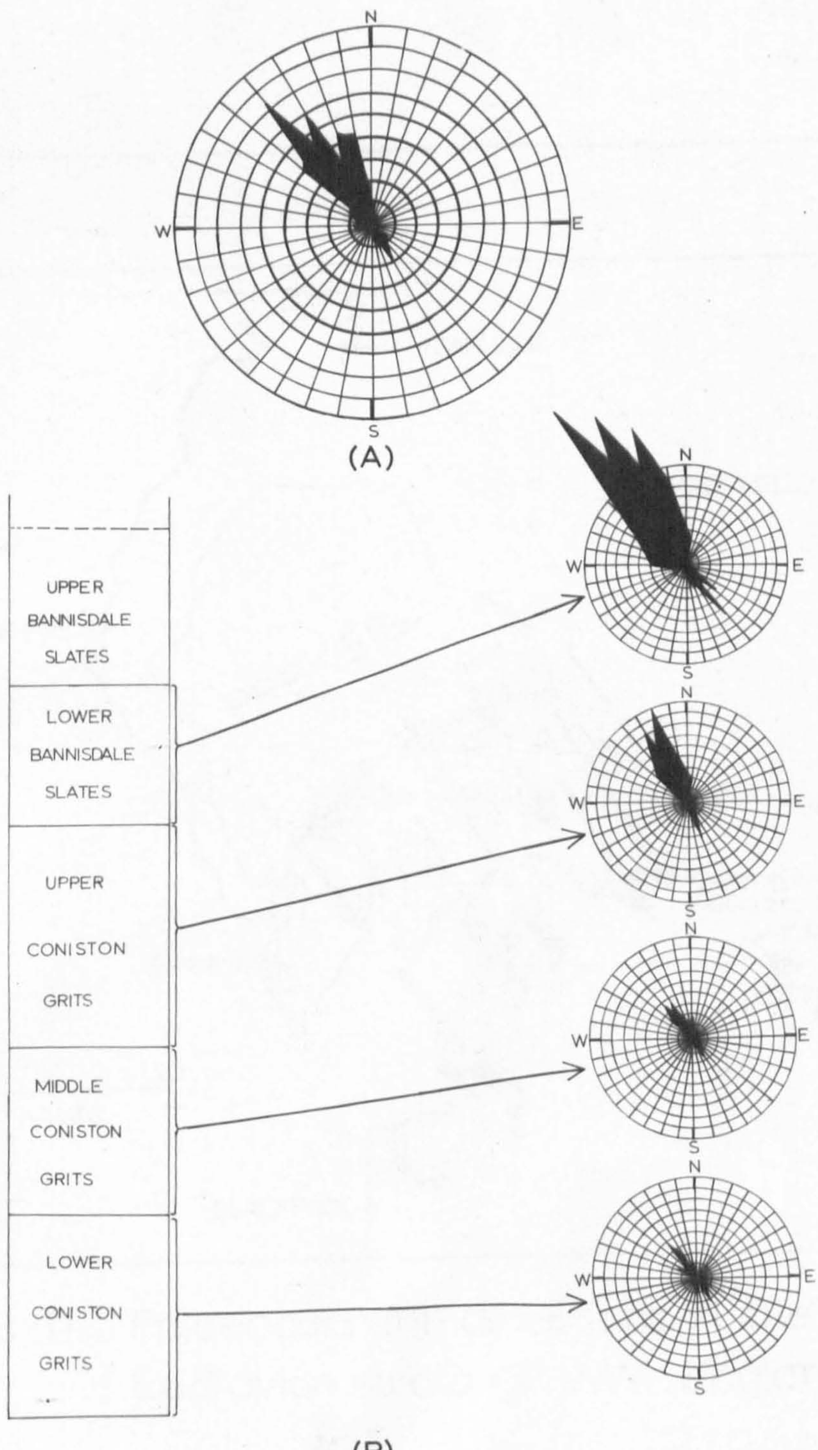



FIG. 8-10. Rose diagrams of current directions indicated by sole markings.
(A). Composite diagram of all the 220 readings. (Each concentric circle is equal to 5 readings).
(B). The current directions in each division of the Ludlow Series. (Each concentric circle is equal to 2 readings)

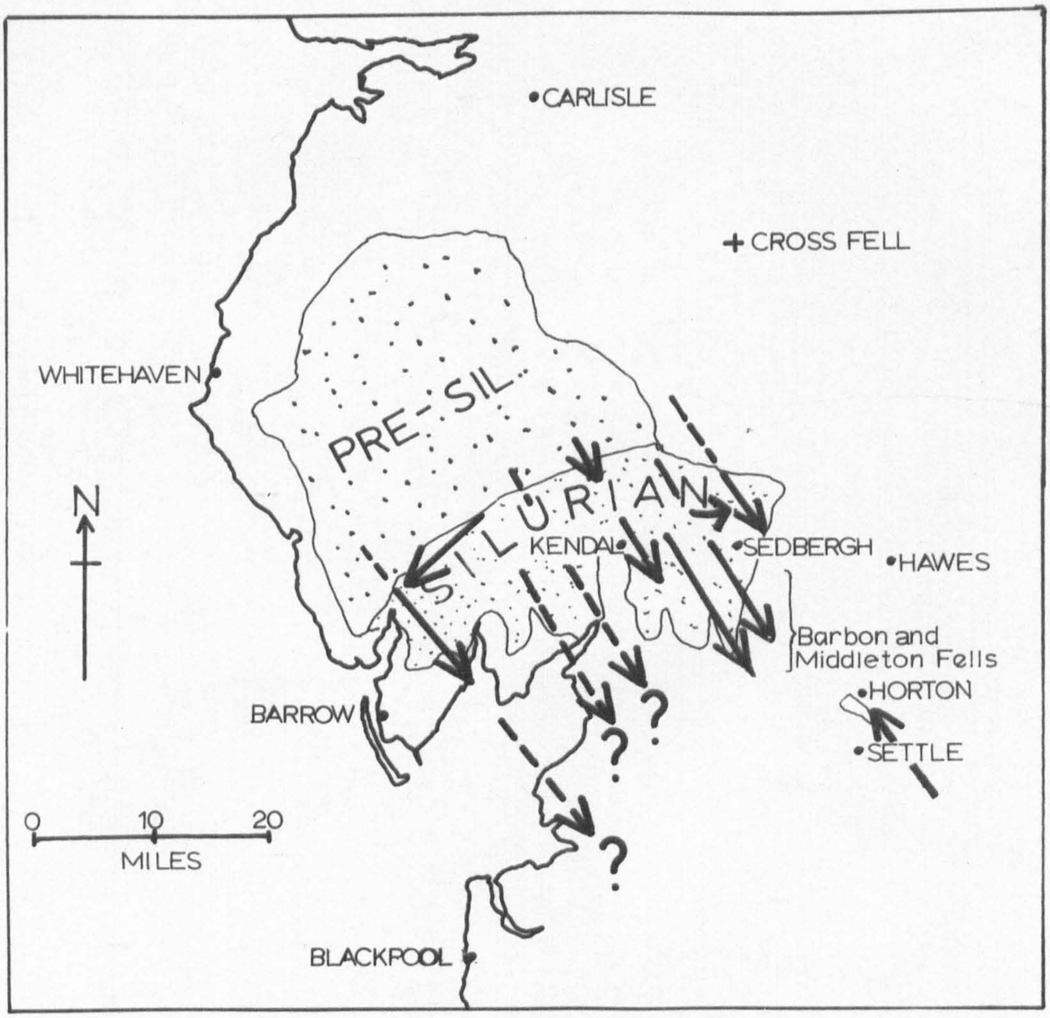



FIG. 8-11. Palaeocurrent directions in the Ludlovian strata of NW England.

direction. The variations seen in some areas are considered to be of local significance only, and do not affect the overall picture. The petrography of the greywackes discussed in chapter 5 suggested that this land mass lay in the position of the present northern belt of the Southern Uplands. Sediments eroded from this land mass were probably deposited on the continental shelf for a short period, before being redeposited by turbidity currents flowing into the trough to the south-east. These conclusions are considered further in the following two chapters dealing with the conditions of deposition and palaeogeography.

(d) General Conclusions

(1) The different types of graded bedding present within the greywackes of the Barbon and Middleton Fells indicate that the turbidity currents which swept across the area, flowed for varying periods of time. Some currents flowed continuously for long periods, and appear to have been responsible for the coarser poorly graded greywackes, whereas at other times the currents were shorter lived and pulsating in nature.

(2) The laminated bedding seen in the finest greywackes consists of alternations of silt and mudstone, and appears to be an intermediate stage between normal greywacke and graptolitic siltstone.

(3) Flute and groove moulds are abundant in the area, and are commonly emphasized by post-depositional loading. In the Barbon and Middleton Fells, these structures are of uniform size throughout the succession, and are smaller than those in the Howgill Fells. This is considered to be evidence of much more marked turbulence and stronger currents in the latter area, due perhaps to a steeper slope. The uniformity and smaller size in the Barbon and Middleton Fells, suggests a shallower slope and quieter conditions of deposition.

(4) The flute moulds are valuable palaeocurrent indicators, but require correcting for the effects of dip in areas of strong folding, if false directions are to be avoided.

(5) Turbidity currents throughout the Barbon and Middleton Fells, and most other parts of north-western England, appear to have originated predominantly from the north-west, with only minor local variations. This is in agreement with the petrographical evidence (chapter 5).

# CHAPTER 9

## SEDIMENTATION AND CONDITIONS OF DEPOSITION

### (a) Review of conclusions drawn in previous chapters

In this chapter, the conclusions drawn in chapters 3 to 8 are reviewed with regard to sedimentation and conditions of deposition through the Silurian period as a whole.

The grading and general poorly sorted texture of the greywackes suggests deposition from high density turbidity currents, in deep water (Kuenen 1952). The mineralogy of the sediments indicates that these currents may have flowed into the area from the north-west, from the northern belt of the Southern Uplands. Palaeocurrent evidence from flute moulds and other sole markings agrees with this conclusion.

The finer grained graptolitic siltstones and banded units discussed in chapter 7, however, indicate that from time to time conditions of deposition became much quieter, and the strong high density currents were replaced by weaker currents capable of carrying only fine sediment. The description of the Stratigraphical Succession in chapter 3, showed that this finer sedimentation becomes important for a time in the

Middle Coniston Grits, and again in the Lower Bannisdale Slates, and finally predominant in the Upper Bannisdale Slates. In the Wenlockian, the graptolitic siltstone lithology is predominant throughout the Series.

Grain size analyses (chapter 6), show little general change in the mean grain size of the greywackes throughout the succession, except that the units at the very base of the Ludlow Series are somewhat coarser. The grain size of the graptolitic siltstones is too fine to measure accurately with a point counter, but appears to be comparatively coarse in the Coniston Grits, and fine in the Wenlock Series and Bannisdale Slates.

Comparisons with the Howgill Fells show many close similarities, indicating that conditions of deposition were almost identical to those in the Barbon and Middleton Fells. The thickness of strata in the Howgills, however, is much less, and this is considered to be a result of the deepening of the geosynclinal trough to the south. This thickening takes place very quickly in a distance of less than 15 miles, and thus the floor of the trough must drop considerably. Evidence that this steepening takes place in the region of the Howgill Fells is seen in the generally coarser grain size of the greywackes and the large dimensions of the flute moulds in that area. This is taken to indicate the passage of currents down this slope, into the area to the south, which were strong enough to prevent all but the coarser greywackes being deposited, at least in Coniston Grit times. This steepening of the trough is only a localised feature. In the Barbon and Middleton Fells, several factors, such as the absence of slump bedding, the finer grain size, and the smaller and uniform size of the sole markings suggest a slackening of the slope. This would result in the currents slowing down, and the deposition of large amounts of finer sediment along with any coarse material still in suspension. The reduction in speed of the current, however, is probably only very slight, as Heezen et al (1952), and Menard (1955), have shown that modern turbidity currents, once they have developed on the continental slope, can flow for hundreds of miles across the abyssal plain. The small reduction in grain size from north to south suggests that this deduction is correct. Comparisons with the Lake District also show many close similarities.

From these conclusions it is possible to build up a picture of the depositional history of the Silurian strata in north-western England, which reflects a series of gradual changes through the succession. These are described below.

(b) Depositional History of the Silurian Strata of the Barbon and Middleton Fells and Adjacent areas.

The basal Silurian limestone is not exposed in the Barbon and Middleton Fells, but in the Howgill Fells is considered by Rickards to represent fairly clear water conditions. The overlying Stockdale Shales also do not occur in this area, but have been described in detail by Marr (1925), Wilson (1954), and Rickards (1963). These authors considered that these fine grained, largely black graptolitic shales represented deposition under very quiet anaerobic conditions, which largely prevented a benthonic fauna from establishing itself. Thus the only fossils found in these rocks are the planktonic graptolites which floated in the fresher water well away from the bottom. The comparatively high percentage of carbon (3.68%), found by Rickards in these shales, suggests that conditions were indeed similar to those described by Ruedemann (1935), Krumbein et al (1949), and Dunham (1961). These authors concluded that anaerobic bacteria partly decomposed carbonaceous material which in turn reacted with sulphates to produce hydrogen sulphide and finally black iron sulphide. The controlling factor is a lack of oxygen, thus the Stockdale Shales were probably deposited in a deep stagnant part of the sea floor.

Green beds developed at some horizons within the Stockdale Shales also appear to represent deposition under reducing conditions, but in which carbonaceous material was absent, thus preventing the action of anaerobic bacteria producing hydrogen sulphide, and ultimately the black shales. In the Cautley district, oxidising conditions developed towards the end of the Upper Llandoverian, and red mudstones containing a small benthonic fauna were deposited. In normal conditions, iron compounds are reduced to ferrous compounds to produce the green beds, or, in the presence of carbonaceous material and anaerobic bacteria, to sulphides. The red beds exist around an axis of uplift proved by Wilson (1954) to exist in this area, and in the shallow water thus produced remain in their original oxidised condition. It is considered here that the iron salts through most of the Llandoverian were probably brought into the sea as oxides, but were reduced to sulphides in the deep stagnant water which prevailed for most of the period.

The Stockdale Shales are considered by Marr (1925) and Rickards (1963), to be the lateral equivalents at a great distance of coarse greywackes. This suggestion appears to be plausible, as coarse greywackes were being deposited in the Southern Uplands at this time. It is shown in chapter 10, that the Lake District and Southern Uplands areas of deposition were probably separated only by a shallowing in the border area, during the Wenlockian and Ludlovian (fig. 10-1). If this feature existed during the Llandoverian the Stockdale Shales may represent fine material carried over the shallowing in the higher parts of turbidity currents, and deposited almost from suspension in the area to the south. Most of this sediment was originally deposited in an oxidised state, but was quickly reduced in the anaerobic conditions prevailing at depth. In the Upper Llandoverian, however, the localised upwarp which developed may just have reached to within the limit of wave action, thus accounting for the absence of red beds on the crest of the structure. The sediment deposited in the very shallow aerated water around this axis would not be reduced, and would thus remain red, (see figure 9-1). The stages between red mudstone and black shales may be represented schematically as follows, (cf. Marr 1925, p.128):-

| | | | | |
|---|---|---|---|---|
| Very Shallow Water | → | Deep Water | → | Deep Water |
| Oxidising Conditions | | Reducing Conditions | | Reducing Conditions +Carbonaceous material |
| Red Beds | → | Green Beds | → | Black (iron sulphide) mudstones. |

The Llandoverian thus shows predominantly deep water stagnant reducing conditions, in which sediment was deposited quietly, and in which there was only very localised areas of shallow water.

In the Wenlockian, anaerobic conditions continued, and are represented by graptolitic mudstones. As higher parts of the succession are reached, however, the grain size becomes somewhat coarser, and conditions generally appear to be less anaerobic. The mudstones are replaced by siltstones, and at one or two horizons bands of greywacke an inch or so in thickness are developed. In the upper part of the Wenlockian, the great increase in thickness between the Howgills and Barbon and Middleton Fells becomes apparent, indicating a deepening of the trough in the south. Towards the end of this period, a change to clearer aerated water conditions

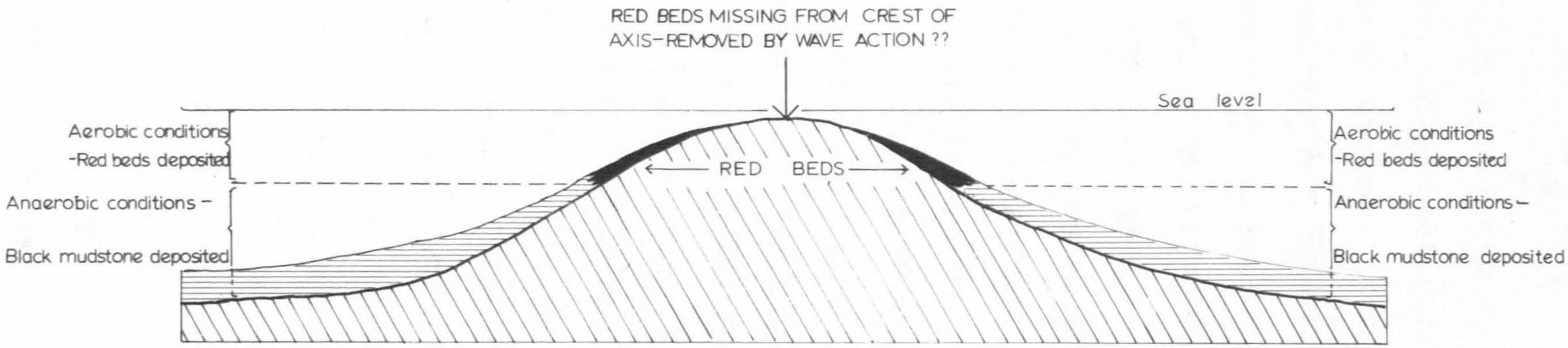



FIG. 9-1. Diagramatic representation of the upwarp surrounded by red mudstones in the Llandoverian strata of the Cautley area.

becomes noticeable, as the strata become progressively richer in carbonate. Clear water conditions reached their maximum development at the base of the Ludlow Series when two impure limestone beds were deposited.

Following this, however, coarse sedimentation becomes dominant. High density turbidity currents flowed into the area from the north-west and quickly deposited thick beds of poorly sorted graded sediments. The marked turbulence brought by this influx of coarse sediment is considered to have resulted in comparatively aerated water conditions, as a result of which carbonaceous material and graptolites of the Wenlockian returned for a short period, and graptolitic siltstones were deposited. These siltstones, however, are coarser than those in the Wenlockian, and generally appear to have been deposited under only slightly anaerobic conditions. In the Middle Coniston Grits, quieter conditions again become more prevalent, and alternate with periods of coarse turbulent deposition. The banded units deposited during these quieter intervals represent periods when even the small turbidity currents which deposited the siltstone laminae, were only of intermittent importance. The alternating mudstone laminae are here considered to be more indicative of deposition from suspension. The pyritic films within the siltstone laminae show that conditions of deposition were anaerobic. The absence of these films from the mudstone laminae is considered to be a result of the reworking of the fine sediment by burrowing worms. The Upper Coniston Grits represent the return of coarse grained turbulent sedimentation, with strong currents flowing in from the north-west. Conditions were similar to the Lower Coniston Grits, and quiescent periods were short lived. The Lower Bannisdale Slates again show the return of alternating periods of turbulent and quiet conditions. This time, however, quiescent periods become gradually more and more important, until in the Upper Bannisdale Slates, deposition from low grade turbidity currents under slightly anaerobic conditions is dominant.

In the Howgill Fells, a similar sequence of events is seen, except that the succession is generally thinner, and the sediments coarser, indicating stronger turbidity currents. The fine grained Bannisdale Slate lithology, representative of quieter conditions develops somewhat earlier in that area, however. This is against the normal pattern and is difficult to explain. When traced from the Howgills into the Barbon and Middleton Fells (as described in chapter 3), the banded units become much thinner, and in the latter area alternate with greywacke units to form the distinctive Lower Bannisdale Slates division. Sole markings show all the sediments to have been derived from the north-west, so the difficulty cannot be explained by a change of source. The very widespread occurrence of thick greywacke units through most of the Ludlow Series, suggests the inflow of sheets of sediment rather than small scale individual currents. The absence of greywacke units at the horizon of the Lower Bannisdale Slates, in the Howgill Fells, however, suggests that this mechanism was no longer operating, but had been replaced by more localised coarse sedimentation, perhaps radiating out from a submarine canyon (cf. Ericson et al 1952). Eventually, however, even this coarse sedimentation died out, and fine sediment was deposited in all regions. Figure 9-2 after Potter and Pettijohn (1963 p.132), shows how this mechanism could be expected to operate. This probably also explains the apparent southwesterly origin of some greywacke units in the Howgill Fells, suggesting that the sheets of sediment were probably made up of flows from a number of closely spaced submarine canyons.

In the Lake District also, sedimentation appears to have followed the same general pattern which is seen in other parts of the country, such as North Wales and the Southern Uplands, though at slightly different times in these last two areas.

Sedimentation throughout the Silurian geosyncline thus appears to represent an interplay between coarse turbulent sedimentation, which brought oxidising conditions to the deeper stagnant waters of the trough, and quieter periods of fine grained sedimentation, which allowed the re-establishment of anaerobic conditions.

