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T H E G R E A T C Y C L O T H E M

O F

N O R T H E R N E N G L A N D

by

Brian Leslie Hodge, B.Sc., F.G.S., A.M.I.M.M.

A. THESIS PRESENTED IN CANDIDATURE FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY IN THE UNIVERSITY OF DURHAM.

January, 1965





Frontispiece. A sandstone-filled subsidiary washout-channel above the Great Limestone truncating the Low and High Coal Sill sheet sandstones, but with the High Coal Sill coal continuous above it; Rogerley Quarry, Weardale.

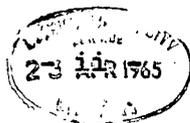
ABSTRACT

The Great Cyclothem is comprised of the Great Limestone and equivalents at the base, its upper part being formed by the Coal Sills Group and equivalents which immediately overlies the limestone. The detailed variations in this thin but widely persistent group of strata in its 6,500 square miles area of development in Northern England are considered and evaluated primarily in order to assess the conditions of deposition, sedimentary history and palaeogeography of the region during formation of the cyclothem.

Critical palaeontological evidence is presented to show that the cyclothem lies at the very base of the Upper Carboniferous succession of Northern England, the base of the Great Limestone and equivalents being taken as the Viséan-Namurian junction.

A detailed stratigraphical and palaeontological consideration of the Great Limestone and equivalents is made. Separate detailed studies are also presented of the stratigraphy, petrology, sedimentary structures and palaeontology of the overlying Coal Sills Group and equivalents, these beds consisting of alternating shales, sandstones and coals with thin lenticular marine bands and a restricted chert development.

An analysis of the above information is made and it is postulated that the cyclothem's basal limestone was laid down in a widespread shallow clear sea, the sea being eventually encroached upon by deltaic sediments consisting essentially of material now represented by the shales, sandstones and coals. The deltaic conditions built out from land to the north and north-west, the sediment source consisting predominantly of pre-existing sediments. Evidence exists to show that the deltaic conditions were subject to local and regional regressions during formation of the cyclothem, thus giving rise to the latter's composite nature, each sheet sandstone with its overlying coal seam representing the final stage in each phase of delta building. The control which the trough and block features of Northern England exercised upon the overall thickness of terrigenous sediments deposited is clearly illustrated and the complete wedging out of terrigenous sediments to the south-east is demonstrated. In the deltaic sediments the courses of prominent infilled river channels occupying washouts have been delimited. The restricted formation of chert



is related to the deposition of primary colloidal silica under marine conditions, the required silica-rich waters having been fed into the specific area by a contemporaneous river "channel" whose course is delimited.

The mechanism which controlled the formation of the rhythmic sequence of the cyclothem is discussed, and it is concluded that the major role was played by tectonic activity which involved uplift in the source area followed by erosion to base level, with complementary diastrophic subsidence in the area of deposition; the rhythmic tectonic activity is related to the pulsating movements of the Sudetic period which heralded the Hercynian orogeny.

In an appendix the widespread and marked devolatilization of the coal seams on the Alston Block is discussed and tentatively related to greater than normal heat-flow from the pre-Carboniferous "Weardale granite". The first recorded occurrence in Great Britain of ovoidal bodies called nigger-heads is reported from these heat affected coals.

ACKNOWLEDGEMENTS

The work documented herein was carried out in the University of Durham Geology Department under the supervision of Professor K. C. Dunham, F.R.S., to whom I wish to express my thanks for initially suggesting the subject for research and for his invaluable advice, help and encouragement during its progress. Fellow students and members of staff in the Geology Department have provided material aid and taken part in many helpful discussions pertaining to the work; of these persons I would like to pay especial thanks to Dr. G. A. L. Johnson and Dr. N. H. Harbord. Mr. C. Chaplin and his technical staff have also been of great assistance and their help is gratefully acknowledged.

In order to consider the large areal development of the Great Cyclothem, information bearing on it has been extracted from various sources which are acknowledged in the text of the work. In particular, however, Dr. A. J. Rowell has been especially helpful in kindly providing more detailed information relating to his published works.

Various departments of the National Coal Board have provided help and advice relating to the coal seams of the cyclothem; in particular, I am most grateful for the analytical work carried out by the North-eastern Division Scientific Department (Coal Survey). Also, the B. P. Exploration Company Limited and the Gas Council have kindly allowed use of that part of the Harton Borehole log involving the Great Cyclothem.

Acknowledgement is made to Her Majesty's Geological Survey for permitting access to records and maps. Permission to reproduce parts of certain maps was kindly given by the Controller of Her Majesty's Stationery Office.

During the course of the work considerable information, help and advice of various kinds has been sought and given freely from many quarters other than the above; to those organizations and persons involved who are not mentioned specifically, I wish to express my sincere thanks.

Finally, the financial help of the Department of Scientific and Industrial Research is gratefully acknowledged.

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PUBLICATIONS

(Contained in separate folder)

Granite beneath the Northern Pennines.

The base of the Namurian and of the Millstone Grit in north-eastern England.

CHAPTER I

INTRODUCTION

GENERAL

The purpose of the investigation to be recorded here was to trace and evaluate the detailed variations in a thin but widely persistent group of strata known as the Great Cyclothem. Evidence will be presented to show that this group lies at the very base of the Upper Carboniferous succession of Northern England. Although the whole group never exceeds 286 feet in thickness, it embraces calcareous, argillaceous, arenaceous, siliceous and carbonaceous strata, thus recording a marked variety of environments of sedimentation. It forms one recognizable unit in the great rhythmic sequence of the Yoredale Series, and as a complete unit, the group may aptly be described as a composite cyclothem, within the terms of the original definition by Wanless and Weller (1932).

The cyclothem as a whole is best developed within the structural unit originally defined by Marr (1921) as the Northumbrian Fault-Block (Fig. 2); that is, within the area now recognized as the northern division of the Pennine ridge. Two sub-units have been defined within the Northumbrian Fault-Block, namely, the Alston Block (Trotter and Hollingworth, 1928), extending from the Roman Wall country southwards to the Cotherstone (Stainmore) Syncline, and the Askrigg Block (Hudson, 1938), covering the area from Cotherstone southward to the Craven District. In addition to the development on the Northumbrian Fault-Block, the cyclothem is represented in other parts of Northern England as specified in the section below pertaining to the regional distribution.

In naming the cyclothem after the limestone which forms its basal member, the practice established by Dunham (1950) and later used by other workers is followed. Some difficulty arises here, however, since the basal limestone is known by different names in the various regions of Northern England where the cyclothem or its equivalent is developed. Nevertheless, it may reasonably be considered that the type locality of the limestone is on the Alston Block and more specifically on Alston Moor, near the mountain of Cross Fell in Cumberland. Throughout the Alston Block the

name Great Limestone is used, this name probably having been erected by the lead miners of the Northern Pennines many centuries ago, although its earliest publication as part of a complete sequence for the Carboniferous "Lead Measures" was by Westgarth Forster (1809). However, as indicated above, under different names the limestone runs with a fair amount of thickness variation but a reasonably uniform lithology throughout many parts of Northern England, and especially through the dales of the Northern Pennines. For instance, on the Askrigg Block in North-west Yorkshire it is known as the Main Limestone, this name having been first published by John Phillips (1836), and probably it too was derived from the local lead mining industry. In addition, in the other regions where it is developed the limestone has different names which will be mentioned later in the pertinent chapter. Nevertheless, for the present purpose, and particularly because the basal limestone is known as the Great at what may be regarded as its type locality, the cyclothem will be described as the Great Cyclothem throughout Northern England.

Above the basal limestone are the essentially non-calcareous measures of the cyclothem. Over much of the area to be considered in detail, these consist of shales, sandstones and coals, the thin marine bands which are locally present sometimes developing to arenaceous or argillaceous limestones. On the Alston Block, particularly on Alston Moor, a characteristic sequence of these beds was recognized by the old lead miners, within which the sandstones were found to be overlain by thin coal seams. Hence the sandstones became known as Coal Sills, a term set in perpetuity by Westgarth Forster (1809). Forster named the sandstones of the cyclothem, in ascending order, the Low Coal Sill and High Coal Sill. Much higher up the "Lead Measures" sequence, he named the sandstone beneath his Fell Top Limestone, the Upper Coal Sill. However, this sandstone occurs well above the top of the Great Cyclothem, the latter being limited at the top by the base of the Upper Little Limestone. Thus, on the Alston Block there is a characteristic development of the non-calcareous measures of the cyclothem, consisting of alternating shales and sandstones, the latter generally being overlain by thin coal seams. Up to three such sandstone-coal horizons have been recognized and as a result, these measures have become known collectively as the Coal Sills Group. Since the Group has been found to contain more than one sedimentary cycle with thin impersistent marine horizons

associated in places, it must comprise part of a composite cyclothem. To the south of the Alston Block in the northern and western parts of the Askrigg Block and in the Cotherstone Syncline, a sequence of comparable lithology to the Coal Sills Group of the type area has been recognized by the authors of the Mallerstang Memoir (Dakyns et al., 1891), Wells (1955a, 1955b and 1957), Rowell and Scanlon (1957a) and Hicks (1958). However, Wells (op. cit.) has also shown that there is a large area of chert development in the north-east quarter of the Askrigg Block; this chert is in part the lateral representative of the Coal Sills Group of the north and west. An area not within the Northumbrian Fault-Block where the non-calcareous measures of the Great Cyclothem have been referred to as the Coal Sills Group is the Stainmore area of Turner (1935); this area is closely related to the Block, however. Beyond the margins of the Block in the Northumbrian Trough, coals occur in the cyclothem and are especially prominent in the Tyne Valley. However, the repeated sandstone-coal relationship which gives rise to the name Coal Sills Group is not generally seen, although Trotter and Hollingworth (1927) refer to the beds above the Snope Burn Band in the Brampton area as 'Coal Sills'. In passing it might be mentioned that the Snope Burn Band is a prominent and relatively persistent marine horizon occurring in the middle of the cyclothem; therefore, in this area the cyclothem is again composite. Thus, the Coal Sills Group type of lithology is restricted to the development on the Northumbrian Fault-Block, and more particularly to that on the Alston Block. Elsewhere, the beds generally form part of the Great Cyclothem with no specific collective name. In West Cumberland, however, the lower part of the Hensingham Group is probably the lateral representative.

As already mentioned, the top of the cyclothem is defined by the base of the Upper Little Limestone or its lateral representative.

SCOPE OF THE WORK

Previous to this work no attempt had been made to study a single cyclothem over a very large area of its development. The more recent works which are dealt with in the "history of research" have each considered all the cyclothem developed in specific and restricted areas. However, Wells (1955a and 1955b) did extend his original area and covered some 450 square

miles of the Askrigg Block during his study of a series of cherty beds which include the representatives of this cyclothem. The present work is really a continuation of that of Wells, the main purpose being to assess the conditions of deposition and reconstruct the palaeogeography of the Yoredale delta and adjacent areas prior to and during one of the delta's major advances. Subsequently it has proved desirable to investigate the extent of the devolatilization of the coals developed within the cyclothem on the Alston Block and in adjacent areas.

Original work by the author has been mainly confined to the type area of the cyclothem; that is to say, the Alston Block, an area of 650 square miles which embraces Weardale, Teesdale, Alston Moor, the Pennine Escarpment and the Allendales. Detailed field mapping on Ordnance Survey 1:10,560 and occasionally 1:2,500 scale maps has been carried out and all available sub-surface data has been collected together in as comprehensive a manner as possible. In particular, the whole outcrop of the cyclothem in County Durham has been resurveyed apart from a small area covered by Jones (1956) recently. Thus, some 100 miles of outcrop has been investigated in detail and every available section has been measured. In the Frosterly-Stanhope area 12 miles of continuous exposure of much of the cyclothem is to be found in the quarries from which the Great Limestone has been extensively wrought. All the important quarry faces have been photographed to facilitate measurement and also to form a permanent record of those which are becoming covered with vegetation. Apart from the quarries, over 140 detailed sections have been measured as well as numerous partial sections. As already mentioned, all available sub-surface information for the whole of the Block has been gathered together. This has been forthcoming from underground workings of lead, fluorspar and barytes mines, and from the numerous records of shafts sunk in connection with these. A number of boreholes have also been drilled in the area recently, and in some cases it has been possible to have access to the core. Important borehole records for the concealed part of the Block have also been obtained; those for Roddymoor, Elstob and Chopwell Woods are from published information, whilst the Harton record has been kindly made available by the B. P. Exploration Company Limited and the Gas Council. A total of 120 sections are at hand from the above sources. Large gaps in the distribution of sub-surface information have been filled by mapping and measuring sections at the necessary local-

ities where possible. Thus, over 300 sections have been obtained for the Alston Block alone. Some ten months were spent on field-work collecting this information and during this period over 15,000 miles were travelled by motor-cycle and van.

To extend the investigation over a wider area, information bearing on the occurrence of the cyclothem, or the beds equivalent to it, has been collected from published sources which are summarized on Fig. 2. By synthesizing all the information it has proved possible to consider the full 6,500 square miles area of development of the cyclothem and its equivalents in Northern England. In order to satisfactorily link the Alston Block with adjacent areas, excursions have been made into the Northumbrian Trough and the Cotherstone Syncline. In particular, boreholes from Fallowfield Mine, Northumberland, and the Lunehead Mine area in the Cotherstone Syncline have been logged.

Laboratory work has consisted of the following:-

- (i) The examination of over 200 thin sections; these were mainly of sandstones but other lithologies have also been considered.
- (ii) Heavy mineral separations have been made from sandstones of a known constant horizon and also from random horizons.
- (iii) Where necessary, X-ray photography or differential thermal analysis has been used to determine the composition of certain sandstone cements.
- (iv) Specimens of "pyrite" from various environments have been polished and examined in reflected light to ascertain their definite composition.
- (v) Analyses have been obtained for several coal samples collected from widespread localities on the Alston Block and in adjacent areas. Several more analyses for coals of a similar horizon have been collected from the records of the National Coal Board by kind permission of that body.
- (vi) The fauna collected from various horizons within the cyclothem has been identified.
- (vii) Every available source of information of sub-

surface and surface data has been perused in order to obtain as full a coverage of the area as possible.

REGIONAL DISTRIBUTION

On the Northumbrian Fault-Block (Figs. 1 and 2) the cyclothem has a widespread distribution and forms a relatively continuous band around the valley sides of most of the rivers. The detailed distribution on the Alston Block and in the Cotherstone Syncline is shown on Plate IA, whilst that on the Askrigg Block is shown on Plate IB. In addition, valuable information is available from five deep boreholes drilled into the concealed area up to 25 miles east of the nearest exposures on the Block. These boreholes were drilled at Roddymoor, Chopwell Woods, Elstob, Harton and Chopgate in the Cleveland Hills, their positions being shown on Fig. 1.

South of the Block, in the Bowland Trough, the marked facies change which takes place does not allow for an accurate delimitation of the exact equivalent of the cyclothem. However, Black (1950) has shown the Scale Haw Limestone of the Bowland Shale sequence to be the equivalent of the Main Limestone. A similar facies to the Bowland Shales completely obscures the cyclothem in the Furness District. In this latter area it seems certain that beds of similar age to the cyclothem form part of the shaly Gleaston Group, however.

To the west of the Block, the cyclothem can be recognized in the Kirkby Lonsdale area but it occurs in poorly exposed ground. The largest area of development to the west of the Block is that surrounding the northern half of the Lake District where Carboniferous rocks form a rim around a core of Lower Palaeozoics. Here, the beds representing the cyclothem can be traced from west of Appleby around the northern end of the massif, by way of Caldbeck and Gilcrux, to Egremont where they disappear beneath younger deposits. Strata representing the cyclothem have also been penetrated by a borehole drilled in the northern part of the Isle of Man.

In the Northumbrian Trough the cyclothem has a more restricted outcrop than on the Block to the south. It can be traced from the northern end of the Pennine Escarpment, south-east of Brampton, in an east-north-east direction to Matfen, from whence it trends north to Greenleighton, and then north-east to the vicinity of Howick where it runs out to sea.

Fig. 1

The Geology of Northern England

Reference map showing the general regional relationship of the areas in which the Great Cyclothem is developed. To be used in conjunction with Fig. 2 to comprehend the regional distribution of the Great Cyclothem.

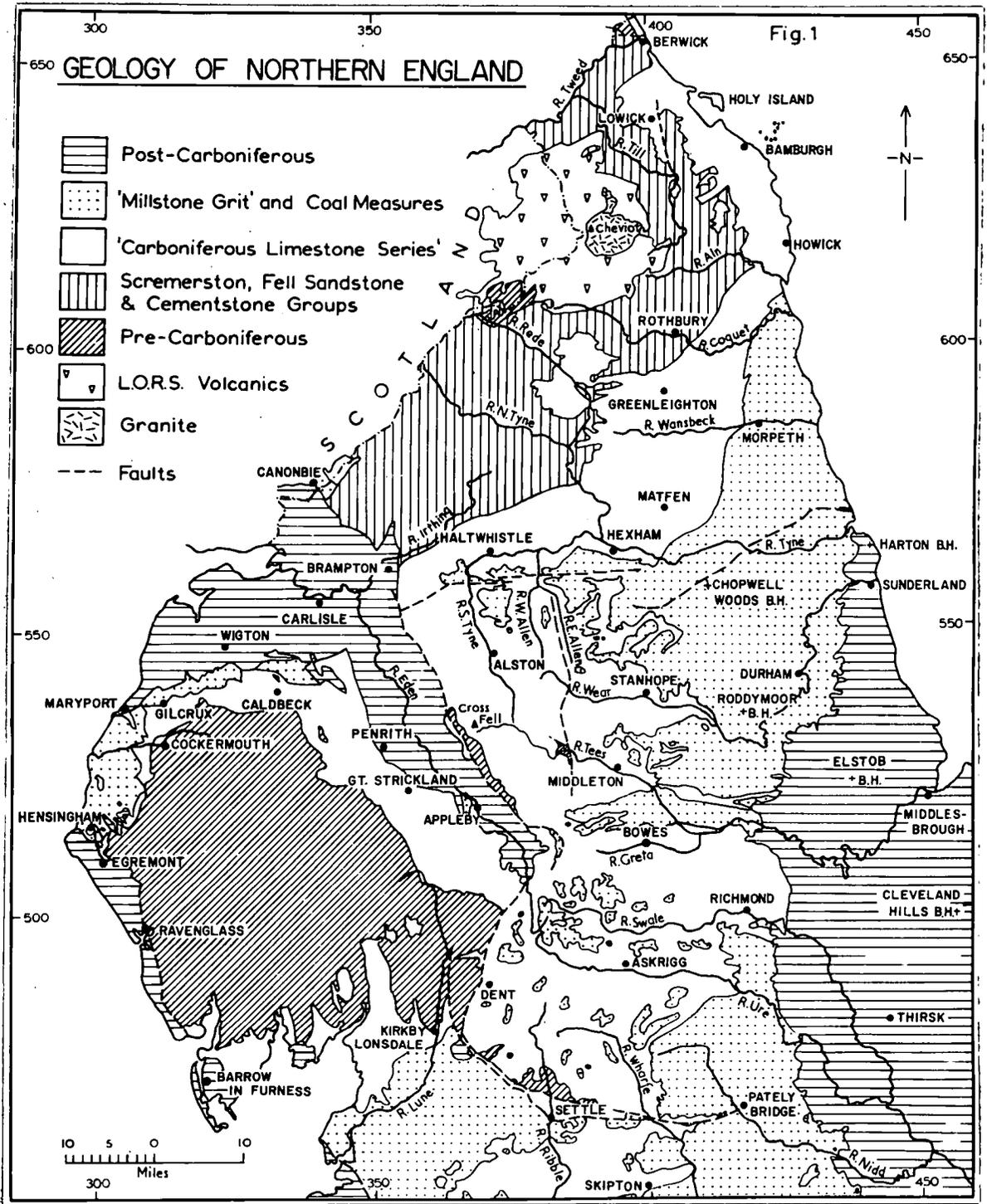


Fig. 2

Summary of the areas covered by various authors.

The structural units of Northern England are also indicated upon this map. The Northumbrian Fault-Block is divisible into the Alston and Askrigg Blocks which are separated by the Cotherstone Syncline, (Reading, 21).

- | | |
|-----------------------------------|----------------------------------|
| 1. Fowler, 1926 | 18. Simpson, 1902 |
| 2. Carruthers et al., 1927 | 19. Woolacott, 1923 |
| 3. Carruthers et al., 1930 | 20. Smith, 1912 |
| 4. Fowler, 1936 | 21. Reading, 1954 and 1957 |
| 5. Hedley and Waite, 1928 | 22. Turner, 1927 and 1935 |
| 6. Johnson, 1959 | 23. Wells, 1955a, 1955b and 1957 |
| 7. Trotter and Hollingworth, 1932 | 24. Rowell, 1953 |
| 8. Peach and Horne, 1903 | 25. Scanlon, 1955 |
| Barrett and Richey, 1945 | 1957a and 1957b |
| Lumsden and Wilson, 1961 | 26. Dakyns et al., 1891 |
| 9. Eastwood et al., 1931 | 27. Miller and Turner, 1931 |
| 10. Eastwood, 1930 | 28. Moore, 1955 and 1958 |
| 11. Eastwood, 1931 | 29. Wilson, 1957 and 1960 |
| 12. Dakyns et al., 1897 | 30. Fowler, 1944 |
| 13. Dunham and Rose, 1941 | 31. Hicks, 1958 and 1959 |
| 14. Short, 1954 | 32. Dakyns et al., 1890 |
| 15. Dunham, 1948 and 1950 | 33. Aveline et al., 1872 |
| 16. Johnson and Dunham, 1962 | Hicks, 1958 |
| 17. Jones, 1956 | 34. Black, 1950 |

It also occurs in three small synclines north of Lowick. The distribution in this region is shown on Plates I and IC. Also within the confines of the Trough, straddling the Anglo-Scottish border, there is a small occurrence of the cyclothem in the vicinity of Canonbie.

In the Midland Valley of Scotland the beds representing the cyclothem have a widespread distribution in a series of dis-connected basins, but it is beyond the scope of this work to consider these.

HISTORY OF RESEARCH

The name Great Cyclothem dates only from Dunham (1950), but the limestone member was probably named many centuries before by the lead miners of the Northern Pennines. Subsequent to its introduction by Dunham, the method of particularizing the cyclothem, by pre-fixing the name of the limestone forming its basal member, has been adopted by various workers.

Early records of the strata encountered during lead mining operations on the Alston Block are to be found on various old mine plans. For example, a plan, dated 1775, of the Nentforce Drainage Level, which was driven from Alston to Nenthead, has a section on it which includes the beds of the Great Cyclothem. The relevant part is given below:-

- 10' Little Limestone
- 6' Little Hazel (Sandstone)
- 10' Plate Bed (Shale)
- 10' Hazel called the High Coal Sill
- 5' Plate Bed
- 8' Hazel called the Low Coal Sill
- 25' Plate Bed
- 65' Great Limestone including Tumblers

William Hutchinson's History of Durham (1794) contains what must be one of the first published references to the Great Limestone. Giving an account of the lead trade in Teesdale, he says, "The strata or bearing sills are various, which carry ore, the greypost bears well, but the best is the great limestone, both for quantity and quality; which is about 70 fathoms in thickness". An accompanying section shows:-

Grey Rubble
 Blue Sandy Slate, 18
 Freestone, 22
 Bastard Whin, 16
 Great Limestone, 70f

It is a pity that this early record of the Great Limestone and associated beds should apparently be spoilt owing to the author's confusion of feet with fathoms.

Sopwith, writing in 1833, records "An engraved section exhibiting the various succession of the strata, from the highest in Alston Moor to the lowest on the north-east side of the Keswick Hills", published by W. Millar of Carlisle in 1800. It has unfortunately not proved possible to trace this section despite a thorough search.

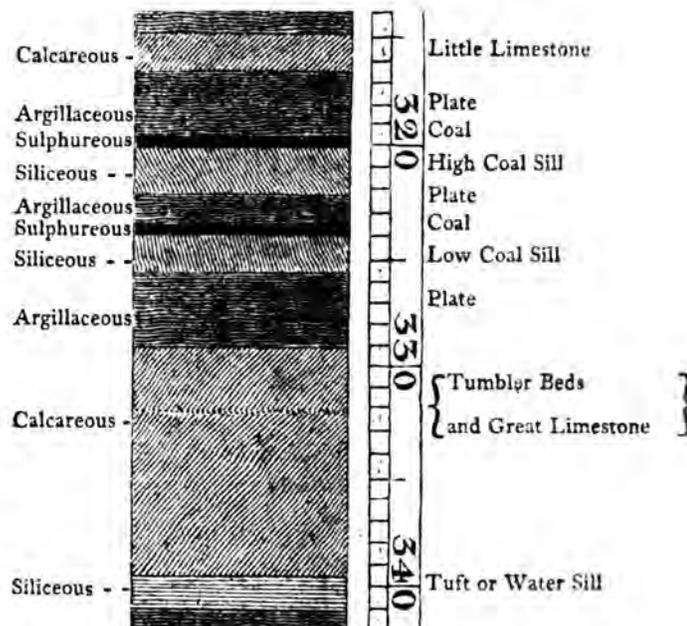


Fig. 3. Westgarth Forster's section of the Great Cyclothem, (each small division of the scale = 1 fathom).

A household word to students of geology in the Northern Pennines is the name of Westgarth Forster whose classic "Treatise on a Section of the Strata" (first edition, 1809) contains an organized stratigraphical sequence for the Alston Block. The names used for individual beds are those which were derived during centuries of lead mining in the area.

The first edition of the "Strata" was published in the same year as William Smith's first geological map of England and it may be claimed as the earliest comprehensive section of strata extant in this country. Many of the names of individual beds that are still in current use over much of Northern England were derived from it. A copy of Forster's section of the Great Cyclothem is shown in Fig. 3. Tumbler Beds is the term used to describe the alternating limestones and calcareous shales which form the upper part of the Great Limestone; Forster states in the text that they are separated from the massive limestone by about 1 foot of soft shaly material, known as the Black Bed. The massive limestone itself is divided into high, middle and low flats by thin shaly partings, these flats having shown favourability to replacement during mineralization. Only two sandstones are shown between the top of the Great and the base of the Little Limestone but a section from Cross Fell lead mine with three sandstones developed is mentioned in the text; in this section the upper-most sandstone is called the White Hazle. The sandstones presumably became known as Coal Sills because of their close overlay by coal seams, the term sill being locally employed to denote a bed or stratum, usually of sandstone. A section compiled from mines in Arken- dale and Swaledale on the Askrigg Block is also contained in the "Strata". Two further editions of the "Strata" appeared in 1821 and 1883 respectively, the latter posthumously revised and corrected by the Rev. W. Nall. There is no difference in the basic information contained, but a number of new sections are presented which show variations from the standard Alston Moor sequence.

Winch (1817) published similar information to Forster except that on his section for Alston Moor he shows a thin sandstone occurring immediately below the Little Limestone named the Little Hazle. He also stated that, "the coals being very uncertain in their extent are seldom noticed in the lead mine sections".

Sedgwick (1827) records a section from Old Langdon Mine, Teesdale whilst Sopwith (1829) published sections of Holyfield and Hudgill lead mines and in 1833 gave an account of the stratigraphy of Alston Moor which confirmed Forster's findings. Only Sedgwick's section shows any marked variation from the established one for Alston Moor; in this section an 82 feet thick combined High and Low Coal Sill is recorded as

immediately overlying the Great Limestone. In 1835 Sedgwick contributed to the geology of the Askrigg Block by describing a series of longitudinal and transverse sections. On these he named the bed equivalent to the Great Limestone, the Twelve Fathom Limestone.

John Phillips' (1836) work on the Askrigg Block is as well known as that of Forster on the Alston Block. He named the rhythmic sequence the Yoredale Series and demonstrated its continuation northward from Swaledale, correlating his Main Limestone with the Great Limestone. The Red Beds were also equated with the Little Limestone, a correlation which Wells (1957) considers to differ from his own mainly by a detail of nomenclature.

Some variation from the standard Alston Moor sequence is indicated by Wallace (1861) who presents a section of the much thicker sequence of the Great Cyclothem at Fallowfield Mine, Northumberland. On this section a prominent coal seam, shown as the Fallowfield Coal but also known as the Little Limestone Coal, is well exhibited in the upper part of the cyclothem. The presence of a sandstone, the White Hazle, immediately below the Little Limestone in the Alston Moor sequence is also emphasized. It is interesting to note that Wallace attempts to reconstruct the conditions of deposition during the formation of the Yoredales and succeeds in erecting a fairly accurate rudimentary pattern.

Armstrong et al. (1864) present a section by Sopwith, compiled from the Allenheads lead mines, on which excessively thick coal seams are indicated in the Coal Sills Group.

Lebour did much to elucidate the stratigraphy of Northumberland. In particular, his works on the Little Limestone and its accompanying coal (1874), and the Great Limestone and its associated beds (1875) in south Northumberland may be noted. These works have been incorporated into Smith (1912) but it is important to record that in the former work Lebour gave the first comprehensive account of the Little Limestone Coals. These coals have been extensively worked along the Tyne Valley, the history of working, which dates back to 1522, being summarized by Trotter and Hollingworth (1932). In the other paper mentioned, the Ebbs Snook Limestone of the Alnwick District was correlated with the Great Limestone. Variations within the south Northumberland sequence were considered, the thick sandstone developed in the cyclothem around Brunton being named

the Black Pasture Stone. A faunal list for the Great Limestone was also given.

The stratigraphical sequence for West Cumberland was worked out by Kendall (1885) but his correlation of the limestones with those of other districts has subsequently been shown to be incorrect.

Between the years 1878 and 1910 the borings and sinkings of Northumberland and Durham were compiled and published in six volumes by the North of England Institute of Mining Engineers. A careful search of these records reveals many sections through the Great Cyclothem.

Subsequent to the primary geological survey of Northern England, only two sheet memoirs were published for the Askrigg Block, these being for the Ingleborough (97 S.W.:Dakyns et al., 1890) and Mallerstang (97 N.W.:Dakyns et al., 1891) sheets. Both of these contain useful information as regards the Great Cyclothem, but, as throughout the sequence, most emphasis is placed on the limestone. The cherts overlying the Main (= Great) Limestone in Swaledale were recognized and it was considered that the Main Chert and the cherty Black and Red Beds "passed westward and northward into a series of grits, sandstones and shales, known in the north as the 'coal-sills', capped by a bed of chert or limestone called the Little Limestone." It is interesting to note that the term coal-sills was adopted despite the relative paucity of coal seams associated with the sandstones. Faunal lists for the Main Limestone and the beds above it are presented in the Mallerstang Memoir. Previous to these memoirs, one was produced for the Kirkby Lonsdale area (98 S.E.:Aveline et al., 1872), west of the Askrigg Block, where a small ill-exposed area of outcrop of the Great Cyclothem occurs. No memoirs at all appeared for the Alston Block but it is obvious from the six inch maps that the surveyors noted some variations from the standard sequence established for Alston Moor. Despite this lack of memoirs, much valuable information, mainly derived from the lead mines, was published on the three Geological Survey Vertical Section Sheets for the area (62, 1877; 63, 1878; 66, 1878), all of which were prepared by David Burns. A sheet for the Little Limestone Coal in Northumberland and Cumberland (South Tyne District) was also compiled by Burns (56, 1878). Gunn (1897) produced two memoirs for parts of north Northumberland, but these contain details which have been corrected and incorporated in more recent Survey

publications. Some information regarding the Great Limestone, but little else for the cyclothem, is to be found in the Appleby Memoir (102 S.W.: Dakyns et al., 1897). The whole of the area under consideration is covered by Old Series one inch to the mile Geological Survey maps which were published between the years 1869 and 1895. The sheet numbers are as follows (New Series numbers in brackets):-

110 N.E. (2), 110 S.E. (4), 109 N.W. (6), 109 S.W. (9),
105 N.W. (14), 106 N.E. (13), 106 S.E. (19), 106 S.W. (18),
101 N.W. (22), 101 S.W. (28), 101 N.E. (23), 102 S.W. (30),
102 N.E. (25), 102 S.E. (31), 103 N.W. (26), 103 S.W. (32),
97 S.W. (50), 97 N.E. (41), 97 S.E. (51), 98 S.E. (49),
92 N.W. (60), 92 N.E. (61).

The Dryburn Limestone of Northumberland was correlated with the Main of Yorkshire and the Top Hosie ("the limestone which lies below the Edge Coals") of Scotland, as well as with the Great Limestone of Durham, by Gunn (1898). In his correlation of the Great and Dryburn Limestones he concurred with Lebour (1889).

The Chopwell Woods deep borehole is recorded by Simpson (1902); this borehole penetrated the cyclothem in the concealed area several miles south-east and east of the outcrops in the Tyne Valley and on the Alston Block respectively.

Also in 1902, Hind presented lists of fossils from Weardale for the various members of the cyclothem; it would appear that the fossils listed for the Little Limestone are actually from the Crag Limestone, however. A further contribution to the palaeontology of the Great Limestone is to be found in Smith (1910), the fauna established by him being incorporated by Hill (1938).

An extremely interesting paper by Clough (1903) shows how, in Upper Teesdale, the full 55 feet of Great Limestone can be replaced by 10 - 12 feet of soft ochreous clay due to "famping", a process of conversion into ochre.

The small area of Carboniferous rocks around Canonbie was dealt with by Peach and Horne (1903) in the early part of this century and more recently by Barrett and Richey (1945). In the former paper the relationship of the rocks to those of Northern England and Central Scotland was considered, but not altogether satisfactorily. In their report on the

recently drilled Archerbeck Borehole in this region, Lumsden and Wilson (1961) correlate the Catsbit and Blae Pot Limestones with the Great and Little Limestones respectively. This correlation is entirely satisfactory, especially since the beds between the two first-named limestones are similar in lithology to those found between the Great and Little elsewhere.

The development of coal in the cyclothem was fully reviewed by Smith (1912) for the whole of Northern England. Some of his correlations of seams in Northumberland have been shown to be incorrect but this is of small matter when the large area that was considered is taken into account.

Revision of the mapping of Cumberland, Westmorland, Northumberland and Durham by the Geological Survey was begun in 1920 and is still being carried on. Much useful information acquired during the mapping was published in Summary of Progress for the years between 1920 and 1930 but most of this has been incorporated in the memoirs for the relevant areas where these have appeared. Of particular interest, however, is the paper by Bernard Smith (1927) in which a section through what is probably the Great Cyclothem is reported from one of the boreholes drilled at the northern end of the Isle of Man. The only published information pertaining to the area at the northern end of the Lake District, except for that by Trotter (in Trueman, 1954), is to be found in Summary of Progress (Eastwood, 1931); however, the one-inch geological map for the latter area (Sheet 23) has appeared recently. A list of one-inch maps and memoirs for the re-surveyed areas which are relevant to this work is given below:-

Sheet Number	Date Published	Name	Author of Memoir and Date published
2	1925	Berwick-on-Tweed	Fowler (1926)
4	1925	Holy Island	Carruthers et al. (1927)
6	1930	Alnwick	Carruthers et al. (1930)
9	1934	Rothbury	Fowler (1936)
14	1955	Morpeth	Not published
18	1930	Brampton	Trotter and Hollingworth (1932)
19	1956	Hexham	Not published
22	1930	Maryport	Eastwood (1930)
23	1959	Cockermouth	Not published
28	1929	Whitehaven	Eastwood et al. (1931)

From the foregoing it can be seen that the major part of the relevant area of Northumberland has been re-surveyed and for much of it there are memoirs available. Memoirs are also at hand for north-east Cumberland and the west side of the Lake District, but unfortunately the one for the Cockermouth sheet, although in preparation, has not yet appeared. From the information available, however, it would appear that the Little Limestone becomes an impersistent horizon westward across this last named sheet. If this is so there is then no well defined upper boundary for the cyclothem. No detailed consideration of the information which has been obtained from the memoirs will be made here, since it will be fully referred to later. However, it is of interest to note that in the Brampton Memoir (Trotter and Hollingworth, 1932) the first real attempt was made at an organized study of lateral variation within the cyclothem, the problem considered being the variable development of the Little Limestone Coals.