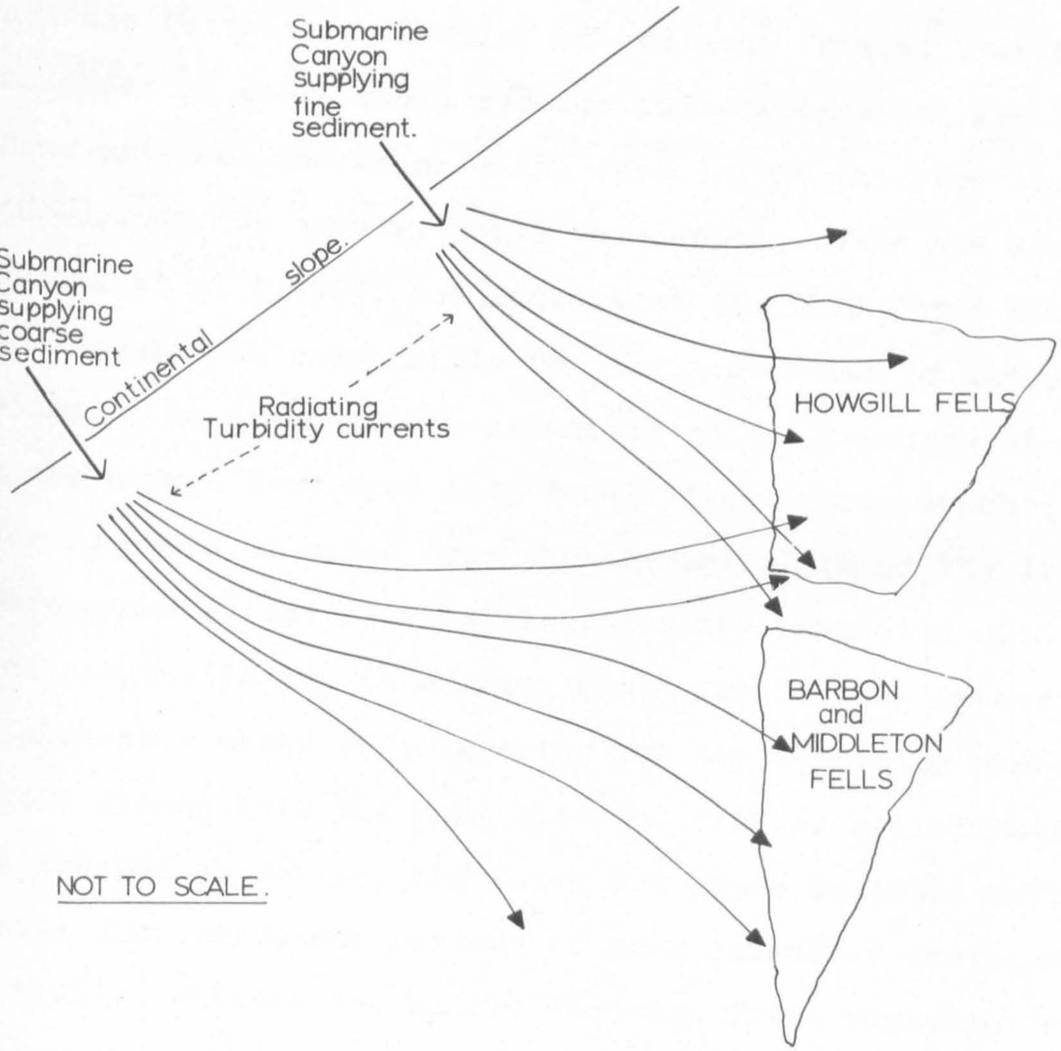



FIG. 9-2. Sketch showing the mechanism by which coarse sediment continued to be deposited in the Barbon and Middleton Fells during Lower Bannisdale Slate times, whilst finer sediment was deposited in the Howgill Fells. In the central part of the region coarse and fine sedimentation were almost of equal importance. (Based on Potter and Pettijohn, 1963).

(c) The Origin of the Turbidity Currents

In the Silurian geosyncline over wide areas of the country, there are thus definite phases of coarse sedimentation separated by quieter periods. It is difficult to imagine how the fortuitous slumping of sediment from an overloaded continental shelf could produce these widespread similarities. Some external mechanism which operated at the same time throughout the country would thus appear to be the answer. Heezen et al (1952), concluded that the 1929 Grand Banks earthquake was responsible for the production of large scale slumping in the sediments deposited on the continental slope. These slumps developed into turbidity currents which flowed for hundreds of miles over the abyssal plain of the Atlantic. Earthquake shocks of this kind, perhaps connected with uplift and orogeny in the Caledonian Chain, would thus appear to be a plausible means of triggering off the turbidity currents which flowed into the Lake District area of sedimentation. In the Ludlow Series, the Lower and Upper Coniston Grits would thus represent periods of more intensive earthquake activity, whereas the Middle Coniston Grits represent a quieter interval. The increasing dominance of fine grained sedimentation upwards, in the Bannisdale Slates, indicates perhaps, that these preliminary movements of the Caledonian orogeny died away for a time before the commencement of fullscale uplift and folding. The fine grained Llandoverian and Wenlockian sedimentation cannot necessarily be taken as an indication of quiescent conditions, however, as during at least part of this period, the Lake District is considered by the present writer to have been cut off from the coarse sedimentation of the Southern Uplands, by a shallowing in the Border area. The evidence for this conclusion is considered further in the subsequent chapter.

Earth movements are thus the ultimate controlling factor in the s-edimentation and conditions of deposition during the Silurian period.

# CHAPTER 10

## PALAEOGEOGRAPHY

The sole markings described and discussed in Chapter 8, indicated that currents had flowed into the area of the Barbon and Middleton Fells from the north-west, throughout Ludlow time. Work by Llewellyn (1960), and Norman (1961) in the Lake District, and Rickards (1963), in the Howgill Fells, showed that in these areas also, northwesterly currents were predominant. This suggests the existence of a land mass to the north-west of the area of deposition; but its exact position has been the subject of much controversy.

Marr (1916), considered the Lake District Ludlovian sediments to represent the gradual southerly and westerly extension of the coarse sedimentation, which occurred during the Llandoverian and Wenlockian in the Southern Uplands. He concluded that throughout Lower Palaeozoic times, the coast line gradually migrated south, resulting in coarse sediment being deposited on top of fine. The sediments in the Lake District were thus derived from the Southern Uplands, partly from the reworking of earlier deposited sediments.

Jones (1938), however, considered that the Lake District had closer affinities to the Welsh area of deposition, and thus the Irish Sea land mass probably extended to the north-east to separate the Lake District and Southern Uplands areas of sedimentation. Wills (1951, pl.III, p13), reviewed this earlier work and published a series of maps showing the extent and nature of the geosyncline throughout the Silurian. He considered that a narrow extension of the Irish Sea land mass separated the Lake District from the Southern Uplands throughout the Llandoverian. In the Wenlockian, this land may have receded as far south-west as the Isle of Man. By Lower Ludlow time, however, it had re-extended right across the Irish Sea to link up with the rising mountain chains in Southern Scotland. Black (1957), also considered that a land mass existed in the border area. This was apparently confirmed by the work of Llewellyn (1960), and Norman (1961), who concluded that the petrography of the greywackes in the Lake District indicated derivation from an area of Borrowdale Volcanic rocks lying to the north of the Lake District. Norman also found evidence of currents flowing from the north-east, which he considered to represent flow along the axis of a trough plunging to the south-west. He thus concluded that land may also have existed to the north-east. Warren (1963), however, after briefly comparing the petrography of the Coniston Grits with that of the Hawick greywackes, concluded that both were derived from a similar area of spilites and radiolarian cherts, that is, the northern belt of the Southern Uplands.

The present work has shown that the rock fragments contained by the greywackes show only superficial similarities to the Borrowdale Volcanic Series, and are much more closely comparable with the alkali rich Ballantrae Volcanic Series of the Southern Uplands. This evidence thus appears to disprove the arguments in favour of a border land mass. There is the possibility, however, that a land mass formed of rocks of this type could have existed to the north of the Lake District, as the steeper geosynclinal slope seen in the area of the Howgill Fells suggests a marked shallowing in this direction. If a land mass did cut across the border area, however, evidence of its existence could be expected to be found in the Silurian greywackes of southern Scotland. In this respect, the work of Warren (1963), in the Hawick area showed that currents flowed predominantly from the north-west and north-east, very few in fact came in from the south-east. In the Kircudbright area, (Craig and Walton 1962), the main direction of flow was from the north-east, along the axis, but with only minor flows from the north-west and south-east. There is thus little evidence for a prominent border land mass. The few current directions from the south in the Kircudbright area, may indicate the presence of land off the present Cumberland coast. Those in the Hawick area show that land may have existed in the region of the Northumberland coast.

If the Borrowdale Volcanic land mass proposed by Llewellyn and Norman did exist, its position would be so close to the area of deposition, even allowing for later crustal shortening, that extremely steep continental slopes must have existed. Norman, however, states that widespread slumped bedding is absent in the Blawith area. According to Kuenen (1956), this indicates that the area of deposition sloped at little more than 1 degree. Similarly in the Barbon and Middleton Fells, slumped bedding is absent, and thus the area of deposition must have been largely flat lying. In the Howgill Fells, however, slumped bedding does occur, and together with the evidence of large flute markings and coarser grain size, suggests a rather steeper slope in this region. This appears to be only a local feature, and there is not sufficient evidence to indicate that the slope was steep enough to result in land rising above the sea 30 to 40 miles to the north. Thus although no one line of evidence is sufficient to disprove the existence of a border land mass completely, the combined evidence of current directions and predominantly gentle depositional slopes suggests that land did not exist in this area.

Although there is little evidence for a continuous border land mass, the steepening of slope in the Howgill Fells suggests that there was probably a shallowing of the geosyncline in the border area, which brought about a ponding back of the turbidity currents to the north (figure 10-1). The result of this was that coarse sedimentation in the Wenlockian was confined almost entirely to the Southern Uplands. The Wenlockian graptolitic silts and mudstones in the Lake District may represent fine material carried at a higher level in the turbidity currents, and which was thus able to cross over this shallowing. Rickards (personal communication), however, points out that orientated graptolites indicate east-west current directions at some horizons within the Wenlockian. This, together with a coarsening of the sediments to the west, tentatively suggests that some at least, of this sediment, may in fact be derived from the Irish Sea land mass, considered to exist in the region of the Isle of Man. Only by Ludlow time had enough sediment built up in the Southern Uplands for the turbidity currents to be able to flow over this shallowing easily, and deposit coarse sediment in the deeper waters to the south, to form the Coniston Grits (see figure 10-1). The thinning and coarsening of the Coniston Grits from south to north across the Barbon and Middleton Fells, supports this hypothesis of a shallowing of the trough towards the border.

Although the sediments are thus considered to be derived from the Southern Uplands, it is possible that they were produced merely by the reworking of uplifted Wenlockian greywackes in that area (cf. Marr 1916). The predominantly fresh and angular to sub-angular nature of the rock fragments

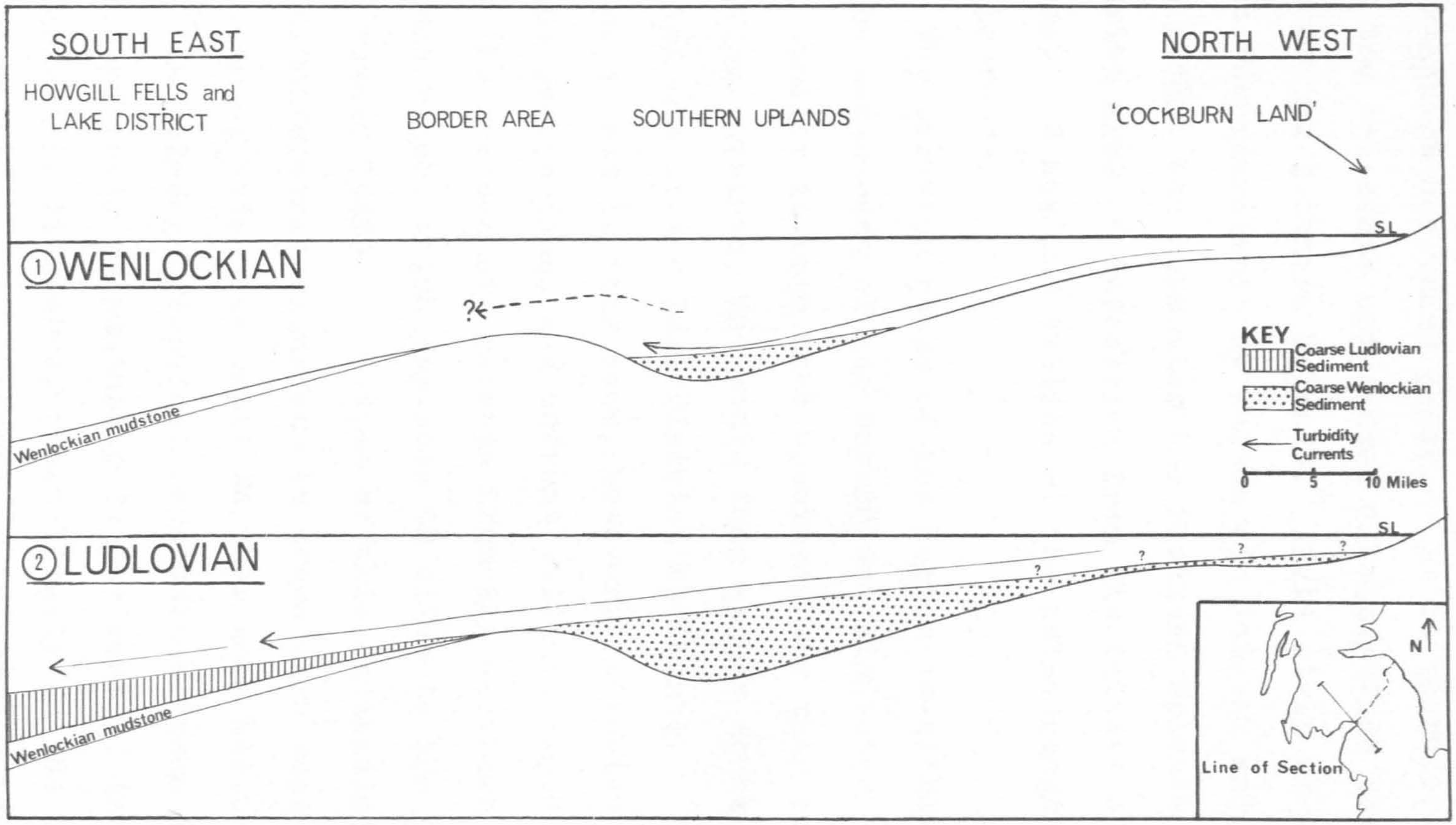



FIG. 10-1.

SECTION FROM THE LAKE DISTRICT TO COCKBURNLAND.

(1). Coarse Wenlockian sedimentation restricted to the Southern Uplands, with mudstone only being deposited in the Lake District.

(2). Coarse Ludlovian sedimentation occurring predominantly in the Lake District, after the infilling of the Southern Uplands area of deposition.

and mineral grains, however, suggests that only one stage of transport has taken place. It is therefore concluded that the sediments originated directly from the northern belt of the Southern Uplands. This strip of land has been named "Cockburnland" by Walton (in Johnson and Stewart 1963 p.88), and separates the Southern Uplands and Lake District area of deposition from the inliers of the Midland Valley. A map and section of the palaeogeography is shown in figure 10-2.

The Silurian rocks of the Horton-in-Ribblesdale inlier to the south-east of the Barbon and Middleton Fells, are very similar in both hand specimens and thin sections, but are finer grained, and would thus appear to be the distal equivalents of the Lake District sediments. The thinning of the strata in this area, however, indicates a shallowing of the geosyncline, and current evidence suggests derivation from the south-east, perhaps from the northern edge of the Midland block, which lay some 40 miles to the south (cf. Turner 1949). In view of this contradictory evidence, no definite conclusions can be drawn with regard to the position of this area until further work has been carried out.

The palaeogeographical conclusions drawn in the present work, and their relationship to the rest of the country are summarised in figure 10-2, based largely on the work of Wills (1951), Cummins (1959b), Rolfe (1960, 1961), Craig and Walton (1962), and Warren (1963).

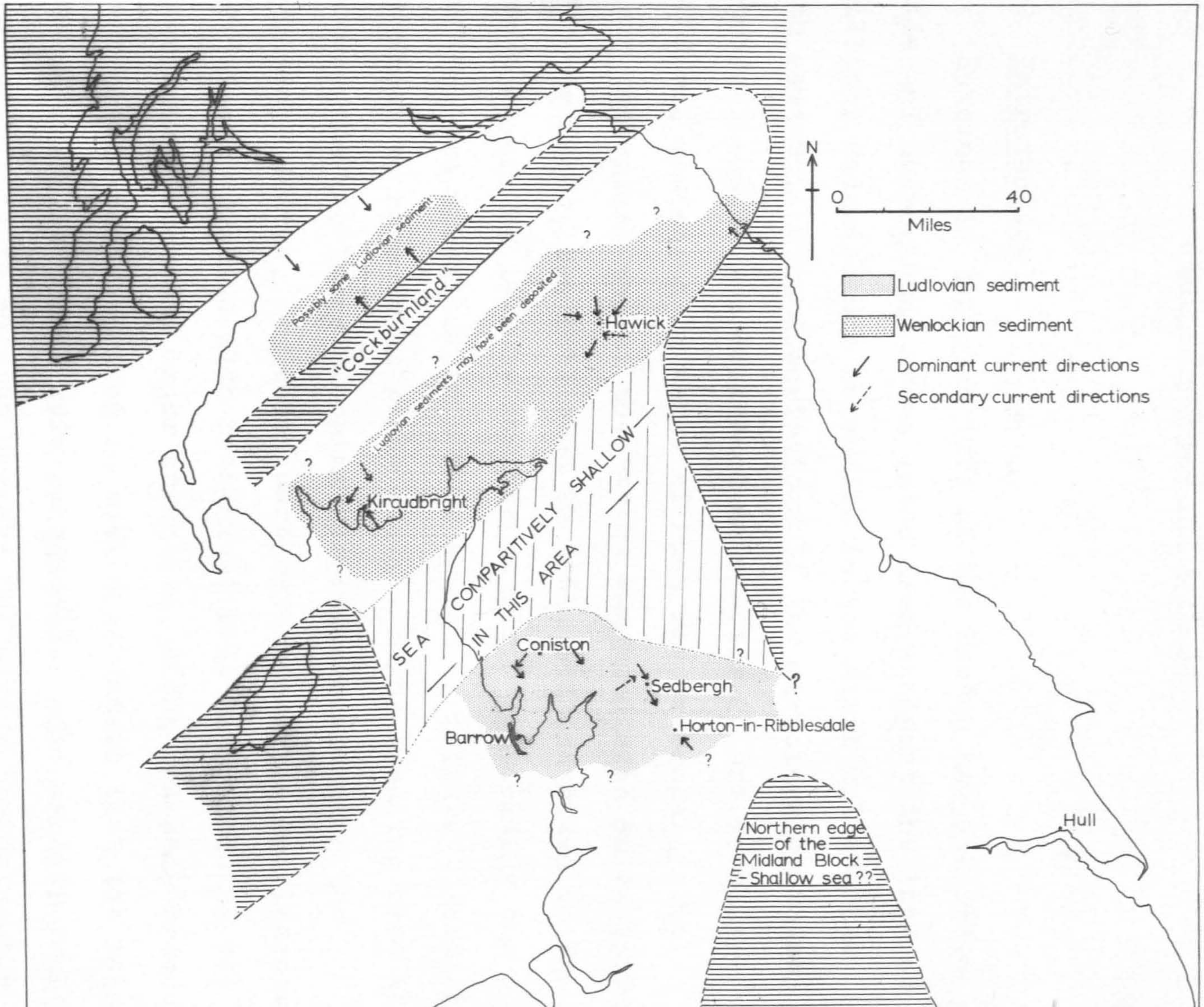



FIG. 10-2 Silurian palaeogeography during Wenlockian and Ludlovian times. Coarse sediment only is indicated. (Adapted after Wills, Cummins, Rolfe, Craig and Walton, and Warren.)

# CHAPTER 11

## THE TECTONIC STRUCTURE

### (a) Introduction

Interest in the structure of the Barbon and Middleton Fells and surrounding areas dates from at least the time of Phillips, Sedgwick and Marshall, in the first half of the 19th century. The descriptions of the structure by these authors, however, as mentioned in chapter 2, are usually brief and contained in works of much larger scope. The first geological map of the Barbon and Middleton Fells (part of Sheet 98SE), was published in 1869, and described in the Survey Memoir of 1872 by Aveline et al. The folding and faulting was described in a fair amount of detail. Folding was shown to have taken place along WNW-ESE trending axes to produce the two large plunging synclines containing the Bannisdale Slates, and which were separated by a complementary anticline. Aveline also recognised that minor folding was superimposed upon the major structure, along the same trend. The faulting was described in even more detail than the folding, and two distinct phases were recognised. The earlier faults produced by the Caledonian orogeny followed a predominantly WNW-ESE direction, and were concentrated in certain areas such as the southern slopes of Barbondale and Dentdale.

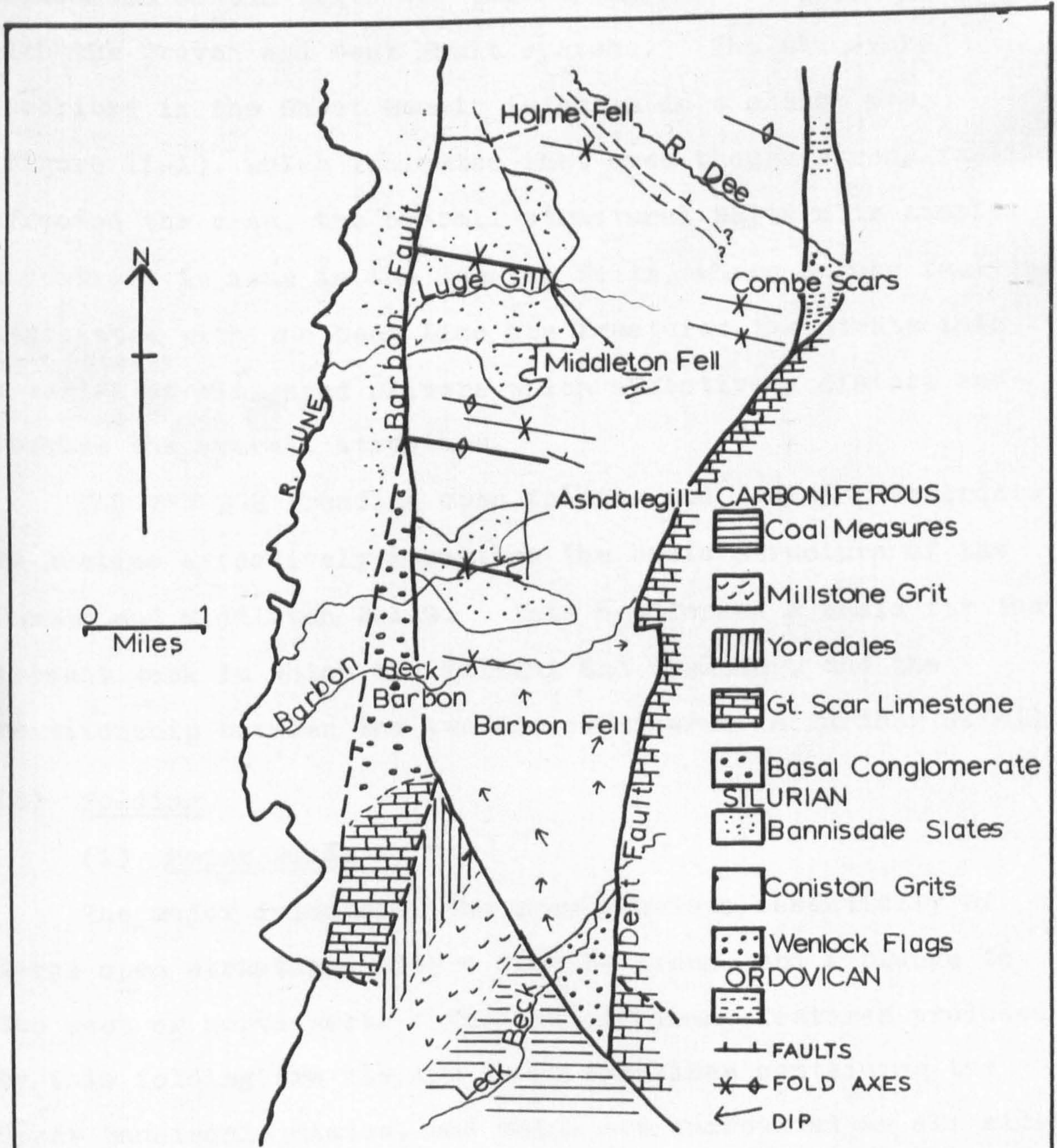



FIG. 11-1. The structure of the Barbon and Middleton Fells as described in the Geological Survey Memoir of 1872.

Cutting across this set of faults and producing the geological boundaries of the fells was the strong N-S faulting associated with the Craven and Dent Fault systems. The structure described in the Sheet Memoir is shown in a sketch map (figure 11-1), which indicates that even though strong faulting affected the area, the overall structural pattern is simple. A contrast is seen in the Howgill Fells, where strong faulting associated with the Dent Line has fractured the strata into a series of elongated slivers which effectively distort and obscure the overall structure.

The WNW-ESE trending open folding and faulting described by Aveline effectively describes the basic structure of the Barbon and Middleton Fells. This has formed a basis for the present work in which the folding and faulting, and the relationship between the two are considered in further detail.

(b) Folding

(i) Major Folds

The major folding of the area consists essentially of large open structures with a WNW-ESE trend, and a plunge to the west or north-west. The most dominant features produced by this folding are the two large synclines containing the Upper Bannisdale Slates, and which are surrounded on all sides but the west, by the lower divisions of the Ludlow Series. Nowhere is overfolding or overturning of the strata seen.

The axis of the more northerly of the two synclines follows roughly the line of the upper part of Luge Gill (645877). The slopes of Holme Fell form the northern limb where dips are almost constantly to the south-west at between 8 and 15 degrees, except where complicated by minor folding or faulting. On the southern limb dips are largely to the north-east or north-north-east, but are rather more variable in direction and amount due to the greater effect of the minor folding. On the whole dips on this limb are somewhat steeper at about 20 degrees, making the syncline slightly asymmetrical. The wave length of the syncline cannot be accurately estimated, as the northern limb extends into the poorly exposed ground to the north of the area, but it would appear to be at least 3 miles.

The southern syncline, centred just to the south of Ashdale Gill (640839) is also asymmetrical, but in this case, it is the northern limb which is the steeper. Minor folding makes it difficult to ascertain the overall direction and amount of dip, but it would appear to be to the south or south-south-east at about 25 degrees. The southern limb of this syncline extends as far south as Leck Beck. Dips in this area are very variable in amount due to strong faulting in some localities, but in uncomplicated regions range between 15 and 20 degrees. The amount of variation in direction, however, is much less than on the northern limb, and is almost constantly to the north or north-north-west. The wave length of this fold is at least 3½ miles.

The major structure of the Barbon and Middleton Fells is thus fairly straightforward. The northern part of the region dips gently to the south-west, and the southern part gently to the north-west. The area may thus be regarded as a large shallow syncline divided into smaller structures by a comparatively steep sided anticline. A WNW trending fault associated with broken and crumpled strata occurs almost along the axis of this anticline, in Millhouse Beck (638854), (figure 11-4a). This suggests that the central anticline has probably originated by crumpling in the core of the large syncline under pressure from north-east and south-west. A block diagram showing the structure with minor folding omitted, is shown in figure 11-3.

(ii) Minor Folds

Although the major structure is essentially straightforward it is complicated by a series of small scale folds superimposed upon it, and which also have a predominant WNW-ESE trend. Within the central parts of the major synclines the effect of these structures is small, and produces only slight variations in the direction and amount of regional dip. Along the periphery of the area, however, (except in the south), the effect of this folding is rather more dominant, and in some localities the regional structure is completely obscured. The wave length of these minor folds is commonly 30-40 yards, allowing them to be mapped and traced in the field from one locality to the next. Two types of structure occur, a very open usually slightly asymmetrical fold with a gentle dip on the limbs, and monoclinal structures, which when traced along the strike often develop into reversed faults.

Open Folding

This type is almost completely absent from the southern part of the region, south of Barbondale, where the strata dip constantly to the north or north-north-west. Variations in the direction of dip in this part of the area are usually accounted for by faulting. To the north of Barbondale, however, open folds of this type are common. A good example is seen in the Whiskey Gill area (648829), where the core of a small almost asymmetrical syncline trending 70 degrees west of north can be traced in a series of crag exposures. The crest of a complementary anticline is also exposed to the north-east of this fold. Folds of the same kind are developed notably on the north side of Ashdale Gill, to the north and south of Combe Scars, Dentdale, in Brow Gill (644865), Wyegraft Gill (648875), and Riddings Beck (645890). In all these localities the trends of the fold axes range between 50 and 65 degrees west of north. Many other rather poorly developed open folds occur throughout the area, and are shown on the structural map figure 11-2.

Monoclinal Folding

These structures are much less abundant than the open folds, and are largely concentrated in two narrow zones, to the south of Barbondale, and on the southern side of Dentdale. The steep limb of the monocline is usually 15 to 20 feet in height with a dip of between 40 and 70 degrees and produces

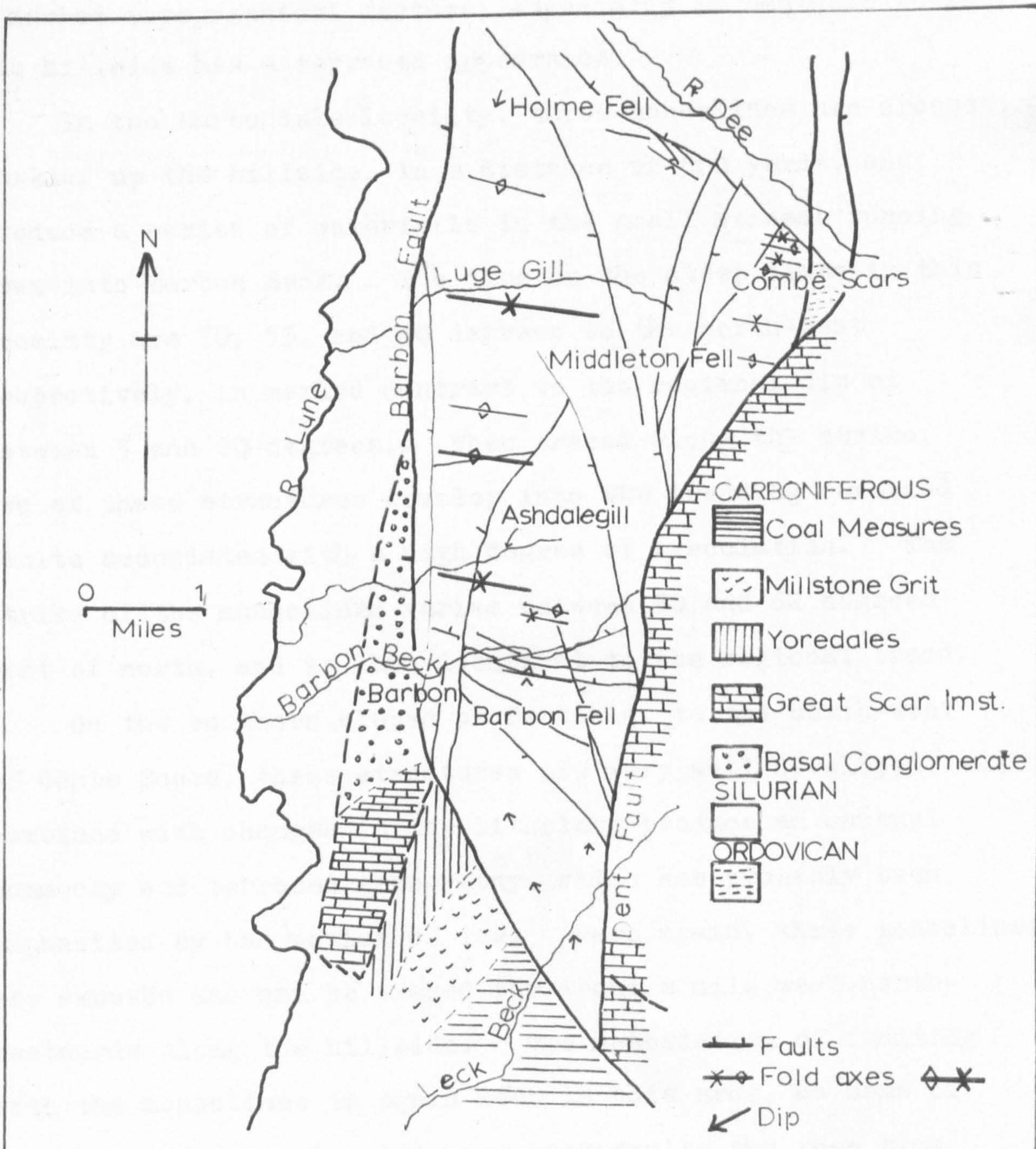



FIG. 11-2. The structure of the Barbon and Middleton Fells as established in the present work.

a marked topographical feature, especially in Dentdale where the hillside has a terraced appearance.

In the Barbondale locality, three monoclines are crossed, working up the hillside, in a distance of 500 yards, and produce a series of waterfalls in the small streams running down into Barbon Beck. The dips on the steep limbs in this locality are 70, 53, and 40 degrees to the north-east respectively, in marked contrast to the regional dip of between 5 and 20 degrees. When traced along the strike, two of these structures develop into WNW trending reversed faults associated with a high degree of brecciation. The strike of the monoclines varies between 50 and 62 degrees west of north, and is thus identical to the regional trend.

On the southern slopes of Dentdale, to the north-west of Combe Scars, these structures are very well developed, and combined with changes in the lithology produce an unusual hummocky and terraced topography, which has probably been emphasized by the action of ice. Here again, three monoclines are exposed and can be traced for about a mile west-north-westwards along the hillside. The association of faulting with the monoclines is again seen in this area, as some of the structures develop into reversed faults and then back into monoclines, in a distance of only a few hundred yards. The steep limbs in this area dip to the north-east or north-north-east, but only at about 40 degrees. This is against the regional dip which is to the south-west. The structures

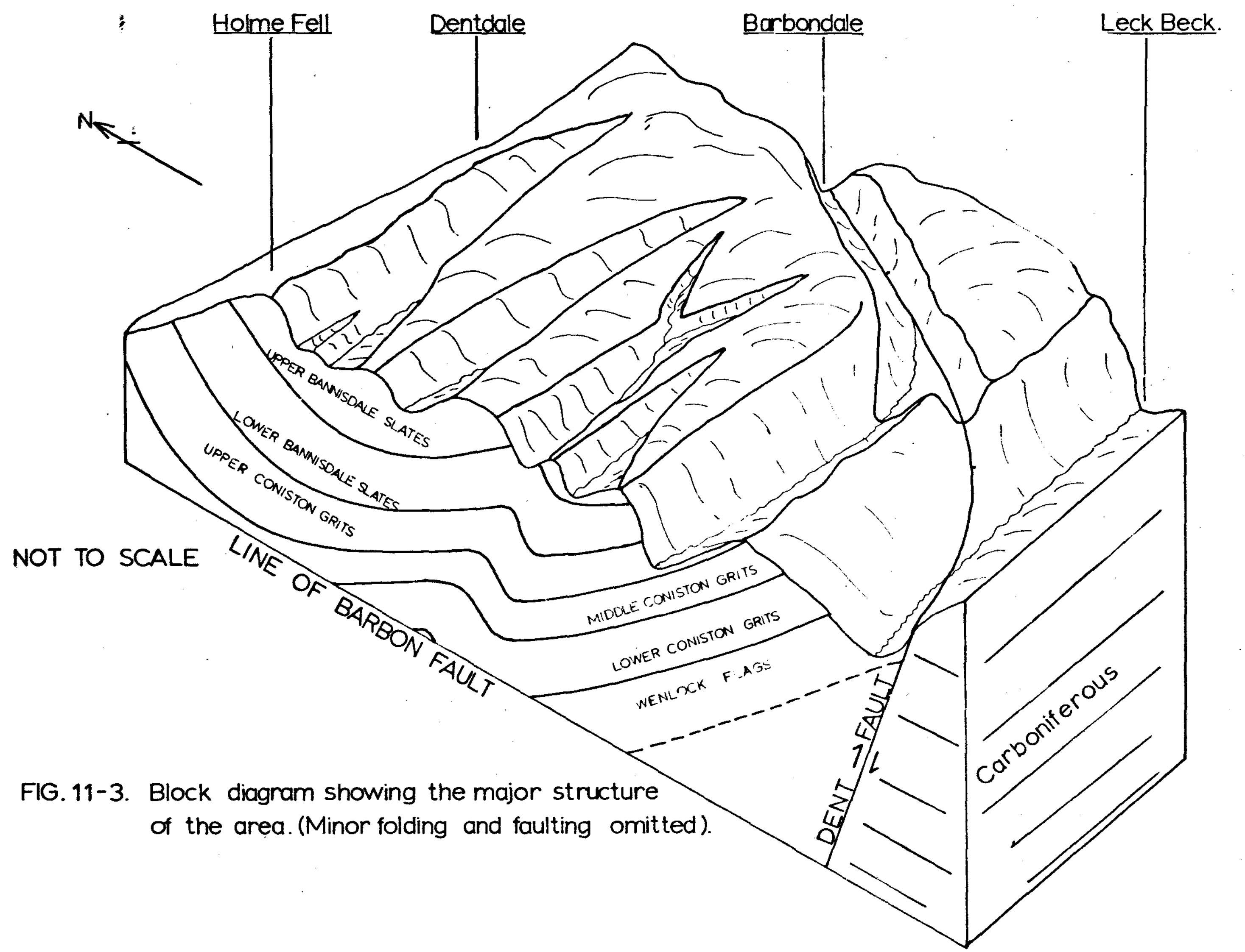



FIG. 11-3. Block diagram showing the major structure of the area. (Minor folding and faulting omitted).

finally die out on the northern slopes of Holme Fell. The only other monoclinal structure in the area of this size is in Luge Gill (640876), where a WNW trending structure cuts across the stream at a low angle.

The monoclinal structures do, however, also occur commonly on a very small scale, producing small flexures a foot or so in amplitude within the general dip of the strata. They are extremely well displayed in Millhouse Beck (figure 11-4c), in the disturbed strata associated with the central anticline, and where many of them are reverse faulted. They are so small, however, that they cannot be mapped even on a scale of 24 inches to the mile, but the trend can be measured directly in the field, and is in every case between 60 and 70 degrees west of north.

(iii) Cleavage

Associated with the WNW trending folding is fracture cleavage. This is well developed and closely spaced especially in the finer grained strata, but is also developed to a certain extent in the coarse greywacke (figure 11-4b) in the vicinity of strong folds or faults. In graded greywackes the dip of the cleavage usually drops from almost vertical in the coarser sediment, to a much lower angle in the fine grained top. The cleavage reflects approximately the regional trend of the folding, and dips in the same direction as the bedding planes. During the course of the fieldwork 133 cleavage readings were taken throughout the area, and

Fig. 11-4 a

Contorted strata, Millhouse Beck.

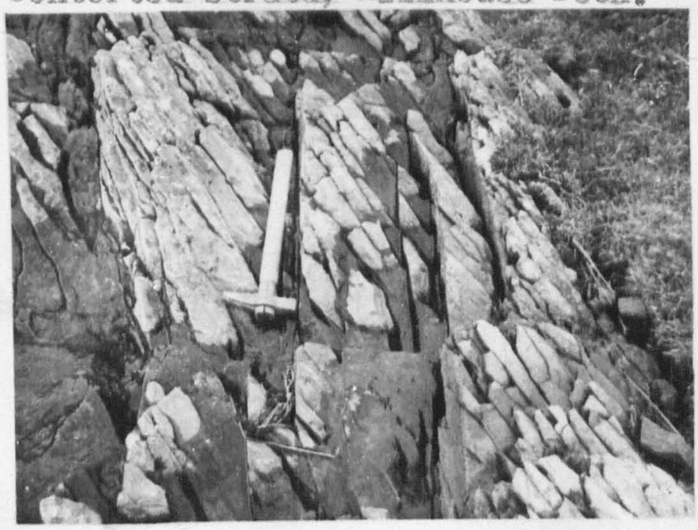


Fig. 11-4 b

Cleaved greywacke.

Fig. 11-4 c

Small scale monocline, Millhouse Beck.

show that the mean trend is 56 degrees west of north. (Individual readings are shown in Appendix VIII ). From north-west to south-east across the area, however, the mean direction changes gradually from 60 degrees west of north in the Dentdale area, to 42 degrees west of north in the vicinity of Leck Beck. This indicates perhaps, a general swing in the trend of the folding. The interpretation and significance of these results has not been taken beyond this point, as structural work of this kind, if it is to be done properly, requires a full time study in itself. It has thus been left for a future occasion.

The structures described above are of Caledonian age. The later Hercynian orogeny, however, did not introduce widespread secondary folding within the Barbon and Middleton Fells. The area appears to have formed a fairly resistant block during this period, and the effect of the orogeny appears to be limited to the introduction of the north-south trending set of faults. The tilting of the area to the north-west, to give the Caledonian folds their plunge, may well also have been introduced at this time.

(c) Faulting

Faults follow two dominant directions. The earlier Caledonian fractures follow almost exactly the trend of the folding, i.e. WNW to ESE. Associated with the Hercynian orogeny are the N-S trending Barbon Fault, and NE-SW trending Dent Fault, which form the western and eastern boundaries of the region. Branches of these faults cut across the Silurian strata and displace the earlier Caledonian structures.

(i) Caledonian Faults

The WNW trending Caledonian faults are in many cases associated with the monoclinal structures, and thus tend to be concentrated in the same areas of Barbondale and Dentdale. The high degree of shattering and crushing associated with them suggests that many are reversed faults, although at a high angle, as the faults cut across country in almost straight lines. This can be proved in some localities on the southern slopes of Barbondale, where the steep limbs of the monoclines are fractured into high angle reversed faults, with a small downthrow to the north. The exact amount of displacement is difficult to prove in many cases, owing to the highly shattered nature of the strata, and the lack of closely spaced marker bands. In Barbondale, however, it is considered to be small, as the faults appear to be only in the process of development from the monoclines.