Earle (1921) and Edmonds (1922) both correlated the First Limestone of West Cumberland with the Great Limestone, the former by mapping around the northern end of the Lake District, and the latter on the basis of lithological and faunal characteristics. This correlation has been upheld by the Survey (Eastwood et al., 1931).

Records of certain shaft sections are to be found in the Special Reports on Mineral Resources (Lead and zinc ores) by Carruthers and Strahan (1923, Durham, Yorkshire and Derbyshire) and Smith and Carruthers (1923, Northumberland and Alston Moor).

A further contribution to the knowledge of the cyclothem in the region east of the outcrops on the Alston Block was made by Woolacott (1923) and Lee (1924) in their accounts of the Roddymoor boring, Crook.

An addition to the knowledge of the fauna of the Great (= Main) Limestone was made by Garwood and Goodyear (1924) who also mentioned the fossil list of Hughes (1908) for the same limestone. Turner (1927) also published a faunal list for the Great Limestone.

Hudson (1924 and 1941) considered the 'Red Beds' and 'Black Beds' of Swaledale to be the lateral equivalents of the Coal Sills Group and to underlie the Little Limestone, as did Dakyns et al. (1890 and 1891). However, Hudson only made incidental reference to the above correlation.

Further details of the development of the Little Limestone Coals

are given by Hedley and Waite (1928) for the district north of Corbridge. The thick sandstone which occurs below the coals and the Snope Burn Marine Band in the Tyne Valley region is named the Black Pasture Sill (after Lebour, 1875). Hedley (in Hickling, 1931) only gives a very general account of the cyclothem in Northumberland but it is interesting to note that the Little Limestone of the south is correlated with the Cushat Limestone of the north, thus fixing the upper limit of the cyclothem farther afield. This followed the correlation established by the Survey (Summ. Prog. G.S.G.B., 1925).

In his introduction to Scottish Carboniferous stratigraphy MacGregor (1929) correlated the Top Hosie Limestone, which forms the base of the Limestone Coal Group, with the Great of Northumberland, but no equivalent of the Little Limestone was suggested to fix the upper limit of the cyclothem.

Miller and Turner (1931) working in the Dent Fault and Shap districts correlated the Main Limestone of the block with the Great Strickland or Kings Meaburn Limestone of the latter district. They thus re-iterated the correlation established by the authors of the Appleby Memoir (Dakyns et al., 1897). The Bewley Castle Limestone of the Shap district was correlated with the Crow Limestone whilst the representative of the Upper Little Limestone was taken as a thin limestone which was observed in the River Lowther, one of the rivers of the Shap district. A faunal list was also given for the Main Limestone, containing specimens collected from both areas. The Stainmore area of Westmorland was dealt with by Turner (1935) mainly from a tectonic viewpoint but the presence of the Coal Sills was demonstrated and the Great Limestone was mapped into the Main across the highly faulted ground of this region.

Carruthers' "Adventure in Stratigraphy" (1938) was somewhat ill-fated as far as the correlation of the Coal Sills Group from the Alston to Askrigg Blocks is concerned since the Ten Fathom Grit of Rogan's Seat and Arkengethdale was equated with the "Upper Coal Sill (and possibly the lower one also) of the Teesdale sequence". The Crow Limestone overlies the Ten Fathom Grit in Swaledale and Carruthers considered this to be the equivalent of the Little Limestone of Teesdale, the name Little Limestone being used for a bed which he considered to lie below the Coal Sills in Swaledale. There is no doubt that Carruthers was misled by the

dying out of the arenaceous members of the group and their partial lateral replacement by chert to the south (Wells, 1955a and 1955b). This mis-correlation does not completely detract the value from the work, because a few useful sections are quoted for the Alston Block. However, it does give a plain warning that the use of measured sections alone for correlation is inadvisable.

The cyclothem cannot be recognized as such in the Furness District, as indicated by Dunham and Rose (1941), because of the marked facies change. However, beds of similar age undoubtedly form part of the predominantly shaly Gleaston Group.

The deep borehole in the Cleveland Hills (Fowler, 1944) gives yet another record of the cyclothem well detached from the outcrops to the west of it.

Black (1950) tentatively correlated the Great Limestone with the Scale Haw Limestone which occurs in the Bowland Shales and from which Hudson and Cotton (1943) have recorded an E_1a fauna.

Trotter (1952) considered the Namurian from the point of view of sedimentation facies and demonstrated how an important facies change takes place above the Great Limestone. He tentatively suggested that the Johnstone Shell Bed of Scotland may be the deteriorated representative of the Little Limestone of Northern England, as well as re-stating the Top Hosie - Great Limestone correlation.

Some general information is to be found in the Regional Guides for Northern England (Eastwood, 1953) and the Pennines and adjacent areas (Edwards and Trotter, 1954).

The authors of the guide to Ingleborough (Dunham et al, 1953) and Hicks (1959) noted no limestone in the 200 feet interval between the top of the Main Limestone and the grit that caps the mountain. However, the exposure of the beds at this point is by no means perfect.

In her concise review of the Lower Carboniferous rocks in the North of England, Rayner (1953) suggested that the Viséan-Namurian junction lies between the Great and Four Fathom Limestones and that the base of the Great Limestone should be defined as this boundary. Currie (1954), working quite independently, showed that the Top Hosie Limestone of Scotland lies at the base of the Namurian. Also in 1954, Craig gave a very interesting account of the palaeoecology of the Top Hosie Shale.

Brief mention of the cyclothem is made in the guide to the Alnwick district (Westoll et al., 1955).

The fauna and lithology of three biostromes developed in the Great Limestone were described in detail by Johnson (1958). In ascending order they are the Chaetetes Band, Brunton Band and Frosterley [Marble] Band. The first two were new whilst the other had been described by Dunham (1948). In his account of the Roman Wall district, Johnson (1959) dealt mainly with the Great Limestone, but some sections for the whole cyclothem and a general account of the same were given. More evidence was also put forward for defining the base of the Great Limestone as the Viséan-Namurian boundary.

The Bewley Castle Limestone of the Appleby district was correlated with the Little Limestone by Versey (1960).

Ferguson (1961) gives an interesting account of the fauna of the Tumbler Beds from where they are well developed at the top of the Great Limestone in the quarries around Stanhope, Weardale. The new genus Claviradix is more particularly considered than the rest of the fauna. A thickness of 94 feet is also recorded for the Great Limestone; this thickness is inaccurate and considerably in excess of that actually present.

Details for a very poorly exposed area are given by Dunham and Johnson (1962) in their detailed stratigraphical and palaeontological account of four boreholes drilled on Swinhope Moor, East Allendale.

The position of the Viséan-Namurian boundary in north-east England is further clarified by Johnson, Hodge and Fairbairn (1962) who report a number of new goniatite finds relevant to this problem. The pertinent details are contained in the "stratigraphical position" chapter and a reprint of the paper is enclosed. Suffice to say, the boundary is placed at the base of the Great Limestone.

Turner (1962) has described the distribution of the Chaetetes band in the north-west quarter of the Askrigg Block.

The works of Dunham (1948 and 1950) have been omitted until here because they are the basic models for a series of more recent contributions, each of which consider and evaluate lateral variation within the cyclothem of specific areas. In the Northern Pennine Orefield (Dunham, 1948), in addition to dealing with the other cyclothem of the sequence, a succinct

account of the variations in the development of the Great Cyclothem on the Alston Block is given, and the presence of sandstone-filled washout channels is first suggested. Other variations from Forster's standard Alston Moor sequence (with Wallace's White Hazle inserted) are also given. The 1950 paper of Dunham considers the Lower Carboniferous from the point of view of sedimentation, but it is based on 112 sections of strata compiled from records of boreholes, mine-shafts and underground workings, as well as surface exposures. 69 of these sections contain a record through the Great Cyclothem and these have been placed at the author's disposal. It was in this paper that the term Great Cyclothem first appeared in print.

Recently, the geology of the Moor House Nature Reserve has been investigated in great detail by Johnson (Johnson and Dunham, 1962). During this survey the development of the cyclothem in the Cross Fell-Great Dun Fell area was examined.

The works referred to below, each of which considers the cyclothem within a specific area, are either theses or papers based on theses which were presented for the degree of Doctor of Philosophy by the various authors. Little information regarding them will be given here as they will be fully referred to in the text. Fig. 2 shows the positions of the areas involved in these works, as well as those for some of the more important works mentioned above.

Short (1954) covered the northern part of the Pennine Escarpment from Ardale, below Cross Fell, to Croglin Water, thus overlapping on to the southern part of the Brampton sheet (Trotter and Hollingworth, 1932).

The south-east part of the Alston Block, between Middleton-in-Teesdale and Woodlands, was considered by Jones (1956).

The Cotherstone Syncline and Askrigg Block have been almost completely resurveyed by recent workers, the only large area of Carboniferous rocks remaining to be studied being that between Ingleborough and Coverdale, south of the Ure.

Reading (1954 and 1957) investigated the Cotherstone Syncline, overlapping the ground considered by Turner (1935) to a small extent in the west. Reading, however, gives complete stratigraphical details whereas Turner was mainly interested in the tectonics of the area.

An extremely large area was covered by Wells (1955a, 1955b and 1957)

who, in particular, investigated the development of chert within the Great Cyclothem and the cyclothem immediately above and below. Altogether 450 square miles of North Yorkshire were considered. Wells showed that Dakyns et al. (1890 and 1891) and Hudson (1924 and 1941) were incorrect in correlating the cherty Black and Red Beds with the 'Coal Sills' because the Red Beds are components of his Richmond Chert Series which overlies the Little Limestone, the base of which forms the top of the Coal Sills Group.

Rowell and Scanlon (Rowell, 1953 and Scanlon, 1955; jointly, 1957a and 1957b), working to the west of Wells, investigated the north-west quarter of the Askrigg Block. The Little Limestone "Pipe Bed", which has since proved to be an extremely useful marker horizon, was initially discovered by these workers and then independently recognized by Wells (op. cit.) and Wilson (1957 and 1960).

Only the beds up to the top of the Great Limestone were examined by Moore (1955, 1958, 1959 and 1960) in Upper Wensleydale and the adjoining areas since the higher strata had been adequately considered by Wells (op. cit.). On the basis of his investigation Moore puts forward a revolutionary theory to explain the sedimentation in the Yoredales.

Hicks (1958 and 1959) completed the coverage of the west side of the Askrigg Block working to the south of Rowell and Scanlon. Of particular interest in his area is the coarse grained, garnet-rich sandstone of the Coal Sills Group which Wells (op. cit.) mistook as the basal Millstone Grit component.

The only other recent work on the Askrigg Block which is of importance here is that of Wilson (1957 and 1960). The area examined lies in the south-east part of the Block, embracing Coverdale and the adjacent valleys. Small isolated patches of chert and shale were shown to be developed between the Great and Little Limestones of this area, but normally the two limestones are in contact and frequently cannot be recognized as separate units. Wilson's area overlaps that of Wells to a small extent in the north.

Summarizing the situation as it was at the commencement of the present investigation, a great deal of detailed information regarding the Great Cyclothem, widely scattered over Northern England had appeared, but apart from the limited work of Wells (op. cit.) on the cherty facies,

no attempt had been made to organize the data so as to obtain a picture of the changing conditions of sedimentation at the inception of Upper Carboniferous times. The following work is an attempt to remedy this situation in order to assess the conditions of deposition and reconstruct the palaeogeography of the Yoredale delta and adjacent areas prior to and during one of the delta's major advances.

CHAPTER II

STRATIGRAPHICAL POSITION

The position of the Great Cyclothem in relation to adjacent units of the lithological sequence is shown in the following table which lists the limestones forming the basal members of the cyclothem above and below it on the Northumbrian Block.

<u>ALSTON BLOCK</u>		<u>ASKRIGG BLOCK</u>
Crag Limestone		Crow Limestone
Little Limestone	} Great Cyclothem {	Little Limestone
Great Limestone		Main Limestone
Four Fathom Limestone		Undersett Limestone
Three Yard Limestone		Three Yard Limestone

Phillips' (1836) Yoredale Series had as its upper-most member the Main (= Great) Limestone, the strata above this being included in the Millstone Grit Series. The Yoredale Series has since been extended considerably higher than that of Phillips, the various surveyors (for example, the Primary Surveyors, 1860 - 1890) and authors making their own particular selection for a base to the Millstone Grit. More recently Yoredale or Yoredaleian has been employed as a facies term to describe the alternating limestone, shale, sandstone sequence typical of the Lower Carboniferous in much of Northern England; for example, Hickling (1931). Thus, despite the decision of a Committee of the British Association in 1925, the term has latterly been used with no very strict stratigraphical meaning but it is a convenient term to describe the facies. A Yoredale facies is developed above the Great Limestone north and west of the type area of Wensleydale.

The base of the Great Limestone was taken as the base of the Bernician Upper Limestone Group by Carruthers (1923), a practice adopted subsequently by various authors, for example, Trotter and Hollingworth (1932) and Dunham (1948). This grouping was based on the coral-brachiopod zones established by Smith (1910) who was aided in his work in Northumberland by Vaughan, the originator of the coral-brachiopod zonal

sequence for the Bristol area (1905). The Middle-Upper Limestone Group junction, at the base of the Great Limestone, corresponded to Smith's D_{2-3}/D_y boundary. Johnson (1959) has reviewed the coral-brachiopod zonal position of the Carboniferous rocks in western Northumberland and concluded that the top of the *Dibunophyllum* zone lies between the Four Fathom and Great Limestones. Thus the Great Cyclothem and succeeding strata lie above the D zone of Vaughan. Obviously, this is why Smith had to erect his extra sub-zone, D_y , in order to fit the upper part of the so-called Lower Carboniferous sequence of Northern England into the coral-brachiopod zonal scheme.

Only recently has it been possible to place the Carboniferous sequence of north-east England into its correct position in the goniatite zonal scheme originated by W. S. Bisat (1924). Although the distribution of goniatites is relatively sparse in rocks of Yoredale facies, careful and diligent search has brought to light several goniatite-bearing horizons in the last few years. The discovery by the author and Dr. G. A. L. Johnson of several small goniatites in shales just above the Little Limestone warrants an appraisal of those previous goniatite finds which have a bearing on the zonal position of the Great Cyclothem. Also, during the last few years an amateur geologist friend of the author, Mr. R. A. Fairbairn, has collected six goniatites from the shales which occur immediately above the Great Limestone at Greenleighton Quarry, Northumberland. The critical zonal significance of these goniatites was not realized initially by Mr. Fairbairn, but the author has had them examined by Dr. Ramsbottom and Mr. Bisat who confirmed his and Dr. Johnson's tentative identification of them. The horizons from which goniatites and related faunas have been collected are enumerated below. The list has been compiled from works by Dunham (1948), Trotter (1952), Rayner (1953), Rowell and Scanlon (1957), Johnson (1959), Wilson (1960) and original work by the author and his co-workers (Johnson, Hodge and Fairbairn, 1962):-

- (i) *Sudeticeras adeps* Moore, P_2 , from shales above the Acre Limestone on Holy Island and c.f. *Sudeticeras adeps* Moore, from a similar horizon at Ancroftsteads Limeworks, three miles north of Lowick. Both were collected by J. Rhodes (Trotter, 1952 and Rayner, 1953). The Acre Lime-

stone has been correlated with the Three Yard Limestone of the Northumbrian Fault-Block (Johnson, 1959).

(ii) Girtyoceras? costatum Ruprecht, high P_2c , associated with Girtyoceras sp., Sudeticeras sp. juv. and Caneyella [Posidonia] membranacea (M'Coy), from shales above the Undersett (= Four Fathom) Limestone in the Mount Pleasant water boring, near Barnard Castle, (see Fig. 4a for the exact horizon). The fauna was collected by Dr. Johnson and the goniatites determined by Dr. Stubblefield and Mr. Bisat (Rayner, 1953 and Johnson, 1959).

(iii) Tylonautilus nodiferus (Armstrong) early mut., in association with Caneyella [Posidonia] membranacea (M'Coy); this find is considered to be indicative of highest P_2 or low E_1 , although Trotter (1952) and Rowell and Scanlon (1957) have indicated that T. nodiferus early mutation ranges throughout E_1 .

The fossils were collected by Dr. Johnson from shales above the Four Fathom Limestone in Chineley Burn, above Bardon Mill, Northumberland (Johnson, 1959).

(iv) ?Cravenoceras sp., E_1 ; collected by Dr. Wilson and identified by Dr. Ramsbottom. The specimen is a single fragmentary goniatite collected from shales approximately 20 feet above the Undersett Limestone (Wilson, 1960).

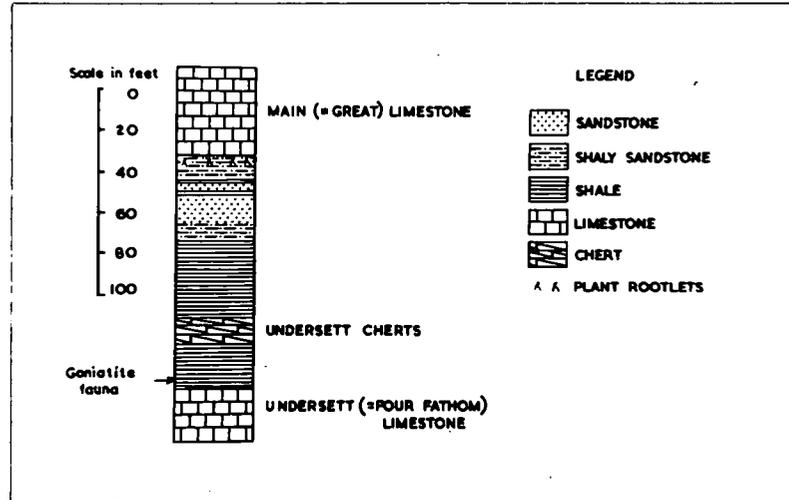
(v) Eumorphoceras pseudobilingue (Bisat), E_1 ; collected by Dr. Hudson from shales immediately below the limestone on Fountains Fell which is usually considered to be the Main. Some doubt has been cast on the identification of this limestone as the Main by Trotter (1952). The limestone occurs in very poorly exposed ground but in the light of the goniatite discoveries listed here it would seem likely that it is the Main. Identification of the goniatite was by Mr. Bisat. This record (Hudson, 1941) is confirmed by Black (1950) though the Eumorphoceras of Black was

Fig. 4

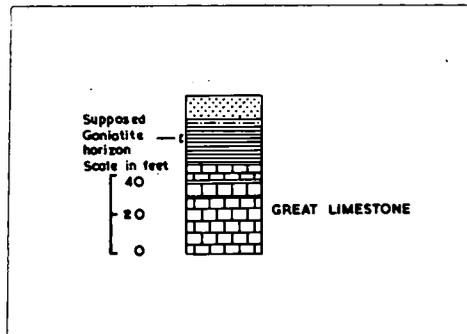
Sections to show the stratigraphical position of
the more important goniatite-bearing horizons.

- (a) Barnard Castle Borehole
- (b) Greenleighton Quarry
- (c) Swinhope area

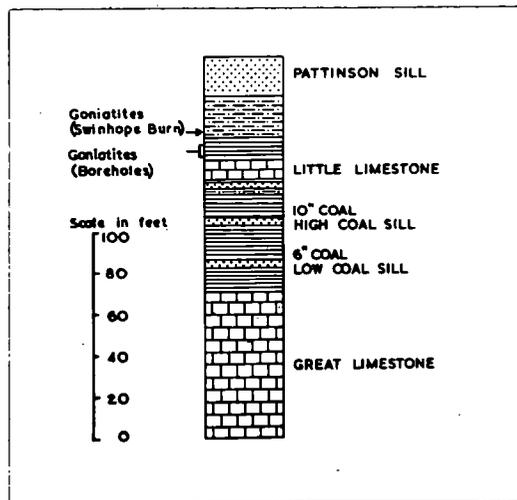
Fig. 4.



(a)



(b)



(c)

1917

considered by Mr. Bisat to be an earlier species than that of Hudson.

(vi) Cravenoceras leion Bisat, E₁, collected by Mr. R. A. Fairbairn and passed on to the author for identification, this being kindly carried out by Dr. Ramsbottom and Mr. Bisat. The six goniatites were all collected from tip material of a quarry which is worked in the Great Limestone near Greenleighton Farm, Northumberland (45/035916)¹. At this quarry a peculiar method of removing the overburden from the limestone is employed because it is bull-dozed to the top of the quarry and piled behind the working face. The goniatites were collected from these piles of tip material and were found to be associated with a characteristic nodule lithology. Nodules of similar lithology are concentrated in situ at a level approximately 12 feet above the limestone top and it seems reasonably certain that this is the horizon from which the goniatites originated. Unfortunately no goniatites have been found in situ but the shales contain a prolific fauna which includes abundant Chonetes and Eomarginifera, as well as Schuchertella, Camarotoechia, Sanguinolites, Edmondia, Nuculopsis, Nuculana, Leptaena, Lingula, Orbiculoidea and large crinoid stems. Occasional thin, impersistent, silty, very fossiliferous calcareous bands occur in the shales which grade into a very flaggy sandstone 23 feet above the limestone top.

Because of their prolific fauna and the presence of thin calcareous bands it is considered that at least the lower part of the shales are laterally equivalent to and have replaced the upper part of the limestone as developed farther south on the Northumbrian Fault-Block.

Fig. 4b shows the section at Greenleighton Quarry and the supposed position of the goniatites, whilst Fig. 5

1: Eight figure numbers in brackets are National Grid References.

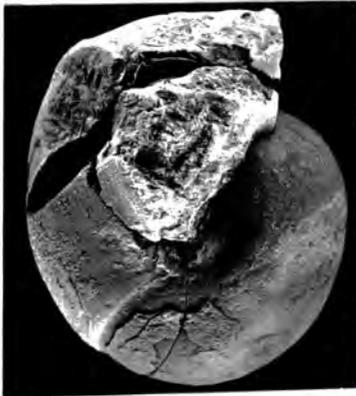
Fig. 5

Cravenoceras leion Bisat, Greenlighton Quarry, Northumberland.

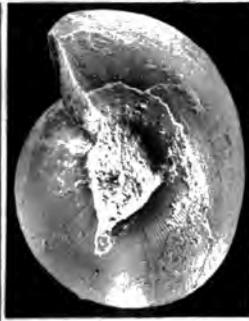
All specimens x 3.5

(Numbers in brackets are Geological Survey specimen catalogue numbers)

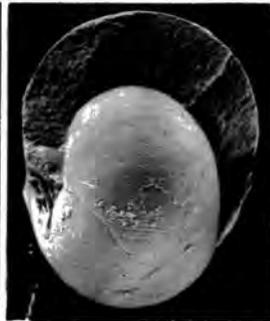
- (a) lateral view of a complete specimen with a constriction (GSL. LZ3406).
- (b) lateral view of specimen (a) broken open to show fine ornament (GSL. LZ3406).
- (c) ventral view of (b) showing fine ornament (GSL. LZ3406).
- (d) as (c) but under liquid and showing a suture which is approximately picked out by a colour change (GSL. LZ3406).
- (e) lateral view of a specimen to show the general form.
- (f) lateral view of general form (specimen slightly distorted).
- (g) ventral view of specimen (f) showing a distorted suture picked out by a colour change.
- (h) lateral view showing fine ornament on a slightly distorted specimen (GSL. LZ3407).
- (i) ventral view of (h) (GSL. LZ3407).
- (j) ventral view of the largest specimen collected (pock-marking is a secondary effect).
- (k) lateral view of (j).



(a)



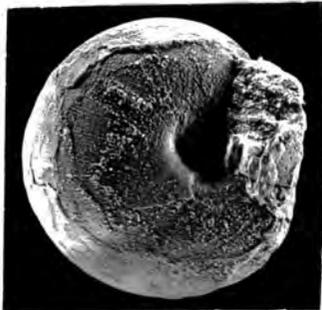
(b)



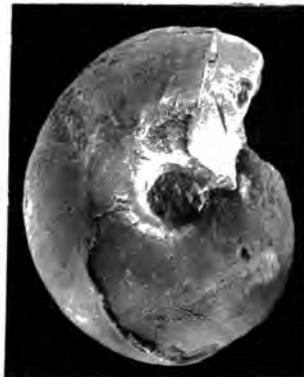
(c)



(d)



(e)



(f)



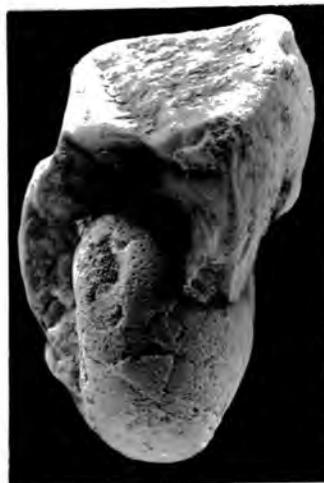
(g)



(h)



(i)



(j)



(k)

shows the general form and specific features of the goniatites. Statistical data for the goniatites are given in Table I. The specimens fit well into the C. leion species group and have shells of subglobose form with an open umbilicus of a width about one-fourth of the diameter of the shell. The venter and flanks are broadly rounded and nearly semicircular in outline. The external ornament is well preserved in some specimens (Fig. 5b, c, h, and i) and consists of closely-set, thin, non-crenulate transverse striae, emerging from the umbilicus in a slightly forward direction and bending to form a very shallow sinus over the venter. Shallow constrictions are developed on the shells. The suture line is well displayed on some of the specimens (Fig. 5d and g) and shows the broadly rounded ventral saddles and narrow lateral lobes.

Table I
Dimensions of Cravenoceras leion Bisat from
Greenleighton Quarry, Northumberland.

Specimen No.	Diameter (mm.)	Thickness (mm.)	Umbilicus (mm.)
5a,b,c and d	13.5	9.5	3.0
5e	11.0	7.0	2.5
5f and g	13.0	8.5	2.5
5h and i	10.5	7.0	2.0
5j and k	14.0	10.5	3.5

Specimens 5a and 5h have been presented to the Geological Survey and are housed at the Leeds Office. Their catalogue numbers are GSL. LZ3406 and GSL. LZ3407 respectively. The rest are in Mr. R. A. Fairbairn's private collection at Newcastle.

Fig. 6

Cravenoceras aff. malhamense (Bisat), Swinhope Burn, East Allendale

All specimens x 5.

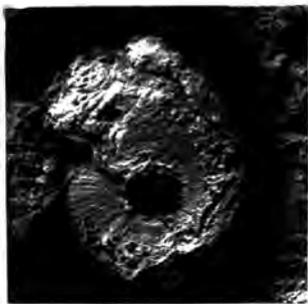
(Numbers in brackets are Geological Survey specimen catalogue numbers)

- (a) lateral view showing the raised umbilical rim (GSL. LZ3409).
- (b) ventral view of a latex cast made from a natural external mold with a suture profile exhibited (GSL. LZ3408).
- (c) lateral view of (b) with poorly defined suture lines (GSL. LZ3408).
- (d) lateral view of a large specimen showing the general form with a constriction.
- (e) ventral view to show ornament with the marked hyponomic sinus (GSL. LZ3410).
- (f) lateral view of (e) showing the wide umbilicus and raised umbilical rim (GSL. LZ3410).
- (g) oblique-lateral view showing the raised umbilical rim (GSL. LZ3411).
- (h) ventral view of (g) showing the marked hyponomic sinus (GSL. LZ3411).

Cravenoceras sp., Swinhope Borehole No. 3, East Allendale

Specimen x 5.

- (i) lateral view of a fragmentary specimen showing the umbilicus and ornament.



(a)



(b)



(c)



(d)



(e)



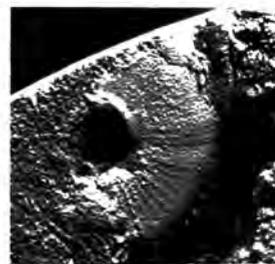
(f)



(g)



(h)



(i)

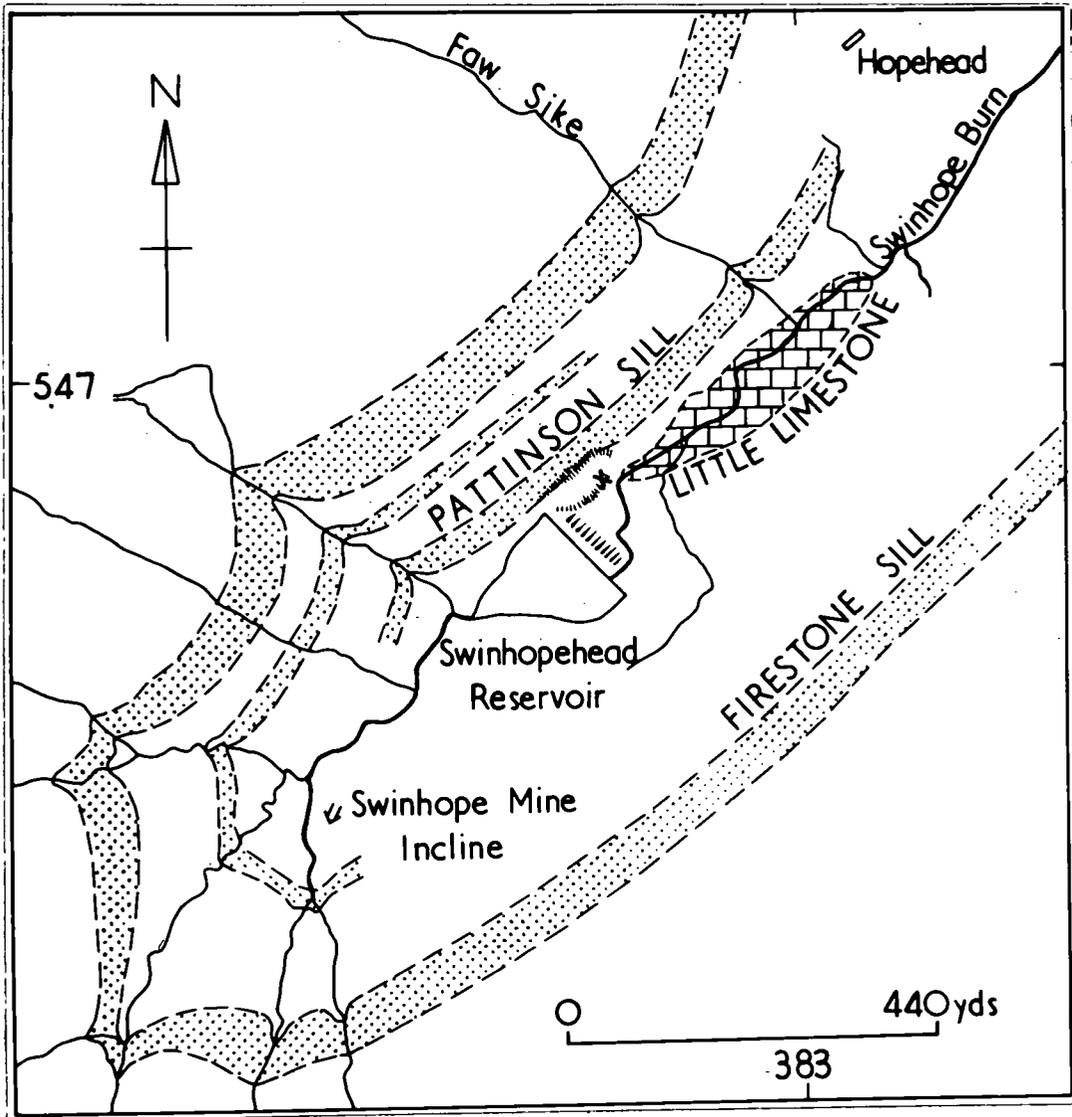


Fig. 7. Geological Sketch Map of the Swinhope Area.
 The goniatite locality is marked X.

(vii) Tylonutilus nodiferus (Armstrong) early mut., E₁; collected by Rhodes (Hind 1901) from the upper leaf of the Great Limestone in Smithy Gill, Swarth Fell (34/774963). The history of this specimen is reviewed by Rowell and Scanlon (1957a).

(viii) Cravenoceras sp., "between malhamense and cowlingense", and Eumorphoceras sp. were reported from a faulted block of what was considered to be possibly the Tumbler Beds of the Great Limestone by Shotton and Trotter (1936), the locality being at Star Hows, Ardale Beck, below Cross Fell. Johnson (1959) has recently collected Cravenoceras sp. nov. and Kazakhoceras [Neodimorphoceras] sp. from the same locality, the identification being carried out by Mr. Bisat. These goniatites indicate an E age but Johnson (op. cit.) considers the horizon to be above the Great Limestone. Short (1954) also decided, on the basis of the micro-fauna, that this horizon was considerably higher than the Great Limestone as had Johnson (in litt. to Rayner, 1953) on a similar basis.

(ix) Cravenoceras aff. malhamense (Bisat), E₁, collected by the author and Dr. G. A. L. Johnson from shales 14'6" above the top of the Upper Little Limestone in Swinhope Burn, East Allendale. Similar fragmentary goniatites, identified as Cravenoceras sp., were found almost synchronously in the New Consolidated Goldfields Swinhope Boreholes at approximately the same horizon (Dunham and Johnson, 1962). The goniatite horizons are shown on Fig. 4c and the surface locality on Fig. 7. The surface specimens were kindly examined by Dr. Ramsbottom and Mr. Bisat, the former giving the following identification and description:-

"These are Cravenoceras sp., but there are a number of unusual features - notably the raised

umbilical rim (Fig. 6a) and the marked hyponomic sinus (Fig. 6e).

"A raised umbilical rim is known in examples of comparable size in both C. leion and less definitely in C. malhamense, but these species do not show any hyponomic sinus. The only Cravenoceras example seen which shows any hyponomic sinus at this size (c. 8 mm.) is C. cowlingsense from the same erratic block in Keighley churchyard which yielded the types of Anthracoseras cherryi (Bisat).

"The ornament of the specimens is, apart from the sinus, very close to that of C. malhamense and Cravenoceras aff. malhamense (Bisat) would seem to be the best name for these specimens until more is known about the Cravenoceras succession in E₁."

Table II

Dimensions of Cravenoceras aff. malhamense (Bisat) from Swinhope Burn, East Allendale, Northumberland.

Specimen No.	Diameter (mm.)	Thickness (mm.)	Umbilicus (mm.)
6a	6.0	-	2.0
6b and c	4.0	3.5	1.5
6d	8.0	4.5	2.0
6e and f	5.0	4.0+	2.5
6g and h	3.0	2.0	1.0
6i	5.0	-	1.5

Specimens 6a, 6b, 6e and 6g have been presented to the Geological Survey and are housed at the Leeds Office. Their catalogue numbers are GSL. LZ3409, GSL. LZ3408, GSL. LZ3410 and GSL. LZ3411 respectively. The other specimens are in the collection of the Department of Geology at Durham.