On the southern slopes of Dentdale, the WNW trending faults are very closely spaced, and well exposed, allowing the direction and amount of throw to be estimated in many cases, especially where there are rapid changes of lithology. All of these faults throwdown to the north-north-east. The amount of throw varies along the strike, as some of them merge into unfaulted monoclines, but is usually not more than 20 to 30 feet.

Caledonian faulting does also occur outside these two narrow belts, but is comparatively uncommon. To the south of Barbondale for example, only one poorly exposed WNW trending fault occurs, on the summit of Nonslope Moss (651812). This fault is largely inferred from a series of veined and brecciated exposures of greywacke, and dry steep sided gullies. Field evidence and changes in lithology suggest that the downthrow in this case, is on the north-north-eastern side, and is approximately 100 feet. From the evidence available, it is not possible to prove whether this is also a reverse fault or not. The fault cuts across country in almost a straight line, however, indicating that the fault plane is almost vertical. North of Barbondale, an almost E-W trending fault runs down the Millhouse Beck valley. The almost straight line of the structure again suggests that the fault plane is almost vertical, and the broken and compressed nature of the strata indicate that it is probably reversed. The downthrow is to the south, but it is not possible to say precisely by how much, as there is no means of defining the horizon of the few scattered outcrops of greywacke on its north side. An E-W trending fault is also developed in places in Luge Gill from the monocline running down the valley. Like the other structures of this type, however, an actual fault is developed only in a few places, and then the throw to the north is always small, and never more than 20-30 feet.

Caledonian faulting is thus developed on a comparatively small scale, largely as a result of compressive forces. Apart from the Dentdale and Barbondale areas, the overall effect on the structure is slight due to the small amount of displacement which has taken place.

(ii) Hercynian Faults

The two major Hercynian faults, i.e. the N-S trending Barbon Fault, which is considered to be a continuation of the Craven Line, and the NE trending Dent Fault, are both very poorly exposed. The actual plane of the Dent Fault is not exposed at any point in the area, but its position can be mapped to within 2 to 3 feet by exposures of Silurian and Carboniferous limestone on either side of Barbon Beck, and by the marked changes in vegetation. The Silurian strata are highly crushed and veined in the vicinity of the fault, which in this area appears to be represented by a single fracture. The high degree of crushing supports Dakyns et al (1890), Strahan (1891), and Turner (1935), who considered that the Dent Fault was reversed, and thus the Silurian strata had been thrust over the Carboniferous to the east. The almost straight line of the fault indicates that the thrust is very steeply inclined. The Carboniferous was believed by Phillips (1836), to have been displaced downwards by 2-3000 feet. Aveline (1872), however, after estimating the thicknesses of the Carboniferous and Silurian strata in the area, and the horizons thrown against each other, considered that the throw was in the order of 5000 feet. As a result of the present work, and bearing in mind that the upper limit of the Silurian is not seen in the Barbon and Middleton Fells, the throw of the Dent Fault in this area is considered to be approximately 4000 feet.

The only point at which the Barbon Fault is well exposed is in Barbon Beck about 100 yards to the east of Barbon Church (631825), (figure 11-5). This is not a simple fault, but a wide crush zone in which several N-S trending fractures can be detected. The Carboniferous limestone to the west of the main fault zone is arched up into an extremely tight anticline, the eastern limb of which is almost vertical, as if the strata has been subjected to strong pressure. Very near the contact, however, it is broken and brecciated. The Silurian strata are broken and crushed for a distance of 150 yards beyond the contact with the Carboniferous. The mapping of the section on a scale of 24 inches to the mile (figure 11-5), revealed the presence of 7 individual N-S trending steeply reversed fractures downthrowing to the west, within this fault zone. Between the fault planes which are marked by bands of blue clay and red staining, dips are predominantly downstream, although somewhat variable in amount and direction, due to the broken nature of the strata. The Silurian thus appears to have been thrust over the Carboniferous. The horizons exposed within the strata on either side of the fault suggest that the downthrow is of the order of 4000 feet to the west.

Turner (1935), considered that the Barbon Fault was a dextral tear fault, (cf. Garwood and Goodyear 1924). The

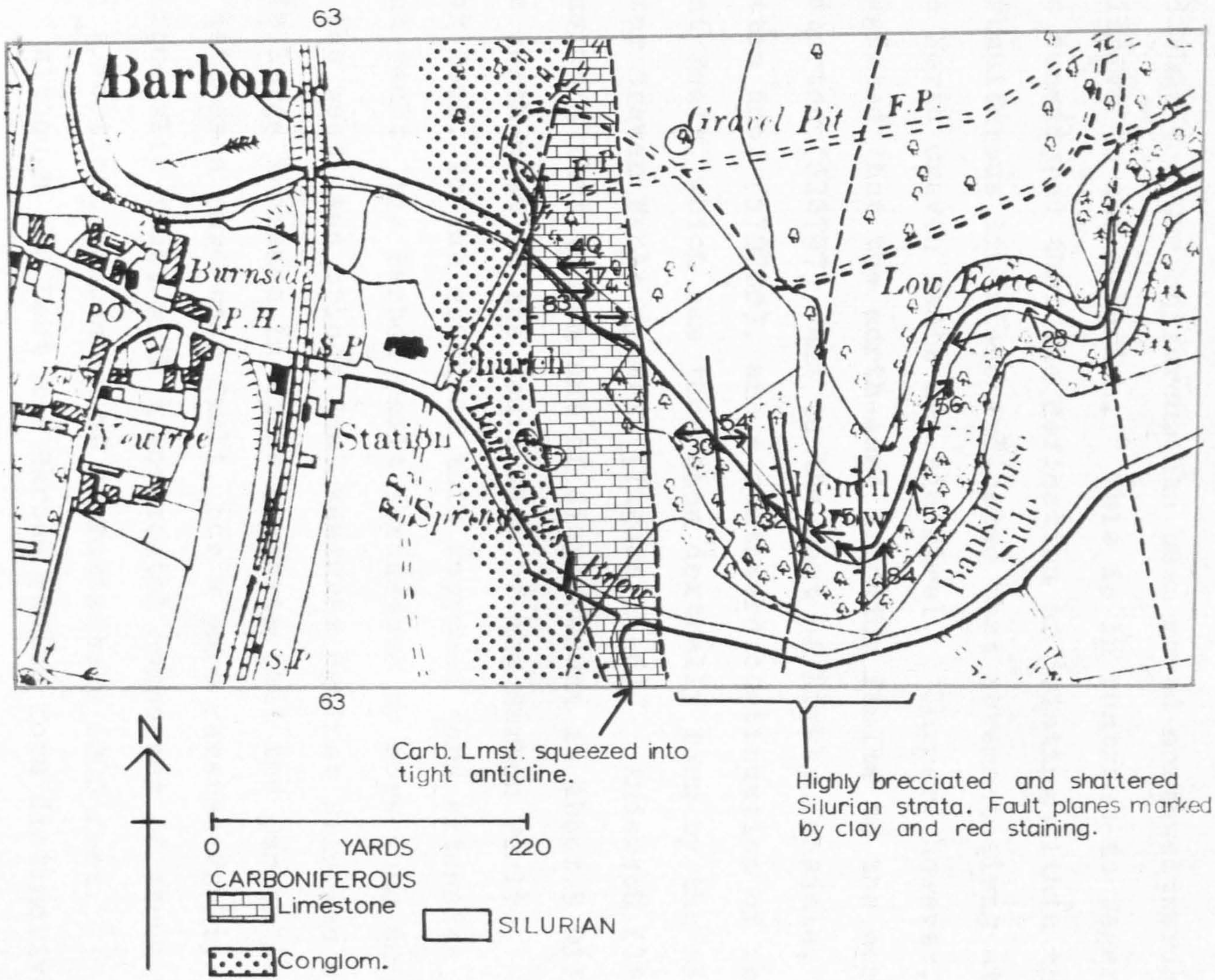



FIG. 11-5. Section through the Barbon Fault in Barbon Beck.

extremely wide smash zone, and some horizontal slickensiding seen in Barbon Beck, suggests that this conclusion is correct, and thus the Carboniferous has been moved northwestwards relative to the Silurian. This is in contrast to Wager (1931), who considered that the deflection of jointing within the Carboniferous limestone indicated that movement along at least the North Craven Fault was sinistral. Turner, however, suggested that the north-east trending faults to the east of Casterton (626797), and to the west of Kirkby Lonsdale, near Hutton Roof (570780), are a southward continuation of the Dent Fault, which has thus been dextrally torn by the slightly later Craven Fault system. (figure 11-6). Anderson (1942 p 81), considers that the amount of displacement is about 5 miles to the north-west on the south side of the Barbon Fault. In Leck Beck, to the south of this supposed torn extension of the Dent Fault, the Barbon Fault throwsdown by more than 6000 feet to the west, and brings Coal Measures against Silurian strata. This large increase in throw suggests that the Barbon Fault is neither a pure tear fault, nor a pure reverse fault, but an oblique slip fault with a horizontal component of about 5 miles, and a vertical component of approximately 6000 feet.

Although the Dent and Barbon Faults form distinctive structural boundaries to the area, Hercynian faulting does affect the Silurian strata to a marked extent, but with only a comparatively small amount of displacement in most cases. Branches of the Dent Fault, and to a lesser extent the Barbon

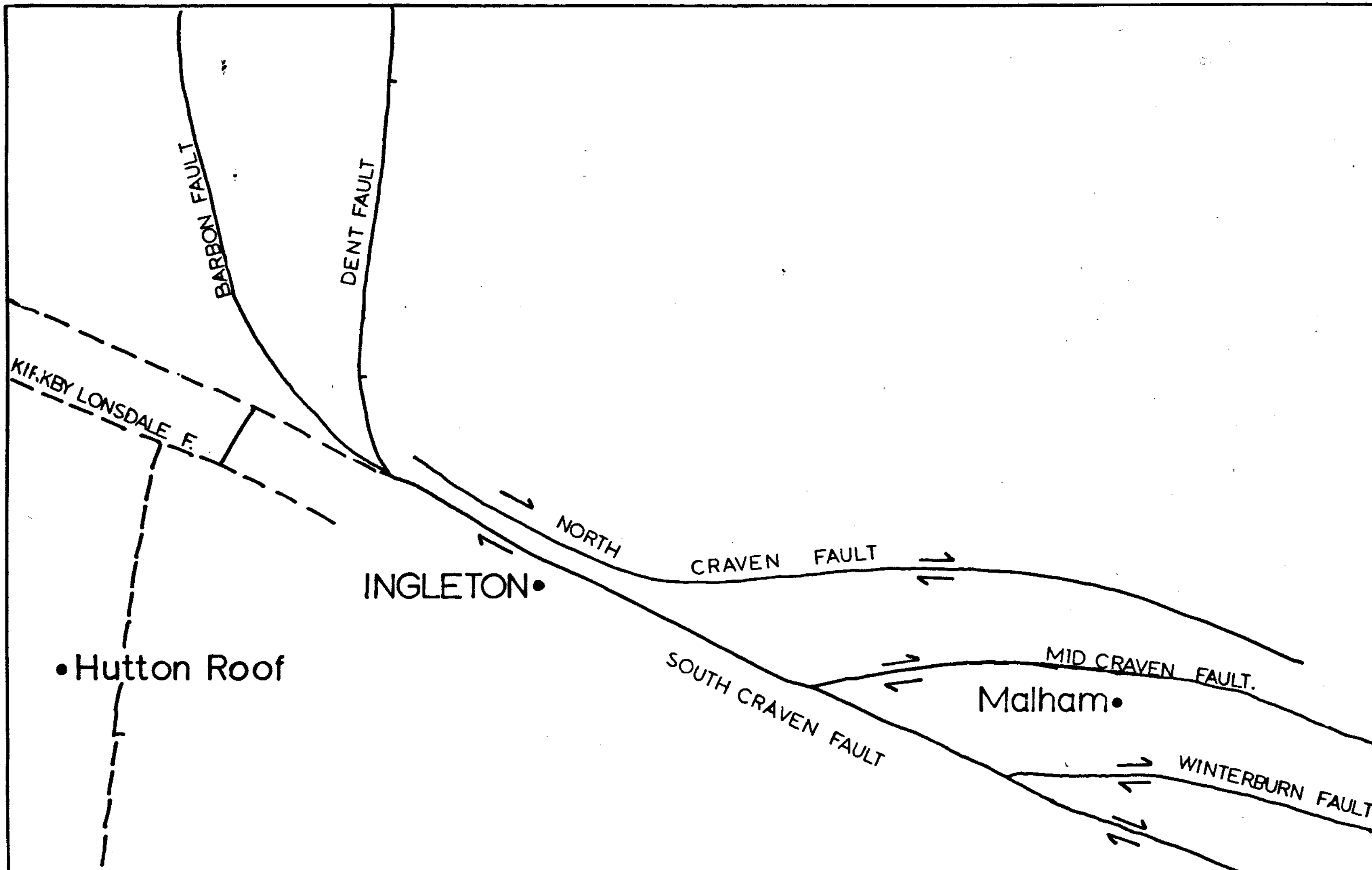



FIG.11-6 The Craven and Dent Fault systems, and the supposed torn southerly extension of the Dent Fault. (After Hudson, Turner, and Anderson).

Fault, cut across the Fells in predominantly NNW to NNE directions, but on the whole are rather poorly exposed, and can usually only be traced by erosional features, or by sudden changes in lithology along the strike. As a result, the relationships between individual faults cannot always be deduced satisfactorily.

In the south of the area, a NW-SE trending fault cuts across the upper part of Grove Gill and south-eastwards through a distinctive hollow in Brownthwaite Moss, to join with the Dent Fault in Leck Beck. The throw is of the order of 150 feet to the south-west. Similar structures, but with a more north-north-westerly trend, branch off from the Dent Fault in the Gale Garth (656808), and Bullpot Farm (663815) areas. The more southerly of these two fractures, which has a downthrow to the east of 180 feet, cannot be traced beyond the heavily faulted and broken strata on the southern side of Barbondale. The northern one, however, which throws to the west, can be traced for 3 miles to the north-north-west, in an almost straight line, by a series of stream exposures and spring lines, into the Bannisdale Slates of Brow Gill. It is not continued beyond this point on the map, due to the poor degree of exposure. The throw throughout its length appears to remain at about 150 feet.

Further fractures with a north-north-westerly trend branch away from the Dent Fault in Barbondale. These faults, however, are also poorly exposed, but field evidence suggests that they link up with 3 north and north-east trending faults which can be traced up the southern slopes of Dentdale. This interpretation is shown on the 6 inch inset maps. The throw of these faults at their northern ends in Dentdale, is to the east or north-east, and the amounts of displacement are approximately 150 feet, 180 feet and 80 feet respectively from east to west. The fault running south-eastwards from Holme Fell, and throwing the Upper Bannisdale Slates against the lower divisions of the Ludlow Series may be a branch of this system. It is not exposed south of Raismoor Beck (652887), however, and thus the relationship is doubtful.

Fractures branching off from the Barbon Fault are less common, but this in part may be due to the much poorer degree of exposure along the western edge of the region. In the Grove Gill area, however, two NNE trending faults downthrowing to the west, break away from this fault. The most westerly of the two can be followed only as far as Barbon Beck, and has a small throw. The easterly one, however, has been traced for 2 miles to the north-north-east in an almost straight line, across Barbondale and into Ashdale Gill. The throw in this case appears to be approximately 350 feet to the west, becoming rather less to the north of Ashdale Gill. In Barbon Beck, this fault is marked by a heavily crushed zone several feet in width. The horizons present on either side of the fault in this locality are difficult to determine, however, due to the lack of marker bands and the heavy WNW trending faulting.

Associated with the Barbon Fault in the central part of the region, is a parallel fracture running several hundred yards to the east of the main fault plane. This branches off just to the south of Barbon Beck, and can be traced in the lower reaches of all the stream sections, as far north as Luge Gill, but north of this point appears to rejoin the main fault. The throw is to the west, but the amount is uncertain due to the monotonous lithology on either side of the fault plane.

Hercynian faulting is thus rather more dominant and has a greater effect on the structure than the Caledonian fractures. The amount of displacement, however, although greater than the WNW trending faults, is small in comparison with the movement on the parent Dent and Barbon Faults, which thus apparently cushioned the area from the main orogenic forces.

## General Conclusions

(1) The Barbon and Middleton Fells are folded into two open WNW trending synclines, separated by a small crumpled anticline.

(2) Superimposed on the major structure are minor folds of the same age, and which also have a WNW trend. These folds can be sub-divided into open slightly asymmetrical structures, and monoclinal structures.

(3) A preliminary survey shows that the trend of the highly developed fracture cleavage swings slightly towards the north, in the south-east of the area, indicating

perhaps a gradual change in the trend of the folding.

(4) Caledonian faulting follows the trend of the folding, and is closely associated with the monoclinal structures. The throw is small in most cases.

(5) The effect of the Hercynian orogeny has been to tilt the strata slightly to the north-west, and introduce a set of N-S or NE-SW trending faults.

(6) The boundaries of the area are formed by the later Hercynian Dent and Barbon Faults. Both of these faults are reversed and downthrow between 4000 and 5000 feet. In addition the Barbon Fault is considered to be dextrally torn, and displaces the southern part of the Dent Fault.

(7) Branches of these faults cut across the Silurian strata and have a greater effect on the structure than the Caledonian faulting. The amount of displacement is comparatively small, however, as it appears that the boundary faults cushioned the area from the main orogenic forces.

# CHAPTER 12

## SUMMARY OF CONCLUSIONS

(1) The stratigraphical succession consisting of Brathay Flags, Coniston Grits and Bannisdale Slates is considered to have been deposited from turbidity currents. It may be sub-divided on a lithological basis, depending on the proportion of coarse greywacke to finer sediment. Within these divisions the lundgreni, nilssoni-scanicus, leintwardinensis incipiens and leintwardinensis graptolite zones have been recognised. A marked thickening of the strata from north to south suggests a considerable deepening of the geosyncline in this direction. (Chapter 3).

(2) The lithological types described from the Barbon and Middleton Fells are also found in the Silurian strata of many other parts of the British Isles, and indicate that deposition from turbidity currents was a widespread feature of Silurian sedimentation. (Chapter 4).

(3) Petrographical studies show that the coarse sediments fall on the edge of the greywacke field, towards the subgreywacke class, and that the matrix is largely secondary. Grain size analyses show that almost all of

the greywackes are poorly sorted, sub-angular and of silt grade. This indicates rapid mechanical disintegration of the source rocks, and deposition from comparatively slow moving turbidity currents. (Chapters 5 and 6).

(4) The finer grained sediments, i.e. the graptolitic siltstones and banded units were deposited during quiescent periods by low grade turbidity currents. The pyritic films in these rocks have probably resulted from the anaerobic alteration of annually deposited carbonaceous material. The absence of these films from the mudstone laminae of the banded units is considered to be due to the re-working of this finer sediment by burrowing worms. (Chapters 7 and 9).

(5) Sedimentary structures indicate that the greywackes were carried into the area from the north-west, down the side of the trough, by very variable turbidity currents. Rock fragments within the sediments suggest that the land which lay in this direction was in the northern belt of the Southern Uplands, and not the Lake District. This hypothesis is strengthened by a consideration of palaeocurrent and stratigraphical evidence from the Lake District, Howgill Fells and Southern Uplands, which shows that the existence of a border land mass is unlikely. The absence of coarse sediments in the earlier part of the Silurian period, however, is explained by a shallowing in the border area. (Chapters 3, 5, 9 and 10).

(6) The sediments deposited in the Barbon and Middleton Fells were later folded during the Caledonian orogeny into open WNW trending folds, on which minor folding and faulting with the same trend was superimposed. The later Hercynian orogeny introduced a set of N-S, and NE-SW trending faults which are subsidiary features of the Dent and Barbon Faults. (Chapter 11).

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## APPENDIX I

## SAMPLE LOCALITIES

Sampling localities are numbered from S1 to S125, starting from the Wenlock Series. In the list below, the lithology, bed number, locality and grid reference of each specimen is given, along with an indication of any thin sections made from the specimen. Thin sections of the greywacke units are numbered from 1-26 starting at the base of the Lower Coniston Grits. Graptolitic siltstone slides are indicated by an X. Heavy Mineral Separations are numbered from H1-15 again starting from the base of the Lower Coniston Grits.