Several specimens were collected and the

better ones are shown in Fig. 6 to illustrate their general form and the specific features mentioned by Dr. Ramsbottom. Table II gives statistical details for the goniatites. The shells are of cadicone form with wide umbilicus and broad venter (Fig. 6a to h). External ornament consists of delicate, transverse striae, non-crenulate and non-dichotomizing, with a marked hyponomic sinus on the venter (Fig. 6e). The sutures are not well shown but the general outline can be made out in some of the specimens (Fig. 6b and c).

The stratigraphical position of these goniatites was not certain when they were first discovered. The limestone exposed below the shale in which they occur was mapped as an inlier of Little Limestone by the Primary Surveyors. It was nevertheless thought at first that this exposed limestone was really the upper part of the Great Limestone, because its top lies 22 feet below the proved top of the Great Limestone and 86 feet below the Little Limestone top in the Swinhope Mine Incline. The incline head is 1,650 feet west of the nearest limestone outcrops and no faults were proved in the intervening ground during mining operations. However, a dip of 3° in an easterly direction was noted in the strata of the incline; this would precisely carry the Little Limestone down to the position of the limestone outcrops in Swinhope Burn if it was maintained. In order to establish the identification of the limestone as the Little, the stratigraphy of the area was investigated more fully, the results being shown in Figs. 4c and 7. The vertical section (Fig. 4c) shows that there is no thin coal in the beds overlying the limestone in the stream (shown as the Little Limestone) whereas in the incline section a 6" shaly coal occurs 15 feet above the Great Limestone top. This thin coal seam is known

Table III

The goniatite zonal scheme about the Viséan-Namurian boundary

Age	Stage	Zone	Sub-zone	Faunal association
UPPER CARBONIFEROUS	Pendleian, E ₁	<u>C. malhamense</u> , E _{1c}	not divided	<u>C. malhamense</u> , <u>Muensteroceras invaginatum</u> , <u>Kazakhoceras hawkinsi</u>
		<u>Eumorphoceras pseudobilingue</u> , E _{1b}	not divided	b) <u>E. pseudobilingue</u> , <u>Dimorphoceras complex</u> , <u>E. angustum</u> a) <u>E. nodosocarlinatum</u> , M.S.
LOWER CARBONIFEROUS	Upper Boll- andian, P ₂	<u>Cravenoceras leion</u> , E _{1a}	<u>E. hudsoni</u>	<u>E. hudsoni</u> , <u>C. aff. leion</u>
		<u>Lyrogoniatites georgiensis</u> , P _{2c}	not divided	<u>E. stubblefieldi</u> , <u>E. bisati</u> , <u>E. pseudocoronula</u> , <u>C. leion</u> , <u>Cravenites varians</u> , <u>L. tonksi</u> , <u>D. inflatum</u> , <u>D. plicatile</u> , <u>D. wiswellense</u> , <u>?Sudeticeras</u> sp.
LOWER CARBONIFEROUS	Upper Boll- andian, P ₂	<u>Neoglyphioceras subcirculare</u> , P _{2b}	not divided	<u>E. tornquisti</u> , <u>C. leion</u>
		<u>Goniatites granosus</u> , P _{2a}	not divided	<u>L. georgiensis</u> , <u>Girtyoceras shorrocksi</u> , <u>G. ? costatum</u> <u>Sudeticeras</u> of the <u>stolbergi</u> group <u>N. subcirculare</u> , <u>S. splendens</u> , <u>D. varians</u> , <u>D. marioni</u> , <u>G. weetsense</u> , <u>S. procerum</u> <u>G. multicameratum</u> , <u>S. ordinatum</u> , <u>S. adeps</u> <u>G. granosus</u> , <u>S. subtile</u> <u>S. srenistriatum</u> , <u>N. c. f. caneyanum</u>

to persist over a wide area, but it can be seen that this is almost exactly the position above the limestone in question that the goniatites were discovered. Mapping also showed that the Pattinson Sill and Firestone Sill could be traced around the area (Fig. 7) giving a completely different sequence from that occurring immediately above the Great Limestone in the incline. It was thus concluded that the goniatites occur 14'6" above the Little Limestone, the identification of the limestone by the Primary Surveyors being substantiated.

The goniatites, which appear to be confined to one band, were found in a micaceous, slightly silty shale with small ironstone nodules; contained in the shale is some comminuted plant material and the occasional brachiopod and lamellibranch including Chonetes and indeterminate Orthotetids. The shale becomes more silty upwards and grades into the Pattinson Sill.

A wider and, in parts, more comprehensive account of the goniatites and related faunas pertaining to the Viséan-Namurian boundary is to be found in Johnson, Hodge and Fairbairn (1962).

The goniatite zonal scheme involving the species listed above is summarized in Table III which has been drawn up from the work of Bisat (1924, 1928, 1930 and 1950), Stubblefield (in Stephens et al., 1953) Ramsbottom (in Earp et al., 1961) and Ramsbottom and Hodson (personal communication by Dr. Ramsbottom).

From a consideration of all the records, and in particular (ii), (iii), (iv) and (vi), it is obvious that the Viséan-Namurian boundary lies some little way above the top of the Four Fathom Limestone. Thus, the Great Cyclothem lies completely in E_1 , ranging from E_1a upwards. However, the full range of the cyclothem cannot be given because of the impossibility of being absolutely specific in the identification of the goniatites from Swinhope (ix). It would not be prudent to be more than speculative about their absolute age especially when their characteristics comparable with C. leion (E_1a) and C. cowlingsense (low E_2) are taken into consideration. How much emphasis can be placed upon the

E. pseudobilingue find from Fountains Fell (v) is debatable because of the uncertain horizon at this locality. The goniatites from Cross Fell (viii) are of no importance here as it is almost certain that they come from a higher level in the sequence than originally suggested. Also, it cannot be claimed that there is no doubt surrounding the T. nodiferus record from the upper leaf of the Main Limestone (vii). There has been some confusion as to its correct stratigraphical horizon but Rowell and Scanlon (1957a) assert that it comes from the horizon stated above, rather than the Upper Little Limestone. Nevertheless, it is unimportant to be specific about the horizon since it is known that this fossil ranges throughout E_1 (Trotter, 1952) and, on the basis of independent evidence, it is certain that both the Great and Little Limestones occur within E_1 .

The most important conclusion of this deliberation is that the Viséan-Namurian (P_2/E_1) junction lies between the Four Fathom and Great Limestones. This conclusion had tentatively been reached by Rayner (1953) and more certainly by Rowell and Scanlon (1957a) and Johnson (1959). It has been suggested that the base of the Great Limestone be defined as the Viséan-Namurian boundary (Rayner, op. cit., concurred by Johnson, op. cit.). There would then be a zonal boundary combined with a good mappable horizon to demarcate the junction between the Lower and Upper Carboniferous (Millstone Grit Series). It must be emphasized that this suggestion is in harmony with all the new and existing evidence. The only district in Northern England in which this combination might be difficult to apply is West Cumberland where the Survey did not find it possible to map the representatives of the Four Fathom and Great Limestones as separate units. This does not imply that there is not a parting between the limestones since between 5 and 27 feet of strata have been reported between the two (Eastwood et al., 1931). Now that the full significance of the Great Limestone base is realized it may eventually prove possible to separate the two limestones.

On the other hand, on the basis of thickness and lithology the Great is comparable with those limestones occurring below it rather than those above. Consequently Trotter (1960) has suggested that it would be more satisfactory to place the Viséan-Namurian boundary at the top of the Great Limestone, rather than the base. In fact, on the 1st Geological

Survey Cockermouth Sheet. (New Series 23, 1959), the boundary has been drawn in this position. The Millstone Grit Series does not then include the thickest Yoredale limestone. Nevertheless, this is here considered to be inadvisable for the following reasons:-

(i) The top of the limestone is not as easily and accurately mapped as the base.

(ii) As compared with the base, the limestone top is markedly diachronous, the top of the mappable and massive part of the limestone being progressively replaced northwards by calcareous shale containing occasional thin limestone bands. This does not deny that there may be slight diachronism at the limestone base (though this has never been demonstrated), but onset of limestone deposition, particularly that of the Great, is usually taken to represent a sudden and widespread marine transgression over the whole area of Northern England.

(iii) The base of the Great Limestone is a very close approximation to the P_2/E_1 time line and the use of it avoids the introduction of any substantial discrepancy, which would be introduced if the limestone top were used. The Four Fathom Limestone top could not be used for the same reasons as those stated against the use of the limestone top in 1 and 2.

(iv) The use of the goniatite zonal scheme is an attempt to bring order to the earlier somewhat arbitrary and local division of the Carboniferous. Any attempt to depart further than necessary from the systematically defined boundary is to be avoided since this would be a partial return to the original arbitrary system. In certain areas local conditions have dictated some departure from the scheme, for example, as in the Clitheroe Memoir (Earp et al., 1961), for mapping purposes, but whether this is advisable is debatable.

Thus, it can be seen from the above that it is more reasonable to place the boundary between the Lower and Upper Carboniferous in Northern

England at the Great Limestone base in the absence of a mappable horizon at the specific junction.

On the basis of independent palaeontological evidence, Currie (1954) has shown that in the Midland Valley of Scotland the base of the Top Hosie Limestone lies at the base of the E zone. This is confirmation of the position of the Viséan-Namurian boundary because it has been "generally agreed" that the Top Hosie is the lateral equivalent of the Great Limestone (Trotter, 1952).

CHAPTER III

THE GREAT LIMESTONE AND ITS LATERAL EQUIVALENTS

GENERAL

The Great Limestone is known throughout Northern England but has been given different names in the various areas which it is found. Equivalent strata in the Midland Valley of Scotland also go under a variety of names as a result of the widely separated outcrops. The different names arose before geology became a systematized science but subsequently correlations have been achieved by direct mapping and by utilizing the palaeontology. The correlations so established are shown in Table IV.

The Great is the thickest limestone of the Yoredale facies and it also retains a reasonably persistent lithology and fauna. Usually, if not masked by boulder clay or peat, the limestone supports a short sweet green grass which in many cases is clearly distinguishable from that supported by other rocks and, therefore, aids in mapping. Because of its thickness the limestone frequently forms a prominent feature, its top is almost invariably marked by large shake holes and outcrops are not uncommon. Consequently it can be mapped accurately and the base of it forms an excellent datum line. It might be emphasized here that care has to be exercised in the use of feature-mapping for delimiting the limestone base, since it has been found that in a few places the apparent feature may suddenly transgress the full thickness of the limestone; this usually appears to be due to boulder-clay or peat masking the true feature. In general, however, the limestone forms a steep scarp with the base of the slope at or near the base of the limestone (Fig. 8). The use of the limestone base as a datum line for elucidating the structure of the North-umbrian Fault-Block is well known (Dunham, 1948 and 1959).

The limestone is important economically as the richest single ore-bearing horizon of the Northern Pennine Orefield, its thickness, hardness and lithology having had a direct effect upon the mineralization it contains, since approximately 30 per cent of the worked vein oreshoots and 70 per cent of the flat oreshoots on the Alston Block occur in it (Dunham, 1948). Further details of the mineralization are to be found in Dunham (op. cit.). At a number of localities the limestone has been

Table IV

Correlation of the Great Limestone equivalents
in Northern England and Scotland.

<u>Area</u>	<u>Names of Limestone</u>
Midland Valley of Scotland.	Top Hosie, Calderwood Cement.
Dunbar.	Barness East.
North Northumberland.	Dryburn, Ebbs Snook, No. 1, Great.
Central Northumberland.	Great, Ten Yard.
South Northumberland.	Great.
Canonbie District.	Catsbit.
Alston Block.	Great.
Cotherstone Syncline.	Great (in north), Main (in south).
Askrigg Block.	Main, Coverhead, Twelve Fathom, Upper Scar.
Craven Lowlands.	Scale Haw.
Kirkby Lonsdale.	Main.
Vale of Eden.	Great Strickland, Kings Meaburn, Main, Great.
North of Lake District.	Great, First.
West of Lake District.	First, Brigham, Bigrigg, Langhorn, Top.
North of Isle of Man.	First, Great.

extensively quarried for ironworks flux, road-stone and lime-burning, but in recent years its use, except as a source of lime, has declined considerably.

A two-fold lithological division, with massive wavy-bedded limestone below, and limestone-with-shale above, can be recognized widely in the Great Limestone and its equivalents. Three persistent bios-tromes have been recognized within the massive limestone, the Chaetetes Band near the base, the Brunton Band below the middle, and the Frosterley [Marble] Band above the middle.

SUMMARIZED STRATIGRAPHY

Thickness Variation

The Great is the thickest of the Yoredale limestones but a considerable range in thickness is exhibited over the whole area of its development.

The variation in thickness on the Alston Block is illustrated on Plate II. In this region the average thickness lies between 60 and 65 feet but in the Stanhope neighbourhood the thickness does not fall below 70 feet and actually reaches 82 feet at one point. At three other localities on the Block a thickness of 70 feet is exceeded whilst at one a minimum thickness of 40 feet has been recorded. There is a regional thinning of the limestone towards the northern and north-western extremities of the Block bordering the Northumbrian Trough; in this direction it appears that the upper part of the limestone passes into shale thus reducing its thickness to between 40 and 50 feet and possibly less in places. Another cause of thinning is erosion at the base of a washout-channel in the overlying Coal Sills Group, the limestone having been reduced in thickness to a minimum of 27 feet along a strip which can be traced from St. John's Chapel southward to Barras. Still another cause of thinning is a process of mineralization and weathering known as "famping", which has caused the limestone to be altered to an ochreous clay (famp) at a number of localities on the Alston Block. This famping involves a considerable reduction in thickness of the limestone down to a minimum thickness of 13 feet.

In the Cotherstone Syncline the limestone shows rapid variation between 40 and 85 feet thick, the variations also being shown on Plate II. A thickness of 102 feet may be attained at Lunehead Mine and 108

feet of limestone has been recorded in the River Belah to the west of the syncline.

The average thickness in the northern part of the Askrigg Block is similar to that for the Alston Block. However, in the central region of the Block the average thickness is over 80 feet with a maximum of 130 feet being reached on Kisdon. In the south-west and south-east extremities of the Block a rapid regional thinning of the limestone has been noted, particularly to the south-east in Coverdale where the limestone thins from 83 feet thick to 5 or 10 feet thick within three miles in a south-east direction; in the south-west a thickness of 20 feet is rarely exceeded, the thickness falling as low as 10 feet on Crag Hill and 15 feet in the Kirkby Lonsdale area to the west of the Block. There are also indications of a southerly thinning but the evidence for this is not absolute. The thinning appears to be due to overlap against the uplifted ground known to have been developed in late P₂ times along the line of the Middle Craven Fault. To the south of the uplifted ground the Scale Haw Limestone was laid down concurrently; this limestone also thins against the uplift. The thinning is completely independent of the unconformable transgression at the base of the Grassington Grit as well as the postulated erosion surface at the base of the Little Limestone.

East of the exposed part of the Northumbrian Fault-Block the limestone shows no abrupt thinning but variations in thickness still occur.

The thinning of the limestone passing into the Northumbrian Trough has already been mentioned. In the southern part of the Trough the average thickness is around 40 feet, the range in thickness being 35 to 50 feet. These conditions appear to persist as far north as the River Wansbeck which forms the approximate southern boundary of an area in which the limestone expands in thickness due to the replacement by a "Tumbler Bed" lithology (alternating shales and limestone beds) of the lower part of the thick shale sequence which normally overlies the limestone. In the centre of this area, between the River Coquet and Howick, the limestone varies in thickness between 70 and 89 feet with an average of 85 feet. To the north and south of the latter area a similar situation exists but the total thickness of the limestone does not exceed 45 feet. In the isolated area north of Lowick the limestone is between 25 and 30 feet thick.

In the Canonbie district, which is situated towards the northern side of the Northumbrian Trough, the limestone has been proved in two boreholes to be 77 feet 9 inches and 73 feet 9 inches thick respectively; it is never well exposed, however.

Between Penrith and Appleby, in the Vale of Eden, the limestone normally varies between 35 feet and 70 feet thick but a thickness of 120 feet is attained locally; however, the average lies nearer to 35 or 40 feet thick. At the north end of the Lake District the average thickness is of the order of 65 feet whilst on the west side of the massif the average thickness falls to 45 feet, with a range between 27 and 67 feet.

At the northern end of the Isle of Man the limestone which is probably equivalent to the Great was proved in a borehole to be 43 feet thick.

Lithology

Over much of Northern England the limestone is divisible into two distinct components, the lower of massive limestone and the upper an alternating series of shales and limestones known as the Tumbler Beds. The relative proportions of the two components is variable and sometimes Tumbler Beds may be completely absent.

Massive Limestone.- The base of the limestone is frequently sharp but at a number of localities there is a gradation up from fossiliferous calcareous sandstone. The basal few feet are generally dolomitized and brownish in colour, but overall the massive component is blue-grey to pale grey in colour and fine grained. However, in north Northumberland the full thickness is often considerably dolomitized. The massive component was designated the Main Posts by Trotter and Hollingworth (1932) and it is usually divisible into a series of posts¹ of variable thickness which are often separated from one another by characteristic wavy bedding planes; individual posts appear to be persistent over a considerable area. Stylolites are very common and irregular streaks of crinoidal bituminous material are frequently seen. Chert nodules up to 1 foot long are present in bands between 6 and 17 feet above the limestone base on the Alston Block and are scattered throughout the limestone on the Askrigg Block. In the north-east part of the Askrigg Block the silica content of the limestone

1: Individual layers within the limestone separated by bedding planes. The term is also used to describe beds of sandstone.

is as high as 10 per cent whereas it rarely rises above 1 to 2 per cent around Stanhope on the Alston Block. In West Cumberland lenticles of laminated or calcareous sandstone occur in the body of the limestone.

The thickness of the massive limestone varies considerably and on the Alston Block ranges from 57 feet to 28 feet. To the south, on the Askrigg Block, the Tumbler Beds are poorly developed or absent and often there is over 80 feet of massive limestone. In the Northumbrian Trough the upper part of the massive limestone of the Block is replaced by Tumbler Beds and shale and consequently it is thinner, varying from 18 to 37 feet thick. However, in the Canonbie district practically the whole of the limestone is massive. At the northern end of the Lake District there is 25 feet of massive limestone whilst in West Cumberland the whole of the limestone is massive. Some 25 feet of the limestone developed at the northern end of the Isle of Man is also massive.

Tumbler Beds.- This component consists in general of an alternating series of limestones and shales, the two lithologies comprising variable proportions at different localities. Within the sequence, at limestone/shale interfaces, "cauda-galli" are frequently present.

The Tumbler Beds are prominently developed on the Alston Block where they attain a maximum thickness of 34 feet 6 inches; locally they are completely absent and consequently the full thickness of the limestone is massive. On the Block there is also a regional southward decrease in importance of the shale members of the Tumbler Beds as compared with the limestones. In the Cotherstone Syncline the Tumbler Beds are only locally developed, the maximum thickness recorded being 16 feet. On the Askrigg Block they are really only present in the north-east part and even then are only poorly and locally represented; however, a thick shale developed locally in the upper part of the limestone on the east side of Swarth Fell probably represents the lithology. East of the exposed part of the Northumbrian Fault-Block boreholes have shown that there is a variation similar to that in the exposed area. The Tumbler Beds of the Alston Block are almost certainly replaced by highly fossiliferous shale passing northward into the Northumbrian Trough. Therefore, the Tumblers of the southern part of the latter area must be at a lower horizon in the limestone. In the southern part of the Trough the beds vary between 20 and 30 feet thick but proceeding northward as far as the River Coquet they thin to 16 feet thick. North of the Coquet there is an expansion of the Tumbler Beds due

to the development of limestone bands in the shale above the normal limestone top. Consequently a thickness varying between 0 and 66 feet is attained, no Tumbler Beds being present in one section. In this region of thick development the shales and limestone of the Tumbler Beds tend to be sandy. Farther north at Beadnell the beds have thinned to 20 feet and in the Lowick district, in the extreme northern part of the Trough, they are not well developed at all. Towards the northern side of the Trough in the Canonbie district there are only a few calcareous mudstone bands in the limestone, whereas at the northern end of the Lake District there are 40 feet of Tumbler Beds developed. No such lithology has been recorded to the west of the Lake District but Tumbler Beds are probably present to the east. At the northern end of the Isle of Man there are 18 feet of Tumbler Beds developed, however.

Fauna

Three distinct biostromes have been recognized within the limestone, the Chaetetes Band at the base, the Brunton Band below the middle and the Frosterley Band above the middle. Bioherms consisting of crinoid ossicles also occur and there is a reasonably prolific fauna scattered throughout the limestone.

The Chaetetes Band.- This band, which lies close to the base of the limestone, is characterized by the tabulate coral Chaetetes depressus (Fleming) but it also contains other corals, bryozoans, annelids and brachiopods. Sometimes Chaetetes is absent and the band is then usually dominated by either Diphyphyllum lateseptatum M'Coy or Lonsdaleia laticlavia S. Smith. The band by no means forms a continuous horizon but it may have been more extensive originally since it shows some signs of having been affected by current activity. It attains a maximum thickness of 4 feet 6 inches but can be as thin as 1 inch thick where it is weakly developed. On the Northumbrian Fault-Block it has a widespread distribution even though it is represented by a modified lithostrotionid-clisiophyllid fauna in the southern part of the Askrigg Block. In the Northumbrian Trough it is known as far north as Beadnell and to the west it has been recognized in the Vale of Eden as well as in West Cumberland.

The Brunton Band.- This band differs from the other two biostromes in that it is composed of microfossils which are dominated by the algal genus Calcifolium bruntonense Johnson, the characteristic fossil of the

band; it also contains abundant foraminifera and other calcareous algae. Where the Frosterley Band is present this band essentially occurs below it and thus it occupies a position below the middle of the limestone. Because of its character it is difficult to delimit but it appears to have a maximum thickness of at least 19 feet. It is probably a more reliable and widespread horizon than the other two biostromes since it has been proved in most sections that it has been searched for in over the whole area between Morpeth in the north and Coverdale in the south.

The Frosterley Band.- This band lies near the middle of the limestone and is composed of a series of bands dominated by either Dibunophyllum bipartitum (M'Coy) or Gigantoproductus latissimus (J. Sowerby). Gigantoproductus is most common at the base, Dibunophyllum most common in the middle, whilst a more varied fauna is evident in the upper part. One of the bands near the middle which is almost entirely composed of a tightly packed mass of Dibunophyllum bipartitum is known and was formerly worked as the Frosterley Marble; this band is only of restricted extent in Wear-dale, however. The maximum thickness attained by the biostrome is 21 feet but it is frequently much thinner, mainly due to the upper members of it dying out. Laterally the biostrome is completely absent and sometimes there appears to be an indirect correlation between its absence and the marked thickening of the Tumbler Beds and accompanying thinning of the massive limestone. The variable position in the limestone of thin representatives of the band is due to them being developed at different horizons within the restricted range of the complete biostrome; often, however, the representative occurs in the position of the lower Gigantoproductus beds which do appear to be more persistent than the rest of the biostrome. Some lensing of individual bands can be seen but it is not often apparent although undoubtedly it does take place quite commonly. At occasional localities similar faunal bands to the above occur well below the normal base of the biostrome. The band has a more restricted distribution than the other biostromes since it appears to be virtually confined to the Northumbrian Fault-Block. It is best developed on the Alston Block, particularly in the quarries around Stanhope, but even then it is not invariably present and often is only poorly represented. Only a poor representative occurs in the eastern part of the Cotherstone Syncline and the north-west and north-east parts of the Askrigg Block.

However, in the central part of the Askrigg Block prominent Gigantoproductid beds up to 20 feet thick are developed and although they have a modified fauna when compared with the biostrome of the type area, they are probably equivalent to it. The band weakens in a northerly direction on the Alston Block and it is not definitely present at all in the Northumbrian Trough. However, it may be represented by a thin clisiophyllid band in the Dryburn Limestone of the Lowick district in north Northumberland. Where developed, often the band has obviously been affected by some current activity. Current activity is not considered to have caused the failure or poor development of the band over wide areas, however, but some local concentration of the fauna may be due to it. The regional distribution of the band is probably an original feature, perhaps related to environment, and currents were probably only of local significance.

Crinoid banks.- The banks are confined to the south-west part of the Askrigg Block, south of Swaledale, where they generally occur below the Gigantoproductus beds if the latter are present. Essentially they are composed of columns of crinoid ossicles up to 1 foot long. Around Hawes there appears to have been a continuous bed over an extensive area with an average thickness of 20 feet; north and west of this area discrete reefs were developed up to 10 feet thick. The restriction of these banks to the south-west part of the Askrigg Block may be of some environmental significance.

General Fauna.- The most prominent member of the fauna scattered throughout the limestone is Lonsdaleia laticlavia, the so-called index fossil of the Great Limestone. Many workers have collected faunas from the limestone and their works are listed in the detailed section of this chapter.

DETAILED STRATIGRAPHY

Thickness Variation

Overall, the limestone is the thickest in the Yoredales, but it shows considerable variation in thickness between the maximum of 130 feet recorded on Kisdon (Rowell and Scanlon, 1957a) and the minimum of 5 to 10 feet found on the south-east side of Coverdale (Wilson, 1957 and 1960).

On the Alston Block the limestone never attains these extremes, the maximum thickness recorded being 82 feet in Ashes Quarry, Stanhope.

Even this thickness is a very local one due to the development of an extra 6 feet lens of limestone in the shales which overlie the normal limestone top. Some 500 yards south-east in the same quarry the thickness has diminished to 67 feet and in a similar distance north-west a reduction to 78 feet has taken place. This serves to indicate how rapid the variations in thickness may be. Plate II shows the overall variation in thickness of the limestone on the Alston Block and in adjacent areas; it is based on approximately 260 separate points.

Within a large area centred upon Stanhope the limestone maintains a thickness of over 70 feet, reaching 82 feet, and has been extensively quarried for road-stone, lime-burning and steel-flux. The thickness decreases in all directions away from this but at three separate localities 70 feet is also exceeded. Except to the west of the South Tyne the limestone only decreases naturally below a thickness of 50 feet in one small area at the head of Westernhope Burn. Here, 40 feet of limestone occurs within a quarter of a mile of a more normal 70 feet. From north of St. John's Chapel a strip within which the limestone is consistently below 60 feet thick can be traced southward by way of Langdon Beck and Barras. Within its confines the limestone has been considerably reduced in thickness due to erosion by the major washout-channel which occurs in the overlying Coal Sills Group (see Chapter IV). North of St. John's Chapel very coarse sandstone can be seen to overlie limestone containing the Frosterley Band and thus the channel has cut to within approximately 40 feet of the limestone base. However, north of Langdon Beck it is considered that the channel base lies within 27 feet of the limestone base, but fanning of the limestone may have contributed to this low figure (see below). This erosion of the limestone has also been noted on Mickle Fell and in Borrowdale Beck, east of Brough. Where the washout channel can be traced northwards by sub-surface data it does not appear to have cut into the limestone. In Sunny Brow Mine Quarry, north-west of St. John's Chapel, the junction between coarse sandstone and limestone is irregular.

A further factor has also resulted in the limestone being very considerably reduced in thickness. To the south of Burnhope Seat, in the headwaters of Harwood Beck, the full 60 feet of limestone is, in places, represented by only a few feet of unctuous ochreous clay which may contain remnants of limonitized and partly altered limestone. This

phenomenon has been noted for a considerable distance along the outcrop at this locality and it has also been recognized elsewhere as follows:-

- (a) Silverband Mine and Dun Fell Hush on Great Dun Fell.
- (b) Horse Edge, two miles west-south-west of Alston.
- (c) The Pike Law hushes.
- (d) Probably the Old Langdon hushes.

The effect is known locally as "famping" and the clay produced is called famp. It would appear to be due to limestone which had been partially converted to ankeritic or sideritic ironstone during mineralization being subjected to oxidation and leaching under the influence of humic acids from the peat, with an accompanying reduction in thickness. In some places it is not certain that the phase of primary mineralization has preceded the leaching. Clough (1903) noted that the limestone was not as much famped further in from the outcrop, and the effect is confined to the zone of oxidation. The direct results are that the limestone is much reduced in thickness, the features disappear and small faults are initiated in the overlying beds. The minimum thickness of famp seen representing the limestone is 13 feet.

On the basis of the present evidence it would appear that the limestone's average thickness is of the order of 60 to 65 feet for the greater part of the Alston Block. West of the River South Tyne the thickness falls below 50 feet, or even 40 feet in places, a thickness more in line with that for the limestone in the Northumbrian Trough.

Reading (1954 and 1957) and Wells (1955a and 1957) have shown that rapid variation in thickness between 85 feet and less than 40 feet takes place in the Cotherstone Syncline, the variations being shown on Plate II. According to the London Lead Company's mine section, the limestone locally reaches a thickness of 102 feet in Lunehead Mine (Dunham, 1948, p.26). However, a recent extensive boring programme at this locality has not revealed such a thickness, the thickness recorded being 72 feet 6 inches. A thickness of 102 feet may be attained locally but it may also be that the thickness is inaccurate and due to faulting repeating some of the limestone in a composite section. The latter suggestion seems possible especially when it is realised that the 102 feet was recorded along Hunter's Vein which has a throw of 30 feet ($72 + 30 = 102$ feet). West

of the syncline in the area to the south-east of Brough Dr. A. J. Rowell (personal communication) has recorded 108 feet of Main Limestone in the River Belah and 90 feet in Mousegill Beck.

The Main Limestone has an average thickness of over 80 feet in the central part of the Askrigg Block, south of the Swale (Moore, 1955 and 1958; Wilson, 1957 and 1960), whereas its average thickness in the northern part of the Block is closely comparable with that for the Alston Block (Wells, 1955a and 1957; Dakyns et al, 1891). In the central region a maximum thickness of 130 feet has been recorded on Kisdon (Rowell and Scanlon, 1957a) and thicknesses in excess of 100 feet have been found at several other localities (Moore, op. cit.). However, on south-west Swarth Fell, Baugh Fell, Rise Hill, Crag Hill and the north end of Whernside, in the south-west part of the Block, the limestone rarely attains a thickness of over 20 feet and is as thin as 10 feet on Crag Hill (Dakyns et al, 1890; Miller and Turner, 1931; Hicks, 1958). The Main Limestone in the Kirkby Lonsdale area, just to the west of the Block, is 15 feet thick (Hicks, op. cit.). Wilson (op. cit.) has shown how in the south-east part of the Block in Coverdale, the limestone thins from 83 feet to between 5 and 10 feet within three miles in a south-east direction. This thinning of the limestone is completely independent of the unconformable transgression at the base of the Grassington Grit, though the latter does eventually cut out the limestone completely south-east of a line which runs in an approximate south-west to north-east direction from south of Fountains Fell, one mile north of Kettlewell, north of Great Whernside along the south-east side of Coverdale to south of Woodale and thence east-west across Masham Moor (Wilson, 1960, Fig. 7, p.303). The thinning also appears to be completely independent of the erosion surface postulated to occur at the base of the Little Limestone (Wells, 1955a and 1955b) since a thin development of chert and shale intervenes between the Main and Little Limestones at localities where the Main is very thin. Furthermore, Wilson (op. cit.) has shown that on the north flank of Penhill there is evidence for an easterly thinning of the posts of the Main Limestone independent of any supposed transgression at the base of the Little Limestone. These facts would appear to support the suggestion of Rowell and Scanlon (1957b) that the Main Limestone thins out against the north side of the uplifted ground

developed in late P₂ times along the line of the Middle Craven Fault (Hudson, 1933). To the south of the uplifted area the Scale Haw Limestone, tentatively correlated by Black (1950) with the Main, was laid down and it has also been noted to thin against the uplift. Farther west the 55 feet of Main Limestone recorded on Ingleborough does not altogether lend support to the above postulate since Ingleborough is situated much closer to the Craven Faults than the region where thinning takes place in Coverdale. The thickness of the limestone on Ingleborough is, however, considerably less than that recorded for the area only a short distance to the north and it does seem possible that there is a significant regional thinning southward. The very reduced thickness of the limestone in the Crag Hill area, and the Kirkby Lonsdale region could possibly be taken as support for a regional thinning towards uplifted ground developed along the line of Middle Craven Fault.

East of the exposed part of the Northumbrian Fault-Block the limestone has been penetrated in a number of deep boreholes which are listed below:-

<u>Borehole</u>	<u>Thickness of limestone (feet)</u>
Chopgate, Cleveland Hills	68
Elstob	44
Winston	35½
Roddymoor	61
Chopwell Woods, Lintzford	70½
Harton	68

The above thicknesses cannot be incorporated accurately in an isopachyte map but they serve to illustrate that there is no abrupt thinning of the limestone in an easterly direction; variations in thickness still occur, however.

As already mentioned, the limestone is as thin as 40 feet in the north-west part of the Alston Block (Trotter and Hollingworth, 1932) and may be even thinner in places (Short, 1954). A similar thinning takes place in a northerly direction passing into the Northumbrian Trough. In the Brampton district Trotter and Hollingworth (op. cit.) infer a thickness varying between 40 and 50 feet but 40 feet appears to be a normal thickness for the limestone in the southern part of the Trough. A

minimum of 35 feet has been recorded near Thorntree Shaft, Fallowfield Mine, and a maximum of 50 feet was penetrated in the Brokenheugh boring, near Haydon Bridge. Rapid thickness variation is again in evidence because in Fallowfield Mine a thickness of 45 feet has been recorded within half a mile of the 35 feet of limestone. It would appear that conditions similar to the above are maintained northward to the River Coquet which forms the approximate southern boundary of an area in which the limestone expands in thickness due to the replacement by a Tumbler Bed lithology of the lower part of the thick shale sequence which normally overlies the limestone in this region. A series of boreholes and occasional exposures between the River Coquet and Howick show that a basal 18 to 37 feet of massive limestone, with an average thickness of 32 feet, is usually overlain by shale containing thin limestone bands. By analogy with the sequence of the Alston Block these beds are Tumbler Beds and should be included as part of the Great Limestone, even though they are separated from the massive limestone at the base by shale which varies from 25 to 45 feet thick. Therefore, in this region the Great has a thickness varying between 70 and 89 feet with an average of 85 feet, as suggested by Westoll et al. (1955). Three miles north of Howick, between Embleton Bay and Beadnell, a comparable situation to the above is also present where 27 feet of massive limestone is overlain by shale with thin limestone bands giving a total thickness of 48 feet to the Great Limestone; no thick shale intervenes between the massive limestone and true Tumbler Beds here, however. Throughout the whole of this region, north of the Coquet, and even farther south, the Officers of the Geological Survey only mapped the basal massive limestone as the Great and occasionally the thin limestones of the Tumbler Beds were mapped as separate units (New Series 1" Sheet 9, Rothbury, 1934; New Series 1" Sheet 6, Alnwick, 1930). Perhaps the reason for this apparent anomaly lies in the difficulty of accurately delimiting the Tumbler Beds where they are separated from the massive limestone at the base by a thick shale, since Carruthers et al. (1930) were obviously well aware of the situation and recorded the shale with thin limestones as Tumbler Beds in their vertical sections. In the isolated area north of Lowick the Dryburn Limestone has a thickness of between 25 and 30 feet.

A limestone, 77 feet 9 inches thick, which was encountered in the

Catsbit borehole of the isolated Canonbie district (Peach and Horne, 1903; Barrett and Richey, 1945) is probably the representative of the Great Limestone. The above authors did not make this correlation, but Lumsden and Wilson (1961) consider that the same limestone penetrated in the Archerbeck borehole (drilled for the Geological Survey in 1954 to 1955) is equivalent to the Great of the Brampton District and the Top Hosie of the Midland Valley. The limestone in the borehole was 73 feet 9 inches thick and has been named the Catsbit Limestone because it was first recorded in the borehole of that name. No definite palaeontological evidence exists for the above correlation but Cummings (1961) concluded that the foraminifera in the upper part of the Catsbit Limestone and overlying beds are typical of those found in beds of E₁ age in Northern England. Also the beds between the Catsbit Limestone and the overlying Blae Pot Limestone have a striking lithological resemblance to those between the Little and Great Limestones of the Brampton area as will be shown later.

In the Vale of Eden, between Penrith and Appleby, Dakyns et al. (1897) record a maximum thickness of 120 feet for the Great Strickland Limestone but state that normally it varies from 70 feet to about 35 or 40 feet thick, the latter being taken as its average thickness. Miller and Turner (1931) confirm a thickness of 120 feet in the Shap district, that is to say, the area north-west and west of Appleby. At the north end of the Lake District the limestone varies little throughout the area having an average thickness of 65 feet (Summ. Prog. G.S.G.B., 1931). West of the Lake District the thickness of the First Limestone lies between 27 and 67 feet with an average of 45 feet (Eastwood, 1930; Eastwood et al., 1931).

Smith (1927) has tentatively suggested that a 25 feet limestone recorded in a borehole at the northern end of the Isle of Man is the representative of the First or Great Limestone. Some 2 to 3 feet of shale and limestone occurring 15 feet above, and separated from it by fossiliferous shale, should probably be included as part of the limestone, giving a total thickness of 43 feet.

Lithology

Over a large part of the area under consideration the limestone is conveniently divisible into two distinct components. The lower component



Fig. 8. Feature of the Great Limestone on High Hurth Edge, Teesdale. The actual feature is marked F.



Fig. 9. Posts and wavy bedding in the massive part of the Great Limestone, Rogerley Quarry, Weardale. The massive component of the limestone is overlain by the Tumbler Beds. The approximate scale is 1 inch to 20 feet.

consists of massive limestone which is made up of a number of posts; above this are the Tumbler Beds, an alternating series of shales and limestones in which the proportion of the two lithologies is very variable. The relative proportions of massive limestone and Tumbler Beds is variable and Tumbler Beds are completely absent in some areas.

Lithologically the limestone is more closely comparable with limestones of the Middle Limestone Group rather than those of the Upper Limestone Group of which it forms the basal member. Consequently, Trotter (1952) regarded it as the upper-most member of his Yoredale Limestone facies, the overlying beds being included in the Yoredale Grit facies.

Massive Limestone.- The base of the limestone is frequently sharp and may be underlain by a coal seam; for example, a 2 feet seam was exposed beneath the limestone west of Harrowbank Quarry in a temporary excavation which is now infilled. The 10 inch thick coal seam recorded by Smith (1912) as occurring in the middle of the Main Limestone at Cover Scars in Coverdale, south of Middleham, on the Askrigg Block, is in reality a seam below the limestone. The confusion probably arose because the measures between the Main and Undersett Limestones are very thin (about 11 feet) at Cover Scars, the Undersett being taken as a lower leaf of the Main Limestone. At a number of other localities limestone can be seen to grade up from a fossiliferous calcareous sandstone.

Usually the basal few feet of the limestone are dolomitized and have a brown colouration. Wells (1957) considered that in his area this was due to the percolation of magnesium-rich ground waters, probably during the time when it was overlain by the Permian Magnesian Limestone; percolation of such waters, not necessarily from the Magnesian Limestone, would appear to be a satisfactory explanation of this lithology, although the possibility of it being an original depositional feature cannot be ruled out. Above this the limestone is normally fine grained and blue-grey to pale grey in colour, but in north Northumberland the full thickness is often considerably dolomitized and if fresh has a distinct pinkish tinge.

The massive limestone, which was designated the Main Posts by Trotter and Hollingworth (1932), has a characteristic undulating or wavy bedding which divides it into a series of posts (Fig. 9). These may be as thin as a few inches or may be a few feet thick. Often they are separated

Table V

Posts of the Great Limestone in Newlandside Quarry, Stanhope.

Red Indian	4' 0"			
Plate Bed	1' 4"			
Very top post	1' 4"			
Plate Bed	1' 6"		Tumbler Beds	
Top Post	3' 10"			
Plate Bed	1' 2"			
Second Post	2' 2"			
Third Post	1' 4"			
Gray Post	3' 10"			
Second Gray Post	1' 2"			
Loggerhead	4' 8"	-	occasionally fossiliferous	Frosterley Band
Toby Giles	1' 6"	-	occasionally fossiliferous	
Crabby	6' 6"	-	fossiliferous	
Mucky Post	2' 2"	-	fossiliferous	
Pea Post	6"	-	fossiliferous	
Elsy	2' 2"	-	Frosterley Marble horizon	
Thin Cockle	7"	-	fossiliferous	
Thick Cockle	2' 7"	-	fossiliferous	
Three Toms	2' 1"			
Black Bed	2' 8"			
Five Thin Posts	2' 8"			
Dun Kit	4' 0"			
Bastard	4' 2"			
Dun Jin	2' 4"			
Stiff Dick	1' 3"			
Whaley	3' 6"			
Jack Post	6"			
Yard Post	2' 6"			
Newcastle	1' 9"		Chaetetes Band	
Bottom Post	2' 0"			

from each other by thin shale partings which may be partially stylolitic, stylolites being extremely common, although they are usually best displayed in borehole cores. In the area around Stanhope the quarrymen have given the individual posts separate names which are often highly descriptive. The names vary to some extent locally and Table V gives those for Newlandside Quarry. The individual posts are certainly remarkably persistent locally and can be traced throughout the Stanhope Quarries. However, Mr. R. A. Fairbairn (personal communication), who has measured numerous detailed sections in Weardale, the Allendales, Tynedale and around Alston, claims that it is possible to correlate the posts of these areas apart from Tynedale. The author's observations would lend support to the above in so far as it has been possible to recognize the combination of the lower four posts at a large number of widespread localities in Weardale and even in Ashgill Beck, a tributary of Harwood Beck at the head of Teesdale. It has also been reported (Summ. Prog. G.S.G.B., 1925) that individual posts of the First (= Great) Limestone are persistent for several miles around Broughton Craggs Quarry in West Cumberland.

Although the massive limestone is essentially blue-grey to pale grey in colour, it does contain darker streaks of bituminous material which are often crinoidal; the latter are best observed in borehole cores, however. The colour of the limestone appears to be due to finely divided carbonaceous matter since solution of the rock in hydrochloric acid leaves a black inert residue.

Over the major part of the Alston Block, especially in Weardale and Teesdale, bands of chert nodules have been recognized between 6 and 17 feet above the limestone base. The maximum number of bands at any one locality is three and the maximum size of the nodules is 1 foot long by 3 inches wide (Fig. 10). They are made up of a ground mass of intimately related cryptocrystalline silica and calcite which contains small patches of chalcedony and 25 to 30 per cent of euhedral "porphyroblasts" of zoned dolomite which range from 0.05 m.m. to 0.15 m.m. in size. It would appear that the nodules have arisen due to the segregation of their components from the enclosing limestone. Chert nodules are also scattered throughout the limestone on the Askrigg Block (Wells, 1955a, and 1957; Hicks, 1958). Wells (op. cit.) has shown that in the north-east part of the Askrigg Block the main bulk of the limestone has a silica content as high as 10 per cent even though the mineral is rarely seen in thin section. In the



Fig. 10. Chert-dolomite nodules in the Great Limestone, Rogerley Quarry, Weardale.

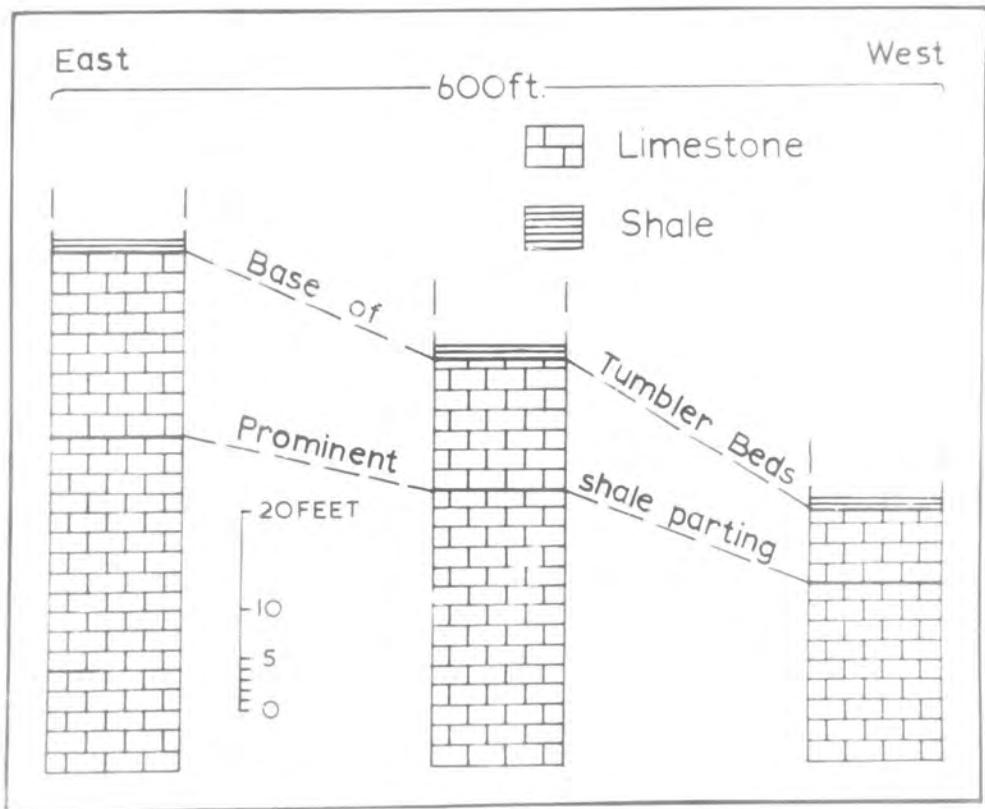


Fig. 11. Diagrammatic representation of the thinning of the massive part of the Great Limestone in South Washpool Crags Quarry, Bollihope.

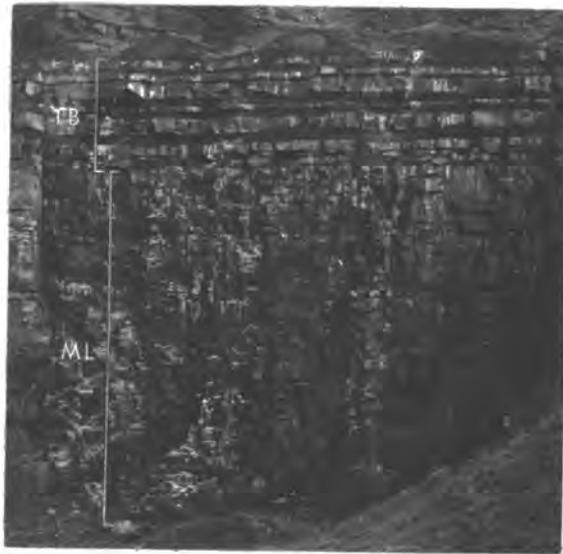
worked area around Stanhope the silica content rarely rises above 1 to 2 per cent and Dun Kit post is extremely pure.

In West Cumberland lenticles of interbedded laminated or calcareous sandstone up to 2 feet in length appear in the body of the limestone (Eastwood et al, 1931) in the vicinity of Egremont.

The thickness of the massive limestone varies considerably since in the Stanhope region it is usually around 55 feet thick, but in Harrowbank Quarry, north-east of Eastgate, where there is an extremely thick development of Tumbler Beds, a minimum of 28 feet is reached. For the Alston Block as a whole the thickness varies between 28 feet and 57 feet. In some areas, especially to the south, the Tumbler Beds are poorly developed or absent and consequently a greater thickness of massive limestone is present; for example, on the Askrigg Block, especially south of the Swale, there is over 80 feet of massive limestone. In the Northumbrian Trough the massive limestone varies between 18 and 37 feet in thickness whilst to the west in the Canonbie District, the full 73 feet 9 inches of the limestone in the Archerbeck borehole is essentially massive. However, at the northern end of the Lake District it is only 25 feet thick. West of the Lake District no Tumbler Beds are developed apparently, so that the full thickness of limestone is massive.

Tumbler Beds.- This component is made up of a series of alternating calcareous bituminous shales and dark muddy limestones. The name was derived in the mining field probably because these beds were liable to collapse into the workings driven in them. In the quarries around Stanhope the lithology is known locally by the quarrymen as "Famps".

The Tumbler Beds are prominently developed on the Alston Block and are best seen in the Stanhope quarries (Figs. 12a and 13, 1). Here, shale and limestone are sometimes in equal proportions but limestone usually dominates. Lateral passage of limestone into shale and vice versa often takes place but, despite this marked variation, the base of the Tumbler Beds is maintained at a constant horizon. However, this cannot be said for the top since an extra limestone, up to 6 feet thick, occurs locally in the shale above the normal limestone top. In the quarries the thickness of the Tumbler Beds varies between 13 feet and 32 feet within a quarter of a mile, whilst in Harrowbank Quarry a maximum thickness of 34 feet 6 inches is found, but only very locally,



(a)



(b)

Fig. 12. Comparative sections of the Great Limestone to illustrate the variable proportions of massive limestone and Tumbler Beds. The approximate scale of each photograph is 1 inch to 30 feet.

- (a) West Pasture South Quarry, Stanhope Burn, Weardale. The limestone is worked to its base.
- (b) Harrowbank Quarry, Weardale. 7 feet of limestone lies below the quarry floor.

since in the same quarry the Tumbler Beds thin considerably at the expense of the massive limestone. This rapid thickness variation of the Tumbler Beds is not due to the development of extra shales in the underlying massive limestone, since it can be shown that the posts of the limestone thin in the direction of increase in thickness of the Tumbler Beds, whilst the components of the latter thicken correspondingly. Apart from Harrowbank Quarry, this feature is also well exhibited in Rogerley Quarry, between Stanhope and Frosterley, where the Tumbler Beds thicken from 15 feet to 28 feet in less than a quarter of a mile, whilst the massive limestone below thins from 55 feet to 46 feet in the same direction. A similar but more marked thinning of the massive limestone posts can be seen two miles south-west of Stanhope in South Washpool Crags Quarry, Bollihope, but the overlying Tumbler Beds are mainly obscured (Fig. 11). Fig. 12a shows a normal section of the Tumbler Beds whilst Fig. 12b shows the expanded sequence of Harrowbank Quarry. In upper Weardale, although the Tumbler Beds can be recognized, they are dominantly limestone and locally shales may be completely absent. The lithology is well developed in the Alston Moor region and it is probably in this area that the name Tumbler Beds arose; a number of the underground records indicate a thickness rarely exceeding 15 feet for the Tumbler Beds. In Teesdale, around Middleton, Jones (1956) recorded thicknesses of up to 30 feet of Tumbler Beds but in these the maximum thickness of the shales is 1 foot and usually 6 inches or less, whereas in the Stanhope region the shales are generally over 1 foot thick with a maximum of over 3 feet. The Tumbler Beds lithology is poorly developed in upper Teesdale as in Weardale.

Reading (1954 and 1957) showed that the Tumbler Beds are only locally developed in the Cotherstone Syncline where they attain a maximum thickness of 16 feet. He considered them to be in part the lateral equivalent of the massive limestone; the present work confirms this and indicates that they are virtually the complete lateral equivalent of the upper part of the limestone.

On the Askrigg Block the Tumbler Beds are only found in the north-east part (Wells, 1955a and 1957) and even then they are poorly and locally developed. In the south-west part of the Block, on the east side of Swarth Fell, Rowell and Scanlon (1957a) record a shale with a

maximum thickness of 19 feet situated 5 feet below the limestone top. It may be that this shale completely replaces the upper part of the limestone in the Crag Hill region and thus accounts for the marked thinning of it already noted. This may not be the full explanation of the thinning since the shale is known to die out to the south as well as the north. However, the area where the limestone is thin lies on the west side of Swarth Fell and to the south-west of that.

East of the exposed part of the Northumbrian Fault-Block two shales were recorded in the upper 30 feet of the limestone in the Harton borehole, and the upper 7 feet in the Winston and Mount Pleasant boreholes were of Tumbler Bed lithology.

In the northern part of the Alston Block a shale, sometimes with thin argillaceous limestones and up to 20 feet thick (the Black Bed, Fig. 13, 2 and 3), occurs in the upper part of the limestone. It seems highly probable that this shale eventually replaces the upper part of the limestone completely and results in the thinning which is known to take place into the Trough (Fig. 13). This seems even more probable when the highly fossiliferous nature of the shale with limy bands which is sometimes found above the limestone in the Trough is compared with the relatively barren shale in a similar position on the Block. The Tumbler Beds of the Trough must therefore be developed at a lower horizon in the limestone if the above suggestion is correct. Trotter and Hollingworth (1932) have shown that they vary in thickness between 20 and 30 feet in the Brampton District. They thin eastward to be 20 feet thick at Brunton Bank Quarry (Fig. 13, 4), north-east of Fallowfield. At Greenleighton Quarry, to the north, they are 16 feet thick and limestone is dominant, whereas two miles to the south of Greenleighton, in Delf Burn, 15 feet of fossiliferous shale occurs within the Tumbler Beds (Fowler, 1936); two miles north-east a similar situation is present in a quarry 300 yards south of Ritton White House where the Tumbler Bed limestone is replaced by fossiliferous sandstone. The development of the Tumbler Beds north of the River Coquet has already been mentioned. The actual alternating limestone-shale sequence is separated from the massive limestone by a shale which varies in thickness from 25 to 45 feet; this shale is included in the Tumbler Beds which thus have a thickness varying between 0 and 66 feet, no Tumbler

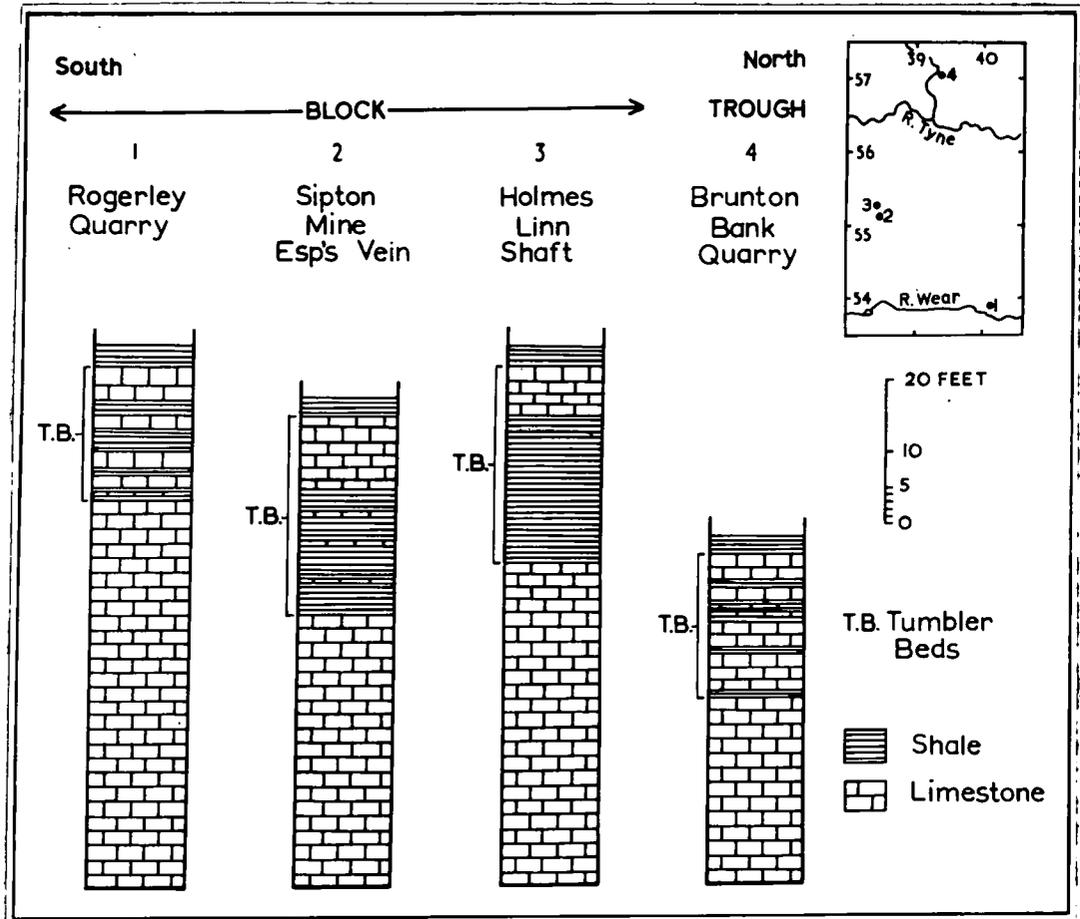


Fig. 13. Sections to illustrate the northward changes in the upper part of the Great Limestone in the northern part of the Alston Block and the southern part of the Northumbrian Trough.

Beds being present in one section. Both the shales and limestones of the sequence show a tendency to be sandy and apparently the upper part is locally replaced by sandstone and sandy shale. Between Embleton Bay and Beadnell the Tumbler Beds are 20 feet thick. Farther north in the Lowick area the lithology is not significantly developed.

In the Canonbie district on the north side of the Northumbrian Trough, bands of dark grey calcareous mudstone occur in the Catsbit Limestone (Lumsden and Wilson, 1961) but their horizon is not specified. Thin limestone bands are also present for 20 feet 6 inches in the overlying shale which also contains sandy bands and ironstone nodules and bands.

At the northern end of the Lake District the Survey (Summ. Prog. G.S.G.B., 1931) record 40 feet of the Great Limestone as Tumbler Beds. This lithology has not been recorded to the east or west of the Lake District but 18 feet of the limestone identified as the Great in the borehole at the north end of the Isle of Man may be classed as Tumbler Beds although it is a predominantly shaly sequence.

In the well exposed area around Stanhope the presence of well developed "cauda-galli" markings in the Tumbler Beds is obvious. The markings are common throughout rocks of Carboniferous age but their origin has always been problematical. It has been suggested that they were formed by the remains of marine vegetation but their apparent lack of internal structure does not support this. Similarly, neither is there much evidence for an organic origin for them. A sedimentary origin, perhaps emphasized by weathering, appears to be more in keeping as an explanation of the present observations since the markings usually occur in the limestones at limestone-shale interfaces.

Fauna

The most obvious components of the fauna are the biostromes which have already been mentioned. Two of these, the Chaetetes Band at the base and the Frosterley Band in the middle, are composed of macro-fossils whilst the third, the Brunton Band, which occurs between the two, contains abundant remains of the new algal genus, Calcifolium bruntonense Johnson. In the southern part of the Askrigg Block prominent crinoid banks which may be classed as bioherms have been recognized (Moore, 1955 and 1958; Hicks, 1958 and 1959). As well as the above there is quite an abundant fauna

scattered throughout the limestone.

The Chaetetes Band.- The type locality of the band is Brunton Bank Quarry, Northumberland, and from here it was originally described by Johnson (1958). In this quarry it attains a thickness of 4 feet 6 inches and is at its maximum development.

The band is characterized by the tabulate coral Chaetetes depressus (Fleming) which occurs in approximately 1 inch thick slightly undulating sheets which are piled one on top of the other. In places a sheet may occur wrapped around solitary corals. Diphyphyllum lateseptatum M'Coy is also a common constituent of the band and it occurs in lenticular colonies interbedded with Chaetetes. Lonsdaleia laticlavata S. Smith is also common and sometimes it appears that colonies of it have been eroded; this coral is not as abundant as the other two members of the fauna already mentioned but often it occurs at the horizon of the band where both of the other members are absent. Syringopora geniculata (Phillips) is also associated with Chaetetes at some localities. The above four corals are the dominant members of the fauna of this biostrome but there are also bryozoans, annelids, brachiopods, and other corals associated (Johnson, op. cit.).

In Northumberland the band lies 3 feet above the base of the limestone and is overlain by a richly fossiliferous dark shale parting. However, on the Alston Block it is sometimes developed to within 6 inches of the limestone base and may even occur at the base in Elmford Cleugh, one third of a mile east of Wearhead. On an average the band lies 1 foot above the base of the limestone on the Block; no prominent shale is developed above it but the dolomitic matrix to the band noted by Johnson (op. cit.) is almost invariably present.

The farthest point north that the band is known is Beadnell where, in the natural break-water of Beadnell Harbour formed by the Great Limestone, a band of Lonsdaleia and other compound corals was recorded 3 feet from the limestone base by Carruthers et al. (1927). A similar band is to be found on Muckle Carr, off Craster, north of Howick. Johnson (op. cit.) also records that the band is known in the Alnwick District but then there is a gap southwards to the Brunton Bank locality. Close to Brunton Bank Quarry Diphyphyllum has been recorded by the author from the base of the limestone in a borehole at Fallowfield Mine. These are the only known



Fig. 14. The Chaetetes Band, Chesterarth Quarry, Rookhope, Weardale.



Fig. 15. An up-turned Chaetetes colony, South Washpool Craggs Quarry, Bollihope.

occurrences of the biostrome in the Trough, but there sparsity is probably due to poor exposure rather than non-development of the band.

The band is known at 35 separate and widespread localities on the Alston Block, 30 of these being new ones discovered by the author. It is seen where the limestone emerges from the bed of the Wear at Frosterley in the east and to the west it occurs on Great Dun Fell underground in Silverband Mine and south of Cross Fell in Crowdundle Beck. At several localities the basal part of the limestone can be seen clearly but no representative of the band is present. Occasionally there may be a concentration of crinoid debris or shells at this horizon when the band is absent; for example, a lens of beautifully preserved Eomarginifera sp. was found east of Harrowbank quarry. Near Dirt Pot, north of Allenheads, a maximum thickness of 4 feet 4 inches is attained but here the band is very poor in Chaetetes and contains over 3 feet of unfossiliferous limestone. However, 4 feet of limestone, packed with Chaetetes and Diphyphyllum is to be seen in Elmford Cleugh and also in Ayle Burn Quarry, one mile east-north-east of Ayle. The band is liable to die out or become much reduced laterally and this is well exemplified in the area around Rookhope. In Chestergarth Quarry, which is now a scheduled site of special scientific interest preserved by the Nature Conservancy, an excellent development of the Chaetetes Band with Diphyphyllum (Fig. 14) attains a thickness of 3 feet. This band is represented by one wisp of Chaetetes, an inch thick, in the Rookhope Borehole which was drilled a little over half a mile to the north-west. On the Alston Block there is some indication that current activity affected the band in the presence of eroded Lonsdaleia colonies; also the lenticularity may be due to currents destroying a formation which was once more continuous. In South Washpool Craggs Quarry, Bollihope, an up-turned small colony of Chaetetes (Fig. 15) occurs 10 feet above the limestone base. Although its position may have been due to current activity it is probably un-related to the main Chaetetes Band, however, since supposedly continuous posts of limestone occur between the two horizons.

The biostrome has only been recorded in the southern part of the Cotherstone Syncline, a poor representative being found in the Barnard Castle neighbourhood where the dolomitic matrix also persists (Johnson, op. cit.). In the north-east part of the Askrigg Block Wells (1955a and

1957) discovered two localities of the band in close proximity to each other in Whitcliffe Scar approximately three miles west of Richmond; one of these contained Chaetetes and the other Lonsdaleia. Lonsdaleia was also recorded from the limestone base on the north side of Eel Hill, three miles south-west of Barningham. On the west side of the Askrigg Block, Turner (1962) has shown that the Chaetetes Band is extensively developed in the upper part of the Vale of Eden and also in upper Wensleydale, 23 localities being recorded in all. As on the Alston Block there are places where the lowest part of the limestone is clearly seen but is unfossiliferous. Associated with the Chaetetes in this area are Palaeosmilia regia (Phillips) and Lonsdaleia floriformis. The band also occurs on the Buttertubs, two miles south-west of Thwaite. This northern part of the Askrigg Block in which the Chaetetes Band is found flanks an area to the south in which Moore (1955 and 1958) has recognized a widespread band with a dominant lithostrotionid and clisiophyllid fauna near the base of the limestone. This is certainly the coral band which Hudson (1924) recorded in Wensleydale. Moore has shown that this band is best developed to the south of the River Ure where it has an average thickness of 4 feet and a maximum thickness of 5 feet. Northwards it dies out between Wensleydale and Swaledale, only being poorly represented on the south side of the River Swale. The southern boundary has not been delimited but Hicks (1958) did not record it in the south-west part of the Block and Wilson (1960) remarks upon the paucity of fossils in the limestone in the south-east part of the Block. The band is dominantly composed of Diphyphyllum fasciculatum (Fleming) but rolled clisiophyllids may also be present and in the north-west part of the area of occurrence the latter are the major constituents of the band. Lonsdaleia is quite common whilst Clisiophyllum and Aulophyllum are always subsidiary. In the north-western part of the area mentioned above there is virtually an overlap with the true Chaetetes Band at the Buttertubs and there seems no doubt that this modified fauna represents the same basal biostrome of the limestone. The change in fauna may be indicative of some environmental variation.

To the west of the Block the Chaetetes Band has been found in the Great Strickland Limestone at King's Meaburn, near Appleby (Johnson, 1958), and it may be present in the River Leith below Waterfalls Bridge,

north of Great Strickland, where Miller and Turner (1931) recorded Alveolites as being common.

In West Cumberland, west of Cockermouth, a band of Diphyphyllum c.f. gracile M'Coy was recorded as being of general occurrence (Eastwood, 1930) in a brown-weathering limestone about 3 feet above the limestone base; this is probably the representative of the Chaetetes Band in West Cumberland.

The Brunton Band.- The type locality for this band is at Brunton Bank Quarry from where it was also originally described by Johnson (1958). No original work has been carried out on it by the author since it is not possible to recognize it in the field.

It is characterized by the algal genus Calcifolium bruntonense Johnson and contains abundant foraminifera and other calcareous algae. Macro-fossils are virtually absent but occasional brachiopods are sometimes associated.

At its type locality it lies 18 feet above the limestone base and is approximately 12 feet thick. In Middle Tongue Beck on Great Dun Fell it expands to 19 feet thick.

The band invariably appears to occur directly below the Frosterley Band where the latter is present, although occasional fragments of Calcifolium have been found above.

The biostrome has a widespread distribution having been recognized as far north as the Morpeth district and in Coverdale to the south, with discoveries over the whole area in between. Further information regarding this biostrome may be found in Johnson (op. cit.).

The Frosterley Band.- The type locality of this band is Harehope Quarry, Frosterley, where it was formerly worked for the well-known ornamental stone named Frosterley Marble. The quarry, owned by Mr. J. Emerson, is now only worked for limestone which is burnt to produce high quality lime. The Marble was first mentioned in the literature by Winch (1817) and subsequently by Hind (1902). Dunham (1948) inferred that it may be a widespread horizon and this was substantiated by Johnson (1958) who showed that the band as a whole was of quite widespread occurrence.

The actual Frosterley Marble component is formed of a tightly packed mass of Dibunophyllum bipartitum (M'Coy) with subsidiary Koninckophyllum,



Fig. 16a. The Frosterley Marble Band, Harehope Quarry, Weardale.



Fig. 16b. Close-up of the above Frosterley Marble Band.

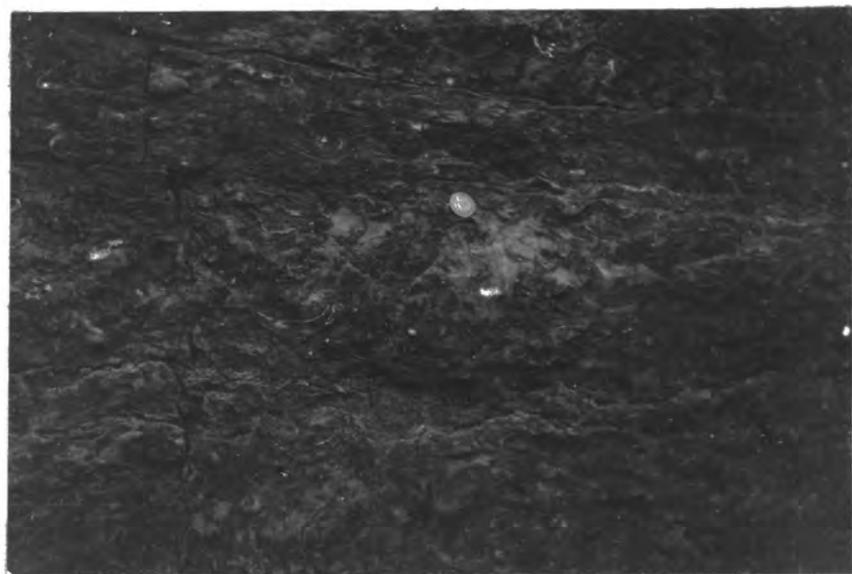
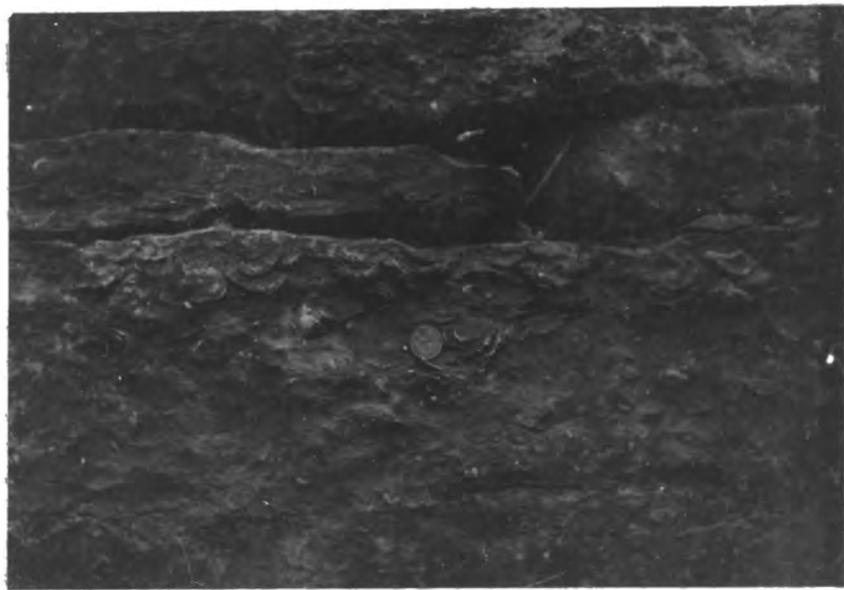


Fig. 17. Gigantoproductus bands in the Frosterley Band, Ashes East Quarry, Weardale.