Abbreviations:- G or GreyW = Greywacke
GS = Graptolitic Siltstone
BU = Banded Unit

(i) Brathay Flags

| Sample No. | Lithology | Locality | Grid Ref | Thin Sections G | Thin Sections GS | Heavy Min.S. |
|---|---|---|---|---|---|---|
| S6 | Grap Silt | Leck Beck | 655791 | | | |
| S5 | " " | " " | 655790 | | X | |
| S4 | " " | " " | 654787 | | | |
| S3 | " " | " " | 652786 | | | |
| S2 | " " | " " | 649783 | | | |
| S1 | " " | " " | 648780 | | X | |

# APPENDIX I

## SAMPLE LOCALITIES (CONT.)

### (ii) Lower Coniston Grits

| Sample No. | Lithology+ Bed No. | Locality | Grid Ref | Thin Sections G Slide No. | GS BU | Heavy Min S |
|---|---|---|---|---|---|---|
| S33 | GreyW LCG15 | NW Fell Road | 644808 | 10 | | H5 |
| S32 | GreyW LCG15 | NW Fell Road | 645808 | 9 | | |
| S31 | GrapS LCG14 | NW Fell Road | 647807 | | | |
| S30 | GrapS LCG14 | NW Fell Road | 648807 | | X | |
| S29 | GreyW LCG13 | NW Fell Road | 648806 | | | H4 |
| S28 | GreyW LCG13 | NW Fell Road | 648805 | 8 | | |
| S27 | GrapS LCG12 | NW Fell Road | 649804 | | X | |
| S26 | GreyW LCG11 | NW Fell Road | 650803 | 7 | | |
| S25 | GreyW LCG11 | NW Fell Road | 650802 | | | H3 |
| S24 | GreyW LCG11 | NW Fell Road | 650801 | 6 | | |
| S23 | GrapS LCG10 | NW Fell Road | 650800 | | X | |
| S22 | GreyW LCG 9 | Fell Road | 649800 | | | |
| S21 | GreyW LCG 9 | Fell Road | 649799 | | | |
| S20 | GreyW LCG 9 | Fell Road | 649798 | 5 | | |
| S19 | B.U. LCG 8 | Fell Road | 649797 | | X | |
| S18 | GreyW LCG 7 | Fell Road | 650797 | 4 | | |
| S17 | GrapS LCG 6 | NW Leck Beck | 650795 | | X | |
| S16 | GreyW LCG 5 | NW Leck Beck | 658799 | | | H2 |
| S15 | GreyW LCG 5 | NW Leck Beck | 653798 | 3 | | |
| S14 | GrapS LCG 4 | NW Leck Beck | 655797 | | X | |
| S13 | GrapS LCG 4 | NW Leck Beck | 652793 | | | |
| S12 | GreyW LCG 3 | NW Leck Beck | 652794 | | | |
| S11 | GreyW LCG 3 | NW Leck Beck | 653793 | 2 | | |
| S10 | GrapS LCG 2 | NW Leck Beck | 655794 | | | |
| S 9 | GrapS LCG 2 | Leck Beck | 657796 | | X | |
| S 8 | GreyW LCG 1 | Leck Beck | 657795 | | | H1 |
| S 7 | GreyW LCG1 | Leck Beck | 657794 | 1 | | |

APPENDIX I

SAMPLE LOCALITIES (CONT.)

(iii) Middle Coniston Grits

| Sample No. | Lithology+ | Bed No. | Locality | Grid Ref | Thin Sections G Slide No. | Thin Sections GS BU | Heavy Min S. |
|---|---|---|---|---|---|---|---|
| S49 | BU | MCG 8 | Aygill | 656829 | | | |
| S48 | BU | MCG 8 | Aygill | 657829 | | X | |
| S47 | BU | MCG 8 | Aygill | 658828 | | | |
| S46 | BU | MCG 8 | Howegill | 650821 | | | |
| S45 | GrapS | MCG 7 | Howegill | 650820 | | X | |
| S44 | GreyW | MCG 6 | Howegill | 648818 | 14 | | H8 |
| S43 | BU | MCG 5 | Nonslope M | 647817 | | X | |
| S42 | BU | MCG 5 | Nonslope M | 652817 | | | |
| S41 | GreyW | MCG 4 | Nonslope Moss | 652816 | 13 | | H7 |
| S40 | GreyW | MCG 4 | Nonslope Moss | 652814 | 12 | | |
| S39 | BU | MCG 3 | Grove Gill | 644813 | | X | |
| S38 | GreyW | MCG 2 | Grove Gill | 642813 | | | H6 |
| S37 | GreyW | MCG 2 | Grove Gill | 641813 | 11 | | |
| S36 | BU | MCG 1 | Grove Gill | 639813 | | | |
| S35 | BU | MCG 1 | Dry Gill | 644808 | | | |
| S34 | BU | MCG 1 | Brownthwaite M. | 647808 | | X | |

APPENDIX I

SAMPLE LOCALITIES (CONT.)

(iv) Upper Coniston Grits

| Sample No. | Lithology+ Bed No. | Locality | Grid Ref | Sections G Slide No. | GS BU | Heavy Min S |
|---|---|---|---|---|---|---|
| S76 | GreyW UCG11 | Holme Fell | 649902 | | | - |
| S75 | GreyW UCG11 | Holme Fell | 641903 | | | H13 |
| S74 | GreyW UCG11 | Castle Knott | 658839 | | | |
| S73 | GreyW UCG11 | Castle Knott | 662843 | 23 | | |
| S72 | GrapS UCG10 | Holme Fell | 643904 | | | |
| S71 | GrapS UCG10 | Holme Fell | 641903 | | X | |
| S70 | GrapS UCG10 | Castle Knott | 659839 | | | |
| S69 | GrapS UCG10 | Castle Knott | 658837 | | | |
| S68 | GreyW UCG 9 | Holme Fell | 648903 | 22 | | H12 |
| S67 | GreyW UCG 9 | E Whiskey Gill | 651834 | | | |
| S66 | BU UCG 8 | Holme Fell | 645903 | | | |
| S65 | BU UCG 8 | E Whiskey Gill | 651835 | | X | |
| S64 | GreyW UCG 7 | Holme Fell | 644904 | | | H11 |
| S63 | GreyW UCG 7 | Holme Fell | 644905 | | | |
| S62 | GreyW UCG 7 | E Whiskey Gill | 653834 | | | |
| S61 | GreyW UCG 7 | E Whiskey Gill | 653832 | 21 | | |
| S60 | GrapS UCG 6 | Holme Fell | 642906 | | X | |
| S59 | GrapS UCG 6 | E Whiskey Gill | 651832 | | | |
| S58 | GreyW UCG 5 | E Whiskey Gill | 654831 | 20 | | |
| S57 | GreyW UCG 5 | Barbon Beck | 658830 | 19 | | H10 |
| S56 | BU UCG 4 | Whiskey Gill | 647830 | | X | |
| S55 | GreyW UCG 3 | Whiskey Gill | 647829 | 18 | | |
| S54 | GreyW UCG 3 | Barbon Beck | 647827 | 17 | | |
| S53 | GreyW UCG 3 | Barbon Beck | 654828 | 16 | | |
| S52 | GrapS UCG 2 | Barbon Beck | 651827 | | X | |
| S51 | GreyW UCG 1 | Barbon Beck | 649827 | | | H 9 |
| S50 | GreyW UCG 1 | Barbon Beck | 651826 | 15 | | |

APPENDIX I

SAMPLE LOCALITIES (CONT.)

(v) Lower Bannisdale Slates

| Sample No. | Lithology+ | | Locality | Grid Ref | Thin Sections G Slide No. | GS BU | Heavy Min S |
|---|---|---|---|---|---|---|---|
| S112 | GreyW | LBS6 | Raismoor B | 654888 | 26 | | |
| S111 | GreyW | LBS6 | Raismoor B | 653888 | | | H14 |
| S110 | GreyW | LBS6 | SE Brack G | 657882 | | | |
| S109 | GreyW | LBS6 | Wrestle G | 658869 | | | |
| S108 | BU | LBS5 | Holme Fell | 648893 | | | |
| S107 | BU | LBS5 | Holme Fell | 647895 | | X | |
| S106 | BU | LBS5 | W Brack G | 658884 | | | |
| S105 | BU | LBS5 | W Combe Scars | 665875 | | | |
| S104 | GreyW | LBS4 | Holme Fell | 645897 | | | |
| S103 | GreyW | LBS4 | Holme Fell | 645896 | | | |
| S102 | GreyW | LBS4 | Holme Fell | 645895 | | | |
| S101 | GreyW | LBS4 | Brack Gill | 660883 | | | |
| S100 | GreyW | LBS4 | Brack Gill | 660884 | | | |
| S 99 | GreyW | LBS4 | Combe Scars | 675880 | | | |
| S 98 | GreyW | LBS4 | Combe Scars | 676880 | 25 | | |
| S 97 | BU | LBS3 | Holme Fell | 643895 | | | |
| S 96 | BU | LBS3 | Holme Fell | 643896 | | | |
| S 95 | BU | LBS3 | Holme Fell | 643897 | | | |
| S 94 | BU | LBS3 | Holme Fell | 643899 | | | |
| S 93 | BU | LBS3 | Brack G | 665885 | | X | |
| S 92 | BU | LBS3 | Barkin Fell | 665858 | | | |
| S 91 | BU | LBS3 | Barkin Fell | 665857 | | | |
| S 90 | BU | LBS3 | Barkin Fell | 665855 | | | |
| S 89 | GreyW | LBS2 | Holme Fell | 650900 | | | |
| S 88 | GreyW | LBS2 | Holme Fell | 642898 | | | H15 |
| S 87 | GreyW | LBS2 | Holme Fell | 642900 | | | |
| S 86 | GreyW | LBS2 | Brack G | 664887 | | | |
| S 85 | GreyW | LBS2 | Barkin Fell | 672862 | 24 | | |
| S 84 | BU | LBS1 | Holme Fell | 650901 | | | |
| S 83 | BU | LBS1 | Holme Fell | 650902 | | X | |
| S 82 | BU | LBS1 | Holme Fell | 643902 | | | |
| S 81 | BU | LBS1 | Holme Fell | 642903 | | | |
| S 80 | BU | LBS1 | Brack G | 665888 | | | |
| S 79 | BU | LBS1 | Brack G | 665889 | | | |
| S 78 | BU | LBS1 | Barkin Fell | 670861 | | | |
| S 77 | BU | LBS1 | Barkin Fell | 670860 | | | |

## APPENDIX I

### SAMPLE LOCALITIES (CONT.)

(vi) Upper Bannisdale Slates

| Sample No. | Lithology+ Bed No. | Locality | Grid Ref | Sections G Slide No. | Sections GS BU | Heavy Min S |
|---|---|---|---|---|---|---|
| S125 | BU UBS2 | Ashd Gill | 635838 | | | |
| S124 | BU UBS2 | Luge Gill | 639878 | | X | |
| S123 | BU UBS2 | Luge Gill | 638877 | | | |
| S122 | BU UBS2 | Luge Gill | 637877 | | | |
| S121 | BU UBS2 | Luge Gill | 636877 | | | |
| S120 | BU UBS1 | Ashd Gill | 641843 | | | |
| S119 | BU UBS1 | Ashd Gill | 641845 | | | |
| S118 | BU UBS1 | Ashd Gill | 638836 | | | |
| S117 | BU UBS1 | Ashd Gill | 638833 | | | |
| S116 | BU UBS1 | Luge Gill | 643878 | | X | |
| S115 | BU UBS1 | Luge Gill | 645878 | | | |
| S114 | BU UBS1 | Luge Gill | 648878 | | | |
| S113 | BU UBS1 | Luge Gill | 654878 | | X | |

### FAUNAL LOCALITIES

These are described in the text, and so have not been listed here.

## APPENDIX II

Specimens in the Collection of the University of Hull, Dept. of Geology

Thin sections have been made of all specimens listed below.

(i) Brathay Flags

| Sample No. | Bed No. | Lithology | Locality | Grid Ref. | Departmental Catalogue No. |
|---|---|---|---|---|---|
| S1 | - | Grap Silt | Leck Beck | 648780 | HU/Fu/L1 |
| S5 | - | Grap Silt | Leck Beck | 655790 | HU/Fu/L2 |

(ii) Lower Coniston Grits

| Sample No. | Bed No. | Lithology | Locality | Grid Ref. | Departmental Catalogue No. |
|---|---|---|---|---|---|
| S7 | LCG 1 | Greywacke | Leck Beck | 657794 | HU/Fu/L3 |
| S9 | LCG 2 | Grap Silt | Leck Beck | 657796 | HU/Fu/L4 |
| S11 | LCG 3 | Greywacke | NW Leck Beck | 653793 | HU/Fu/L5 |
| S14 | LCG 4 | Grap Silt | NW Leck Beck | 655797 | HU/Fu/L6 |
| S15 | LCG 5 | Greywacke | NW Leck Beck | 653798 | HU/Fu/L7 |
| S17 | LCG 6 | Grap Silt | NW Leck Beck | 650795 | HU/Fu/L8 |
| S18 | LCG 7 | Greywacke | Fell Road | 650797 | HU/Fu/L9 |
| S19 | LCG 8 | Banded U. | Fell Road | 649797 | HU/Fu/L10 |
| S20 | LCG 9 | Greywacke | Fell Road | 649798 | HU/Fu/L11 |
| S23 | LCG10 | Grap Silt | NW Fell Road | 650800 | HU/Fu/L12 |
| S24 | LCG11 | Greywacke | NW Fell Road | 650801 | HU/Fu/L13 |
| S26 | LCG11 | Greywacke | NW Fell Road | 650803 | HU/Fu/L14 |
| S27 | LCG12 | Grap Silt | NW Fell Road | 649804 | HU/Fu/L15 |
| S28 | LCG13 | Greywacke | NW Fell Road | 648805 | HU/Fu/L16 |
| S30 | LCG14 | Grap Silt | NW Fell Road | 648807 | HU/Fu/L17 |
| S32 | LCG15 | Greywacke | NW Fell Road | 645808 | HU/Fu/L18 |
| S33 | LCG15 | Greywacke | NW Fell Road | 644808 | HU/Fu/L19 |

(iii) Middle Coniston Grits

| Sample No. | Bed No. | Lithology | Locality | Grid Ref. | Departmental Catalogue No. |
|---|---|---|---|---|---|
| S34 | MCG 1 | Banded U. | Browth. M. | 647808 | HU/Fu/L20 |
| S37 | MCG 2 | Greywacke | Grove Gill | 641813 | HU/Fu/L21 |
| S39 | MCG 3 | Banded U. | Grove Gill | 644813 | HU/Fu/L22 |
| S40 | MCG 4 | Greywacke | Nonslope M. | 652814 | HU/Fu/L23 |
| S41 | MCG 4 | Greywacke | Nonslope M. | 652816 | HU/Fu/L24 |
| S43 | MCG 5 | Banded U. | Nonslope M. | 647817 | HU/Fu/L25 |
| S44 | MCG 6 | Greywacke | Howegill | 648818 | HU/Fu/L26 |
| S45 | MCG 7 | Grap Silt | Howegill | 650820 | HU/Fu/L27 |
| S48 | MCG 8 | Banded U. | Aygill | 657829 | HU/Fu/L28 |

(iv) Upper Coniston Grits

| Sample No. | Bed No. | Lithology | Locality | Grid Ref. | Departmental Catalogue No. |
|---|---|---|---|---|---|
| S50 | UCG 1 | Greywacke | Barbon Beck | 651826 | HU/Fu/L29 |
| S52 | UCG 2 | Grap Silt | Barbon Beck | 651827 | HU/Fu/L30 |
| S53 | UCG 3 | Greywacke | Barbon Beck | 654828 | HU/Fu/L31 |
| S54 | UCG 3 | Greywacke | Barbon Beck | 657827 | HU/Fu/L32 |
| S55 | UCG 3 | Greywacke | Whiskey G | 647829 | HU/Fu/L33 |
| S56 | UCG 4 | Banded U. | Whiskey G | 647830 | HU/Fu/L34 |
| S57 | UCG 5 | Greywacke | Barbon Beck | 658830 | HU/Fu/L35 |
| S58 | UCG 5 | Greywacke | E.Whiskey G | 654831 | HU/Fu/L36 |
| S60 | UCG 6 | Grap Silt | Holme Fell | 642906 | HU/Fu/L37 |
| S61 | UCG 7 | Greywacke | E.Whiskey G | 653832 | HU/Fu/L38 |
| S65 | UCG 8 | Banded U. | E.Whiskey G | 651835 | HU/Fu/L39 |
| S68 | UCG 9 | Greywacke | Holme Fell | 648903 | HU/Fu/L40 |
| S71 | UCG10 | Grap Silt | Holme Fell | 641903 | HU/Fu/L41 |
| S73 | UCG11 | Greywacke | Castle Knott | 662843 | HU/Fu/L42 |

(v) Lower Bannisdale Slates

| Sample No. | Bed No. | Lithology | Locality | Grid Ref. | Departmental Catalogue No. |
|---|---|---|---|---|---|
| S83 | LBS 1 | Banded U. | Holme Fell | 650902 | HU/Fu/L43 |
| S85 | LBS 2 | Greywacke | Barkin Fell | 672862 | HU/Fu/L44 |
| S93 | LBS 3 | Banded U. | Brack.Gill | 665885 | HU/Fu/L45 |
| S98 | LBS 4 | Greywacke | Combe Scars | 676830 | HU/Fu/L46 |
| S107 | LBS 5 | Banded U. | Holme Fell | 647895 | HU/Fu/L47 |
| S112 | LBS 6 | Greywacke | Raismoor B | 654888 | HU/Fu/L48 |

(vi) Upper Bannisdale Slates

| Sample No. | Bed No. | Lithology | Locality | Grid Ref. | Departmental Catalogue No. |
|---|---|---|---|---|---|
| S113 | UBS 1 | Banded U. | Luge Gill | 654878 | HU/Fu/L49 |
| S116 | UBS 1 | Banded U. | Luge Gill | 643878 | HU/Fu/L50 |
| S124 | UBS 2 | Banded U. | Luge Gill | 639878 | HU/Fu/L51 |

## APPENDIX III MINERALOGICAL ANALYSES

Appendix IIIA. The percentages of the important constituent minerals in the 26 greywackes analysed from the Barbon and Middleton Fells.

| Slide No. | % Quartz | % Felspar | % Rock Frag- ments | % Carbonate | % Matrix inc. Mica | % Others |
|---|---|---|---|---|---|---|
| 1 | 55.8 | 10.1 | 5.7 | 4.5 | 23.3 | 0.6 |
| 2 | 50.1 | 7.1 | 18.1 | 5.6 | 18.3 | 0.8 |
| 3 | 34.7 | 9.6 | 25.8 | 3.4 | 25.7 | 0.8 |
| 4 | 46.7 | 11.3 | 5.7 | 6.0 | 29.0 | 1.3 |
| 5 | 50.9 | 11.0 | - | 6.4 | 31.1 | 0.6 |
| 6 | 54.1 | 9.0 | 10.6 | 5.6 | 20.1 | 0.6 |
| 7 | 45.7 | 9.2 | 14.0 | 6.1 | 18.7 | 1.3 |
| 8 | 40.5 | 10.5 | 7.9 | 5.9 | 39.1 | 1.1 |
| 9 | 51.1 | 14.4 | 5.8 | 4.7 | 23.4 | 0.6 |
| 10 | 48.8 | 9.5 | 5.2 | 7.2 | 28.9 | 0.4 |
| 11 | 44.9 | 10.5 | 5.1 | 6.1 | 32.6 | 0.8 |
| 12 | 38.0 | 11.1 | 5.1 | 5.0 | 40.3 | 0.5 |
| 13 | 42.7 | 16.3 | 0.1 | 7.1 | 32.9 | 0.9 |
| 14 | 38.9 | 16.9 | 8.0 | 6.7 | 28.8 | 0.7 |
| 15 | 35.4 | 10.7 | 0.1 | 9.1 | 44.1 | 0.6 |
| 16 | 50.8 | 10.7 | 5.3 | 3.4 | 28.6 | 1.2 |
| 17 | 51.4 | 10.2 | - | 8.0 | 29.4 | 1.0 |
| 18 | 50.4 | 8.5 | 0.1 | 7.6 | 32.8 | 0.6 |
| 19 | 53.5 | 13.5 | 0.1 | 7.3 | 25.1 | 0.5 |
| 20 | 50.0 | 10.5 | 0.5 | 12.0 | 26.0 | 1.0 |
| 21 | 40.2 | 10.5 | 8.3 | 8.1 | 31.5 | 1.4 |
| 22 | 53.0 | 7.3 | 5.1 | 8.9 | 24.9 | 0.8 |
| 23 | 50.4 | 10.6 | 5.0 | 8.0 | 24.9 | 1.1 |
| 24 | 51.5 | 7.4 | 0.2 | 7.4 | 32.8 | 0.7 |
| 25 | 52.4 | 10.5 | 0.2 | 7.6 | 28.4 | 0.9 |
| 26 | 43.4 | 12.3 | 7.7 | 7.3 | 28.5 | 0.8 |
| Mean | 47.5 | 10.7 | 5.7 | 6.7 | 28.6 | 0.8 |

Sections :- At right angles to Bedding
Distance between points :- ¼ mm.
Distance between Traverses :- 1 mm.
No. of grains counted :- 2000 (from two halves of 1000 each)
Magnification :- x65 or x300

Appendix IIIB. The percentages of the important constituent minerals in the 12 greywackes analysed from the Howgill Fells.

| Slide No. | % Quartz | % Felspar | % Rock Fragments | % Cabonate | % Matrix inc. Mica | % Others |
|---|---|---|---|---|---|---|
| S/H 1 | 53.4 | 7.8 | 0.5 | 14.6 | 23.6 | 0.1 |
| S/H 2 | 49.4 | 8.8 | 1.5 | 5.9 | 34.3 | 0.1 |
| S/H 3 | 47.3 | 10.8 | 3.8 | 2.0 | 35.9 | 0.2 |
| S/H 4 | 39.6 | 8.0 | 0.2 | 8.7 | 43.2 | 0.3 |
| S/H 5 | 48.6 | 7.3 | 1.4 | 11.7 | 30.5 | 0.5 |
| S/H 6 | 52.0 | 6.5 | 0.6 | 12.7 | 27.9 | 0.3 |
| S/H 7 | 38.4 | 15.7 | 10.9 | 6.3 | 28.5 | 0.2 |
| S/H 8 | 49.5 | 12.1 | 2.2 | 5.4 | 30.4 | 0.4 |
| S/H 9 | 51.0 | 10.7 | 0.8 | 9.2 | 27.7 | 0.6 |
| S/H10 | 44.3 | 9.8 | 5.8 | 4.7 | 34.5 | 0.9 |
| S/H11 | 43.7 | 11.2 | 6.4 | 3.5 | 34.7 | 0.5 |
| S/H 12 | 50.9 | 8.5 | 4.2 | 5.5 | 30.8 | 0.1 |
| Mean | 47.3 | 9.8 | 3.2 | 7.5 | 31.8 | 0.4 |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses :- 1mm.