Aulophyllum and Caninia (Fig. 16); it is thus composed of simple rugose corals. However, the band which was generally extracted for marble, the Elsy post, is only one of a number of bands which as a whole form the biostrome. Gigantoproductus latissimus (J. Sowerby) is often a prominent constituent of these other bands and may occur intermixed with the simple rugose corals along with Lonsdaleia laticlavia, Diphyphyllum lateseptatum, the occasional Gigantoproductus giganteus (J. Sowerby) and numerous smaller brachiopods such as Dielasma. Gigantoproductus also forms bands in which it is virtually the only constituent (Fig. 17). Chaetetes sp. has been found to be remarkably common upon close examination of the bands and it occurs in small colonies some of which appear to have been eroded. The section at Harehope Quarry gives some idea of the composite nature of the band and is as follows:-

Crinoidal limestone	
Limestone with <u>Dibunophyllum</u> and a <u>Lonsdaleia</u> colony	7"
Limestone	1' 0"
Limestone with occasional <u>Dibunophyllum</u>	3"
Limestone with <u>Lonsdaleia</u> colonies (eroded and one ?overturned), <u>Gigantoproductus</u> and occasional <u>Dibunophyllum</u> - not rich	2' 1"
Limestone with <u>Dibunophyllum</u> , a <u>Diphyphyllum</u> colony, small <u>Lonsdaleia</u> colonies and some <u>Gigantoproductus</u>	2' 2"
Limestone with rare corals	2' 0"
Limestone with <u>Dibunophyllum</u>	5"
Limestone	1' 3"
Limestone with abundant <u>Dibunophyllum</u> (Frosterley Marble)	1' 8"
Limestone with occasional corals and productids	1' 0"
Limestone with <u>Dibunophyllum</u> , <u>Gigantoproductus</u> and <u>Diphyphyllum</u>	1' 0"
Limestone	5"
Limestone with <u>Dibunophyllum</u> and <u>Gigantoproductus</u>	4"
Limestone	3"
Limestone with <u>Gigantoproductus</u>	2"
Limestone with occasional corals and brachiopods	1' 8"
Limestone with <u>Gigantoproductus</u> and <u>Dibunophyllum</u>	4"
Crinoidal limestone	

Elsewhere, the individual fossiliferous bands may be separated by greater thicknesses of unfossiliferous limestone; also, the bands may split and consequently thin, or join together to form a single thicker band. Three points emerge from the section in Harehope Quarry as follows:-

- (i) Gigantoproductus is most common at the base of the biostrome; this explains the derivation of the name of the Cockle posts which contain this fauna (Table V).
- (ii) Dibunophyllum is dominant in the centre and it was from here that the Frosterley Marble was extracted, Elsy post being the most important.
- (iii) A more varied fauna is developed in the upper part but often simple rugose corals are dominant. This is in the Mucky and Crabby posts. The Pea post of Newlandside is only a local development and was probably so named because it contains a colony of Diphyphyllum.

The biostrome attains its maximum development on the Alston Block and is best developed in the Weardale Quarries, particularly those around Stanhope and Frosterley, where the base of it occurs between 25 and 33 feet above the limestone base and its thickness varies from nil to 21 feet with an average of 13 to 14 feet. The variable position of the base is probably mainly due to the variable thickness of the limestone since it seems likely that the lower Gigantoproductus beds are of a persistent horizon (the Cockle posts) and constantly developed except where the whole band is absent. The variable thickness is obviously due to the variable dying out of the upper components because where the biostrome is very thin it can usually be recognized as part of the Gigantoproductus beds and its position in the limestone bears this out. Also there is an obvious correlation between thickening of the overlying Tumbler Beds and complete absence of the biostrome although the two have no direct contact (Table V). This is well illustrated in Harrowbank Quarry where the Tumbler Beds are excessively thick and there is no trace of any fossil bands. In South Washpool Crags Quarry the fauna dies out as the limestone posts thin; also, a similar phenomenon is seen in Ashes Quarry, Stanhope.

The Frosterley Marble component is not widely developed and is only to be found extensively around Stanhope and Frosterley in Harehope, Broadwood and the Parson Byers Quarries. Elsewhere, at other horizons, individual bands occur in which there is a concentration of simple rugose corals but the corals are never so abundant as in the Frosterley Marble and often there is an admixture with the rest of the fauna.

The biostrome is also well developed in Weardale on the north side of the valley as far west as Wearhead but nowhere is it as strong as in the Stanhope-Frosterley region. However, the basal Gigantoproductus beds are usually apparent. A 2 feet thick richly coralline band in Greenfield Quarry, north of Wearhead, completely dies out within 6 feet along the quarry face; the band is probably the representative of the Frosterley Marble. This locality is the only one where such an abrupt thinning of a band is seen, although the lensing out of individual bands is probably quite common but it is not usually conspicuous.

In Teesdale the biostrome is well represented in the area north of Middleton where Jones (1956) recognized that it was made up of a number of individual bands. It is not as strongly developed as in the Stanhope Quarries, however.

Over the remainder of the southern part of the Alston Block the biostrome can frequently be recognized, although it is often composed of a single band no more than 2 feet thick and sometimes only a few inches. It may attain the average thickness reached in the Stanhope Quarries but its components are then usually only weakly developed. It has been found to be completely absent at some localities. Where it is a single band the position in the limestone is variable from locality to locality, but in a number of cases it occurs in the position of the Gigantoproductus beds and contains the typical fauna of these, often with G.giganteus. Elsewhere, the band lies within the range of position that the biostrome occupies in the Stanhope Quarries. No doubt this is due to the bands being individual lenses developed at different horizons within the restricted range of the complete biostrome. The lenticular nature is not apparent except in Greenfield Quarry and the individual lenses must be of considerable extent.

North of a line across the Alston Block, running east-west along the water-shed between Weardale and the Allendales, the Frosterley Band is

weakly represented whereas south of the line the band is strongly developed in the Rookhope neighbourhood and around Wearhead. Around Allenheads and in the Swinhope boreholes (Dunham and Johnson, 1962) it is only poorly and sporadically represented. In Thorn Green Quarry, one mile north-west of Allenheads, a band with Gigantoproductus is present. The band has not been recognized in West Allendale nor in the vicinity of Blagill, but a thin Gigantoproductus band is present in Ayle Burn Quarry where G.giganteus is quite common. No trace of the band was reported by Short (1954) for the north-west part of the Block although Trotter and Hollingworth (1932) record abundant Dibunophyllum from Croglin Water.

Below the base of the biostrome on the Alston Block, especially in Weardale, thin lenses with a similar fauna have been recognized as low as 10 feet above the limestone base, but they are usually only a few inches thick and markedly lenticular. However, in Teesdale on West Binks Edge, one mile south-west of Pike Law, poor coral-brachiopod bands occur through 16 feet of strata, starting only 11 feet above the limestone base.

The biostrome occurs in the north-east part of the Cotherstone Syncline but dies out west of Grassholme Reservoir (Reading, 1954 and 1957). Wells (1955 and 1957) has recorded it in the extreme north-east part of the Askrigg Block where it occurs in the River Greta, Sleightholme Beck and Eller Beck. At none of these localities is it prominent but further south Moore (1955, 1958) has recorded his Gigantoproductid beds in the central part of the Block at a similar position in the limestone. These beds are best developed north of Hawes where they attain a thickness of nearly 20 feet. Usually the series of beds is composed of various forms of Gigantoproductus with subsidiary corals, the most important of which are Chaetetes radians (Fischer de Waldheim), Lonsdaleia sp., Dibunophyllum bipartitum, Aullophyllum fungites (Fleming) and Syringopora sp. These forms are similar to those in the Frosterley Band of the type locality and in the northern part of the area considered by Moore, near Muker, corals become the dominant component of the fauna. In all directions away from Hawes the band is reduced in thickness. It is unknown in the south-east part of the Block and was not recorded on the west side by either Hicks (1958) or Rowell and Scanlon (1957a).

However, what is probably a thin representative has been found in the upper Eden valley south of Kirkby Stephen (Johnson, 1958) by Mr. J. S. Turner.

The dying out of the biostrome in a northerly direction on the Alston Block has already been noted and Johnson (1958) reports that it has not been recognized north of the Stublick Faults. However, scattered simple corals do occur at approximately the correct horizon in the Brunton Bank area of the Northumbrian Trough and occasional productids have been noted in Greenleighton quarry at a similar horizon. In the Lowick district of north Northumberland, near Dryburn, Carruthers et al. (1927) recorded a 1 foot band with clisiophyllids which occurs 6 feet below the top of the 25 feet thick Dryburn limestone; this may be the representative of the Frosterley Band.

The Frosterley Band has not been recorded in any other regions but the above. Thus, it is virtually confined to the Northumbrian Fault-Block and, therefore, it has a more restricted distribution than the other two biostromes.

Where it is represented the biostrome has undoubtedly been affected by some current activity since the simple corals are frequently devoid of their epithecal walls and have sometimes been fragmented, both of the latter being reasonable indices of movement by currents. However, in other cases the epithecal walls are completely intact in a whole band. Almost invariably the corals occur in a horizontal position, but this feature could be explained satisfactorily by collapse of the individuals after death rather than by current action. Some of the Lonsdaleia colonies have been eroded and one in Harehope quarry appears to be overturned (Fig. 18). Relatively few of the productids are overturned, most of them occurring with their concave side upwards in the position of growth (Fig. 17). However, at a number of localities, a local preferred orientation of the shells is apparent; presumably this orientation is due to current movements which were not strong enough to overturn the shells from their position of growth into a so-called stable position, but were of sufficient strength to shift individuals about in a horizontal plane. Further work upon the orientation may prove useful and allow an elucidation of current directions, their persistence and strength. Thus, it seems likely that there was some current activity



Fig. 18a. A Diphyphyllum colony with an over-turned Lonsdaleia colony above it in the upper part of the Frosterley Band, Harehope Quarry, Weardale.



Fig. 18b. Close-up of the above over-turned Lonsdaleia colony.

but in the author's opinion it was only of local significance and not adequate to cause the failure or poor development of the band over wide areas. The regional distribution of the concentrated coral-brachiopod fauna is believed to be an original feature, probably related in some way to other environmental conditions. However, some concentration of the fauna may be due to current activity piling up the fossils locally.

Crinoid Banks.- In the south-west part of the Askrigg Block, south of Wensleydale, crinoid banks have been recognized by Moore (1955 and 1958) and Hicks (1958 and 1959) in their nearly adjacent areas. Where the Gigantoproductus beds are present the banks usually occur below them but they are sometimes interbedded. When the productid beds are absent the banks may extend higher up in the limestone, as, for example, at Greensett Craggs, Whernside. They are composed of articulated columns of crinoid ossicles up to 1 foot in length and contain virtually no supporting fauna.

A little to the north, but mainly to the south of Hawes there appears to have been a continuous bed over an extensive area, averaging 20 feet thick with a maximum of 28 feet 6 inches (Moore, op. cit.). North and west of this area, discrete reefs were developed which are usually about ten feet thick. The limestone of Ingleborough is highly crinoidal and was probably formed as a flanking deposit to one of the reefs. Extensive reefs are not known north of Swaledale, although Reading (1954) records 10 feet of very crystalline limestone containing masses of crinoid ossicles of all sizes near the top of the Main Limestone on the south limb of the Cotherstone Syncline, west of Aygill Cottages. The limestone penetrated in boreholes near Rowton Sike, south of Lunehead, is also very crinoidal. In other areas the limestone contains much crinoid debris but nothing comparable with the crinoid banks is developed.

The banks are best described as bioherms since they are not of any great lateral extent usually and are generally of lens-like form. Their restriction to the south-west part of the Askrigg Block may be of some environmental significance.

General Fauna.- Distributed throughout the limestone there is a fairly prolific fauna apart from that contained in the biostromes. Faunal lists for the limestone have been given by the following authors:-

Phillips (1836), Lebour (1875), Dakyns et al. (1891), Hind (1902), Hughes (1908), Smith (1910), Garwood and Goodyear (1924), Lee (1924), Turner (1927), Trotter and Hollingworth (1927 and 1932), Eastwood (1930), Eastwood et al. (1931), Miller and Turner (1931), Hill (1938), Dunham (1948), Reading (1954), Short (1954), Wells (1955a), Jones (1956), Rowell and Scanlon (1957a), Johnson (1958 and 1959), Moore (1958), Wilson (1960), Hicks (1958), Ferguson (1961).

A prominent member of the fauna distributed throughout the massive limestone is Lonsdaleia laticlavia, the so-called index fossil of the Great Limestone. It occurs in small colonies of up to 1 foot diameter which often appear to have been eroded to some extent. Dibunophyllum bipartitum and other simple rugose corals are also common. Of the compound corals Syringopora is the most common but Chaetetes is also present as well as Diphyphyllum. Lithostrotion junceum has not been found in the Great Limestone by the author or other recent workers although it was reported by Trotter (1952) as being present. Much crinoid debris and fragmentary shell material occurs in the limestone.

The Tumbler Beds shales often contain a prolific fauna which has been recorded by Ferguson (op. cit.). Of particular interest in this are the problematic Palaeocoryne and related new genus Claviradix. The fossils are often in close association with the bryozoan Fenestella, to which they bear some similarity, but they are separate organisms whose exact affinities are unknown. The author has collected some of these fossils but the material has been presented to Mr. Ferguson. Within the shales the mucronate trilobite Weberides mucronatus (Martin) is quite commonly found. The Tumbler Bed limestones are locally very fossiliferous and contain numerous small and occasionally larger brachiopods. In Middlehope Burn, north of Westgate, numerous Dibunophyllum occur in limestone which is interpolated as being close to the Great Limestone top and consequently within the Tumbler Beds. Exposure is very poor in the area and it is impossible to determine the exact position, however. A similar occurrence of corals at the top of the limestone in Eggleston Burn, Teesdale, was noted by Jones (1956). In the Stanhope quarries Chaetetes has been found within the Tumbler Beds.

where it forms bulges on the surface of the limestone posts; these project into the overlying or underlying shales.

CHAPTER IV

THE COAL SILLS GROUP AND ITS LATERAL EQUIVALENTS

GENERAL

The strata to be considered here are the essentially non-calcareous measures of the cyclothem which succeed the limestone and for the main part consist of shales and sandstones with subsidiary coals and thin marine bands. A large area where chert was formed also exists in the north-east part of the Askrigg Block, however.

The area of Northern England can be conveniently sub-divided for the purpose of describing these beds. This does not infer in any way that there were separate areas of deposition during their formation, except the well known division between the Fault-Block and the Bowland Trough. The following divisions of the area are proposed:-

- The Alston Block
- The Askrigg Block and Cotherstone (Stainmore) Syncline
- The Northumbrian Trough
- The Canonbie District
- The East and North rim of the Lake District
- The West rim of the Lake District
- The Kirkby Lonsdale Area
- The Isle of Man
- The Craven District
- The Furness District

The Alston Block will be dealt with more fully than the rest since this is the area which the author has resurveyed in detail. Information for the other regions has been mainly collected from theses and published papers but some field observations have been made by the author also.

The value of the Great Limestone and its equivalents during the examination of this group of beds cannot be over emphasized since the limestone forms an excellent datum line for mapping purposes and, probably more important, its exact top can frequently be seen in sections to be measured. The prominent topographic feature of the limestone has already

been mentioned. This may be compared with the hap-hazard features which are usually formed in the ground on the Fault-Block occupied by the beds to be considered here. There is, however, an exception to this general rule, because where the uppermost sandstone of the cyclothem (the White Hazle of the Alston Block) is well represented, it combines with the overlying Upper Little Limestone to form a prominent combined feature. The thick sandstone of the Northumbrian Trough sequence also forms prominent scarps.

THE ALSTON BLOCK

Introduction

Correlation of individual beds over an extensive area within the Yoredale facies, apart from the prominent limestones, is often difficult. At first sight the Coal Sills Group strata of this region appear to be no exception, but once the detailed stratigraphy is examined the sheet sandstones which comprise the Low and High Coal Sills appear not to be so lenticular as might seem apparent. The High Coal Sill coal also appears to be a widespread horizon and has proved useful for correlation purposes; it is not usually well exposed but because of its usefulness in correlation a large amount of digging has been done to locate it. The other coals of the group are also badly exposed and at many localities they have had to be excavated. The fossils found are useless for correlation purposes in such a small vertical range of strata since they usually belong to facies faunas. Consequently, the lithological variations in a large number of vertical sections have been employed as an aid to correlation. Although dangers exist in using this method it is the only means available.

The typical Coal Sills Group succession is found in this area, the type locality being in Alston Moor. The original succession set down by Westgarth Forster (1809) is shown in Fig. 3 whilst the modifications put forward by other workers have been dealt with in Chapter I. Original work by the author on the basis outlined above indicates that, in general, the typical succession extends over a much wider region than Alston Moor. A number of elaborations and variations have come to light but usually they can be satisfactorily related to the modified standard succession of

Forster (op. cit.). An elaborated but generalized section for the area in which a succession closely related to the type sequence can be recognized is given in Fig. 19. In general, this area lies to the north of a line drawn east-west along the Tees-Wear watershed to the east of the longitude of Alston, but in addition it embraces the Cross Fell range, Rotherhope Fell and the ground to the west of the Burtreeford Disturbance in upper Teesdale which lies north of Harwood Beck. An even more widespread occurrence of the type sequence is illustrated by the remarkable fact that the Harton Borehole (Pl. IV, 1) proved a similar succession even though the hole was drilled some forty miles east-north-east of Alston Moor on the Durham coast. This whole region will be referred to as the type area for descriptive purposes although the original type locality lies in Alston Moor. Within the type area, the typical succession is well developed in the Stanhope quarries where it is completely exposed in Ashes Quarry (Fig. 20) and Newlandside Quarry.

South of the above area, in Teesdale, the sequence is not closely comparable because the Low Coal Sill dies out, or is only very poorly represented, whilst at least one other sandstone becomes a prominent member of the succession; this latter sandstone appears to be correlatable with the lenticular marine band which is found above the High Coal Sill in the type area (Fig. 19). East of the River South Tyne, in the north-west part of the Block, the sequence is more comparable with that of the Northumbrian Trough and consequently it provides a direct link between the Block and Trough.

Thickness Variation

The variation in thickness of the Group as a whole is shown in Plate III. Over most of the Block the range is between a maximum of a little over 120 feet and a minimum of 44 feet, but in the extreme north-west on the Escarpment the maximum may be exceeded in Little Bleaberry Gill, New Water (Trotter and Hollingworth, 1932). The normal thickness lies below 75 feet but is rarely less than 50 feet. Factors pertaining to the thickness variation of the Group are as follows:-

- (i) Local thinning is caused by condensation of the complete sequence as in Rotherhope Fell Mine (pl. IV, 63).
- (ii) Failure or poor development of one or more of the

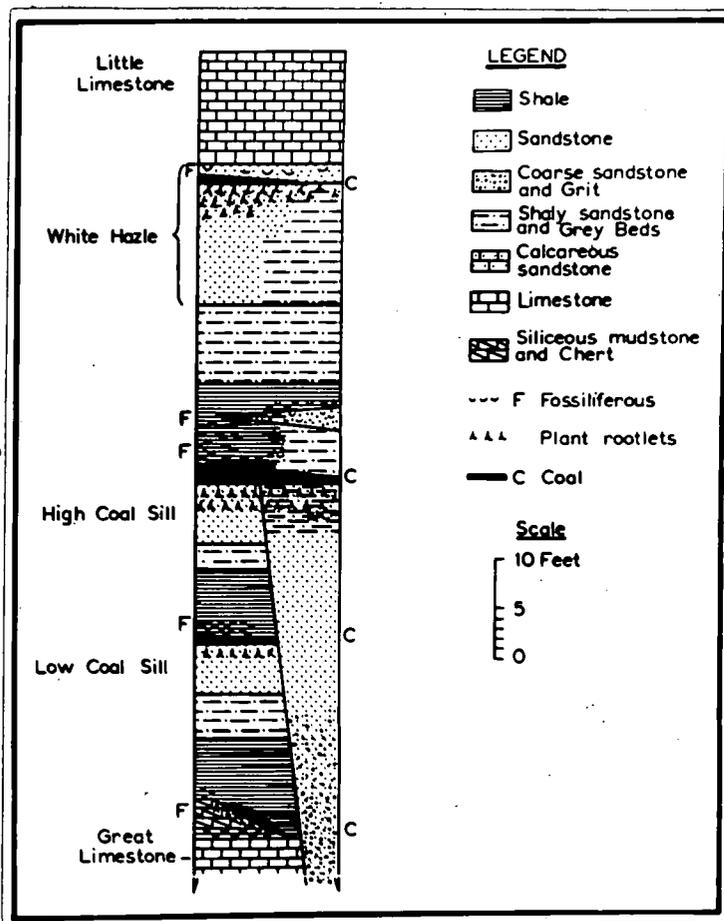


Fig. 19. Generalized section of the Coal Sills Group sequence on the Alston Block.

sheet sandstones may cause a thinning of the sequence, or expansion may cause a thickening.

(iii) Thickening of the sequence also takes place due to the presence of thick channel sandstones, one of which cuts into the Great Limestone along part of its course; this major channel is marked by isopachs of over 100 feet and trends south-south-west from Blanchland (Pl. III).

(iv) Replacement of the upper part of the underlying limestone by shale, similar to that shown in Fig. 13, also results in a thickening of the Group; this phenomenon is probably effective on a regional scale in the north-west part of the Block where the limestone is of a similar thickness to that in the Northumbrian Trough. Conversely, a thinning of the Group may arise due to local replacement by limestone of the shale which occurs above the normal limestone top, as in Ashes Quarry, Stanhope.

(v) A regional thickening takes place towards the north-west corner of the Block and is probably the result of this area sagging in sympathy with the adjacent Trough during deposition. Accompanying this regional thickening there is an increase in the proportion of the complete sequence formed by the beds between the Great Limestone top and the Low Coal Sill coal as compared with the proportion formed by them on the rest of the Block. This feature will be fully dealt with in the Northumbrian Trough section of this chapter since the change is more closely related to that region.

(vi) The apparent regional thickening towards the Pennine Fault System in the west may be due to the latter being a contemporaneous hinge-line during sedimentation, similar to the Stublick Fault System; insufficient detail of thickness variation allows no more than speculation upon this matter, however.

Summarized Stratigraphy

The base of the succession is formed by the top of the Great Limestone whilst the upper limit is defined by the base of the Upper Little Limestone, the latter being by no means as well exposed as the Great.

In describing the stratigraphy of the sequence on the Alston Block the type succession will be systematically dealt with. It will also be related to that proved where there is variation from it. The division of the Block into these areas has already been mentioned.

The Great Shale¹ and associated beds.- Normally the Great Limestone is immediately overlain by a shale² sequence which ranges in thickness from nil to 70 feet but on average is between 10 and 20 feet thick. The shale is thickest in the north-west part of the Block whilst there appears to be a regional thinning to the south. Expansion of this basal shale sequence arises due to local and regional failure of the Low Coal Sill and, on a regional scale, in the northern and north-western parts of the Block by replacement of the Great Limestone top by shale. Local thinning is caused by replacement of the lower part of the shale by the Great Limestone and also by erosion at the base of the washout channels which are developed at a higher level in the sequence.

Generally, the lower few feet of shale are fossiliferous but the fauna is only occasionally rich; sometimes fossils are also present higher in the shale sequence. Ironstone nodules are found in the fossiliferous shale at a few localities but if nodules are developed they are usually more common in the non-fossiliferous shale above.

Around Stanhope, at six separate localities, the lower part of the shale passes laterally into siliceous mudstone with harder chert bands which has a maximum thickness of around 8 feet. These small areas of cherty beds are quite isolated since the nearest Main Chert at the equivalent horizon is found on the north side of the Cotherstone Syncline, some twelve miles to the south-west.

1: The term used by Trotter and Hollingworth (1932) to describe the shale sequence which immediately overlies the Great Limestone.

2: Shale is here used to include normal shale and sandy shale. The latter in grading up to the overlying sandstone may become finely banded and consist of interlamination of sandy shale, shaly sandstone and sometimes fine grained sandstone; it is then known as grey beds, a traditional term of the Northern Pennine Orefield used to describe this lithology.

Immediately above the cherty beds at some localities, and within the lower part of the shale at other sporadically distributed localities, a seam of bright, brittle coal is found. Wherever it is accessible it is always underlain by strata containing Stigmaria in situ and plant rootlets. The seam, which is certainly lenticular, varies in thickness from a few inches to a maximum of 3 feet.

The upper part of the shale sequence gradually becomes sandy and often contains grey beds and thin sandstone bands. Comminuted plant debris is scattered throughout the upper part of the sequence and interfering ripple-marks which cause curly bedding are common.

The Low Coal Sill and coal.- Usually, there is an imperceptible gradation into the Low Coal Sill sandstone which is generally immediately overlain by the Low Coal Sill coal. The sandstone is a reasonably persistent horizon in the type area but it is lenticular to some extent. Normally, it is no thicker than 10 feet in the type area but there is a regional variation in thickness from nil to 28 feet. South of Weardale the sandstone dies out almost completely and is only rarely and poorly represented. In the north-west part of the Block the representative thickens and splits so that a lower component of sandstone, with a thin lenticular marine band (the Snope Burn Band) capping it, is overlain by 10 to 28 feet of shale or sandy shale and then the Low Coal Sill coal. The sandstone here has a maximum thickness of 35 feet but it is lenticular and is completely missing in some sections. Where best developed the Snope Burn Band has a maximum thickness of 4 feet 3 inches but it is also lenticular. Lithologically it is usually a sparingly crinoidal dark sandy limestone which in places is represented by ferruginous or ochreous clay.

In the two main feeder streams of Burnhope Reservoir and in a borehole on Great Dun Fell there are also indications that marine conditions prevailed during the formation of part of the sandstone. In each of the feeder streams a large fossiliferous calcareous sandstone concretion occurs within non-fossiliferous non-calcareous sandstone, whilst in the borehole the top 1 foot of the sandstone contains shells.

Everywhere the Low Coal Sill is a sheet sandstone which has a gradational base, although there are sometimes indications of slight local scour at its base. It thickens to some extent by replacing the underlying sandy shale but the marked local thickenings of it must be

ascribed to an original increase in sedimentation facilitated by greater local subsidence. In addition, however, there does appear to be a regional increase in thickness of the sandstone to the west and north-west towards what was probably the source area of the sediment.

In a number of cases the sandstone is completely massive, but laterally this lithology may pass into one comprised of alternating harder massive bands and softer sandstone or shaly sandstone layers; sometimes sandstone is completely replaced by grey beds or shaly sandstone. At its base the sandstone is very fine to fine grained but it grades upwards to become fine to medium or medium grained¹. "Annelid tracks", shale fragments and ripple marks are common features in the lower part, whilst cross-bedding is frequently present, particularly in the upper part of the sandstone.

The top of the sill almost invariably contains Stigmaria and plant rootlets in situ, these being the root remains of the plants from which the overlying Low Coal Sill coal was formed. The coal seam attains its maximum thickness in the north-west part of the Block where it reaches 1 foot 6 inches thick, but even in this part of the region it is not a completely reliable horizon. To the east, south-east and south there is a regional thinning of the seam and it is rarely over 6 inches thick; often it is absent or only represented by carbonaceous shale. In Teesdale, coal is only found at one locality at this horizon.

Strata between the Low Coal Sill coal and the High Coal Sill.- This sequence is essentially composed of shale which has a maximum thickness of 19 feet but is usually less than 10 feet thick. Where both the Low Coal Sill and its accompanying coal are absent, obviously it is impossible to differentiate the sequence. No regional trend in the thickness variation of the succession is apparent.

At some localities the shale is sandy throughout, but often the lower part is non-sandy. Marine fossils usually occur in the 1 foot of shale at the base of the sequence but they are rarely abundant and often appear to be completely absent. However, there are occasional exceptions to the above rule and in one case the full 13 feet of shale is fossiliferous. Also, at one isolated locality, a fossiliferous calcareous sand-

1: Grain-size nomenclature refers to the Wentworth scale (1922).

stone occurs in the middle of the shale sequence. Occasionally, ironstone nodules and lenses are present in the lower part of the shale but they are never abundant.

The sandy nature of the shale increases upwards and normally it grades into the High Coal Sill. Sedimentary structures similar to those in the sandy shale below the Low Coal Sill are developed.

The High Coal Sill and coal.- The sill is represented by a sheet sandstone phase, which has an extensive spread, and by a washout-channel sandstone phase which is much less extensive. The sheet sandstone is more persistent and more extensive than the Low Coal Sill since it can be recognized over most of the Block, only being absent occasionally. It shows a considerable variation in thickness from nil to approximately 60 feet, but on average it is between 10 and 15 feet thick and, therefore, thicker than the Low Coal Sill. No definite regional trend is apparent in the thickness variation of the sheet sandstone, however. Where it is excessively thick and no down-cutting is discernible at its base, the sandstone must have attained its thickness due to excessive localized sedimentation accompanying greater subsidence. The thickenings would appear to be confined to elongate strips which could at first sight be taken as infilled washout channels; however, their general field-relationships, especially their gradational bases, show that they are not. On the west side of Hudeshope in Teesdale, in an approximate north-north-east to south-south-west trending strip, it is impossible in some sections to differentiate the High Coal Sill from the overlying (and underlying) sandstones since there appears to have been continuous deposition of sandstone along a confined "channel"¹ from at least High Coal Sill times onwards. Similar conditions can be traced to continue northwards into the Bollihope Valley where there is a change to an east-north-east to west-south-west trend in the "channel's" direction (Plate III).

The sheet sandstone phase of the High Coal Sill is similar in most respects to the Low Coal Sill as far as its lithology and sedimentary structures are concerned. It differs in that it tends to be more massive

1: "Channel" is here used to designate a confined narrow and elongate strip containing a thick sandstone development but does not imply that the sandstone has any down-cutting at its base.

but there are soft sandstone and shaly sandstone bands interbedded in it at some places. Also, it is almost invariably medium grained above the base, and locally it is distinctly coarse grained in part. The sandstone contains no fossils but a calcareous nature has been recognized at two isolated localities.

Minor washouts are present cutting into the top of the sheet sandstone. They are related to the same phase of erosive activity as the washout-channels which took place subsequent to the formation of the sheet sandstone but prior to the colonization of its top by the plants from which the overlying coal was formed.

A single major channel can be traced running south-westward across the Block from the vicinity of Hunstanworth by way of St. John's Chapel to Barras, where it is lost since it trends into the area where rocks of this age have been removed by erosion (Plate III); however, it may connect up with a channel proved farther south on Baugh Fell (see later). Three subsidiary channels branch off from this parent channel, all on the east side of the latter and apparently at or near the apex of bends in its course. However, their courses cannot usually be traced for any great distance away from the parent channel which probably indicates that they rapidly died out. A fourth subsidiary channel probably branched off the east side of the major channel in the vicinity of Langdon Beck; relatively recent erosion has removed most of the evidence for its presence, but it is preserved farther south in Hargill Beck on the north side of the Cotherstone Syncline (see later). All the channels cut into the underlying sediments to within a few feet of the Great Limestone top, but from north of St. John's Chapel southwards the major channel has penetrated the Great Limestone along the whole of its course reducing the limestone to a thickness of at least 27 feet north of Langdon Beck.

The major channel, which is generally about one mile wide, has a slightly irregular base and contains a maximum recorded thickness of channel-fill material of 82 feet. At the base this material is composed of very coarse grained cross-bedded massive sandstone which occasionally contains small quartz pebbles and lenses of grit. Upwards, the channel-fill material becomes finer grained and in places at the very top is distinctly shaly. At two separate localities marine fossils have been discovered within the upper part of the channel-fill deposit; this is

possibly indicative of short local marine incursions into the channel but, on the other hand, the fossils could be derived.

The subsidiary channels are generally slightly less than half a mile wide; they also have a slightly irregular base which normally lies about 5 feet above the Great Limestone top and the maximum thickness of channel-fill deposit in them is 40 feet. The lower part of the channel-fill material consists of coarse grained massive sandstone but this rapidly grades up into medium grained sandstone which passes into shaly material at the top of the channel. At the edges of the channel prominent wedge-bedding is found with a strike parallel to and apparently controlled by the sides of the channel. Small scale cross-bedding is also frequently apparent in the lower part of the channel-fill sandstone.

Subsequent to the complete infilling of the channels, most of the area of the Block was colonized by vegetation, the roots of which are preserved in the upper part of the channel-fill deposits as well as the sheet sandstone. From the peat formed by the decayed vegetation the High Coal Sill coal was formed. This seam is the most important and prominent one of the cyclothem and can be traced over the bulk of the Block, only being absent locally. A thickness of 3 to 4 feet is attained in the extreme north-west part of the Block but 2 feet is a more normal thickness for the region around Alston. South and east of this area there is a regional thinning of the seam which in Weardale, the Allendales and on Alston Moor is often up to 1 foot thick and locally may be thicker. A maximum thickness of 6 inches has been recorded in Teesdale and the seam appears to thin even more to the south-east; it is absent within the confines of the Hudeshope "channel", probably due to the continuous deposition of sand inhibiting plant growth. A 2 feet thick seam was proved at this horizon in the Harton Borehole and there thus appears the possibility of a belt of thick coal stretching from the Alston region along the north flank of the Block and bordering the Trough where even thicker coals were formed. The coal is normally bright and brittle and, similar to the other coals in the Group, it has a semi-anthracitic character over much of the Block.

Strata between the High Coal Sill coal and the White Hazle.- This sequence is more variable than that below the High Coal Sill but shale is the essential component. A maximum thickness of 40 feet is attained whilst the average lies between 10 and 15 feet; however, in some cases

the thickness decreases to less than 5 feet. At four localities it is difficult to determine the thickness since the High Coal Sill coal is immediately overlain by sandstone which probably represents this component of the cyclothem in part. Regionally the sequence is thickest in Teesdale and thinnest in the north-west part of the Block.

The shale which normally comprises the bulk of this sequence in the type area is sometimes completely sandy, but often the lower part is not so and it may be markedly fossiliferous. Sometimes it is fossiliferous up to a prominent but lenticular marine band which is developed in the sequence between nil and 10 feet above the High Coal Sill coal. Above the marine band up to 3 feet of shale has also been found to be fossiliferous.

The marine band, which is lenticular, is seen to vary in thickness between 2 inches and 1 foot 9 inches. It is totally absent from a number of sections but, nevertheless, it has a widespread distribution on the Block, especially in the type area. Its lithology is somewhat variable as is the fossil content which may be either sparse or rich. Normally it is a fossiliferous irregularly-bedded calcareous sandstone, but it may be non-calcareous or siliceous and occasionally it is a sandy limestone; comminuted plant debris is often present inter-mixed with the marine fossils.

In the type area, the marine band passes laterally into a markedly lenticular, fine to medium grained sandstone which is seen to vary between 2 and 25 feet thick and has an average thickness of 6 feet. Sometimes the sandstone is fossiliferous but in other cases it is barren. At two localities where it rests directly on the High Coal Sill coal it is markedly cross-bedded. Apparently, it sometimes coalesces with the overlying White Hazle sandstone to form a single thick unit, the shale which normally separates the two disappearing. At four localities there is continuous sandstone between the High Coal Sill coal and the Little Limestone; probably this is due to the White Hazle and the above sandstone having coalesced where the latter immediately overlies the High Coal Sill coal.

In Teesdale, the sandstone becomes a prominent and persistent horizon which lies between nil and 20 feet above the High Coal Sill seam. It varies between 1 and 24 feet in thickness, but on average is approximately 12 feet thick. Within the strip on the west side of Hudeshope it

apparently forms part of the thick "channel" sandstone and cannot be delimited. Normally it is a fine to medium grained sandstone, but often in the upper part there is an admixture of coarse grained milky quartz. Almost invariably the sandstone is fossiliferous, the richest fauna being concentrated in the upper 2 to 3 feet; occasionally it is wholly fossiliferous, but it is also known to be completely barren in some places. Some of the fossils appear to be derived or at least winnowed since they are broken up, but there are also whole shells present. Comminuted plant debris is scattered amongst the fossils in some cases and at two adjacent localities the sandstone contains plant rootlets in situ near the base. Stellate saucer-shaped impressions which are possibly related to some form of plant have been recorded from this sandstone, but only at one locality.

The shale above the marine band and the laterally-equivalent sandstone contains ironstone nodules which are very prominent occasionally. Normally this shale becomes sandy upwards and grades into the White Hazle.

The White Hazle.- This sandstone is clearly divisible into two components over much of the Block, the upper of which is the basal member of the overlying cyclothem. Data regarding this upper component are dealt with in the detailed stratigraphical section but they will not be mentioned here since they are not really pertinent to this work.

The lower component is thickest within the confines of the "channel" shown on Plate III. In the centre of the "channel" it is combined with the sandstones below it, as mentioned previously, to form one thick unit; consequently, it cannot be delimited but it is probably thinner than where it is a separate unit. The margins of the so-called "channel" have been fixed quite arbitrarily to enclose an area in which this sandstone exceeds 35 feet thick. The maximum thickness recorded was 62 feet but there is a possibility that this thickness has been attained by coalescence with the sandstone which is the lateral representative of the marine band mentioned earlier. Outside the confines of the "channel" there is a gradual decrease in thickness of the sandstone which varies from nil to 35 feet thick, except for two localities where 35 feet may be exceeded. Thicknesses in excess of 20 feet are generally found close to the "channel"; over the rest of the area the sandstone usually has a thickness of between 5 and 15 feet. Local and rapid thickness variations

take place and where the sandstone is not developed as such it is represented by sandy shale or shaly sandstone.

The sandstone is usually massive and normally it grades up from the underlying sandy shale at whose expense it develops to a greater or less extent. Generally, it is fine grained at the base becoming medium grained upwards; however, at some localities where it is at its thickest it contains coarse grained lenses; abnormally it is completely coarse grained. In some cases the sandstone passes laterally into shaly sandstone or sandy shale.

At two widely separated localities coal with a maximum thickness of 1 foot 6 inches is present within the lower part of the sandstone. Although coal has not been found elsewhere at this horizon, plant rootlets in situ do occur at some localities. They are often present in the middle of the thick "channel" sandstone where they are overlain by up to 12 feet of fossiliferous sandstone. Outside the confines of the "channel" this lower component of the White Hazle has only proved to be fossiliferous at one locality.

Sedimentary structures similar to those in the Low and High Coal Sills are present in the sandstone; in particular, cross-bedding is sometimes very obvious.

The upper part of the sandstone almost invariably contains abundant plant rootlets and Stigmara in situ, as does the shaly lateral representative of the sandstone. The coal seam overlying the sandstone and forming the upper member of the cyclothem is not a persistent horizon. It varies in thickness from nil to 2 feet 2 inches, but more normally it is less than 3 inches thick. Apparently it had a more widespread distribution originally since fragments of coal are frequently found in the overlying fossiliferous sandstone where the seam is now absent. Regionally the seam is most reliable in the north-west part of the Block whilst it is least persistent to the south in Teesdale.

Detailed Stratigraphy

The Great Shale and associated beds.- Normally the Great Limestone is succeeded by shale which, where delimited by the Low Coal Sill, has a variable thickness ranging from 1 foot in Stony Hill Shaft, Boltsburn West Mine (Pl. IV, 13), to 36 feet in Plantation Rise, Esp's Vein

(Pl. IV, 58). At Coalcleugh (Pl. IV, 57), where the Low Coal Sill is absent, a thickness of 46 feet is attained. However, in Teesdale, even though this sandstone is not usually developed, the shale may be as thin as 3 feet thick and does not exceed a maximum thickness of 15 feet (Pl. IV, 35). The maximum thickness of shale above the limestone occurs in the north-west part of the Block where in Lunchy Beck (Pl. IV, 76), Croglin Water, approximately 2 miles east-north-east of Croglin, 70 feet of shale containing the Snope Burn Band (see later) is found between the limestone top and the Low Coal Sill coal; however, where the representative of the Low Coal Sill is present in this area the thickness of shale is much reduced but it is still quite thick even so.

Locally shale may be completely absent or at least much reduced in thickness due to the washout channels which cut down from a higher level in the sequence into the underlying strata (Pl. IV, 16 and 41). Replacement by limestone of the shale which immediately overlies the normal limestone top also causes a thinning. This effect is only of local significance and the maximum thickness of shale so affected is found in Ashes Quarry, Stanhope, where 7 feet is replaced by limestone, which within 200 yards along the quarry face virtually dies out. On the other hand, there is a regional thickening of the shale by replacement of the Great Limestone top in the northern and north-western parts of the Block.

In the type area the shale normally has a thickness of between 10 and 20 feet and is usually delimited by the Low Coal Sill. However, it is extremely difficult to generalize about the thickness because it does vary between the limits already stated above. Northward and north-westward from the type area there is an overall regional thickening of the shale whilst there is a thinning towards the south.

Immediately above the limestone marine fossils are frequently present including brachiopods, lamellibranchs, crinoid ossicles, bryozoans, trilobites and gastropods. Generally the fauna is not very rich but immediately above the limestone there may be some concentration of the fossils locally. Normally the lower 2 to 3 feet of shale is fossiliferous but occasionally the fauna extends higher and up to 8 feet of fossiliferous shale has been recorded. A scattered fauna has also been found even higher in the shale but it appears to be dissociated from that at the base and is only of very local extent; the shale in which it is contained

may be sandy.

Ironstone nodules are not common but they have been found within the fossiliferous shale and where they do occur they are relatively numerous; lenses of ironstone material are usually associated and the nodules are frequently in bands. In Clarghyll Burn (Pl. IV, 71), one mile due east of Ayle, nodules of up to 9 inches diameter are present; they are sometimes bell-shaped and are frequently septarian, containing a concentric and radiating network of calcite veinlets; nodules with aggregated and disseminated pyrite also exist. The nodules persist higher up the shale than the fossils; for example, the shale contains nodules from 3 feet to 14 feet above the Great Limestone top in Clarghyll Burn. At Redmires Quarry, one mile south-west of Stanhope, the fossils have been completely pyritized in many cases and frequently form the nuclei of pyrite nodules which are scattered throughout the lower part of the shale; where it is possible to extract the fossils they are beautifully preserved.

At six localities around Stanhope (Plate III) the lower part of the shale passes laterally into siliceous mudstone which contains harder chert bands. Material collected from these beds compares favourably with some of that in the type chert collection of Dr. A. J. Wells (1955a and 1955b) which is housed in the Department of Geology at Durham. X-ray powder photography of the cherty material reveals a basic silica pattern despite the amorphous nature of most of the silica in chert. The cherty beds are separated from the limestone by a foot or so of shale and attain a maximum thickness of over 8 feet. They are sometimes very fossiliferous with a rich brachiopod-lamellibranch fauna, but at other localities they are virtually barren. The siliceous mudstone passes laterally into normal shale and the individual developments of it appear to be quite isolated. The nearest Main Chert to this area is found on the north side of the Cotherstone Syncline in Hargill Beck where the author has discovered up to 4 feet of flinty chert immediately overlying the Great Limestone.

In the localities north of Stanhope Stigmaria and plant rootlets in situ occur in the upper part of the cherty beds which are overlain by a seam of bright, brittle coal up to 7 inches thick (Pl. IV, 15). This coal is not restricted to the regions where chert was laid down and has been found in widely separated areas. Up to 6 feet of strata intervene between the coal and the limestone top but in the Pike Law Hushes (Pl. IV,

37), Teesdale, the two are separated by a minimum of 2 inches of yellow limonitic clay which contains indistinct plant rootlets. Though the coal is found a variable distance above the limestone top it is considered to occupy a similar horizon everywhere, its variable position being ascribed to differing accumulations of sediment above the Great Limestone top before it was formed, although slight diachronism of the Great Limestone top could be another explanation. Normally shale or cherty material forms the floor of the seam but in the extreme north-eastern workings of Boltsburn Mine (Pl, IV, 14), one mile south-east of Bolt's Law, 2 feet of sandstone was recorded between the Great Limestone top and a 1 foot 6 inch thick coal seam; however, it may be that the supposed sandstone is siliceous mudstone. To the north, in the Hunstanworth Mines north-east of Ramshaw, the maximum thickness of coal at this horizon was recorded in Jeffries Engine Shaft (Pl, IV, 9) where a 3 feet seam was found immediately above the limestone. The impersistence of the seam is illustrated by the fact that it was not found farther west in the same mining area. In Teesdale the coal can be traced for 3 miles along the outcrop from Pike Law westward to High Hurth Edge; it varies from 6 to 10 inches thick and has been extensively wrought by means of bell pits and short adits along the whole length of outcrop. Although the above is not an exhaustive account of the distribution of coal at this horizon there are only a few other places where it has been located. The part of the sequence in which it is found is usually obscured but excavations at numerous localities have proved the absence of coal, and where exposure is good it is often not present. The seam has been noted to thin from 7 inches to a quarter of an inch within a mile in the quarries north of Stanhope, whilst in some of the quarries there is no sign of it at all. Thus, it is not a persistent horizon.

The strata below the seam may be fossiliferous but no fauna has been discovered above it on the Alston Block; sometimes, small ironstone or pyrite nodules are present in the shale immediately above. Normally, however, the shale becomes sandy only a short distance above the coal and grades up into the Low Coal Sill. In West Pasture Mine Quarry, approximately one mile north of Stanhope, where the seam is at its maximum distance above the limestone top, it is immediately overlain by the Low Coal Sill.

Where no coal is present at the above horizon the shale develops a sandy character upwards and also grades to the Low Coal Sill, but the horizon at which a sandy nature becomes apparent is very variable. However, where it is fossiliferous the shale is not sandy, but only a short distance above, where fossils die out it usually becomes so. It thus seems that the incoming of sand caused the disappearance of the fauna since in Snodberry Cleugh (Pl. IV, 45), one mile north-east of Cowhorse Hill, no fossils are present where sandy shale was formed only 2 feet above the limestone top, whereas fossils are present higher than this above the limestone top where no sandy character is apparent.

The shale sequence becomes more arenaceous upwards whilst in the upper part grey beds are usually apparent and sometimes thin sandstone bands are inter-bedded. Plant debris in a comminuted state is scattered throughout the upper part of this sequence and interfering ripple-marks, indicative of relatively shallow water deposition, are a common feature.

The Low Coal Sill and coal.- There is normally an imperceptible gradation into the Low Coal Sill sandstone, the base of which is quite arbitrarily defined in the field, as are the lower limits of the other sheet sandstones in the Coal Sills Group. The base has been taken at the position where sand grade material is obviously dominant; this often coincides with the position where the rock is becoming lithified, but not always since the lower part of the sandstone may be quite soft.

In the type area the sandstone attains its maximum thickness in Sally Grain (Pl. IV, 49), two miles west of Burnhope Reservoir, where it reaches at least 28 feet thick. As already mentioned, the sandstone was not deposited everywhere but it is reasonably persistent in the type area. Where it is not present its horizon may be marked by an increase in sandiness of the shale, as, for example, in Swinhope Borehole Number 4 (Dunham and Johnson, 1962 and Pl. IV, 46). The coal which normally overlies it may also mark its horizon, as in Clarghyll Burn (Pl. IV, 71) where the sill is represented by grey beds and shaly sandstone. In addition, it is cut out completely along the courses of the washout channels which are associated with the High Coal Sill. As a sandstone it thus varies from nil to 28 feet in thickness in the type area but normally is no thicker than 10 feet and is often less than 5 feet thick; on Cross Fell, and Great Dun Fell (Pl. IV, 70), however, it is usually over 15 feet thick

with a maximum of 26 feet in the East Cross Fell Mines (Pl. IV, 64).

Apparently sand grade material did not reach much farther south than the Tees-Wear watershed during this period because the sill is only poorly and locally represented in Teesdale; for example, in Harthope Beck (Pl. IV, 39) it is little over 1 foot thick. Part of the predominantly sandstone sequence found on the west side of Hudeshope (Pl. IV, 26-31), north of Middleton-in-Teesdale, may represent the Low Coal Sill but this is not certain. Between Weardale and Teesdale at the head of Westernhope, three miles south-west of Eastgate, it is certainly absent in one section (Pl. IV, 33) and appears to be wanting in four of the other five sections exposed.

In the north-west part of the Block a further complication sets in since the sandstone expands in thickness and also it splits. The sections in Coal Sike, Ayle (Pl. IV, 72), a small stream south of Blackcleugh Burn, a quarter of a mile north-east of Barhaugh (Pl. IV, 73), Snope Burn (Pl. IV, 74), Little Bleaberry Gill, New Water, two miles east of Cumrew (Pl. IV, 77), and Lunchy Beck, Croglin Water (Pl. IV, 76), illustrate this change. In Coal Sike the 11 feet thick unfossiliferous Low Coal Sill is directly overlain by a thin coal which was proved by boring at the old Ayle Colliery close by (personal communication by Mr. S. Shepherd, manager of Ayle Colliery). Less than two miles to the north-west, in the stream near Blackcleugh Burn, a thick massive sandstone which is approximately 35 feet thick and contains fossils in its upper part is overlain by a thin dark limestone of indeterminate thickness. This limestone is almost certainly the representative of the Snope Burn Band, a marine band which lies some way below the 2 inches of coal in Little Bleaberry Gill and Lunchy Beck, and the 1 foot seam in Snope Burn, all of which are considered to represent the Low Coal Sill coal. In the stream near Blackcleugh Burn this coal is not exposed but workings into the High Coal Sill coal, which normally lies only a short distance above the lower seam, occur some 30 feet above the thin limestone. Normally shale intervenes between the Low Coal Sill coal and the Snope Burn Band, but sandy shale is present above the marine band in the Faugh Cleugh Borehole (Pl. IV, 75) where no Low Coal Sill coal was proved to delimit the sequence. Thus, the Low Coal Sill of the type area is considerably expanded and divided into two components by the Snope Burn Band. Below the marine band is a sandstone

which attains a maximum thickness of about 35 feet but is completely absent in Croglin Water (Pl. IV, 76) and its tributaries, as previously mentioned. In Snope Burn (Pl. IV, 74), the sandstone was noted to contain prominent wedge-bedding by Trotter and Hollingworth (1932). The lenticular Snope Burn Band has a maximum thickness of 4 feet 3 inches; normally it is a sparingly crinoidal dark sandy limestone but, according to Trotter and Hollingworth (op. cit), it may pass laterally in places into a soft ferruginous or ochreous clay which may be sandy. Above the marine band up to the overlying Low Coal Sill coal there is a predominantly shaly (shale or sandy shale) sequence which varies in thickness between 10 and 28 feet.

The only indication of marine conditions prevailing during the formation of part of the sill elsewhere on the Block is found in the two main feeder-streams of Burnhope Reservoir and in one of the numerous boreholes drilled in the vicinity of Silverband Mine, Great Dun Fell. In Sally Grain, Burnhope (Pl. IV, 49), an isolated concretion of brown-weathering, richly calcareous fossiliferous sandstone (or sandy limestone since it contains up to 65 per cent carbonate) is situated within non-calcareous non-fossiliferous massive sandstone. It occurs 4 feet above the basal exposure of the 28 feet thick sandstone and is 9 feet long by 3 feet high approximately; its margins are vertical and sharp although in places there is a thin weathered shell; at the base, which occupies a slightly transgressive horizon, it may grade up rapidly from the underlying sandstone; its top is not well exposed. There is certainly no faulting associated and it may be that it is the remnant of a more extensive bed or lens which has been almost completely destroyed by authigenesis. All traces of fossils in the surrounding sandstone have disappeared if they were ever present and no carbonate matrix is left at all; the carbonate has probably been removed by percolating ground waters although concentration of some of it into the calcareous patch cannot be over-looked. A similar fossiliferous calcareous concretion occurs at approximately the same horizon in Scraith Burn (Pl. IV, 50), one mile south of the above locality, but it is not as well exposed. In Silverband Mine Borehole Number 3 (Pl. IV, 68) the top 1 foot of the sandstone was found to contain shells even though laterally it is overlain by a thin coal seam.

Channel sandstones with an erosive base have not been recognized at

this horizon so that the Low Coal Sill is everywhere a sheet sandstone. The base of the sheet sandstone appears to be slightly erosive in some exposures, however, but this is probably due to local scour prior to deposition rather than down-channelling. It normally grades up from the sandy shale below and is very fine to fine grained at the base becoming fine to medium and medium grained at the top. Undoubtedly it thickens to some extent by replacing the underlying sandy shale but this would not account for the thickest developments of the sandstone since they often occur where the shale below is also thick. This thickening must, therefore, be ascribed to an original increase in sedimentation which was probably facilitated by greater local subsidence. In addition, there also appears to be a regional increase in thickness of the sandstone to the west and north-west towards what was probably the source area of the sediment.

Where the sill is quite thin it often consists of harder massive bands inter-bedded with softer sandstone or shaly sandstone layers (Fig. 21), the different lithologies passing laterally into each other; the complete passage into grey beds or shaly sandstone has already been mentioned; ironstone nodules may occur within the representative stratum where it is shaly, as in Clarghyll Burn (Pl. IV, 71). However, the sill may also be completely composed of massive hard sandstone and this is particularly so where it is thickest.

In the lower part so-called "annelid tracks" have been noted quite frequently but they are usually best seen in detached blocks rather than in situ. Small angular and rounded fragments of shale are also occasionally present in the lower part of the sandstone. Ripple marking is a common feature throughout but it is best developed in the lower part; usually it is of the interference type which gives rise to a characteristic curly bedding. In most exposures the sandstone is cross-bedded to some extent but the units are usually small (about 1 foot thick) and they have individual laminae which vary in thickness between $\frac{1}{4}$ inch and 2 inches. Of restricted occurrence are small rounded nodules which were found in the upper part of the sill in Snodberry Cleugh. These are approximately 1 inch in diameter and quite discretely enclosed in sandstone which is completely different from them. The matrix sandstone contains no carbonate at all whereas the nodules are composed of poorly



Fig. 20. The complete typical Great Cyclothem sequence of the Alston Block, Ashes West Quarry, Weardale. G.L. - Great Limestone with Tumbler Beds; L.C.S. - Low Coal Sill; H.C.S. - High Coal Sill; W.H. - White Hazle; L.L. - Little Limestone.



Fig. 21. The Low Coal Sill (L.C.S.) and High Coal Sill (H.C.S.) above the Great Limestone (G.L.), Rogerley Quarry, Weardale. The general character of the sills is illustrated, the High Coal Sill being more massive than the Low Coal Sill but both contain bands of softer material.

sorted sand in a matrix of siderite.

The top of the sill, which is frequently formed of soft shaly sandstone in the upper few inches, almost invariably contains the remains of vegetation in the form of Stigmaria and plant rootlets in situ. Rootlets are the most obvious but Stigmaria are seen sometimes in flat exposed surfaces (Fig. 22); a thin coal film may be preserved along the walls of some Stigmaria. The plants which colonized the top of the sandstone and left these traces presumably also formed the peat from which the overlying coal originated. The coal is a widespread horizon but there are places where it was not formed or, at least, is not preserved. Even if it is absent plant remains still occur in the upper part of the Low Coal Sill although usually they are not as abundant as when the coal is present.

The seam is at its thickest in the north-west part of the Block where, in a small stream near Tows Bank, three miles north of Slaggyford, 1 foot 6 inches of coal is found at this horizon. However, it is not consistently thick even in this sector since in Little Bleaberry Gill (Pl. IV, 77) only 2 inches of coal were found and in the Faugh Cleugh Borehole (Pl. IV, 75) the seam was not recognized at all (this could be due to poor core recovery, however). Nevertheless, when considered regionally, the seam is thickest to the north, north-west and a little to the north-east of Alston, where on an average a 1 foot seam is found. It has been worked to a small extent in the above region but is not as important as the High Coal Sill coal in this respect. South and east of Alston the coal is normally 6 inches thick, or less, but locally a maximum thickness of 1 foot 3 inches is attained. This maximum thickness was proved on Great Dun Fell, near Dun Fell Hush, where a borehole close to the hush proved 1 foot 3 inches of coal (Pl. IV, 67) whereas the exposed seam is less than 3 inches thick (Pl. IV, 65). At the head of Wellhope Burn (Pl. IV, 47), one mile south-east of Cowhorse Hill, thin streaks of bright coal are distributed within 1 foot of sandy shale immediately above the Low Coal Sill. In the region around Stanhope the seam is very much reduced and never more than 1 inch thick; it may be represented by a mere smut or else a few inches of carbonaceous shale above the rooty sandstone. In other parts of the region coal is locally absent from this horizon too.

East of the exposed part of the Block the seam was proved in the Chopwell Woods and Roddymoor Boreholes (Pl. IV, 2 and 3) where it is 3



Fig. 22. *Stigmaria* in situ (indicated by an S) with rootlets (indicated by an R) associated in the massive Low Coal Sill, Wellhope Burn, Upper Weardale.

inches and 4 inches thick respectively. At Harton (Pl. IV, 1), however, 1 foot of coal is present above the Low Coal Sill; this could indicate either a local thickening of the seam or, perhaps, even a regional thickening.

In Teesdale coal is found only at this horizon in Harthope Beck (Pl. IV, 39). The formation at this locality is quite unique since thin layers of coal are interbanded with layers of carbonaceous shale for a thickness of at least 2 feet and within the layers distinct plant impressions can be made out. The outcrop occurs 3 feet directly above the 1 foot thick sandstone which is considered to represent the Low Coal Sill; thus there could possibly be a greater thickness of similar lithology developed and it may be that this is the locality at Old Langdon where Adam Sedgwick (1827) recorded a considerable thickness of "coal or a variety of carbonaceous shale". It might be argued that the coal which occurs almost immediately above the Great Limestone in Teesdale is the representative of the Low Coal Sill coal. This seems unlikely since the coal-carbonaceous shale formation is found some 10 feet above the limestone less than one mile from where the other coal seam lies only 1 foot above the limestone.

Where a distinct seam is present the coal is mainly bright and brittle but the upper part may be distinctly shaly. In some places, for example, in the Stanhope neighbourhood, it is totally represented by carbonaceous shale. Over most of the Block it probably has a semi-anthracitic character similar to the coal above the High Coal Sill; this feature will be considered more fully elsewhere since it is almost certainly due to changes subsequent to the formation of the coals.

Strata between the Low Coal Sill coal and the High Coal Sill.- These beds, which are essentially composed of shale, have a maximum thickness of 19 feet in the type area but they are usually less than 10 feet thick and may be much thinner than this. In both the Roddymoor and Chopwell Woods Boreholes (Pl. IV, 3 and 2) they are entirely absent or represented by sandstone, since the High Coal Sill rests directly on the coal above the Low Coal Sill. Naturally it is impossible to differentiate the sequence where no Low Coal Sill or its accompanying coal is developed, as in most of Teesdale. The previously mentioned washout channels obliterate this part of the sequence along their courses as they do the beds below. In the north-west part of the Block, when it is possible to

differentiate the equivalent strata, they are certainly no thicker than in the type area and if anything are thinner on average. Thus, no marked regional trend in the thickness variation of the succession can be made out.

As already mentioned, these beds are essentially composed of shale which in a number of cases is sandy throughout; in other cases, the shale is not sandy except in its upper part. At only a few localities have marine fossils been recognized, whilst at many localities they appear to be completely absent. If fossils are present they are usually found in the lower 1 foot of non-sandy shale at the base of the sequence, but this is not invariably so since occasional fossils have been recovered from the sandy shale higher up the succession. A notable exception to the above has been found in Swinhope Borehole Number 2 (Pl. IV, 54) where the 13 feet of shale between the Low and High Coal Sills, all of which is non-sandy, proved to be fossiliferous throughout; however, two of the four Swinhope boreholes (Pl. IV, 55 and 56) have completely barren shale, except for plant debris, at this horizon. Fossils are rarely abundant anywhere in this part of the sequence, but in Snodberry Cleugh (Pl. IV, 45) a thin concentrated band of pyritized shells and shell debris occurs within a disseminated pyrite matrix in 1 foot of slightly sandy fossiliferous shale 3 feet above the Low Coal Sill. In Wellhope Burn (Pl. IV, 47) 1 foot 3 inches of fossiliferous dark calcareous sandstone is found in the middle of the sequence which is only 5 feet thick altogether; no equivalent of this band has been discovered elsewhere. There is a possibility that it is the basal part of the overlying High Coal Sill, which is also calcareous at the base, but this is not considered likely since the sill contains no fossils and is of entirely different lithology.

In the lower part of the sequence ironstone nodules are present in both shale and sandy shale but they never attain the size of those in the Great Shale, are never abundant and are only sporadically distributed; lenses of ironstone are sometimes associated.

Upwards the sandy nature of the shale becomes more apparent and normally it grades into the High Coal Sill. Similar sedimentary features to those described in the sandy shale below the Low Coal Sill are apparent.

The High Coal Sill and coal.- Two distinct forms of the High Coal Sill sandstone can be recognized. One form is comprised of an extensive

sheet sandstone with an essentially gradational base, whilst the other is represented by restricted washout-channel sandstones with markedly erosive and unconformable bases.

(i) Sheet sandstone: This form of the sandstone is the one which was most extensively laid down and is thus the typical member of the sequence. It is similar to the Low Coal Sill but does show some variation from it.

Its position in the sequence with regard to the Low Coal Sill coal has already been defined but where the latter is absent it is obviously impossible to fix in such a manner. Thus, in Teesdale the sill lies between 3 and 15 feet above the Great Limestone top. Unfortunately, in Harthope Beck (Pl. IV, 39), the only place where the Low Coal Sill is recognizable in this area, the High Coal Sill is represented by a channel sandstone, the base of which lies only a few inches above the peculiar coal-carbonaceous shale horizon which has already been mentioned.

The sheet sandstone varies considerably in thickness over the type area with a maximum of more than 35 feet in Silverband Mine Borehole Number 5 (Pl. IV, 69). On average it is between 10 and 15 feet thick and consequently thicker than the Low Coal Sill. However, it does become thinner in some places, as in the Stanhope quarries. Like the Low Coal Sill it is locally absent, although on the whole it appears to be a more persistent horizon and is certainly more extensive.

For most of Teesdale an average thickness similar to the type area is in keeping, but in the vicinity of Hudeshope it is difficult to differentiate the High Coal Sill from the overlying (and ?underlying) sandstone. However, a shale parting may be developed above it (Pl. IV, 26) and in at least one section (Pl. IV, 30) the High Coal Sill coal is present although it is immediately overlain by sandstone. Where it does prove possible to distinguish the lower sandstone it is usually thick and, as previously mentioned, may in part represent the Low Coal Sill. The limits of the combined thick sandstone trend in a north-north-east to south-south-west direction on the west side of Hudeshope (Plate III); northwards, related conditions can be traced by way of Cornish Hush Air Shaft (Pl. IV, 23) to the south side of Bollihope Burn where the limits of thick sandstone have an approximate east-north-east to west-south-west trend. In the latter area, however, it is often possible to differentiate the High Coal Sill,

which has an average thickness, from the overlying abnormally thick sandstone. The accumulation of such a thickness of sandstone within this belt can best be explained by continuous deposition of sand in a restricted "channel" contemporaneous with the formation of the adjacent alternating sandstone-shale sequence; the coal and thin shale partings within the thick sandstone would be formed during halts in the deposition of sand, probably near the edges of the "channel". This "channel" sandstone is not comparable with the infilled washout-channels to be described later since it was formed at the same time as the sediments in which it is contained and with which it probably inter-digitates. Neither does it have a markedly erosive base as do the washout-channels. The sandstone in the "channel" usually grades up from the underlying sediments and is not coarse grained in its lower part as in the washout-channels. However, the base may be locally erosive, as for example, in the vicinity of the Pikestone Brow Shaft (Pl. IV, 24) where the thick sandstone, abnormally for it, is in contact with the Great Limestone. It must be emphasized too that the High Coal Sill only forms part of this "channel" whereas the washout-channels are completely related to the High Coal Sill and contain a maximum thickness of sandstone at least equal to that in the complete "channel". This is in spite of the fact that the washout-channels were apparently cut and infilled in a considerably shorter period of time than it took for the complete "channel" sandstone to accumulate.

In the north-west part of the Block the representative of the High Coal Sill shows considerable variation in thickness. Immediately to the west of the South Tyne there is no sandstone present at all, whereas on the Escarpment 50 to 60 feet has been recorded at this horizon in Little Bleaberry Gill (Pl. IV, 77). In Lunchy Beck, Croglin Water (Pl. IV, 76), less than two miles to the south-east, the same sandstone is only 6 feet thick approximately. Short (1954) considered that the thick sandstone was the continuation of a "washout" which he traced, mainly by features, from the north end of Cross Fell northwards and parallel to the Pennine Faults. The specific horizon of the so-called "washout" was not made clear, however. Although the thick sandstone of Little Bleaberry Gill has a coarse base, it is not considered to occupy a washout-channel since it lies at a similar level above the Low Coal Sill coal as the sheet sandstone of Lunchy Beck which is much thinner and also has a coarse base. However,

it is possible that the thickening of the sandstone may be confined to a channel-like strip which Short mistook for a "washout".

Thick developments of the sheet sandstone in the type area are probably also confined to such strips which usually can be seen to have a gradational base. To accommodate the greater thickness of sand which accumulated in these restricted zones without displacement of the strata below, there must have been a certain amount of differential and localized subsidence during deposition.

From the above, it can be seen that there is no definite regional trend in the thickness variation of the sheet sandstone. Thickening appears to be a local effect confined to narrow channel-like strips.

The sheet sandstone normally grades up from the sandy shale below but in places the base is slightly erosive, as for example, in Parson Byers Quarry, Stanhope. The erosive character is only a very local effect, probably due to scour, since laterally in the same quarry a normal gradational base can be observed. Sometimes sandstone develops at the expense of the underlying sandy shale; this is at its extreme in the Roddymoor and Chopwell Woods Boreholes (Pl. IV, 3 and 2) where sandstone has completely replaced the shale and sandy shale and rests immediately on the Low Coal Sill coal.

The sill is fine grained at the base and becomes medium grained upwards normally. Locally, however, it is distinctly coarse grained in part and in Dry Sike (Pl. IV, 51), Burnhope, less than one mile east of Burnhope Seat, it contains pebbles of milky quartz up to approximately 7 mm. in diameter. Generally, the coarse grained nature is found in the thicker developments of the sheet sandstone but this is not always so because in Cowhorse Hush (Pl. IV, 46), below Cowhorse Hill, the 6 feet thick High Coal Sill is coarse grained.

The sandstone is normally quite massive where it is reasonably thick but prominent soft sandstone and shaly sandstone bands are inter-bedded sometimes. Generally it is more massive than the Low Coal Sill (Fig. 21) but where it becomes thinner the soft sandstone and shaly sandstone bands form a larger proportion of it than normal. It is also poorly represented in places and it may degrade completely to a shaly sandstone or even grey beds. In the north-west it appears that locally the sill is not represented at all, but fortunately the High Coal Sill coal is a thick reliable

seam over the whole of that area so that the horizon can be recognized easily.

No fossils indicating marine conditions have been found in the sandstone unless the fossiliferous calcareous band which lies below the main exposure in Wellhope Burn (Pl. IV, 47) is part of it. As already stated, this is not considered so even though the basal part of the sill has proved to be calcareous as well as coarse grained. The only other locality where a distinctly calcareous nature has been recognized is Lunchy Beck (Pl. IV, 76). Here, the sandstone has a calcareous top which is separated from the overlying coal by a foot or so of shale; no fauna was recorded from the calcareous horizon by Trotter and Hollingworth (1932).

"Annelid tracks", ripple-markings, shale fragments, plant debris and cross-bedding are all recognizable features which occupy their appropriate positions in the sandstone as in the Low Coal Sill. Ripple-marking and cross-bedding are most commonly seen.

Because of the excellent exposure in the Stanhope quarries another feature affecting the High Coal Sill has come to light. This takes the form of minor washouts which cut into the top of the sandstone but do not cut it out completely. They are almost certainly related to the same phase of erosive activity as the washout-channels and thus aid in pinpointing the exact time of formation of the latter. The largest washout is seen in Parson Byers Quarry (Fig. 23a) where it is about 70 yards wide and cuts down for a maximum of 6 feet into the 7 feet thick High Coal Sill; this channel appears as though it was not completely infilled with shaly material before the formation of the overlying coal which consequently bends down into the washout; the differential compaction of shaly and sandy sediments could account for this flexure, however. The coal is no thicker within the washout than elsewhere although it might have been expected to be so if the washout was not completely infilled since there would then have been the facility for the accumulation of a greater thickness of peat. Other washouts are seen in Ashes Quarry (Fig. 23b) but they never have an amplitude of more than a foot or so; it appears that they were completely infilled with shale before the formation of peat, but it is impossible to ascertain this since they are inaccessible.

The upper part of the sill almost invariably contains abundant Stigmaria and plant rootlets in situ which are generally much more common



Fig. 23a. A large but minor washout in the High Coal Sill (H.C.S.) above the Great Limestone (G.L.), Parson Byers Quarry, Weardale. The centre of the washout is indicated by a W above it.



Fig. 23b. A very minor washout in the High Coal Sill, Ashes West Quarry, Weardale. Abbreviations indicating strata are as on Fig. 20.

than in the Low Coal Sill. This is only to be expected since the High Coal Sill coal is overall considerably thicker than the coal above the lower sill and would consequently require a greater accumulation of peat from which to form. The very top of the sill immediately beneath the coal is frequently soft and shaly.

(fi) Washout-channel sandstones: The channels were apparently formed subsequent to the deposition of the High Coal Sill sheet sandstone at any one point but prior to the colonization of the latter's top by the vegetation which gave rise to the overlying coal. Critical evidence for this is found in Rogerley Quarry, between Stanhope and Frosterley, where an infilled washout is seen to cut out the sheet sandstone and underlying beds but is itself overlain by the continuous High Coal Sill coal (Frontispiece and Figs. 24a and 24b). The presence of smaller washouts in the top of the High Coal Sill also indicates that the period of channelling followed the formation of the sheet sandstone. By reasonable extrapolation it seems likely that all the infilled channels are of similar age even though they are not so well exposed. All are immediately overlain by the High Coal Sill coal and are probably related to the channels along which sediment was introduced to the area and then spread out to form the shales and sheet sandstone of the normal sequence. Whilst the latter was being formed the channels generally lay outside the present area of deposition and only transgressed over it after the formation of the High Coal Sill sheet sandstone and prior to the formation of the overlying High Coal Sill coal. In advancing they cut deep courses which were subsequently alluviated by the essentially sand grade material now found in them in a consolidated state.

It is considered that all the washout channels are inter-related and the deduced channel pattern is shown on Plate III. There is one major channel with a width of about one mile which can be traced southward across the whole of the Block from the vicinity of Hunstanworth. It probably continues northward but unfortunately there is no information available to fix its course. To the south of the Block, which will be dealt with here for convenience, the channel is known in the neighbourhood of Borrowdale Beck, three miles east-north-east of Brough. Its continuation south beyond this locality is unknown and open to speculation, no critical exposures being available since the channel trends into the area



Fig. 24a. A sandstone-filled subsidiary washout-channel truncating the Low and High Coal Sill sheet sandstones, Rogerley Quarry, Weardale. The washout is indicated by a W whilst the other beds are indicated as on Fig. 20.