No. of grains counted :- 2000 (from two halves of 1000 each)

Magnification :- x65 or x300

Appendix IIIC. The percentages of the important constituent minerals in the 3 specimens of the Winder Grit from the Howgill Fells.

| Slide No. | % Quartz | % Felspar | % Rock Frag-ments | % Carbonate | % Matrix inc. Mica | % Others |
|---|---|---|---|---|---|---|
| WG 1 | 32.2 | 8.2 | 32.4 | 9.0 | 17.7 | 0.5 |
| WG 2 | 23.6 | 6.0 | 46.8 | 3.0 | 19.9 | 0.7 |
| WG 3 | 38.1 | 7.9 | 30.3 | 4.1 | 19.4 | 0.2 |
| Mean | 31.4 | 7.5 | 36.5 | 5.1 | 19.0 | 0.5 |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses :- 1 mm.

No. of Grains counted :- 2000 (from two halves of 1000 each)

Magnification :- x65

Appendix IIID. The percentages of the important constituent minerals in the 10 greywackes analysed from the Blawith area.

| Slide No. | % Quartz | % Felspar | % Rock Frag-ments | % Carbonate | % Matrix inc. Mica | % Others |
|---|---|---|---|---|---|---|
| S/B 1 | 46.5 | 6.4 | - | 11.7 | 35.1 | 0.3 |
| S/B 2 | 68.1 | 3.1 | - | 1.5 | 26.8 | 0.5 |
| S/B 3 | 55.2 | 6.1 | 0.1 | 9.0 | 29.6 | - |
| S/B 4 | 49.4 | 5.8 | - | 10.7 | 34.0 | 0.1 |
| S/B 5 | 52.5 | 7.0 | 1.0 | 3.1 | 35.8 | 0.6 |
| S/B 6 | 53.2 | 8.0 | 0.4 | 10.0 | 28.2 | 0.2 |
| S/B 7 | 50.6 | 4.9 | - | 7.6 | 36.4 | 0.5 |
| S/B 8 | 45.8 | 6.8 | 2.6 | 8.3 | 35.9 | 0.6 |
| S/B 9 | 51.9 | 5.2 | 0.9 | 10.4 | 31.0 | 0.6 |
| S/B10 | 56.3 | 9.1 | 1.0 | 9.8 | 23.4 | 0.4 |
| Mean | 52.9 | 6.2 | 0.6 | 8.2 | 31.6 | 0.5 |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses:- 1mm.

No. of grains counted :- 2000 (from two halves of 1000 each)

Magnification :- x65 or x300

Appendix IIIE. The percentages of the important constituent minerals in the 4 greywackes analysed from the Horton-in-Ribblesdale area.

| Slide No. | % Quartz | % Felspar | % Rock Frag-ments | % Carbonate | % Matrix inc. Mica | % Others |
|---|---|---|---|---|---|---|
| S/A 1 | 35.9 | 13.0 | 0.2 | 10.0 | 40.2 | 0.7 |
| S/A 2 | 40.3 | 8.6 | 0.4 | 11.1 | 39.1 | 0.5 |
| S/A 3 | 44.8 | 13.5 | 0.6 | 9.5 | 31.0 | 0.6 |
| S/A 4 | 43.6 | 11.1 | 0.5 | 9.8 | 34.6 | 0.4 |
| Mean | 41.1 | 11.5 | 0.4 | 10.1 | 36.2 | 0.7 |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses :- 1mm.

No. of grains counted :- 2000 (from two halves of 1000 each)

Magnification :- x65 or x300

Appendix IIIF. The Statistical Significance of the Results.

All slides were split into two halves of apparently identical texture and mineralogy, and 1000 points were counted from each half. If there was a wide discrepancy in the result, the section was completely re-analysed. The examples below show that the r esults are statistically significant and can be re-produced.

| | | Slide S.10 % | Slide S/H 4 % | Slide WG 2 | Slide S/B 1 | Slide S/A 3 |
|---|---|---|---|---|---|---|
| Quartz | Analysis 1 | 48.4% | 39.2% | 24.2% | 45.6% | 45.2% |
| | " 2 | 49.1% | 40.0% | 23.0% | 47.4% | 44.4% |
| | Mean | 48.8% | 39.6% | 23.6% | 46.5% | 44.8% |
| Felspar | Analysis 1 | 9.4% | 8.8% | 5.8% | 6.0% | 12.5% |
| | " 2 | 9.6% | 7.2% | 6.2% | 6.8% | 14.5% |
| | Mean | 9.5% | 8.0% | 6.0% | 6.4% | 13.5% |
| Rock Fragments | Analysis 1 | 4.7% | - | 45.6% | - | 0.7% |
| | " 2 | 5.8% | 0.4% | 48.0% | - | 0.5% |
| | Mean | 5.2% | 0.2% | 46.8% | - | 0.6% |
| Carbonate | Analysis 1 | 7.2% | 9.0% | 2.0% | 11.4% | 9.9% |
| | " 2 | 7.2% | 8.4% | 4.0% | 12.0% | 9.1% |
| | Mean | 7.2% | 8.7% | 3.0% | 11.7% | 9.5% |
| Matrix inc. Mica | Analysis 1 | 29.9% | 42.4% | 21.4% | 36.8% | 31.3% |
| | " 2 | 28.0% | 44.0% | 18.4% | 33.4% | 30.8% |
| | Mean | 28.9% | 43.2% | 19.9% | 35.1% | 31.0% |
| Others | Analysis 1 | 0.4% | 0.6% | 1.0% | 0.2% | 0.4% |
| | " 2 | 0.3% | - | 0.4% | 0.4% | 0.7% |
| | Mean | 0.4% | 0.3% | 0.7% | 0.3% | 0.6% |

As a further check the same parts of some thin sections were completely re-analysed at a later date, when closely comparable results were obtained.

## APPENDIX IV. HEAVY MINERAL ANALYSES

The Results from the 15 quantitative heavy mineral analyses are summarised below. The technique used was largely that proposed by Doeglas (1940), and is described in the text. Sample localities are shown in Appendix I.

| Sample No. | H1 | H2 | H3 | H4 | H5 | H6 | H7 | H8 | H9 | H10 | H11 | H12 | H13 | H14 | H15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | VC | VC | C | VC | VC | VC | VC | VC | VC | C | VC | VC | VC | C | C |
| 2 | C | C | C | P | C | C | P | P | P | C | C | C | C | P | C |
| 3 | VC | C | C | C | C | C | C | C | C | VC | C | C | C | P | C |
| 4 | C | C | P | C | P | C | C | C | C | C | C | C | C | C | P |
| 5 | P | P | P | C | C | P | P | P | P | C | P | R | P | C | C |
| 6 | C | C | P | C | C | C | C | P | C | R | C | C | C | C | C |
| 7 | C | C | C | P | P | P | R | R | C | P | R | R | P | R | P |
| 8 | C | C | C | C | C | C | C | C | C | C | C | C | C | C | C |
| 9 | VC | P | C | C | C | VC | P | VC | C | C | C | P | P | R | VC |
| 10 | C | C | C | C | C | C | C | C | P | C | P | C | C | C | C |
| 11 | R | - | - | - | R | R | R | - | R | R | R | R | R | R | - |
| 12 | P | P | P | P | R | P | P | P | R | R | R | R | P | P | P |
| 13 | - | - | R | - | - | - | - | - | - | - | - | - | R | - | - |
| Wt of Samp Gms. | 498 | 510 | 500 | 508 | 499 | 497 | 501 | 501 | 512 | 500 | 507 | 511 | 500 | 499 | 502 |
| % Heavies | 1.2 | 0.7 | 1.1 | 0.9 | 0.4 | 0.8 | 1.0 | 0.9 | 0.3 | 0.8 | 0.6 | 0.5 | 0.9 | 1.1 | 1.1 |

1 Pyrites
2 Magnetite
3 Ilm.-leucox
4 Purple Zircon
5 Col. Zircon
6 Pink Garnet
7 Col.,Y.Garnet
8 Rutile
9 Biotite
10 Chlorite
11 Tourmaline
12 Apatite
13 Others

VC = Very Common
C = Common
P = Present
R = Rare

# APPENDIX V. GRAIN SIZE ANALYSES

Appendix VA. Full grain size analyses of the 26 greywacke specimens from the Barbon and Middleton Fells.

| Slide No. | % Sand ie. grains more than 0.062mm | %Silt ie. grains between 0.062 & 0.004mm | %Clay grains less than 0.004mm | Mean Sand Size mm | Mean Silt Size mm | Mean Size of Sand, Silt and Clay |
|---|---|---|---|---|---|---|
| 1 | 32.0 | 58.0 | 10.0 | 0.094mm | 0.036mm | 0.051mm |
| 2 | 59.0 | 33.0 | 8.0 | 0.180mm | 0.037mm | 0.118mm |
| 3 | 66.0 | 25.0 | 9.0 | 0.242mm | 0.040mm | 0.170mm |
| 4 | 51.0 | 31.5 | 17.5 | 0.165mm | 0.033mm | 0.095mm |
| 5 | 22.5 | 66.5 | 11.0 | 0.083mm | 0.030mm | 0.039mm |
| 6 | 46.0 | 42.0 | 12.0 | 0.160mm | 0.038mm | 0.090mm |
| 7 | 34.5 | 53.5 | 12.0 | 0.113mm | 0.031mm | 0.056mm |
| 8 | 28.5 | 62.5 | 9.0 | 0.092mm | 0.037mm | 0.050mm |
| 9 | 28.5 | 60.5 | 11.0 | 0.165mm | 0.030mm | 0.045mm |
| 10 | 17.0 | 70.0 | 13.0 | 0.087mm | 0.028mm | 0.035mm |
| 11 | 23.5 | 58.5 | 18.0 | 0.086mm | 0.034mm | 0.041mm |
| 12 | 25.0 | 66.0 | 9.0 | 0.087mm | 0.036mm | 0.046mm |
| 13 | 24.0 | 61.0 | 15.0 | 0.084mm | 0.040mm | 0.044mm |
| 14 | 24.0 | 59.5 | 16.5 | 0.086mm | 0.034mm | 0.042mm |
| 15 | 28.5 | 53.5 | 18.0 | 0.091mm | 0.036mm | 0.046mm |
| 16 | 29.5 | 58.0 | 12.5 | 0.084mm | 0.038mm | 0.048mm |
| 17 | 44.0 | 48.0 | 8.0 | 0.096mm | 0.043mm | 0.063mm |
| 18 | 45.5 | 34.5 | 20.0 | 0.138mm | 0.036mm | 0.071mm |
| 19 | 36.0 | 52.0 | 12.0 | 0.100mm | 0.038mm | 0.060mm |
| 20 | 35.5 | 53.5 | 11.0 | 0.088mm | 0.040mm | 0.053mm |
| 21 | 28.0 | 58.5 | 13.5 | 0.090mm | 0.038mm | 0.047mm |
| 22 | 33.5 | 54.5 | 12.0 | 0.084mm | 0.041mm | 0.051mm |
| 23 | 25.5 | 59.0 | 15.5 | 0.097mm | 0.039mm | 0.050mm |
| 24 | 23.5 | 61.5 | 15.0 | 0.084mm | 0.036mm | 0.042mm |
| 25 | 22.5 | 63.0 | 14.5 | 0.078mm | 0.041mm | 0.044mm |
| 26 | 19.0 | 65.5 | 15.5 | 0.089mm | 0.035mm | 0.040mm |
| Means | 32.8 | 54.2 | 13.0 | 0.109mm | 0.036mm | 0.059mm |

Sections:- At right angles to Bedding. Distance between points:- 1/6 mm.
Distance between Traverses:- 1 mm.
No. of grains measured:- 200 Magnification:- x65 or x300

No allowance was made for the sectioning effect.

Appendix VB. Full grain size analyses of the 12 greywackes from the Howgill Fells.

| Slide No. | % Sand ie. grains more than 0.062mm | %Silt ie. grains between 0.062 & 0.004mm | %Clay grains less than 0.004mm | Mean Sand Size mm | Mean Silt Size mm | Mean Size of Sand, Silt and Clay |
|---|---|---|---|---|---|---|
| S/H 1 | 51.0 | 31.5 | 17.5 | 0.127mm | 0.044mm | 0.080mm |
| S/H 2 | 49.5 | 34.0 | 16.5 | 0.128mm | 0.038mm | 0.077mm |
| S/H 3 | 56.0 | 27.0 | 17.0 | 0.165mm | 0.043mm | 0.104mm |
| S/H 4 | 44.5 | 37.0 | 18.5 | 0.123mm | 0.041mm | 0.066mm |
| S/H 5 | 48.5 | 31.5 | 20.0 | 0.144mm | 0.040mm | 0.083mm |
| S/H 6 | 39.5 | 44.0 | 16.5 | 0.121mm | 0.040mm | 0.066mm |
| S/H 7 | 42.0 | 33.0 | 25.0 | 0.104mm | 0.035mm | 0.056mm |
| S/H 8 | 46.5 | 30.0 | 23.5 | 0.147mm | 0.040mm | 0.081mm |
| S/H 9 | 50.0 | 31.5 | 18.5 | 0.130mm | 0.039mm | 0.078mm |
| S/H10 | 51.5 | 34.0 | 14.5 | 0.098mm | 0.041mm | 0.065mm |
| S/H11 | 45.5 | 44.0 | 10.5 | 0.075mm | 0.037mm | 0.051mm |
| S/H12 | 46.5 | 37.5 | 16.0 | 0.100mm | 0.042mm | 0.062mm |
| Means | 47.6 | 34.6 | 17.8 | 0.122mm | 0.040mm | 0.074mm |

Sections :- At right angles to Bedding
Distance between points :- ¼ mm.
Distance between Traverses :- 1mm.
No. of grains measured :- 200
Magnification :- x65 or x300

No allowance was made for the sectioning effect.

Appendix VC. Full grain size analyses of the 3 specimens of Winder Grit from the Howgill Fells.

| Slide No. | % Sand ie. grains more than 0.062mm | %Silt ie. grains between 0.062 & 0.004mm | %Clay grains less than 0.004mm | Mean Sand Size mm | Mean Silt Size mm | Mean Size of Sand, Silt and Clay |
|---|---|---|---|---|---|---|
| WG 1 | 65.0 | 17.5 | 17.5 | 0.320mm | 0.041mm | 0.285mm |
| WG 2 | 55.5 | 22.5 | 22.0 | 0.470mm | 0.032mm | 0.270mm |
| WG 3 | 56.0 | 28.0 | 16.0 | 0.345mm | 0.038mm | 0.205mm |
| Means | 58.8 | 22.7 | 18.5 | 0.378mm | 0.037mm | 0.253mm |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses :- 1mm.

No. of grains measured :- 200

Magnification :- x65

Sectioning effect not allowed for.

Appendix VD. Full grain size analyses of the 10 greywacke specimens from the Blawith area.

| Slide No. | % Sand ie. grains more than 0.062mm | % Silt ie. grains between 0.062 & 0.004mm | % Clay grains less than 0.004mm | Mean Sand Size mm | Mean Silt Size mm | Mean Size of Sand, Silt and Clay |
|---|---|---|---|---|---|---|
| S/B 1 | 25.0 | 55.0 | 20.0 | 0.105mm | 0.038mm | 0.048mm |
| S/B 2 | 22.0 | 63.0 | 15.0 | 0.085mm | 0.040mm | 0.045mm |
| S/B 3 | 41.5 | 39.5 | 19.0 | 0.120mm | 0.039mm | 0.066mm |
| S/B 4 | 8.0 | 65.0 | 27.0 | 0.080mm | 0.033mm | 0.030mm |
| S/B 5 | 46.0 | 37.0 | 17.0 | 0.133mm | 0.040mm | 0.076mm |
| S/B 6 | 25.0 | 54.0 | 21.0 | 0.135mm | 0.045mm | 0.058mm |
| S/B 7 | 45.5 | 34.5 | 20.0 | 0.090mm | 0.041mm | 0.055mm |
| S/B 8 | 43.5 | 35.0 | 21.5 | 0.100mm | 0.046mm | 0.060mm |
| S/B 9 | 36.0 | 45.0 | 18.5 | 0.080mm | 0.038mm | 0.046mm |
| S/B10 | 48.5 | 36.0 | 15.5 | 0.085mm | 0.045mm | 0.058mm |
| Means | 34.1 | 46.4 | 19.5 | 0.101mm | 0.040mm | 0.054mm |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses :- 1mm.

No. of grains measured :- 200

Magnification :- x65 or x300

No allowance has been made for the sectioning effect.

Appendix VE. Full grain size analyses of the 4 greywacke specimens from the Horton-in-Ribblesdale area.

| Slide No. | % Sand ie. grains more than 0.062mm | %Silt ie. grains between 0.062 & 0.004mm | %Clay grains less than 0.004mm | Mean Sand Size mm | Mean Silt Size mm | Mean Size of Sand, Silt and Clay |
|---|---|---|---|---|---|---|
| S/A 1 | 24.0 | 53.5 | 22.5 | 0.101mm | 0.036mm | 0.044mm |
| S/A 2 | 30.5 | 46.5 | 23.0 | 0.105mm | 0.035mm | 0.049mm |
| S/A 3 | 23.0 | 57.5 | 19.5 | 0.108mm | 0.032mm | 0.044mm |
| S/A 4 | 38.0 | 40.0 | 22.0 | 0.110mm | 0.039mm | 0.058mm |
| Means | 28.8 | 49.4 | 21.8 | 0.106mm | 0.035mm | 0.049mm |

Sections :- At right angles to Bedding

Distance between points :- $\frac{1}{6}$ mm.

Distance between Traverses :- 1mm.

No. of grains measured:- 200

Magnification :- x65 or x300

No allowance has been made for the sectioning effect.

Appendix VF. The statistical significance of the grain size analyses.

To check the accuracy of the grain size measurements, 3 specimens were completely re-analysed. The results are shown below, alongside the original analyses and indicate that the results are statistically valid.

| Slide No. | % Sand ie. grains more than 0.062mm | %Silt ie. grains between 0.062 & 0.004mm | %Clay ie. grains Less than 0.004mm | Mean Sand Size mm | Mean Silt Size mm | Mean Size of Sand, Silt and Clay |
|---|---|---|---|---|---|---|
| S 5 First Anal. | 22.5 | 66.5 | 11.0 | 0.083mm | 0.030mm | 0.039mm |
| Second Anal. | 17.5 | 67.5 | 15.0 | 0.080mm | 0.034mm | 0.038mm |
| S 10 First Anal. | 17.0 | 70.0 | 13.0 | 0.087mm | 0.028mm | 0.035mm |
| Second Anal. | 13.0 | 67.5 | 19.5 | 0.082mm | 0.029mm | 0.035mm |
| S 18 First Anal. | 45.5 | 34.5 | 20.0 | 0.138mm | 0.036mm | 0.071mm |
| Second Anal. | 43.0 | 38.0 | 19.0 | 0.137mm | 0.033mm | 0.074mm |

Anal. = Analysis.

## APPENDIX VI, ROUNDNESS ANALYSES

Appendix VIA. Full roundness analyses of the 26 greywacke specimens from the Barbon and Middleton Fells, using Powers' (1953) Roundness Scale.