Fig. 24b. The edge of the above sandstone-filled washout to show the sharp truncation of the sheet sandstones and the continuous nature of the High Coal Sill coal (H.C.S.C.) above both the washout and the High Coal Sill sheet sandstone.

where rocks of this age have been removed by erosion. However, it may link up with a channel proved farther south on the Askrigg Block in the vicinity of Baugh Fell (see later). Three subsidiary channels which are generally less than half a mile wide branch off from the major channel. They all lie to the east of the major channel and appear to diverge from it at or near where there is a marked change in its course. None of them can be traced for any great distance which probably indicates that they rapidly died out. The possibility that there may be more than three subsidiary channels cannot be ruled out and, in fact, a fourth one probably branched off the east side of the major channel in the vicinity of Langdon Beck. Relatively recent erosion has removed most of the evidence for the presence of this channel but it is preserved farther south in Hargill Beck on the north side of the Cotherstone Syncline (see later).

In the northern part of its course the major channel cuts into the underlying sediments to within a few feet of the Great Limestone top. However, south of a point immediately to the north of St. John's Chapel the Great Limestone has apparently been penetrated along the whole length of the channel and as a result has been reduced to a minimum thickness of 27 feet north of Langdon Beck (Plate II); a deeper incision may have taken place in Borrowdale Beck but this is not certain. The base of the channel is slightly irregular as can be seen in Sunny Brow Mine Quarry, north of St. John's Chapel, where the coarse sandstone infilling of the channel is in irregular contact with the Great Limestone. The channel-fill material in the major channel has a maximum observed thickness of 82 feet in Aller Cleugh (Pl. IV, 41), half a mile north of St. John's Chapel. The Great Limestone has been penetrated at this locality but a thickness of 68 feet is attained in Ramshaw Engine Shaft (Pl. IV, 5), Ramshaw, even where the channel has only down-cut into the sediments above the limestone top.

In some cases the thick channel sandstone now lies within an adjacent sequence of strata which is much thinner than itself, and thus there is the problem of accommodating it. This is exemplified when the adjacent sections in the Hunstanworth Mines at Ramshaw Engine Shaft (Pl. IV, 5) and Taylor's Shaft (Pl. IV, 7) are considered. The 68 feet thick channel sandstone at Ramshaw has to be accommodated within the 9 feet thick shale and coal sequence below the High Coal Sill coal of Taylor's Shaft. Undoubtedly the greater compaction factors of peat and clay, as compared

with sand, will alleviate this anomaly to some extent; however, possibly there was also more subsidence along the channels, thus allowing a thicker accumulation of sand. Where the sandstone occupies a channel cut into the Great Limestone as well as the overlying sediments the problem of accommodating it is not acute.

Very coarse grained feldspathic sandstone was laid down at the base of the major channel; contained in it are occasional lenses of grit with a few milky quartz pebbles of up to approximately 13 mm. in diameter. It is markedly cross-bedded but the units are not large and rarely do they exceed more than 2 feet in thickness. Where the channel-fill sandstone is at its thickest up to 40 feet is coarse grained as above. The coarse grained sandstone grades up into medium grained material which is also cross-bedded but not so markedly as lower in the channel. In Harthope Beck (Pl. IV, 39) and Redgill Sike (Pl. IV, 38), Teesdale, on the east flank of the channel, fossils occur in the sandstone intermixed with shale fragments and plant debris approximately 8 feet below the top. The fossils, which comprise small crinoid ossicles and Orthotetids, are not abundant and appear to be restricted to less than 1 foot of strata; nevertheless, they probably indicate a short marine incursion into the channel, although they could be derived. In Aller Cleugh (Pl. IV, 41), Weardale, the upper 11 feet of the channel is infilled with sandy shale which contains fine grained sandstone bands and also ironstone nodules at the top. Within the sandy shale there is a fossiliferous band in a similar position to the one in Teesdale. The top of the channel-fill is not exposed elsewhere but from shaft records it would appear that it is not often shaly.

The subsidiary channels apparently do not cut into the Great Limestone but they approach very close to the limestone top, one such channel being excellently exposed in Rogerley Quarry (Pl. IV, 16), between Stanhope and Frosterley. Normally the channel-base lies about 5 feet above the limestone top but it can descend lower and in Stotfield Burn Mine, Rookhope, the two come into contact at Number 3 shaft (Pl. IV, 12). Irregularities in the channel base are small but often pronounced (Fig. 25). As previously mentioned, the channels cannot be traced for any great distance. Their shortness may in some measure be apparent and due to lack of exposure, however. This certainly appears to be the case for the easterly channel to some extent but does not seem to be so for the other two, although it



Fig. 25. Irregularities (marked X) at the base of the subsidiary sandstone-filled washout-channel, Rogerley Quarry, Weardale.

could be argued that the middle one continues southward to join up with the "channel" on the west side of Hudeshope. However, on the evidence available it is considered that the Hudeshope "channel" was formed contemporaneously with the deposits in which it is contained and is thus not directly related to the washout-channels. A rapid decrease in the erosive power of the streams which cut the subsidiary channels is a feasible explanation of their disappearance; such a decrease might be expected as the distance from the parent channel increased.

A maximum thickness of 40 feet of channel-fill material in the subsidiary channels is found in Stotfield Burn Mine (Pl. IV, 12) where the base is in contact with the Great Limestone; the average thickness lies nearer to 30 feet, however.

Coarse grained sandstone was laid down only at the base of the subsidiary channels and it rapidly grades up into medium grained sandstone. Within the coarse sandstone at the very base of the channel are fragments of shale and the impressions of plant stems with a diameter of up to 6 inches; shale fragments are present higher up too. Upwards the channel-fill material becomes finer grained and frequently the top 5 feet or so is composed of shaly sandstone which contains small pyrite and ironstone nodules. Near the edge of the channels shaly material may be present even lower down where it is interbedded with massive bands of sandstone, the two lithologies being involved in prominent wedge-bedding which is formed at an angle approximately parallel to the sides of the channel (Fig. 26) and only flattens out towards the channel base. Thus, the wedge-bedding strikes parallel to the course of the channel and dips into the centre of it. Massive sandstone is dominant in the lower part of individual beds involved in the wedge-bedding but towards the top of the channel each bed is partially replaced by shaly sandstone which is dominant at the very top. It is obvious that the channel has had a complex history of alluviation with periods of fill alternating with periods of erosion; this is well illustrated on Fig. 26 which shows an upper wedge-bedded unit cutting across a lower one. Away from the margins of the channel wedge-bedding is not so pronounced and the fill material is comprised of massive sandstone (Fig. 27) except for the upper few feet.

Wedge-bedding can only be distinctly seen in the quarries which expose the eastern subsidiary channel. However, it is probably developed

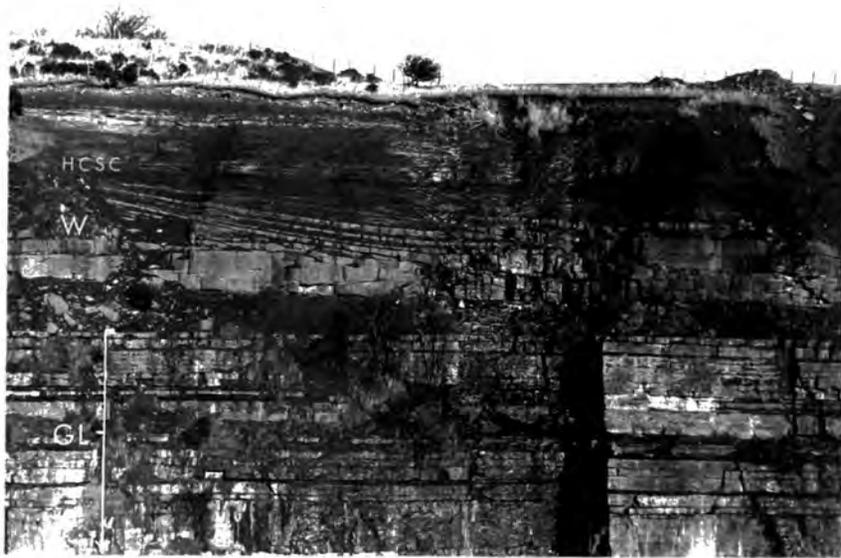


Fig. 26. Wedge-bedding in the fill material near the edge of the subsidiary washout-channel, Rogerley Quarry, Weardale. Individual beds are indicated as previously.



Fig. 27. Essentially massive sandstone filling the centre part of the subsidiary washout-channel, Rogerley Quarry, Weardale. Abbreviations used previously indicate individual beds.

along the margins of all the other washout-channels but has not come to light simply because they are not so well exposed. Its formation is considered to be due to banking-up of sediment on the margins of the channel. Thus, a type of large scale cross-bedding has been formed which has its maximum dip virtually at right angles to the current which flowed along the channel, and not parallel to it. Small scale cross-bedding is also present in the channels, especially in the lower part of the channel-fill deposit.

Following the complete infilling of the channels the whole area was colonized by vegetation except for that area occupied by the "channel" on the east side of Hudeshope which extends into the Bollihope valley. The roots of the vegetation are preserved in the upper part of the channel-fill deposits, as well as the sheet sandstone, and, as mentioned earlier, the root remains are quite abundant.

The High Coal Sill coal which is formed from the remains of the plants that colonized the area is the most important and prominent seam of the cyclothem. Consequently, it can be interpolated that there must have been a considerable period of plant growth in order to accumulate the amount of peat required to form it. It has been proved in nearly every exposed section in the area but may be only sporadically developed in the extreme east part of Teesdale. Only one of the Swinhope Boreholes (Pl. IV, 53 - 56) proved the seam but it is quite possible that it was lost during drilling of the other holes since coal is notoriously difficult to core at a small diameter unless special precautions are taken. Several mine sections do not record the seam either, but as pointed out by Winch (1817), "coals being very uncertain in their extent are seldom noticed in the lead mine sections". Thus, the seam may be absent locally but on the whole it is a reliable horizon over a very large area.

Trotter and Hollingworth (1932) were not aware of the detailed nomenclature and correlation of the seams in the north-west part of the Block with those to the east and south. Consequently, they adopted the terminology used in the Northumbrian Trough farther to the north and north-east and grouped them together as the Little Limestone Coals. The middle seam, which is the High Coal Sill coal, was noted to be the thickest and best in quality usually. Where this seam is worked in the neighbourhood of Alston it is actually called the Little Limestone Coal although it lies

some 16 feet below the limestone.

The seam attains its maximum thickness in the extreme north-west part of the Block where in Gairs Pit, three miles south-east of Talkin, it varies between 3 and 4 feet thick. Regionally it is thickest in an area similar to the coal above the Low Coal Sill; that is to say, the region around Alston, but mainly to the north and north-west. Nowhere else in this region is it as thick as at Gairs Pit but often it is little thinner than 2 feet thick. Because of its thickness and semi-anthracitic character the seam is being actively worked near Alston at four small drift mines for household and industrial purposes. South and east of Alston the seam thins but is frequently as thick as 1 foot and in Shildon Shaft (Pl. IV, 10), near Blanchland, is 2 feet 4 inches thick. It is reduced to a thickness of 2 inches at one locality in Weardale but is usually nearer 1 foot thick. In Teesdale, where a maximum thickness of 6 inches has been recorded, there appears to be a thinning of the seam to the south-east. Within the confines of the "channel" on the west side of Hudeshope no coal was recorded except possibly at the edges; this is probably because adverse conditions in the "channel" almost completely inhibited the plant growth necessary for the formation of coal. There also appears to be a rapid thinning of the seam due south of Alston because from being 1 foot 2 inches thick in Rotherhope Fell Mine (Pl. IV, 63) there is a decrease to a thickness of 3 inches in Silverband Mine (Pl. IV, 70) on Great Dun Fell.

East of the exposures on the Block no coal was recorded in the Chopwell Woods, Roddymoor and Elstob Boreholes (Pl. IV, 2, 3 and 4), but a 2 feet thick seam was proved in the Harton Borehole (Pl. IV, 1) at this horizon. The latter find might be considered as evidence indicative of an area of thick coal formation in the north-east, as well as the north-west part of the Block. In fact, there may be such an area along the whole of the northern edge of the Block, flanking the Trough where even thicker coals were formed. Certainly the Shildon record (Pl. IV, 10) would indicate this, but unfortunately no coal was proved in the Chopwell Woods Borehole (Pl. IV, 2) to substantiate the hypothesis.

Very minor seam-splitting takes place occasionally, as for example, in Ayle Colliery, where 1 inch of coal is separated from the main 1 foot 9 inches thick seam below it by 6 inches of shale. This splitting is

only a local feature and the shale parting rapidly dies out.

Large pyrite concretions, up to 6 inches in diameter, occur within the seam, especially in the area where it is at its thickest. They are extremely common at Barhaugh Pit, but are virtually unknown in the seam at Ayle Colliery only two miles to the south-east.

The coal is normally bright and brittle and is not very often markedly shaly. Invariably it is highly jointed (cleaty) and consequently it breaks up into very small pieces; the small pieces themselves have a sub-conchoidal fracture, probably due to the semi-anthracitic character of the coal. This latter character is widespread but will be dealt with elsewhere since it is probably not an original feature of the coal.

Strata between the High Coal Sill coal and the White Hazle.- This sequence is more variable than that between the Low Coal Sill coal and the base of the High Coal Sill. Its top is also irregularly defined because of the variable development of the White Hazle which is sometimes completely absent allowing the sequence to extend up to the Little Limestone base, as in the Harton Borehole (Pl. IV, 1); however, on the other hand, the sequence is often thinned by the White Hazle thickening at its expense as shown below.

In the type area the beds are essentially of shale which is frequently sandy to a greater or less extent. In the lower part of this shale sequence a lenticular marine band is present which passes laterally and expands into a very sparsely fossiliferous or barren lenticular sandstone; this sandstone is probably the lateral representative of a thick sandstone in the Teesdale sequence which usually has a fossiliferous top.

The maximum thickness of these beds in the type area is attained in the vicinity of a small stream (Pl. IV, 17) which flows through Fine Plantation into Rogerley Quarry, one mile south-east of Stanhope. Here they are 30 feet thick but normally they are much thinner, the average thickness lying between 10 and 15 feet. Where the White Hazle is very thick the sequence is reduced in thickness and can be thinner than 5 feet, as in the streams on the south side of Bollihope Burn; thinning also takes place irrespective of the above replacement by sandstone, however. On the other hand, thickening of the sequence may take place by the White Hazle being poorly developed. At four separate localities (Pl. IV, 60, 57, 59 and 9) the High Coal Sill coal is directly overlain by sandstone which

is continuous up to the Little Limestone base; these special conditions will be dealt with more fully below. In the north-west part of the Block the equivalent strata are thinner than in the type area and, whereas in Clarghyll Burn and Ayle Burn (Pl. IV, 71 and 72) they are 16 feet thick, they thin to 8 feet in Snope Burn (Pl. IV, 74) and are only 3 feet 6 inches thick on the escarpment in Croglin Water (Pl. IV, 76). To the south of the type area, in Teesdale, the incoming of the thick fossiliferous sandstone causes an overall expansion of the sequence which thus has a maximum thickness of 40 feet in How Gill (Pl. IV, 31), one mile north-north-west of Middleton. This thickness may be exceeded within the confines of the "channel" which contains the combined ?Low Coal Sill, High Coal Sill, fossiliferous sandstone and White Hazle, but it is impossible to ascertain this. The sequence rarely has a thickness lower than 20 feet in Teesdale but a minimum of 10 feet is reached in Snaigsill Sike (Pl. IV, 32), less than one mile north-north-east of Middleton.

In the type area the shale which generally comprises these beds is sometimes completely sandy but often the lower part of it is not so. Marine fossils are most common in the basal part where it is non-sandy, but occasionally they are present when a sandy character is obvious. At a few localities a rich fauna is found in the shale immediately overlying the High Coal Sill coal; this has been found to persist for 5 feet up to the marine band in Swinhope Borehole Number 3 (Pl. IV, 55), but normally fossils are only present in the lower 2 feet or so of the shale and are often much more restricted than this. The fauna is certainly more widespread and richer at this horizon than that in an equivalent position above the Low Coal Sill coal but even so it is not developed everywhere. Ironstone nodules are sometimes present in the shale and may be mixed with the fauna; however, if nodules are present fossils are not usually very common.

The prominent marine band previously mentioned was initially discovered in Cow Burn (Pl. IV, 18) which flows into the west end of Parson Byers Quarry, approximately one mile south of Stanhope. Here it is a 1 foot 6 inches thick irregularly bedded calcareous sandstone which lies 7 feet above the High Coal Sill coal. Contained in it are elongate ironstone concretions and a fauna which is dominated by Eomarginifera with subsidiary trilobite pygidia (mucronate), small corals, crinoid ossicles,

gastropods and other brachiopods. The shale which occurs above the prominent band is also fossiliferous for a maximum of 2 feet 6 inches but the fauna is mainly concentrated in the lower part of it.

The band has a widespread distribution but it is certainly lenticular, being absent at some localities. Discoveries of it have been made over the whole of the type area, particularly in Weardale, and the farthest west it has been found is in Ayle Burn (Pl. IV, 72). Its position above the High Coal Sill coal normally varies between 2 and 10 feet, but in a tributary of South Langtae Sike, Harwood Beck, one and a half miles south-east of Burnhope Seat, the possible representative appears to rest directly on the coal. This variation in position might be taken to indicate that more than one band is developed within a restricted vertical range. However, the same horizon can be traced from Parson Byers Quarry to Newlandside Quarry, a distance of one mile in which it descends from 10 feet to 3 feet above the coal. This cannot be regarded as conclusive evidence that there is only one band, but in the type area no locality has been found where there is more than one present in the same section. The evidence from Swinhope Borehole Number 3 and Number 1 (Pl. IV, 55 and 53) indicates that the marine band is closely related to the fossiliferous marine shale below it in spite of the fact that they are separated by apparently barren and often sandy shale in some sections. The two thus form a marine series and condensation or expansion of this series would account for the variable position of the marine band. It is thus considered that there is only one band and though it occupies a reasonably specific horizon it does vary somewhat in position above the High Coal Sill coal.

In the type area the band has a thickness which varies between 2 inches and 1 foot 9 inches but up to 3 feet of shale above it may also be fossiliferous. The lenticular nature of the band is well seen in Sedling Burn (Pl. IV, 42) where it thins from 6 inches to 2 inches within 10 yards.

Lithologically it usually consists of calcareous sandstone which is often irregularly bedded and carbonaceous. In places it is non-calcareous; sometimes this is due to secondary de-calcification but in other cases the sandstone is siliceous and does not appear to have been calcareous originally. On the other extreme, the band may be formed of sandy limestone but this lithology is not very commonly encountered. The fossil content is also variable since at some localities there is a rich fauna

whilst at others it is almost barren. The fauna is dominated by crinoid ossicles and brachiopods, among which Orthotetids (?Schellwienella), Eomarginifera and Camarotoechia are common. Some of the brachiopods have both valves still articulated, and thus it appears that at least some of the fauna may be indigenous. Plant debris is also contained in the marine band but it is invariably comminuted.

Up to 3 feet of shale above the calcareous sandstone is fossiliferous but only the lower part contains a reasonably prolific fauna. Ironstone nodules are sometimes present in this shale immediately above the marine band and in Sedling Burn (Pl. IV, 42) they are common even where there is a rich fauna; at this locality the nodules attain a maximum size of 6 inches long. Above the fossiliferous shale a sandy character usually becomes obvious but if it does not, as in Swinhope Borehole Number 3 (Pl. IV, 55), a scattered fauna can generally be detected. Normally, however, the shale does become sandy and, like that beneath the High and Low Coal Sills, grades upwards into the White Hazle. In its upper part it frequently contains a considerable amount of comminuted plant debris.

In Parson Byers Quarry the marine band mentioned above is clearly exposed at the west end of the quarry face where it is 1 foot 6 inches thick and richly fossiliferous. Traced eastwards along the top of the quarry it passes laterally within 200 yards into a 6 feet thick fine to medium grained sandstone which contains shaly bands and comminuted plant debris but is only very sparsely fossiliferous at the top. The marine band must behave in a similar manner in the Swinhope area since in boreholes 1 and 3 (Pl. IV, 53 and 55) it is present whereas in boreholes 2 and 4 (Pl. IV, 54 and 56) there is a thick unfossiliferous sandstone at a similar horizon. A sandstone in a similar position has been found at a number of other localities where there is no direct connection between it and the marine band. This sandstone sometimes contains no fauna but in other cases it can be partially fossiliferous, as for example, in Wellheads Hush (Pl. IV, 48), two miles west-north-west of Wearhead, where at the base it is very rich in Orthotetids and crinoid ossicles. In Scraith Burn (Pl. IV, 50) it is very cross-bedded at the base and rests directly on the High Coal Sill coal; nowhere else has such marked cross-bedding been seen in this sandstone unless, as seems likely, the lower part of the thick sandstone immediately above the High Coal Sill coal in Blagill



Burn (Pl. IV, 60) is its representative. In both cases there may have been some erosion at the sandstone base.

Dun Fell Borehole Number 5 record (Pl. IV, 67) shows a 6 feet thick sandstone immediately above the High Coal Sill coal which could represent this horizon. However, this record must be regarded with some suspicion since neither the adjacent Number 4 borehole (Pl. IV, 66) or the Dun Fell Hush section (Pl. IV, 65) reveal such a sandstone.

At a maximum the sandstone lies 10 feet above the High Coal Sill coal whilst at a minimum it rests directly on the coal. Normally, it varies between 2 and 12 feet thick but on average it is around 6 feet thick. In Thorngill West Mine (Pl. IV, 62) and Blagill Mine (Pl. IV, 61) the probable representative is 25 feet thick, however. Its lenticularity is obvious since it is absent in many sections. In the Bollihope Valley (Pl. IV, 19, 21 and 22), south-west of Frosterley, where the White Hazle is apparently very thick, it is possible that this sandstone coalesces with it and is thus not recognizable as a separate unit; this may also be the case in the four sections mentioned previously in which the so-called White Hazle lies immediately on the High Coal Sill coal.

The lateral passage of the marine band into a sandstone holds the key to the correlation between the sequence of the type area and Teesdale. In the latter area a prominent and persistent fossiliferous sandstone appears to be the lateral representative. It is this sandstone which is frequently referred to as the High Coal Sill in Teesdale, the actual High Coal Sill then being called the Low Coal Sill. In this region in Rowantreegill Sike (Pl. IV, 36), half a mile east of Pike Law, the sandstone lies approximately 17 feet above the High Coal Sill coal whilst less than one mile to the south-west, in the Pike Law Hushes (Pl. IV, 37), it rests directly on the seam. Throughout Teesdale it normally varies in position between the above two extremes although in Skears Great Rise (Pl. IV, 27) the possible representative lies 20 feet above the High Coal Sill. It comprises part of the thick "channel" sandstone of Hudeshope but cannot be certainly delimited in most cases.

The sandstone usually varies in thickness between 3 and 24 feet but in the upper part of Hudeshope Beck (Pl. IV, 25) the possible representative is only 1 foot thick. However, on average it has a thickness of about 12 feet and can be traced throughout Teesdale.

Normally, it is a fine to medium grained sandstone but in the upper part there is often an admixture of milky quartz grains with a diameter of up to approximately 6 mm. Between Harthope Beck (Pl. IV, 39) and Rowantreegill Sike (Pl. IV, 36) a layer with plant rootlets in situ has been noted close to the base of the sandstone but it is not often developed. Where present it is usually overlain by shaly sandstone which grades up into the normal lithology. The sandstone with plants could be considered as a separate horizon but its intimate association with the overlying sandstone suggests that it is a lenticular component of it.

The whole of the sandstone may be fossiliferous but the richest fauna is contained in the upper 2 to 3 feet. The fauna persists even though a high proportion of large quartz grains giving rise to a grit-like texture may be present in the sandstone, as in the upper 6 inches of it in Redgill Sike (Pl. IV, 38), one mile north-east of Langdon Beck. Limonite is also a common constituent of the sandstone where fossils are abundant and it is probably a replacement product of the original shell material of the fossils since most are preserved as casts. Crinoid ossicles and brachiopods dominate the fauna but gastropods, lamellibranchs and one fish crushing tooth have also been found. Indications of current activity are present in the form of fragmented shells and the occasional concentration of the fossils into pockets; all the shells are not fragmented, however, some being perfectly whole. A small amount of plant debris and occasional shale fragments occur amongst the fossils in some cases. Occasionally no fauna at all has been detected in the sandstone which is considered to be equivalent to the fossiliferous one, but there is generally some plant material present.

One problematical structure has been discovered within this sandstone but it has not been found exactly in situ. It occurs in a large block which is just detached from the outcrops in Ettersgill Sike, two miles east of Langdon Beck. There are a number of specimens spread about on a single bedding plane (Fig. 28a), one being crossed by a segmented "annelid track". In general form the structures are saucer-shaped with a maximum diameter of 6 inches and a depth of 2 inches; superimposed on this shape are a radiating series of prominent grooves (Fig. 28b). Associated with the whole of the structure is a thin film of micaceous carbonaceous material. Thus it might be suggested that they are the impress-



Fig. 28a. Problematical structures in the sandstone lying between the High Coal Sill coal and the White Hazle, Ettersgill Sike, Teesdale.

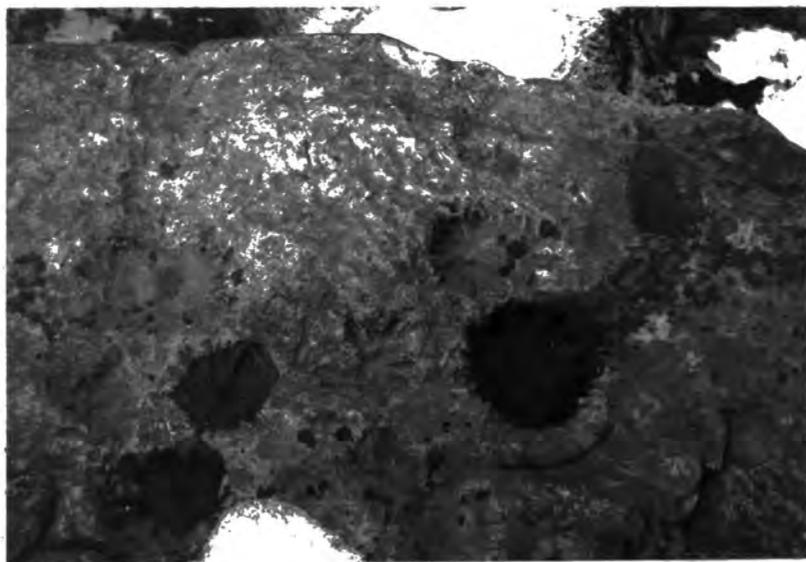


Fig. 28b. Close-up view of some of the above structures.

ions of some form of stellate plant hitherto unrecorded. Similar structures have been collected by Mr. J. Robson from the Harthope Ganister Quarries which are worked in the Coalcleugh Transgression Beds, two and a half miles north of Langdon Beck.

Shale usually intervenes between the sandstone and the High Coal Sill coal; normally it appears to be somewhat sandy but occasionally a sparse fauna has been detected in it. In Broperygill Sike (Pl. IV, 35), near Rowantreegill Sike, a 9 inches thick lenticular fossiliferous sandstone containing shell fragments and crinoid ossicles lies directly on the High Coal Sill coal, whilst the main fossiliferous sandstone, which is separated from it by shale, lies 12 feet above.

The beds above the fossiliferous sandstone are composed of shale and sandy shale, the latter grading up into the White Hazle. Some ironstone nodules have been recorded in the lower part of the shale.

The White Hazle.- This sandstone has been variously named the Little Hazle, White Sill and White Hazle. The term White Sill, however, has priority for a sandstone which lies some way above the Little Limestone (Dunham, 1948, p.31). It is proposed to continue the usage of the term White Hazle in preference to Little Hazle as this will avoid confusion since many authors have adopted the former term (Forster, Nall's revision, 1883, p.57; Dunham, op. cit, p.27).

Hazle is a term peculiar to the North of England meaning, according to Forster (op. cit., p.55), sandstone, harder than freestone, but softer than girdle bed; further clarification of its meaning is found in Arkell and Tomkeieff (1953) where it is defined as a fine grained sandstone. At outcrop the sandstone is never white but it could be so in mine sections where it is un-weathered. There is also no strict conformity with the definition of hazle given above. Thus, White Hazle is a stratigraphical term which has no strict lithological significance. It probably originated in a mine or a number of mines where it does accurately describe the lithology.

In the field it has been found possible to divide the White Hazle into two distinct components which are frequently separated by a very thin coal. Only in rare cases has this division been reported in the sub-surface dat^e, however. The upper component will be described first since

it must be excluded from the main consideration as it is not a member of the Great Cyclothem. The divisions are characterized as follows:

(i) Upper White Hazle: The maximum thickness of this part of the sandstone was recorded in Green Sike (Pl. IV, 34), at the head of Westernhope Burn, where it is 11 feet thick. Normally, however, it is much thinner than this and in some cases cannot be differentiated from the overlying Little Limestone into which it grades. If no sandstone is recognisable the lower few inches of the Little Limestone invariably prove to be very sandy, however. Thus, the sandstone varies from nil to 11 feet thick with the normal thickness lying below 5 feet. The thickest development of it occurs where the underlying component of the White Hazle is also thick.

Usually, it is an ill-sorted fine to medium grained sandstone which also contains a coarse grained fraction; at the top it becomes calcareous and grades rapidly into the Little Limestone. Often it is fossiliferous, the fauna being dominated by Orthotetids and crinoid ossicles; fragments of shell material are also common. The lower part of the sandstone frequently contains scattered coal fragments which have obviously been derived from the underlying coal. Even where the coal is absent as a seam below it, fragments of coal are found in the sandstone; this might be taken to indicate the former presence of the coal at least close by even if not immediately below. If no coal is developed between the upper and lower parts of the sandstone they may be welded together, presumably due to authigenic activity; this is a rare feature, however.

Very occasionally the sandstone is represented in part by shaly beds, as for example, in Ashgill Beck (Pl. IV, 52), one and a half miles south-east of Burnhope Seat, where the basal part of the representative is composed of interbedded sandstone and slightly sandy shale. Where the sandstone is represented in the north-west part of the block its base is also shaly (Pl. IV, 75 and 76).

This component of the sandstone is actually the basal member (Member (i) of Johnson's (1959, p.89) ideal cyclothem) of the overlying Little Cyclothem. It is the initial deposit which was formed prior to the major marine episode of the cyclothem during which the Little Limestone was laid down.

In underground exposures the sandstone is similar in appearance to

the Little Limestone and it seems possible that it has been included with the latter in some sub-surface sections. Support for this suggestion is found in the Sedling area, north of Wearhead, where a 2 feet thick fossiliferous sandstone, which is distinguishable at the surface, was not recorded as a separate unit in the Sedling Mine section (Pl. IV, 43), less than 150 yards from the nearest exposure. However, in Burtree Pasture Engine Shaft (Pl. IV, 44), approximately 400 yards north of the nearest exposure, the sandstone was recorded. In order that the numerous underground sections may be made use of in the following consideration it is necessary to assume that the sandstone has been included with the Little Limestone. This may not be correct in every case but it will make little difference to the basic conclusions since the fossiliferous sandstone is usually thin.

(ii) Lower White Hazle: This sandstone is extensively developed and it exhibits a considerable amount of variation in its character. However, the variation is not such that it will require division of the Block into separate areas for a consideration of it to be made. The position of its base in relation to the High Coal Sill coal has already been defined.

It is at its thickest within the confines of the "channel" whose boundaries are shown on Plate III. On the margins of the "channel" in the Bollihope valley (Pl. IV, 19, 21 and 22), the headwaters of Westernhope Burn (Pl. IV, 33 and 34), Cornish Hush Air Shaft (Pl. IV, 23) and Hudeshope Beck (Pl. IV, 25) it can usually be recognized as a separate unit above the High Coal Sill. However, in the centre of the "channel" it is combined with the sandstones from which it is normally separated to form one thick composite unit; this is well illustrated in the sections from Harehope Gill Mine (Pl. IV, 19), Skears Mine Vein F₄ (Pl. IV, 28) and Skears Mine Vein D₄ (Pl. IV, 29). There must, therefore, have been virtually continuous deposition of sand at the centre of the "channel" during most of Coal Sills Group times; at the margins more normal conditions prevailed but there must have been excessive subsidence during the period in which the White Hazle was laid down for such a thickness of sand to accumulate. The "channel" has thus been delimited in order to embrace the extensive area in which the separate White Hazle is thickly developed as well as the confined strip in which the composite sandstone was formed during and before White Hazle times. The sequence of events

which led to the formation of the thick White Hazle appears to have been as follows:-

(a) The development of a restricted contemporaneous "channel" from at least High Coal Sill times onwards. In the "channel" it appears that virtually continuous deposition of sand took place. The "channel" does not have sharp margins, however, and its deposits interdigitate with the sediments at the edges.

(b) In White Hazle times the "channel" deposits spread over an extensive area between Weardale and Teesdale as shown on Plate III. However, there was no extensive spread from the "channel" in Teesdale on the west side of Hudeshope Beck. At the north-west extremity of thick White Hazle development there is a finger-like extension into the headwaters of Westernhope Burn. The sandstone is probably thickest where it is a separate unit rather than where it forms part of the composite sandstone at the centre of the "channel". This so-called "channel" which embraces the thick White Hazle does not have sharp distinct margins; as inferred above, the edges have been fixed quite arbitrarily so as to enclose an area in which the sandstone exceeds 35 feet thick. Outside the "channel's" confines there is a gradual decrease of the White Hazle to the more normal thickness.

The maximum thickness of the White Hazle within the "channel" was found in Wager Burn (Pl. IV, 21), Bollihope Burn, where there is 62 feet of sandstone at this horizon; other sections reveal a similar thickness, for example, West Grain (Pl. IV, 33), Westernhope Burn. However, there is a possibility that thickening has sometimes taken place by coalescence with the sandstone which is the lateral representative of the marine band mentioned previously. If this is so it is impossible to separate the two and their joint thickness is reported as White Hazle; it must be remembered, however, that the basal part may represent the lower sandstone. As already pointed out, the "channel" has been delimited arbitrarily so

as to enclose an area in which the White Hazle exceeds 35 feet thick. Outside its confines the sandstone varies between nil and 35 feet thick, except in two restricted areas where the maximum is apparently exceeded (see later). The only pattern discernible in the variation is an overall decrease in thickness away from the "channel" which is more rapid in some places than others. Thicknesses in excess of 20 feet are generally found close to the "channel" whilst in the rest of the area the sandstone usually has a thickness of between 5 and 15 feet. However, there may be local and rapid increases such as that which takes place between Dun Fell Boreholes 4 and 5 (Pl. IV, 66 and 67); in borehole 4 the sandstone is only 9 feet thick, whereas in borehole 5 it has increased to 20 feet thick. The sandstone is also absent at a number of localities or else is only a foot or so thick; where sandstone proper is not developed it is usually represented by shaly sandstone or sandy shale, as in Sedling Burn (Pl. IV, 42).