(Limits of Class: .12 .17 .25 .35 .49 .70 1.00

| Mid Point / Slide No. | .14 Very Ang | .21 Ang | .30 Sub Ang | .41 Sub Round | .59 Round | .86 Well Round | % High Sph | % Low Sph | Mean Rnd-ness |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5% | 36% | 53% | 6% | - | - | 53 | 47 | 0.27 SA |
| 2 | 11% | 38% | 43% | 8% | - | - | 62 | 38 | 0.26 SA |
| 3 | 13% | 33% | 45% | 9% | - | - | 55 | 45 | 0.26 SA |
| 4 | 14% | 39% | 42% | 5% | - | - | 70 | 30 | 0.25A/SA |
| 5 | 8% | 29% | 54% | 9% | - | - | 58 | 42 | 0.27 SA |
| 6 | 8% | 46% | 36% | 10% | - | - | 60 | 40 | 0.26 SA |
| 7 | 6% | 38% | 46% | 10% | - | - | 55 | 45 | 0.27 SA |
| 8 | 4% | 40% | 45% | 10% | 1% | - | 63 | 37 | 0.27 SA |
| 9 | 11% | 36% | 49% | 4% | - | - | 52 | 48 | 0.25A/SA |
| 10 | 10% | 35% | 49% | 6% | - | - | 59 | 41 | 0.26 SA |
| 11 | 9% | 27% | 56% | 8% | - | - | 63 | 37 | 0.27 SA |
| 12 | 8% | 39% | 47% | 6% | - | - | 59 | 41 | 0.26 SA |
| 13 | 6% | 37% | 49% | 8% | - | - | 56 | 44 | 0.26 SA |
| 14 | 7% | 42% | 47% | 4% | - | - | 57 | 43 | 0.25A/SA |
| 15 | 6% | 39% | 51% | 4% | - | - | 59 | 41 | 0.26 SA |
| 16 | 13% | 31% | 52% | 4% | - | - | 55 | 45 | 0.25A/SA |
| 17 | 6% | 41% | 48% | 5% | - | - | 63 | 37 | 0.26 SA |
| 18 | 8% | 43% | 38% | 11% | - | - | 56 | 44 | 0.26 SA |
| 19 | 7% | 38% | 48% | 7% | - | - | 51 | 49 | 0.26 SA |
| 20 | 8% | 40% | 45% | 7% | - | - | 50 | 50 | 0.26 SA |
| 21 | 7% | 39% | 46% | 7% | 1% | - | 53 | 47 | 0.26 SA |
| 22 | 8% | 36% | 46% | 10% | - | - | 56 | 44 | 0.26 SA |
| 23 | 10% | 39% | 46% | 5% | - | - | 59 | 41 | 0.25A/SA |
| 24 | 11% | 38% | 47% | 4% | - | - | 60 | 40 | 0.25A/SA |
| 25 | 5% | 43% | 47% | 5% | - | - | 49 | 51 | 0.25A/SA |
| 26 | 8% | 41% | 44% | 7% | - | - | 65 | 35 | 0.26 SA |
| Means | 8% | 38% | 47% | 7% | - | - | 57.6 | 42.4 | 0.26 SA |

A:- Angular SA:- Sub-angular

Sph = Sphericity
Rnd = Round

Sections:- At right angles to Bedding.
Distance between points:- ½ mm.
Distance between Traverses:- 1mm. No. of grains estimated: 100
Magnification:- x65 or x300.

Appendix VIB. Full roundness analyses of the 12 greywacke specimens from the Howgill Fells, using Powers' (1953) Roundness Scale.

(Limits of Class:
( .12 .17 .25 .35 .49 .70 1.00

| Mid Point / Slide No. | .14 Very Ang | .21 Ang | .30 Sub Ang | .41 Sub Round | .59 Round | .86 Well Round | % High Sph | % Low Sph | Mean Rnd-ness |
|---|---|---|---|---|---|---|---|---|---|
| S/H 1 | 9% | 38% | 49% | 4% | - | - | 53 | 47 | 0.25A/SA |
| S/H 2 | 5% | 34% | 56% | 5% | - | - | 44 | 56 | 0.26 SA |
| S/H 3 | 11% | 26% | 59% | 4% | - | - | 49 | 51 | 0.26 SA |
| S/H 4 | 5% | 44% | 47% | 4% | - | - | 49 | 51 | 0.25A/SA |
| S/H 5 | 10% | 31% | 57% | 2% | - | - | 42 | 58 | 0.26 SA |
| S/H 6 | 6% | 36% | 56% | 2% | - | - | 56 | 44 | 0.26 SA |
| S/H 7 | 8% | 40% | 49% | 3% | - | - | 55 | 45 | 0.25A/SA |
| S/H 8 | 12% | 29% | 53% | 5% | 1% | - | 60 | 40 | 0.26 SA |
| S/H 9 | 5% | 36% | 55% | 4% | - | - | 50 | 50 | 0.26 SA |
| S/H10 | 7% | 42% | 47% | 4% | - | - | 51 | 49 | 0.25A/SA |
| S/H11 | 12% | 35% | 49% | 4% | - | - | 54 | 46 | 0.25A/SA |
| S/H12 | 10% | 40% | 48% | 2% | - | - | 49 | 51 | 0.25A/SA |
| Means | 8.4% | 36% | 52% | 3.6% | - | - | 51 | 49 | 0.25A/SA |

A:- Angular. SA:- Sub-angular. Sph = Sphericity
Rnd = Round

Sections :- At right angles to Bedding
Distance between points :- $\frac{1}{6}$ mm.
Distance between Traverses :- 1mm.
No. of grains estimated :- 100
Magnification :- x65 or x300.

Appendix VIC. Full roundness analyses of the 3 specimens of Winder Grit from the Howgill Fells, using Powers'(1953) Roundness Scale.

| (Limits of Class: ( Mid Point / Slide No. | .12 — .17: .14 Very Ang | .17 — .25: .21 Ang | .25 — .35: .30 Sub Ang | .35 — .49: .41 Sub Round | .49 — .70: .59 Round | .70 — 1.00: .86 Well Round | % High Sph | % Low Sph | Mean Rnd-ness |
|---|---|---|---|---|---|---|---|---|---|
| WG 1 | 8% | 37% | 50% | 5% | - | - | 46 | 54 | 0.26 SA |
| WG 2 | 10% | 33% | 46% | 11% | - | - | 45 | 55 | 0.26 SA |
| WG 3 | 11% | 35% | 47% | 7% | - | - | 42 | 58 | 0.26 SA |
| Means | 10% | 35% | 47% | 8% | | | 44 | 56 | 0.26 SA |

SA:- Sub-angular.

Sph = Sphericity
Rnd = Round

Sections :- At right angles to Bedding

Distance between points :- 1/6 mm.

Distance between Traverses :- 1mm.

No. of grains estimated :- 100

Magnification :- x65

Appendix VID. Full roundness analyses of the 10 greywacke specimens from the Blawith area, using Powers' (1953) Roundness Scale.

(Limits of Class: .12 .17 .25 .35 .49 .70 1.00

| Mid Point / Slide No. | .14 Very Ang | .21 Ang | .30 Sub Ang | .41 Sub Round | .59 Round | .86 Well Round | % High Sph | % Low Sph | Mean Rnd-ness |
|---|---|---|---|---|---|---|---|---|---|
| S/B 1 | 6% | 38% | 48% | 8% | - | - | 57 | 43 | 0.26 SA |
| S/B 2 | 14% | 34% | 47% | 5% | - | - | 44 | 56 | 0.25A/SA |
| S/B 3 | 9% | 38% | 50% | 3% | - | - | 55 | 45 | 0.25A/SA |
| S/B 4 | 12% | 46% | 37% | 4% | - | - | 56 | 44 | 0.24 A |
| S/B 5 | 7% | 43% | 44% | 6% | - | - | 47 | 53 | 0.26 SA |
| S/B 6 | 10% | 46% | 39% | 5% | - | - | 49 | 51 | 0.25A/SA |
| S/B 7 | 8% | 44% | 46% | 2% | - | - | 50 | 50 | 0.25A/SA |
| S/B 8 | 7% | 47% | 40% | 6% | - | - | 47 | 53 | 0.25A/SA |
| S/B 9 | 12% | 33% | 51% | 4% | - | - | 55 | 45 | 0.25A/SA |
| S/B10 | 11% | 30% | 49% | 10% | - | - | 59 | 41 | 0.26 SA |
| Means | 9.6% | 40.0% | 45.0% | 5.4% | - | - | 52 | 48 | 0.25A/SA |

A:- Angular SA:- Sub-angular Sph = Sphericity
Rnd = Round

Sections :- At right angles to Bedding

Distance between points :- 1/6 mm.

Distance between Traverses:- 1mm.

No. of grains estimated :- 100

Magnification :- x65 or x300.

Appendix VIE. Full roundness analyses of the 4 greywacke specimens from the Horton-in-Ribblesdale area, using Powers' (1953) Roundness Scale.

(Limits of Class: .12 .17 .25 .35 .49 .70 1.00

| Mid Point / Slide No. | .14 Very Ang | .21 Ang | .30 Sub Ang | .41 Sub Round | .59 Round | .86 Well Round | % High Sph | % Low Sph | Mean Rnd-ness |
|---|---|---|---|---|---|---|---|---|---|
| S/A 1 | 13% | 43% | 43% | 1% | - | - | 52 | 48 | 0.24 A |
| S/A 2 | 15% | 41% | 44% | - | - | - | 55 | 45 | 0.24 A |
| S/A 3 | 17% | 33% | 49% | 1% | - | - | 50 | 50 | 0.24 A |
| S/A 4 | 20% | 40% | 38% | 2% | - | - | 51 | 49 | 0.23 A |
| Means | 16.5% | 39% | 43.5% | 1% | | | 52 | 48 | 0.24 A |

A:- Angular

Sph = Sphericity
Rnd = Round

Sections :- At right angles to bedding

Distance between points :- 1/6 mm.

Distance between Traverses :- 1mm.

No. of grains estimated :- 100

Magnification :- x65 or x300

Appendix VIF. The statistical significance of the roundness analyses.

To check the accuracy of the roundness estimations, 4 specimens were completely re-analysed. These are shown below alongside the original analyses, and indicate that the results are statistically valid.

| (Limits of Class: ( .12 .17 .25 .35 .49 .70 1.00<br>Mid Point<br>Slide No. | .14 Very Ang | .21 Ang | .30 Sub Ang | .41 Sub Round | .59 Round | .86 Well Round | % High Sph | % Low Sph | Mean Rnd-ness |
|---|---|---|---|---|---|---|---|---|---|
| S 9 First Est | 11% | 36% | 49% | 4% | - | - | 52 | 48 | 0.25A/SA |
| Second Est | 10% | 35% | 48% | 7% | - | - | 54 | 46 | 0.26 SA |
| S17 First Est | 6% | 41% | 48% | 5% | - | - | 63 | 37 | 0.26 SA |
| Second Est | 8% | 42% | 44% | 6% | - | - | 62 | 38 | 0.26 SA |
| S24 First Est | 11% | 38% | 47% | 4% | - | - | 60 | 40 | 0.25A/SA |
| Second Est | 14% | 40% | 42% | 4% | - | - | 59 | 41 | 0.25A/SA |
| S25 First Est | 5% | 43% | 47% | 5% | - | - | 49 | 51 | 0.25A/SA |
| Second Est | 9% | 45% | 41% | 5% | - | - | 53 | 47 | 0.25A/SA |

Sph = Sphericity
Rnd = Round

## APPENDIX VII

## CURRENT DIRECTION READINGS

Directional readings taken on sole markings throughout the Ludlow Series. Readings taken from strata dipping at 25 degrees or more, have been corrected stereographically. The method is described in the text.

Dip directions etc. eg. 39N22W = Dip of 39 degrees, at 22 degrees west of north.

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 1 | Haw Gill | 39N22W | 47 WofN | 42 WofN | NW | Flute |
| 2 | " " | 35N25W | 46 WofN | 43 WofN | NW | " |
| 3-5 | " " | 20N29W | 44 WofN | - | NW | " |
| 6 | Leck B. | 20N32W | 66 WofN | - | WNW | " |
| 7 | " " | 19N31W | 55 WofN | - | WNW | " |
| 8 | " " | 23N35W | 45 WofN | - | NW | " |
| 9 | " " | 23N35W | 30 WofN | - | NW | " |
| 10 | " " | 22N30W | 31 WofN | - | NW | " |
| 11 | " " | 20N32W | 10 WofN | - | ?NNW | Groove |
| 12-13 | Combe Scars | 10N25W | 80 WofN | - | W | Flute |
| 14-15 | " " | 9N45W | 32 WofN | - | NW | " |
| 16 | Grove Gill | 56N10W | 5 EofN | 4 WofN | N | " |
| 17 | Leck Beck | 19N35W | 30 WofN | - | NW | Groove |
| 18 | " " | 19N35W | 33 WofN | - | NW | Flute |
| 19 | " " | 19N40W | 20 WofN | - | NNW | " |
| 20 | " " | 23N45W | 45 WofN | - | NW | Groove |
| 21 | " " | 23N45W | 45 WofN | - | NW | " |
| 22 | " " | 29N32W | 35 WofN | 34 WofN | NW | Flute |
| 23 | " " | 30N35W | 42 WofN | 40 WofN | NW | " |
| 24 | " " | 30N35W | 39 WofN | 37 WofN | NW | " |
| 25 | " " | 25N15W | 10 WofN | 10 WofN | NNW | " |
| 26 | " " | 28N20W | 75 WofN | 72 WofN | WNW | Groove |
| 27 | " " | 20N44W | 40 WofN | - | NW | Flute |
| 28 | " " | 20N44W | 40 WofN | - | NW | " |

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 29 | Smithy Hse | 30N10W | 40 WofN | 36 WofN | NW | Flute |
| 30 | Aygill | 18N55E | 26 WofN | - | NNW | " |
| 31 | " | 20N58E | 38 WofN | - | NW | " |
| 32 | " | 35N81W | 34 WofN | 40 WofN | NW | " |
| 33 | " | 35N82W | 35 WofN | 41 WofN | NW | " |
| 34 | " | 44N76W | 27 WofN | 37 WofN | NNW | " |
| 35 | " | 32N25W | 51 WofN | 48 WofN | NW | " |
| 36 | Whelprigg | 32N26W | 51 WofN | 48 WofN | NW | Groove |
| 37 | E.Whisky G. | 31N42E | 28 WofN | 24 WofN | NNW | Flute |
| 38 | " | 31N42E | 33 WofN | 30 WofN | NW | Groove |
| 39 | " | 31N42E | 35 WofN | 32 WofN | NW | " |
| 40 | " | 31N42E | 40 WofN | 38 WofN | NW | " |
| 41 | " | 26N35E | 15 WofN | 12 WofN | NNW | Flute |
| 42 | " | 28N37E | 20 WofN | 16 WofN | NNW | " |
| 43 | " | 28N39E | 31 WofN | 28 WofN | NNW | " |
| 44 | " | 24N39E | 28 WofN | - | NW | " |
| 45 | " | 27N32E | 19 WofN | 16 WofN | NNW | Groove |
| 46 | " | 23N36E | 5 WofN | - | N | Flute |
| 47 | " | 33N41E | 32 WofN | 28 WofN | NNW | " |
| 48 | " | 33N41E | 32 WofN | 28 WofN | NNW | " |
| 49 | " | 20N25E | 15 WofN | - | NNW | " |
| 50 | " | 22N25E | 20 WofN | - | NNW | " |
| 51 | " | 26N24E | 20 WofN | 18 WofN | NNW | " |
| 52 | " | 24N26E | 23 WofN | - | NNW | " |
| 53 | Brackens G. | 24N30W | 21 WofN | - | NNW | " |
| 54 | " | 20N35W | 15 WofN | - | NNW | " |
| 55 | " | 22N35W | 55 WofN | - | NW | " |
| 56 | " | 20N33W | 60 WofN | - | WNW | " |
| 57 | " | 20N35W | 60 WofN | - | WNW | " |
| 58 | " | 20N35W | 52 WofN | - | NW | " |
| 59 | Luge G. | 32N21W | 42 WofN | 38 WofN | NW | " |
| 60 | " | 30N20W | 40 WofN | 38 WofN | NW | " |
| 61 | " | 30N20W | 34 WofN | 32 WofN | NW | " |
| 62 | " | 36N22W | 25 WofN | 24 WofN | NNW | " |

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 63 | Millhouse B | 9N39W | 19 WofN | - | NNW | Flute |
| 64 | " | 35N15E | 50 WofN | 45 WofN | NW | " |
| 65 | " | 40N30W | 35 WofN | 33 WofN | NW | " |
| 66 | " | 40N30W | 70 WofN | 62 WofN | WNW | " |
| 67 | " | 30N35W | 40 WofN | 39 WofN | NW | Groove |
| 68 | " | 25N19W | 34 WofN | 33 WofN | NW | Flute |
| 69 | " | 30N15W | 43 WofN | 40 WofN | NW | " |
| 70 | " | 30N20W | 38 WofN | 36 WofN | NW | " |
| 71 | " | 22N20W | 70 WofN | - | WNW | " |
| 72 | " | 24N19W | 75 WofN | - | WNW | " |
| 73 | " | 24N22W | 50 WofN | - | NW | " |
| 74 | " | 20N30W | 45 WofN | - | NW | Groove |
| 75 | " | 18N28W | 41 WofN | - | NW | Flute |
| 76 | " | 15N30W | 49 WofN | - | NW | " |
| 77 | " | 15N32W | 52 WofN | - | NW | " |
| 78 | " | 10N32W | 51 WofN | - | NW | " |
| 79 | Barkin B. | 18W | 40 WofN | - | NW | " |
| 80 | " | 20N100W | 32 WofN | - | NW | " |
| 81 | Barkin F. | 15N170W | 40 WofN | - | NW | " |
| 82 | " | 20N163W | 43 WofN | - | NW | " |
| 83 | " | 22N158W | 33 WofN | - | NW | " |
| 84 | Barkin B. | 20S | 29 WofN | - | NNW | " |
| 85 | " | 21S | 15 WofN | - | NNW | " |
| 86 | Barkin Fell | 8N135W | 32 WofN | - | NW | " |
| 87 | " | 21N 3E | 50 WofN | - | NW | " |
| 88 | " | 21N 3E | 51 WofN | - | NW | " |
| 89 | " | 24N10E | 65 WofN | - | WNW | Groove |
| 90 | " | 24N10E | 70 WofN | - | WNW | " |
| 91 | " | 26N11E | 66 WofN | 64 WofN | WNW | Flute |
| 92 | " | 28N15E | 44 WofN | 41 WofN | NW | " |
| 93 | Corn Clse | 19N135W | 58 WofN | - | NW | " |
| 94 | " | 19N135W | 47 WofN | - | NW | " |
| 95 | " | 19N135W | 50 WofN | - | NW | " |
| 96 | " | 15N131W | 38 WofN | - | NW | " |

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 97 | Corn Clse | 18N130W | 42 WofN | - | NW | Flute |
| 98 | " | 22N130W | 39 WofN | - | NW | " |
| 99 | " | 24N127W | 40 WofN | - | NW | " |
| 100 | " | 20N130W | 40 WofN | - | NW | " |
| 101-106 | Brow G. | 20N 10E | 43 WofN | - | NW | " |
| 107 | Jordan W. | 39N152W | 51 WofN | 47 WofN | NW | " |
| 108 | " | 39N153W | 46 WofN | 42 WofN | NW | Groove |
| 109 | " | 36N152W | 40 WofN | 37 WofN | NW | " |
| 110 | R. Dee | 10N 85W | 58 WofN | - | WNW | Flute |
| 111 | " | 12W | 20 WofN | - | NNW | " |
| 112 | Combe S. | 3N 45W | 5 WofN | - | N | " |
| 113 | Holme K. | 23N160W | 48 WofN | - | NW | Groove |
| 114 | " | 20N151W | 48 WofN | - | NW | " |
| 115 | " | 18N151W | 49 WofN | - | NW | Flute |
| 116 | " | 22N155W | 50 WofN | - | NW | " |
| 117 | Ruddl.G. | 17N155W | 40 WofN | - | NW | Groove |
| 118 | " | 17N155W | 25 WofN | - | NNW | Flute |
| 119 | " | 20N160W | 20 WofN | - | NNW | " |
| 120 | " | 20N160W | 19 WofN | - | NNW | " |
| 121 | " | 21N170W | 22 WofN | - | NNW | Groove |
| 122 | " | 18N155W | 33 WofN | - | NW | Flute |
| 123 | " | 17N149W | 40 WofN | - | NW | " |
| 124 | Barbon B. | 17N 34E | 17 WofN | - | NNW | " |
| 125 | " | 20N 40E | 30 WofN | - | NNW | Groove |
| 126 | N Dale G. | 23N156W | 90 WofN | - | W | Flute |
| 127 | " | 38N155W | 10 WofN | 6 WofN | NNW | Groove |
| 128 | " | 24N150W | 35 WofN | - | NW | " |
| 129 | " | 30N149W | 40 WofN | 37 WofN | NW | Flute |
| 130 | " | 40N132W | 41 WofN | 41 WofN | NW | " |
| 131 | Combe S. | 10N124W | 75 WofN | - | WNW | " |
| 132 | Millh. B. | 36N 27E | 100 WofN | 95 WofN | W | " |
| 133 | " | 36N 27E | 98 WofN | 94 WofN | W | " |
| 134 | " | 36N 27E | 90 WofN | 85 WofN | W | " |
| 135 | " | 36N 27E | 60 WofN | 58 WofN | WNW | Groove |
| 136 | " | 48N 69W | 65 WofN | 67 WofN | WNW | Flute |

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 137 | Millhs.B. | 15N146W | 62 WofN | - | WNW | Groove |
| 138 | " | 15N146W | 85 WofN | - | W | Flute |
| 139 | " | 15N146W | 85 WofN | - | W | " |
| 140 | " | 20N145W | 95 WofN | - | W | " |
| 141 | " | 20N145W | 65 WofN | - | WNW | " |
| 142-50 | " | 18N149W | 35 WofN | - | NW | " |
| 151 | Leck Beck | 19N 30W | 20 WofN | - | NNW | Groove |
| 152 | " | 20N 30W | 25 WofN | - | NNW | Flute |
| 153 | " | 19N 32W | 24 WofN | - | NNW | " |
| 154 | " | 15N 33W | 22 WofN | - | NNW | " |
| 155 | " | 24N 31W | 44 WofN | - | NW | " |
| 156 | " | 24N 25W | 30 WofN | - | NW | " |
| 157 | " | 18N 32W | 65 WofN | - | WNW | " |
| 158 | " | 20N 30W | 18 WofN | - | NNW | " |
| 159 | " | 22N 40W | 10 WofN | - | N | Groove |
| 160 | " | 21N 45W | 20 WofN | - | NNW | " |
| 161 | " | 21N 41W | 25 WofN | - | NNW | Flute |
| 162 | E.Whisky G | 20N 30E | 20 WofN | - | NNW | Groove |
| 163 | " | 26N 24E | 18 WofN | 14 WofN | NNW | " |
| 164 | " | 32N 40E | 22 WofN | 18 WofN | NNW | Flute |
| 165 | " | 30N 45E | 79 WofN | 75 WofN | W | " |
| 166 | " | 24N 45E | 19 WofN | - | NNW | " |
| 167 | " | 24N 45E | 80 WofN | - | W | " |
| 168 | " | 26N 49E | 41 WofN | 39 WofN | NW | " |
| 169 | " | 28N 39E | 42 WofN | 40W ofN | NW | " |
| 170 | Combe S. | 5N 42W | 23 WofN | - | NNW | Groove |
| 171 | " | 5N 42W | 26 WofN | - | NNW | Flute |
| 172 | " | 8N 43W | 4 WofN | - | N | " |
| 173 | " | 6N 45W | 10 WofN | - | N | Groove |
| 174 | Aygill | 21N 65E | 42 WofN | - | NW | " |
| 175 | " | 21N 65E | 40 WofN | - | NW | " |
| 176 | Corn Close | 12N125W | 5 EofN | - | N | Flute |
| 177 | " | 12N125W | 3 EofN | - | N | " |
| 178 | " | 17N121W | 7 EofN | - | N | " |
| 179 | " | 18N119W | 38 WofN | - | NW | " |

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 180 | Corn Close | 24N125W | 41 WofN | - | NW | Flute |
| 181 | " | 21N131W | 42 WofN | - | NW | " |
| 182 | " | 19N135W | 30 WofN | - | NNW | " |
| 183 | N Dale G. | 22N150W | 2 WofN | - | N | " |
| 184 | " | 24N155W | 12 WofN | - | N | " |
| 185 | " | 20N149W | 10 WofN | - | N | Groove |
| 186 | " | 18N148W | 10 WofN | - | N | " |
| 187 | Combe Scars | 8N 30W | 15 WofN | - | NNW | Flute |
| 188 | Holme K. | 26N163W | 50 WofN | 48 WofN | NW | Groove |
| 189 | " | 23N160W | 72 WofN | - | WNW | Flute |
| 190 | " | 23N160W | 89 WofN | - | W | " |
| 191 | Luge G. | 32N 25W | 49 WofN | 46 WofN | NW | " |
| 192 | " | 34N 23W | 39 WofN | 36 WofN | NW | " |
| 193 | " | 24N 29W | 38 WofN | - | NW | " |
| 194 | " | 24N 30W | 51 WofN | - | NW | Groove |
| 195 | " | 25N 35W | 47 WofN | - | NW | Flute |
| 196 | " | 20N 31W | 91 WofN | - | W | " |
| 197 | " | 20N 31W | 30 WofN | - | NNW | " |
| 198-9 | " | 22N 35W | 31 WofN | - | NW | Groove |
| 200 | Combe Scars | horiz. | N | - | N | Flute |
| 201 | " | " | 10 WofN | - | NNW | " |
| 202 | " | 3N 35W | 29 WofN | - | NNW | Groove |
| 203 | " | 3N 35W | 28 WofN | - | NNW | Flute |
| 204 | " | 5N 40W | 32 WofN | - | NNW | " |
| 205 | Aygill | 15N 70E | 30 WofN | - | NNW | " |
| 206 | " | 21N 71E | 30 WofN | - | NNW | " |
| 207 | Wyegrft G. | 26N 7W | 51 WofN | 49 WofN | NW | " |
| 208 | " | 26N 7W | 45 WofN | 43 WofN | NW | " |
| 209 | " | 23N 10W | 28 WofN | - | NNW | Groove |
| 210 | " | 20N 9W | 31 WofN | - | NNW | Flute |
| 211 | " | 20N 9W | 10 WofN | - | N | " |
| 212 | " | 20N 10W | 23 WofN | - | NNW | " |
| 213 | " | 23N 15W | 25 WofN | - | NNW | " |
| 214 | Barbon LF | 15N | 23 WofN | - | NNW | " |
| 215 | " | 16N | 32 WofN | - | NNW | Groove |

| Observn No. | Locality | Dip | Bearing of Lineation | Corrected Bearing | Current From | Type |
|---|---|---|---|---|---|---|
| 216 | Barbon LF | 16N | 30 WofN | - | NNW | Flute |
| 217 | " | 16N 5E | 24 WofN | - | NNW | " |
| 218 | " | 21N10W | 40 WofN | - | NW | " |
| 219 | " | 21N | 42 WofN | - | NW | " |
| 220 | Brow Gill | 31N16W | 15 WofN | 15 WofN | NNW | " |

# APPENDIX VIII

## CLEAVAGE DIRECTION READINGS

Abbreviations:- Lithologies, G = Greywacke,
GS = Graptolitic Siltstone,
M = Mudstone Top,
BU = Banded Unit.

Remarks on degree of Development:- P = Poor, G = Good,
E = Excellent.

Dip directions etc. eg. 36N160W = Dip of 36 degrees, at 160 degrees west of north.

| Observn No. | Locality | Lith | Dip | Direction of Cleavage | Dip of Cleavage | Remarks |
|---|---|---|---|---|---|---|
| 1C | Rash Mill | GS | 36N160W | N52W | 78N130W | P |
| 2C | " " | BU | 23N145W | N75W | - | P |
| 2C | " " | " | " " | N35W | - | P |
| 3C | " " | " | 42N151W | N64W | 82N153W | G |
| 4C | " " | GS | 33N156W | N62W | 80N151W | G |
| 5C | " " | BU | 20N150W | N62W | 60N152W | G |
| 6C | Ruddles Gill | BU | 40N163W | N90W | 25N179W | E |
| 6C | " " | " | " " | N75W | 88N165W | P |
| 7C | " " | GS | 9N109W | N65W | 66N150W | G |
| 8C | Rash Mill Gill | M | 13N131W | N66W | 56N154W | G |
| 9C | " " | " | 34N154W | N65W | 60N156W | G |
| 10C | " " | GS | 16N139W | N43W | 75N133W | E |
| 11C | " " | " | " " | N43W | 80N132W | E |
| 12C | Corn Close | GS | 13N145W | N55W | 90 | G |
| 13C | " " | G | 12N75W | N35W | 80N124W | P |
| 14C | " " | GS | 10N125W | N45W | 90 | G |
| 15C | Rawthey Br. | GS | 20N128W | N63W | 75N153W | G |
| 16C | Brackns.G. | GS | Horiz. | N58W | 68N148W | G |
| 17C | Helm Knott | M | 44N100W | N46W | 80N130W | E |
| 18C | Brow Gill | BU | 31N14W | N68W | 55N158W | E |
| 19C | " " | " | 40N11W | E-W | 55S | P |
| 20C | " " | " | 19N16W | N59W | 88N150W | G |
| 21C | " " | " | 8N130W | N63W | 75N153W | G |

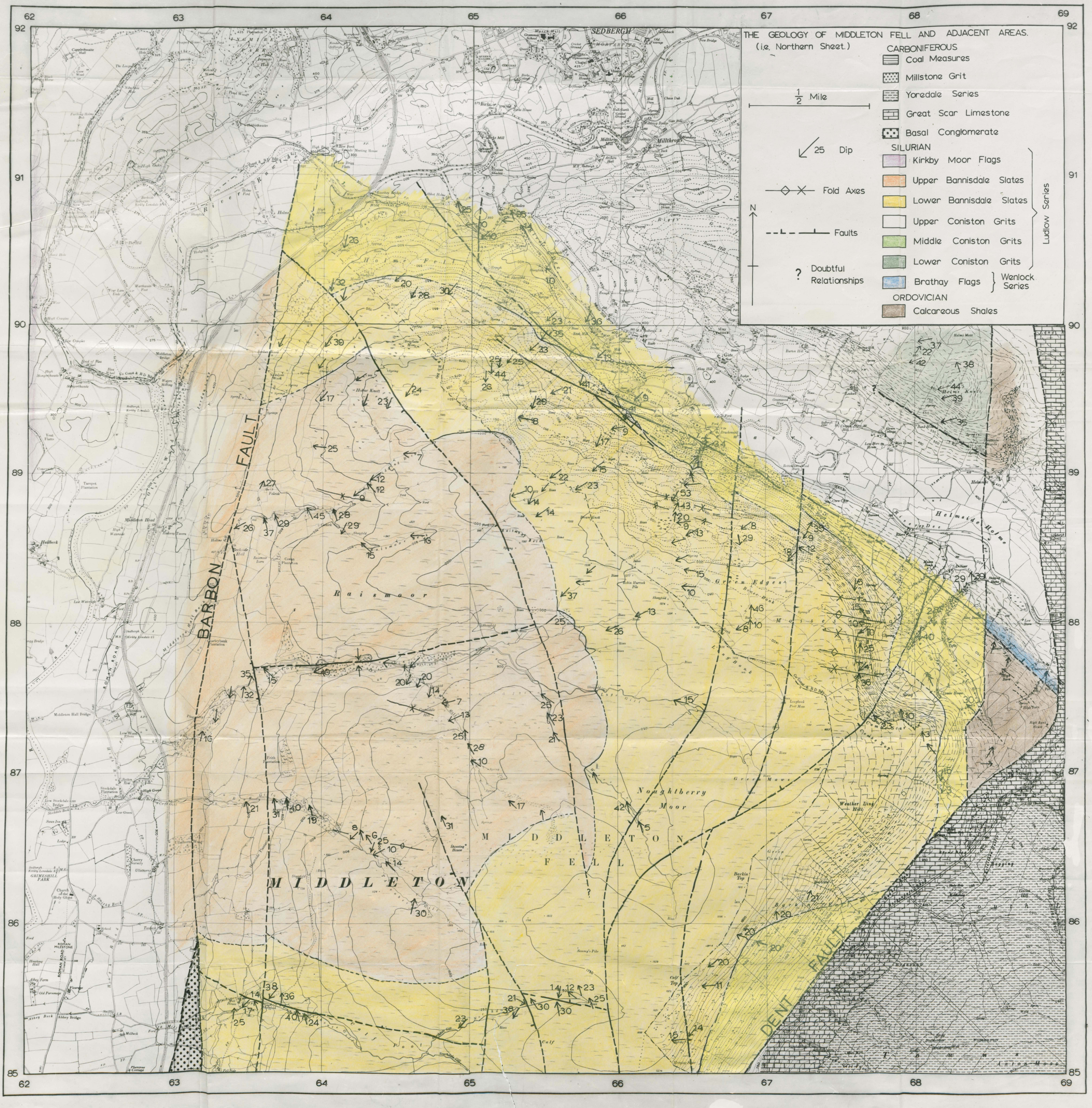
| Observn No. | Locality | Lith | Dip | Direction of Cleavage | Dip of Cleavage | Remarks |
|---|---|---|---|---|---|---|
| 22C | Brow Gill | BU | 20N 10E | N51W | 70N 40E | E |
| 23C | " " | " | 7N155W | N49W | 87N139W | G |
| 24C | " " | " | 10N130W | N64W | 75N154W | E |
| 25C | " " | " | 21N145W | N74W | 80N164W | E |
| 26C | Jordn.Wood | BU | 40N154W | N69W | 89N158W | G |
| 27C | " " | " | 27N118W | N73W | 76N163W | E |
| 28C | " " | " | 39N152W | N76W | 60N166W | E |
| 29C | " " | " | " " | N79W | 69N170W | E |
| 30C | " " | " | 39N152W | N70W | 73N160W | E |
| 32C | Holme Fell | M | 30N159W | N61W | 75N149W | G |
| 33C | R. Dee | " | 36N148E | N80W | - | E |
| 34C | " " | " | 10N127W | N29W | 58N124W | E |
| 35C | " " | GS | 9N 60W | N73W | 87N164W | P |
| 35C | " " | GS | " " | N15W | 85N100W | P |
| 36C | " " | M | 25N 10W | N64W | 83N155W | G |
| 36C | " " | " | " " | N17W | 68N109W | P |
| 37C | " " | GS | 14N 35W | N64W | 48N154W | P |
| 38C | Holme Fell | GS | 32N150W | N65W | 64N25E | G |
| 39C | " " | BU | 28N155W | N54W | 70N145W | P |
| 39C | " " | " | " " | N10W | 80N78E | P |
| 40C | " " | " | 23N170W | N54W | 40N144W | E |
| 41C | " " | " | 23N160W | N62W | 60N152W | E |
| 42C | " " | " | " " | N51W | 52N141W | E |
| 43C | Fellside Fm. | M | 27N 29E | N53W | 69N 37E | P |
| 44C | Midd Hall B. | BU | 26N100W | N48W | 72N138W | G |
| 45C | " " " | " | 29N 45W | N55W | 64N145W | P |
| 46C | " " " | " | 14N 50W | N66W | 80N155W | G |
| 47C | Ridding Beck | " | 13N 85W | N45W | 54N135W | G |
| 48C | " " | " | 9N130W | N53W | 82N143W | G |
| 49C | " " | " | 23N139W | N62W | 86N151W | E |
| 50C | " " | " | 7W | N60W | 68N150W | E |
| 51C | Ruddles Gill | GS | 12N170W | N73W | 70N163W | G |
| 52C | " " | " | 13N145W | N56W | 75N145W | G |
| 53C | Ridding Beck | BU | 25N 85W | N53W | 70N143W | P |

| Observn No. | Locality | Lith | Dip | Direction of Cleavage | Dip of Cleavage | Remarks |
|---|---|---|---|---|---|---|
| 54C | Raismoor B. | BU | 10N120W | N59W | 75N150W | P |
| 55C | " " | " | 15N 85W | N58W | 80N148W | P |
| 56C | " " | " | 16W | N50W | 83N140W | G |
| 57C | " " | " | 8W | N53W | 70N143W | P |
| 58C | N " " | GS | 22N135W | N60W | 75N150W | G |
| 59C | Wrestle G. | G | 26N120W | N55W | - | P |
| 60C | " " | BU | 21N 30W | N59W | 53N149W | G |
| 61C | Helmside | M | 25N40E | N49W | 55N139W | G |
| 62C | " | " | 40N110W | N50W | 75N140W | P |
| 63C | " | " | 15N 65E | N47W | 76N137W | P |
| 65C | Fell House | BU | 45N 74E | N43W | - | G |
| 66C | Barkin B. | G | 34N153E | N54W | 87N 36E | P |
| 68C | Whelprigg | GS | 33N 5W | N40W | 70N 50E | G |
| 69C | Barbon L.F. | GS | 15N | N37W | 76N127W | G |
| 70C | Leck B. | GS | 12N123W | N27W | 68N117W | P |
| 71C | " " | " | 14N 52W | N49W | - | P |
| 72C | Dry Gill | G | 33N 5W | N44W | - | P |
| 73C | Fell Rd. | GS | 36N 20W | N34W | - | P |
| 74C | Gale Grth. | M | 27N 16E | N45W | - | P |
| 75C | Leck Beck | G | 28N | N34W | 90 | G |
| 76C | Barbon B. | G | 31N 24E | N41W | 80N 50E | P |
| 77C | " " | G | 17N 34E | N90W | 50N | P |
| 78C | " " | GS | 34N 18E | N39W | 60N50E | E |
| 79C | Eskholme P. | BU | 35N147W | N47W | 45N137W | E |
| 80C | " " | " | 19N 42E | N56W | 74N 34E | E |
| 81C | Brow Gill | BU | 14N 25W | N66W | 90 | G |
| 82C | Thirnb. G. | BU | 30N 5E | N37W | 80N 53E | P |
| 83C | Brow Gill | " | 31N 16W | N51W | 90 | P |
| 84C | Wyegrft.G. | G | 26N 7W | N43W | 83N133W | G |
| 85C | " " | BU | 17N 58W | N58W | 87N 32E | E |
| 86C | " " | " | 10N 56W | N51W | 90 | G |
| 87C | " " | " | 25N | N54W | 90 | E |
| 88C | " " | " | 7N105W | N55W | 45N145W | G |

| Observn No. | Locality | Lith | Dip | Direction of Cleavage | Dip of Cleavage | Remarks |
|---|---|---|---|---|---|---|
| 89C | Northd G. | M | 38N155W | N48W | 70N138W | G |
| 90C | " " | " | 23N 15W | N90W | 40N | G |
| 91C | Brackns G. | GS | 10N170W | N67W | 74N157W | E |
| 92C | " " | " | 16N129W | N49W | 63N139W | G |
| 93C | " " | " | 10N 95W | N52W | 90 | P |
| 94C | Corn Close | G | 12W | N46W | 80N136W | P |
| 95C | " " | M | 46N 5E | N65W | 66N 25E | G |
| 96C | " " | GS | 21N133W | N51W | 85N141W | P |
| 97C | Rash Mill | " | 25N145W | N60W | 83N150W | G |
| 98C | " " | G | 8N 58W | N64W | 81N154W | G |
| 99C | " " | GS | 29N135W | N53W | 85N143W | G |
| 100C | " " | G | 14N132W | N56W | 90 | P |
| 101C | Gawthrop | M | 23N 50E | N20W | 75N 70E | G |
| 102C | " | " | 20N 26E | N28W | 85N 62E | E |
| 103C | Combe Scars | BU | 36N 18E | N71W | 55N 19E | G |
| 104C | " " | " | 41N125W | N50W | 80N140W | E |
| 105C | " " | " | 16N131W | N45W | 80N134W | P |
| 106C | " " | " | 12N160W | N55W | 65N145W | P |
| 107C | Millhse B. | " | 29N154W | N54W | 78N144W | E |
| 108C | " " | " | 9N 51W | N55W | 52N144W | E |
| 109C | " " | " | 17S | N52W | 75N142W | E |
| 110C | " " | " | 50N 22E | N64W | 79N 26E | G |
| 111C | " " | " | 46N119W | N49W | 88N139W | E |
| 112C | " " | " | 33N 36E | N66W | 80N 24E | E |
| 113C | " " | " | 15N146W | N35W | 40N125W | G |
| 114C | " " | " | 24N146W | N40W | 40N130W | G |
| 114C | " " | " | 24N146W | N60W | 50N148W | G |
| 115C | Helm Knott | G | 22N 35E | N73W | 75N 17E | G |
| 116C | Rottenbutts W. | " | 29N154E | N47W | 78N 43E | P |
| 117C | " " | M | 7N130W | N52W | - | E |
| 118C | Luge Gill | BU | 26N120W | N58W | 80N148W | P |
| 119C | " " | BU | 13N108W | N50W | 60N140W | P |
| 120C | " " | " | 25N140W | N65W | 88N155W | E |

| Observn No. | Locality | Lith | Dip | Direction of Cleavage | Dip of Cleavage | Remarks |
|---|---|---|---|---|---|---|
| 121C | Luge Gill | BU | 25N140W | N64W | 80N156W | E |
| 122C | " " | " | 25N140W | N64W | 85N154W | E |
| 123C | " " | " | 14W | N60W | 86N150W | E |
| 124C | " " | " | 15N139W | N55W | 80N145W | E |
| 130C | " " | " | 20W | N62W | 80N152W | E |
| 131C | " " | " | 15N135W | N63W | 79N153W | E |
| 132C | " " | " | 22N139W | N67W | 82N154W | E |
| 133C | " " | " | 18N140W | N64W | 83N154W | E |
| 134C | " " | " | 14W | N70W | 85N160W | E |
| 135C | " " | " | 15N132W | N69W | 90 | E |

Mean Direction is 56 degrees west of north.



THE GEOLOGY OF MIDDLETON FELL AND ADJACENT AREAS.
(i.e. Northern Sheet.)
1/2 Mile
25 Dip
Fold Axes
N
Faults
? Doubtful Relationships
CARBONIFEROUS
Coal Measures
Millstone Grit
Yoredale Series
Great Scar Limestone
Basal Conglomerate
SILURIAN
Kirkby Moor Flags
Upper Bannisdale Slates
Lower Bannisdale Slates
Upper Coniston Grits
Middle Coniston Grits
Lower Coniston Grits
Ludlow Series
Brathay Flags
Wenlock Series
ORDOVICIAN
Calcareous Shales
SEDBERGH
BARBON FAULT
DENT FAULT
MIDDLETON
MIDDLETON FELL
Raismoor
Noughtberry Moor
Green Edges
Helmside Holme
ROMAN ROAD


THE GEOLOGY OF BARBON FELL AND ADJACENT AREAS.
(i.e. Southern Sheet.)
CARBONIFEROUS
Coal Measures
Millstone Grit
Yoredale Series
Great Scar Limestone
Basal Conglomerate
SILURIAN
Kirkby Moor Flags
Upper Bannisdale Slates
Lower Bannisdale Slates
Upper Coniston Grits
Middle Coniston Grits
Lower Coniston Grits
Brathay Flags
ORDOVICIAN
Calcareous Shales
25 Dip
Fold Axes
Faults
? Doubtful Relationships
N
1/2 Mile
BARBON FAULT
DENT FAULT
BARBON
BARBON LOW FELL
CASTERTON
BURROW WITH BURROW
BARBON HIGH F
Thorn Moor
BARKIN