The two restricted areas in which the sandstone is excessively thick do not appear to have any connection with a "channel". In Blagill Burn (Pl. IV, 60) there is 42 feet of continuous sandstone between the High Coal Sill coal and the base of the Little Limestone. The lower part of the sandstone is markedly cross-bedded and could, in part, represent the sandstone which passes laterally into the marine band; this would mean that the White Hazle had coalesced with the sandstone from which it is normally separated. On the other hand, the observed features could be explained by the down-cutting of a local erosion hollow from the base of the White Hazle which was subsequently infilled by cross-bedded sandstone. The erosion hollow would only be of local extent, however, since similar conditions have not been found elsewhere. The first suggestion invoking coalescence with the sandstone below seems most likely since no evidence of erosion at the White Hazle base has been found elsewhere. Support for this first suggestion can be found in Scraith Burn (Pl. IV, 50) where a separate distinctly cross-bedded sandstone representing the marine band immediately overlies the High Coal Sill coal; replacement by sandstone of the sandy shale which normally separates it from the White Hazle would give rise to the conditions found in Blagill Burn. In fact, the sections from Blagill Mine (Pl. IV, 61), to the east of the burn, and Thorngill West Mine (Pl. IV, 62), to the west, do bear this hypothesis out since

a prominent shale was recorded in the middle of the sandstone in each mine. The actual White Hazle is thus only represented by the upper part of the sandstone in Blagill Burn, whilst in the mine sections it is a distinct unit 3 feet and 7 feet thick respectively. It is possible that a similar state of affairs exists at the other three separate localities (Pl. IV, 9, 57 and 59) where there is continuous sandstone between the High Coal Sill coal and the Little Limestone base; in none of the sections is the sandstone as thick as in Blagill Burn, however. Even so it is quite thick in the region of the Derwent Mines where 24 feet was recorded in Jeffries Engine Shaft (Pl. IV, 9). This thickness is less than that found in Jemmy's Shaft (Pl. IV, 8), the other locality outside the "channel" at which the sandstone is over 35 feet thick. At this latter locality there is 37 feet of sandstone developed in spite of the base being 8 feet above the High Coal Sill coal. However, it has already been shown that the sandstone which is the lateral representative of the marine band has a variable position above the High Coal Sill coal; therefore, it could still form the lower part of the thick sandstone recorded in Jemmy's Shaft.

Normally, the sandstone grades up from the underlying sandy shale and nowhere has it been observed to have a markedly erosive base. There may be local scours at the base but they are of no great magnitude. It seems very probable that sandstone develops at the expense of the underlying shale with the ultimate being reached where there is coalescence with the sandstone below as described above. In its lower part the sandstone is fine grained and usually it contains shaly bands; upwards the fine grained lithology grades into a medium grained one. Where it is thick there are sometimes lenses of coarse grained material interbedded, whilst in Middle Grove Hush, half a mile north-north-east of Cowhorse Hill, almost the whole of the 24 feet thick sandstone is coarse grained; the latter is a very abnormal occurrence, however. It has already been mentioned that in a number of cases the whole of the sandstone is represented laterally by shaly sandstone or sandy shale; the latter may contain ironstone nodules, as in Sedling Burn. At other localities, even where the sandstone is quite thick, its upper part may be distinctly shaly. Normally, the sandstone has a massive character which is more marked than that found in both the High and Low Coal Sills. Obviously it loses this character where a shaly nature becomes apparent and it is quite soft and friable.

Apart from the coal which overlies this part of the White Hazle, coal has been found within the sandstone at two separate localities. In West Beck (Pl. IV, 40), approximately one and a half miles north of Langdon Beck, the seam is 2 to 3 inches thick and lies 4 feet 6 inches above the sandstone base; it has not been discovered elsewhere in the vicinity, however. Two feet of fossiliferous sandstone which contains crinoid ossicles and Orthotetids occurs above it. At a similar horizon, coal was also recorded in two adjacent shafts of the Derwent Mines; however, it was not found in any of the other shafts in the vicinity. In Jemmy's Shaft (Pl. IV, 8) the seam was found to be 1 foot thick whilst in Whiteheaps Shaft (Pl. IV, 6) it was 1 foot 6 inches thick; no details of the surrounding sandstone are known. The very local extent of the seam is illustrated by the fact that it has not been discovered elsewhere; accumulation of peat during this period must, therefore, have been very restricted. However, there are other places where plant rootlets in situ do occur at this horizon. They are often, but not invariably found in the middle of the thick "channel" sandstone which is exposed in the streams flowing into Bollihope Burn (Pl. IV, 19, 21 and 22). In these sections the sandstone with plant rootlets is generally overlain by up to 12 feet of fossiliferous sandstone which contains Orthotetids, crinoid ossicles and bryozoans; intermixed with the fossils there is sometimes a little plant debris and occasional coal fragments. Within the fossiliferous sandstone of Howden Burn (Pl. IV, 22), Bollihope, a number of richly limonitic fossiliferous pockets with a diameter of up to 1 foot were discovered. It seems possible that they are the weathered remains of bullions which originally had an iron-rich calcareous cement. The intimate relationship of "sandstone with plant rootlets" and "fossiliferous sandstone" appears to be restricted to the thick "channel" deposit. Also confined to the "channel" is the fossiliferous nature of the sandstone, except for the isolated occurrence in West Beck. Therefore, it seems possible that the subsidence which allowed the accumulation of such a thickness of sandstone also controlled the encroachment of marine conditions into the restricted area. Plant rootlets have been found within the sandstone at other localities but they are never common.

The presence of fossils within the thick "channel" sandstone could be taken to support the suggestion that the lower part of it represents

the sandstone which passes laterally into the marine band of Cow Burn. If it does, a maximum of 40 feet must be so designated. However, it is impossible to ascertain the true relationships since no absolutely diagnostic characteristics can be recognized.

Comminuted plant debris is common in the lower part of the sandstone. Also reasonably common in this part are so-called "annelid tracks". Shale fragments are found in the lower few feet too. The characteristic curly-bedding caused by interfering ripples is best developed in the basal part of the sandstone but it can usually be recognized to some extent throughout. Cross-bedding is the most obvious sedimentary structure and it can often be recognized throughout the sandstone, but usually it is weak or absent in the upper part. It is most marked within the thickest developments of the sandstone but individual units are generally not large (around 1 to 2 feet thick) and it has not proved possible to trace them over any great distance laterally.

Almost invariably, the upper part of the sandstone contains abundant plant rootlets in situ and occasional associated Stigmaria, the rootlets being present even when the overlying coal seam is not developed. Plant remains are just as common in the shaly lateral representative of the sandstone.

The coal seam which overlies this part of the White Hazle is not a persistent horizon but it has been found at several localities. It seems very probable that it had a more widespread distribution originally because fragments of coal are often found in the overlying sandstone at localities where the seam is now absent; there thus appears to have been some erosion of the seam following its formation. The presence of coal fragments in the overlying sandstone would also appear to indicate that the peat from which the seam was formed had at least become lignified before erosion, since peat itself would probably have become comminuted upon erosion. The maximum thickness of the seam on the Block is attained in the Hartleyburn Shaft borehole, in the north-west part of the Block, where it is 2 feet 2 inches thick. This thickness is abnormally high for the Alston Block, and it is more closely related to that attained in the Northumbrian Trough, which is not surprising since the borehole was only drilled some 100 yards to the south of the Stublick Fault, one mile west-south-west of Coanwood. The greatest thickness of the seam found else-

where on the Block was recorded in the Derwent Mines (Pl. IV, 5 and 8) where a thickness of 1 foot is attained; however, even though the coal is so thick in this region it is not a persistent horizon. Normally, the seam is less than 3 inches thick and is often as thin as 1 inch or less, even in the north-west part of the Block. Overall, it is least persistent to the south in Teesdale; in the north-west part of the Block it appears to be a more reliable horizon and is the seam which should strictly be named the Little Limestone Coal. Lithologically, it is similar to the other coals in the Group. That is to say, it is bright and brittle but may become shaly in places; the semi-anthracitic nature is also developed.

THE ASKRIGG BLOCK AND COTHERSTONE (STAINMORE) SYNCLINE

Introduction

In this region, which forms the southern part of the Northumbrian Fault-Block, a characteristic Coal Sills Group succession similar to that of the Alston Block is not readily apparent since coals are only infrequently developed and the sandstones are apparently much more lenticular. In addition, a prominent chert development, the Main Chert, enters the lower part of the sequence in the northern part of the region and eventually forms the complete succession between the Main and Little Limestones farther south. A further factor of importance is the relative abundance of thin lenticular marine horizons in the succession as compared with the number found in the region farther north. Despite the obvious differences from the sequence on the Alston Block, the arenaceous beds have repeatedly been referred to as Coal Sills by a number of authors, including Dakyns et al. (1890 and 1891), and the complete sequence above the Main Chert in the Cotherstone Syncline has been named the Coal Sills Group (Reading, 1954 and 1957). Therefore, it is intended to retain these terms for this region despite the relative paucity of coals. The succession is then conveniently divisible into two parts with the Main Chert at the base overlain by and passing laterally into the Coal Sills Group, the two combined forming the upper part of the Great (=Main) Cyclothem. The generalized stratigraphy for the region is illustrated on the two sections given in Fig. 29.

Thickness Variation

Of particular importance is the regional variation in thickness of the beds illustrated on Plate III. The isopachytes are based on thicknesses given by Wells (1955a and 1955b), Reading (1954 and 1957), Rowell and Scanlon (1957a, modified by kind personal communications from Dr. Rowell), Wilson (1957 and 1960) and Hicks (1958).

A feature which has helped in the interpretation of measured sections over part of the region is the "pipe bed" which is developed at the top of the Little Limestone. This "pipe bed" was originally discovered by Rowell (1953) and has subsequently been reported to occur over a large part of the Askrigg Block by Wells (1955a and 1957), Rowell and Scanlon (1957a), Hicks (1958) and Wilson (1957 and 1960). It is characterized by cherty tubes, probably infilled annelid borings, which descend into the limestone from a thin overlying siliceous bed. Recognition of the Little Limestone "pipe bed" has, in particular, enabled the Main Chert and the overlying Richmond Chert Series to be differentiated in the region to the north of Swaledale and east of Arkengarthdale where the two are of similar lithology (siliceous platy limestone) and no Coal Sills Group sediments separate the Main Chert from the Little Limestone.

As on the Alston Block, the isopachytes are idealized to some extent, but, nevertheless, they indicate the overall regional pattern. In the region due south of the Moor Cock Inn basic information is very scanty and the position of the isopachytes below 25 feet is uncertain. However, they must trend in an approximate south-west direction since it is reasonably certain that the Main and Little Limestones have coalesced on Dodd Fell Hill and Ingleborough, whereas farther west near Widdale Great Tarn and at the north end of Whernside, Coal Sills Group sediments separate the two limestones. Consequently, the isopachytes for thicknesses below 25 feet are only tentatively shown on Plate III. Three important features regarding the thickness variation in this region are apparent, as follows:-

- (i) The Cotherstone Syncline, centred upon Barnard Castle, acted as a basin of deposition relative to the surrounding area, and in it sediments up to at least 150 feet thick were able to accumulate during this period. The western limit of this basin appears to be around the longitude of Barras. It is impossible to delimit the eastern margin because of lack of information,

the beds to the east being completely covered by newer rocks. The basin of deposition occupies approximately the same position as the present structural syncline and its northern and southern margins were probably controlled by the then existing representatives of the present-day Lunedale - Butterknowle Fault System to the north and the Stainmore Summit - North Spanham - South Spanham Fault System to the south.

(ii) The Dent Fault System, which forms the western margin of the Askrigg Block, is probably the present-day representative of a contemporaneous hinge-line which separated an area of thicker deposition to the west (the Ravenstonedale Gulf) from the Block on the east with its thinner sediments. However, even on the Block there is a distinct westward thickening of the sediments towards the Dent Faults, a thickness of at least 150 feet being deposited during this period adjacent to the fault system on the north-west side of Baugh Fell; this thickening towards the west can be explained by the western margin of the Block sagging in sympathy with the region of subsidence on the opposite side of the hinge-line where there was probably even thicker sedimentation. Thus, the Dent Fault System is similar to the Stublick Fault System, and possibly the Pennine Fault System, in that it separates a relatively stable region with thinner sediments from a region of subsidence with thicker deposits. To what extent this latter region acted as a trough of deposition during Coal Sills times is uncertain due to lack of evidence, but there is some indication in the Hutton Roof area, near Kirkby Lonsdale (see later), that it was similar to the Northumbrian Trough. If Rowell and Scanlon's (1957a) thicknesses (308 feet in Mousegill Beck and 222 feet in the River Belah) for the region to the west of Barras are accepted, there would be evidence for a considerable trough. However, the interpretation

of the above poorly accessible and indifferently exposed sections is open to question since a student-mapping course from Durham, led by Professor K. C. Dunham and Dr. G. A. L. Johnson, recorded smaller thicknesses of strata between the Great and Little Limestones. The thicknesses recorded, which are in the region of 120 feet, could, however, indicate some thickening across the Dent Faults.

(iii) Traced southward and south-eastward across the Askrigg Block, there is a gradual regional thinning of these beds which form the upper part of the cyclothem until they wedge out completely and allow the Little Limestone to rest directly on the Main Limestone. The line which indicates where the beds die out runs approximately east-west along Wensleydale from slightly north of Leyburn to Hawes, where it swings to run south-westward (Pl. III). Its position south-west of Hawes is rather tentative but, as already mentioned, it seems probable that the Main and Little Limestones have coalesced on Dodd Fell Hill and Ingleborough respectively, and, therefore, the line must run to the west of these prominences.

The position of the line east of Hawes is somewhat different to that shown by Wells (1955a and 1955b) since further information presented by Wilson (1957 and 1960) warrants a re-interpretation of the situation. Wells preferred to embrace the 9 feet of beds developed on Thoraby Common (Pl. IV, 96), south-west of Countersett, and the 2 feet 6 inches of sediment found on Wether Fell (Pl. IV, 95), due south of Hawes, within the main area of deposition. However, because of the proximity of sections in which the Main and Little Limestones have coalesced, it seems that a more reasonable interpretation would be that the two localities are situated within small and separate "basins" of sediment south of the main area of deposition; they would then be similar to the isolated occurrences of shale and chert discovered at this horizon by Wilson (op. cit) at Cover Scars (Pl. IV, 97), one mile south of

Middleham, and in Hindlethwaite Gill (Pl. IV, 98), two miles north-east of Woodale. Thus, as might be expected, it would appear that there were small and restricted "basins" of sediment developed to the south of the main area of deposition; four have been discovered so far and it is quite possible that more exist.

It would be convenient to explain the observed regional thinning by an unconformity at the base of the Little Limestone which progressively transgressed towards the Main Limestone southwards until in Wensleydale the two limestones came into contact. Wells (1955a and 1955b) cited evidence from Wensleydale which indicated the presence of such an unconformity but he also stated that "north of Wensleydale there was no evidence in any one section for an erosion surface beneath the Little, although comparison of all the sections made it most probable that one was present". If an unconformity of such magnitude were present it could reasonably be expected to continue southward where it would then account for the marked thinning of the Main Limestone noted by Wilson (1957 and 1960) in Coverdale. However, the thinning of the Main Limestone has already been shown not to be due to this since sediments intervene between it and the Little Limestone where the Main is virtually at its thinnest; also, where the Main and Little Limestones are in contact to the south of Wensleydale there is no perceptible break between them, the Little Limestone only being definitely recognizable where the "pipe bed" is developed at the top of it. Thus, the presence of a widespread unconformity to explain the regional thinning of the beds between the two limestones seems unlikely. The features noted by Wells in Wensleydale may indicate a local and minor unconformity but, also, they could quite well mark the natural wedging out of the beds between the Main and Little Limestones.

It seems most likely that the regional thinning and wedging out of the beds is due to the supply of material

from the north failing to the south and south-east. As might be expected in these circumstances, the southern limit of sandstone lies to the north and north-west of the extreme limit of deposition, shale and chert forming the beds between the two limits. The overall picture must be similar to that envisaged by Hind (1902) and later expanded by Johnson (1960) to explain the formation of the Yoredale sequence, since, in simple terms, both considered that wedges of sediment from the north had been pushed into the massive limestone facies of the south. Thus, to the north, during Coal Sills Group times, the influx of sediment halted the formation of limestone, whereas to the south, limestone deposition was continuous except where it was halted by the formation of the small patches of shale and chert which are found to the south of the main area of sandstone, shale and chert deposition. In the above circumstances it might be expected that the Main Limestone would be thicker in the south than in the north, since presumably it was forming in the south whilst sediment was inhibiting its accumulation to the north. However, overall it is not thicker in the south, and in places is much thinner. The much greater length of time needed for the formation of an equivalent thickness of limestone as compared with the sediments would partly account for this; also, it has been shown that the Main Limestone thins to the south against a late P_2 uplift which was developed along the line of the Middle Craven Fault. This uplift could also have contributed to the wedging out of the sediment since it would tend to hinder the free flow of currents across the region and therefore cause "backing-up" of sediment.

Stratigraphy

At its base, the sequence is delimited by the top of the Main (= Great) Limestone whilst the top is formed by the base of the Little

Limestone, the latter also being known as the Rey Cross Limestone on the southern limb of the Cotherstone Syncline.

Only a summary of the stratigraphy of the region will be given here. Further detailed information can be found in the works of the various authors from which this account has mainly been compiled; a list of these authors and the positions of the areas covered by each of them are given in Fig. 2. The succession in this region is conveniently divisible into two parts, as follows:-

The Main Chert, lying immediately on or a short distance above the Main Limestone over much of the region and passing laterally and upwards into the Coal Sills Group and its equivalents.

The Coal Sills Group and its equivalents, lying above and/or laterally representing the Main Chert and consisting essentially of shales and sandstones with subsidiary lenticular marine bands and occasional thin coal seams.

These two divisions are systematically dealt with below.

The Main Chert.- Wells (1955a and 1955b) has shown that an extensive region of primary chert deposition occupied a lobate area on the Askrigg Block extending from Hoove south-westward to Great Shunner Fell and south-eastward to Richmond (Plate III). The eastern boundary of the lobate area has been slightly modified as compared with that of Wells, but this is only a small matter of detail. North of Hoove, a tongue of chert extends from this lobate area and dips into the Cotherstone Syncline, beneath which structure Wells considered the boundary of chert deposition to close. However, the existence of up to 4 feet of chert in Hargill Beck (Pl. IV, 80) on the north side of the syncline has been proved during the present work, so that it now seems likely that the tongue extends at least to this position northward. A small occurrence of chert to the north-west and apparently isolated from the principal centre was proved by Rowell and Scanlon (1957a) on the northern slopes of Winton Fell, north and north-east of Bastifell. Also, chert is developed to the south of the principal centre in three of the small and restricted "basins" which occur to the south of the main area of deposition (Pl. IV, 96, 97 and 98). The boundaries of the principal area and the small area to the north-west of it in no way represent the edges of basins of chert deposition, but merely mark the position where

chert passes laterally into shale; the exact configuration of the small areas to the south of the principal area is uncertain, but it is probable that they comprise very small isolated patches of chert with no lateral passage into shale even though in each case they are overlain by thin shale developments.

Usually, the chert rests directly on the Main Limestone top but occasionally within the main area of chert development the two are separated by shale which has a maximum observed thickness of 18 feet in Huggill Sike (Pl. IV, 83); generally, however, if shale is present at this horizon it is much thinner, as in Ducking Tub Gill (Pl. IV, 92). At some places within the principal centre, particularly towards the southern margin, the Main Chert forms the complete succession between the Main and Little Limestones, as, for example, in Moresdale Gill (Pl. IV, 94). However, its greatest thickness is not attained in such a section since the maximum of 40 feet is found in West Stonesdale (Pl. IV, 86) where the chert is overlain by a considerable thickness of Coal Sills Group sediments. The thicknesses in measured sections are shown on Plate III; as would be expected, there is a general thinning towards the margin of the principal area, as in Jingle Pot Gill (Pl. IV, 93), and there must be rapid thinning towards the margins of the smaller areas.

Wells (1955a and 1955b) has described in detail the variations in lithology and petrography of the Main Chert which is always represented by either siliceous mudstone, a chalcedonic flinty rock or fossiliferous siliceous limestone. The bulk of the chert is considered to be of primary origin, probably deposited as a gel, although the chalcedonic rock which forms the upper part of it in the Bowes area has probably been derived by secondary silicification. It has been postulated (Wells, *op. cit.*) that this secondary silicification took place penecontemporaneously, before complete lithification, because of the widespread distribution of the phenomenon at a similar horizon.

Such a large area of predominantly primary chert presents some problems as to the source of the silica required for its formation and its conditions of deposition. It is known that at the mouth of a river carrying dissolved silica there will be deposition of the latter because of the low concentration of silica possible in sea water (0.02 grams per ton, as compared with an average of 17 grams per ton in river water are

the figures quoted by Rankama and Sahama, 1950). This suggests the presence of a silica-laden river (or rivers) flowing into the sea to explain the formation of the chert. Also, the heavy load of silica required might be taken to indicate flow from a tropical region where lateritic decomposition was taking place, since it is known that dissolved silica is often abundant in river waters from such an area. From the foregoing, it can easily be seen how Sargent (1923 and 1929) visualized the formation of the chert as a process of simultaneous deposition of calcium carbonate and colloidal silica, as a gel, in a shallow epicontinental sea off the mouth of a large river. The physico-chemical details of the method of precipitation have been discussed by Wells (1955a and 1955b) who showed that it is not a simple process of flocculation by electrolytes but one in which calcium bicarbonate acts as an important precipitant.

Since it can be reasonably construed that the dissolved silica was brought into the sea by a river or rivers, there ought to be some evidence of a channel or channels in beds of equivalent age to the north. Prominent channels have already been shown to exist on the Alston Block and they encroach to some extent into the Cotherstone Syncline and on to the Askrigg Block (see later). However, there is a substantial difficulty here in that the washout-channels were formed after the chert; evidence for this exists in the Stanhope Quarries where it can be seen that the channels were cut and alluviated after the formation of the High Coal Sill, whereas the chert which is equated with the Main Chert was formed prior to the formation of the Low Coal Sill. Also, in Hargill Beck (Pl. IV, 80), on the north side of the Cotherstone Syncline, a subsidiary washout-channel which branches off from the major channel overlies and probably cuts into the Main Chert at the extreme tip of the tongue which extends northward from the principal area; thus, in spite of its intimate association with the chert, the channel cannot have carried the silica-laden water from which the chert was formed. On the other hand, the contemporaneous "channel", which has been shown to exist on the west side of Hudeshope, was probably operative during the period in which the chert was formed; also, the southern end of its course is closely related to the tongue of chert which extends northward from the principal area (Plate III and see later). Thus, it seems possible that the waters of this

"channel" were responsible, at least in part, if not completely, for carrying into the area the dissolved silica from which the Main Chert was formed. The small patches of chert on the Alston Block were probably formed on the flank of the "channel" where conditions were locally suitable. The detached patches on the Askrigg Block are relatively closely associated with the main area and probably bear affinities to it in their mode of formation.

The Coal Sills Group and its equivalents.- As already stated, the Coal Sills Group passes laterally into and also overlies the Main Chert. However, where chert forms the whole of the upper part of the cyclothem above the limestone member, as it does in places (Pl. IV, 94), no sediments of Coal Sills lithology are developed. Conversely, where chert is not developed at all the Coal Sills Group must form the complete upper part of the cyclothem.

True Coal Sills Group sediments (interbedded sandstones, shales and occasional marine bands and thin coals) occur to the north and north-west of the line shown on Plate III which marks the southern limit of Coal Sills sandstones. South and south-east of this line only shale is developed between the Main and Little Limestones, except where the Main Chert is also present; the shale is thus equivalent to the sediments of typical Coal Sills lithology which are developed farther north. The Cleveland Hills Borehole (Pl. IV, 99), which was drilled near Chopgate some 24 miles east of Richmond, proved a sequence consisting essentially of shale, limestone and chert, but no sandstone, at this horizon. Thus, in the concealed area to the east of the Block, comparable conditions to those found on the exposed part of the Block must have existed, with sandstone dying out at a similar latitude or even farther north than it does in the extreme eastern part of the exposed area. To the north-east of the Moor Cock Inn the southern limit of sandstone is reasonably well defined. However, the limit shown by Wells (1955a and 1955b) in the vicinity of Keld has been somewhat modified on the basis of Wells' own published information as well as that of Dakyns et al. (1891) and Rowell and Scanlon (1957a). The difference is one of detail, however, since the limit is only shifted some 3 miles farther south-east so that the boundary runs south-east of Kisdon and Great Shunner Fell where sandstone is known to occur in beds of this age. South of the Moor Cock Inn, information regarding the wedg-

ing out of sandstone is scanty and the boundary shown on Plate III is only tentative; however, there is evidence to show that sandstone is present on Whernside (Hicks, 1958) and near Widdale Great Tarn (Dakyns et al., 1890), whereas it seems likely that beds of equivalent age have died out completely before Dodd Fell Hill and Ingleborough are reached. The boundary limiting the extent of sandstone must, therefore, run between the two sets of localities. It has been shown (Wells, op. cit.) that the upper-most sandstone of the Group, that is to say, the equivalent of the White Hazle of the Alston Block, has a spread farthest south and east. Thus, the limit of sandstone shown on Plate III in general refers to this horizon.

On the north flank of the Cotherstone Syncline there are three sandstones present in the Coal Sills Group sequence, as seen in Hargill Beck (Pl. IV, 80); in this feature the sequence is similar to that of the Alston Block. Farther south, on the southern flank of the syncline and over much of the Askrigg Block, there are generally only two sandstones, as at Thorpe Scar (Pl. IV, 84), and towards the limit of sandstone deposition only one, as, for example, in East Grain (Pl. IV, 87). However, exceptions to this general rule do occur at certain places; for example, in Needlehouse Gill (Pl. IV, 91) and other places in the Rawthey valley it has been shown by Rowell and Scanlon (1957a) and Hicks (1958) that three separate beds are present in the sequence.

Most of the sandstones are of sheet-like form with gradational bases. However, they are apparently more lenticular than the sheet sandstones of the Alston Block, but it seems possible that individual lenses are developed at a particular horizon and, therefore, are correlatable with each other. Thus, there is probably not a hap-hazard distribution of sandstone lenses but an orderly sequence in which at the same horizon sandstone passes laterally into shale or shaly sandstone and back into sandstone. The actual correlation of the sandstones with those on the Alston Block is not certain. However, where three sandstones are present in the sequence, as on the northern limb of the Cotherstone Syncline and in the Rawthey Valley, there is evidence to suggest that they are probably equatable, in ascending order, with the High Coal Sill, the fossiliferous sandstone and the White Hazle of the Alston Block. Farther south, where only two sandstones are developed, it is known that the equivalent of the White

Hazle persists so that one of the two lower sandstones must either lens out or coalesce with one of the two remaining layers. With this in view, it is tentatively suggested that the fossiliferous sandstone equivalent may coalesce with the White Hazle equivalent if it does not lens out completely, since there is some evidence (see later) indicating that it is the lower sandstone, that is to say, the High Coal Sill equivalent, which persists along with the White Hazle equivalent. Towards the limit of sandstone deposition only the White Hazle equivalent persists and it eventually wedges out as described above.

These sandstones with sheet-like form vary considerably in thickness. A maximum thickness of over 50 feet has been recorded in the north-west part of the Askrigg Block in Faraday Gill (Pl. IV, 85), but here two sandstones have probably coalesced. Thick sandstones also occur in the Cotherstone Syncline and on the northern part of the Askrigg Block, but normally the thickness is 30 feet or less. Quite naturally, the greater thicknesses occur well to the north and west of the limit of sandstone, whilst the smaller thicknesses are found closer to the feather edge of sandstone deposition.

So far as grain size is concerned, the sheet-like sandstones are fine, fine to medium or medium grained, grading up from the shale below them through very fine grained shaly sandstone. As on the Alston Block, their tops are usually quite sharply divided from the overlying strata. A flaggy nature is often apparent, particularly in the lower part of the sandstones, but they are often quite massive, especially towards their tops and also where they are thick. Cross-bedding has been noted and occasionally ripple-marks are well developed, the latter usually being of the interfering type which give rise to curly bedding. "Annelid tracks" are present in the sandstones and their profusion in the White Hazle equivalent due south of Sleightholme Beck, in the northern part of the Askrigg Block, gave rise to the name "wormy grits" for this horizon (Dakyns et al., 1891).

The sandstone tops occasionally contain plant rootlets but the latter are not nearly so frequently present or as abundant as on the Alston Block, where the upper parts of the sandstones are almost invariably rich in rootlets. In fact, rootlets in situ only occur in the sandstones well to the north, north-west and west of the limit of sand-

stone deposition. The lower sandstone, which is equated with the High Coal Sill, often contains rootlets in the region of the Cotherstone Syncline, as in the Rowton Sike boreholes (Pl. IV, 81). Farther south rootlets in it are much rarer but they have been recorded. It is partly because of their presence, however, that the lower of the two sandstones on the Askrigg Block is considered to be the equivalent of the High Coal Sill rather than the fossiliferous sandstone since, where three sandstones are developed, the middle one has never been found to contain any plant remains in situ. The White Hazle equivalent often does contain rootlets and in the Rowton Sike area (Pl. IV, 81), in the Cotherstone Syncline, it is similar to its parent on the Alston Block in being characteristically divisible into two components. At the above locality, a sandstone with a rooty top is overlain by a very thin layer of soft coal and then a thin, fossiliferous, occasionally calcareous sandstone, the latter being the lowest component of the overlying cyclothem. This division into two has not been recorded farther south on the Askrigg Block, but there are various references (Rowell and Scanlon, 1957a; Hicks, 1958) to the sandstone immediately beneath the Little Limestone having a rooty or, alternatively, a fossiliferous calcareous top. Where a rooty top is present, as in Goodham Gill (Pl. IV, 88), it must be that the sandy layer at the base of the overlying cyclothem was not formed. On the other hand, there cannot have been any colonization of the sandstone by plants where it has a fossiliferous calcareous top and rootlets are completely absent, as in Round Ing Gill (Pl. IV, 89). There are also the cases where neither rootlets nor a fossiliferous calcareous nature are developed at the top of the sandstone beneath the Little Limestone, as, for example, in Faraday Gill (Pl. IV, 85).

On the Alston Block, the course of an infilled contemporaneous "channel" containing fine and medium grained sandstone has been traced. The probable continuation of this "channel" runs through Easter Beck (Pl. IV, 78) close to the latter's confluence with Grassholme Reservoir in the Cotherstone Syncline (Pl. III). Here, a thick medium grained sandstone lies 4 feet above the Great Limestone top. No trace of the "channel" has been found farther south so that it can be reasonably presumed that it died out. Thus, there is a continuation of the contemporaneous "channel" southward to almost connect up with the area of chert,

the silica for which it is postulated was transported into the area now occupied by the chert by the waters carried along the "channel".

Also on the Alston Block, the courses of sandstone-filled washout-channels have been traced. These channels cut deeply into the underlying strata whereas the sandstone-filled contemporaneous "channel" was formed synchronously with the sediments in which it is contained and with which its fill probably interdigitates. Washout-channels similar to those on the Alston Block have also been recognized in the area under consideration, but they are neither as prominent nor as numerous as farther north. However, they occur at the same horizon and are, therefore, at least indirectly related to those on the Alston Block. It has already been pointed out that the major channel of the Alston Block can be traced into the Cotherstone Syncline where it is seen cutting into the Great Limestone in the vicinity of Borrowdale Beck, three miles east-north-east of Brough. South-west of the above locality the channel is lost since it trends into the area where rocks of this age have been removed by erosion. However, it seems possible that the infilled channel swings round to a south-east course farther south, since on Baugh Fell (for example, in Ceaseat Beck, Pl. IV, 90) and part of Rise Hill a channel which is infilled with coarse, very coarse grained, and frequently pebbly sandstone appears to form the continuation of it (Pl. III). In this region the Main Limestone is never cut into by the channel and the channel sandstone never attains the thickness it reaches farther north, the maximum being a little over 25 feet thick. On the other hand, the channel-fill sandstone has a much wider spread (Pl. III) than in the north. In addition, it has been shown (Hicks, 1958) to wedge out completely to the south-east, north-east and south-west in a manner suggesting that it is the fan-deposit at the seaward end of a washout channel. The coarse grained sandstone filling the channel in this region has been found to contain up to 0.8 per cent garnet (Hicks, op. cit.), a mineral which has not been discovered in such abundance in the channel sandstones farther north despite a careful search. This could be taken to indicate that the channel deposit of Baugh Fell is not directly related to the major channel last seen to the north in Borrowdale Beck. However, the two channel sandstones match each other in respect of their coarse grain size and relative abundance of feldspar, both features being completely atypical

of any other sandstone in the Coal Sills Group. Even if the two channels do not connect to form a single channel it is virtually certain that they occur at the same stratigraphical horizon since they are both overlain by the most prominent and widespread coal seam in the sequence, the High Coal Sill coal. It could be that the two are connected and that the garnet has been brought in by another channel which joins the major channel south of Borrowdale Beck as indicated on Plate III. The only other channel recognized in this region is one which is exposed in Hargill Beck (Pl. IV, 80) on the north side of the Cotherstone Syncline. This channel cuts down to within 4 feet of the Great Limestone top and is filled with 30 feet of sandy beds. At its base the channel-fill material is composed of medium to coarse grained sandstone containing bands of small milky quartz-pebbles (up to 9 mm. in diameter); this eventually passes up into medium to fine grained sandstone with interbedded shaly bands. The above characters, by analogy with the Alston Block, indicate that the channel is one of the subsidiary type which branch off from the major channel and die out a short distance from it. Thus, this channel probably has its source on the east side of the major channel somewhere near Langdon Beck as shown tentatively on Plate III. It probably dies out beneath the Cotherstone Syncline, although there is just a possibility that it persists as far south as Rovegill Beck (Pl. IV, 82) on the south side of the syncline. As might be expected, no channels have been recognized farther south apart from the one in the Bough Fell region which is the only one to transgress on to the Askrigg Block.

The coarse grained nature of the channel-fill sandstones has already been mentioned, the major channel containing much coarser material than the subsidiary one. As well as being coarse grained the sandstones are also cross-bedded, particularly in their lower parts. Their upper parts contain plant rootlets in situ, similar to some of the sheet-like sandstones whose tops were only colonized by plants well to the north, northwest and west of the limit of sandstone deposition. However, it appears that plants were able to grow farther south, and presumably seaward, along the infilled major channel top. The channel is therefore similar to the distributary channels in the Mississippi delta which when abandoned and infilled usually support a marsh-facies that extends seaward from the landward region of marsh (Fisk, 1954).

Coal seams are not commonly found in the area under consideration despite the rather widespread occurrence of plant rootlets in some of the sandstone tops. The plant rootlets are not very abundant, however, and it is probable that only in a few cases was sufficiently luxurious vegetation supported to form peat from which coal could be derived. On the other hand, if peat was formed it is quite probable that it was destroyed and washed away, since there is sufficient evidence to show that this region lay closer to the sea than the area to the north where coals are prominently developed. On the Alston Block a general southward thinning of the coal seams was noted, a feature which presumably continued into this region. In fact, the seams are confined to the extreme northern and western limits of the area and even then, except in one case, they are thin and only present sporadically. The coal seams appear to be developed at three specific horizons. In Easter Beck (Pl. IV, 78), on the south-east side of Grassholme Reservoir, and in the vicinity of Reigill (Faraday Gill), three miles south-east of Kirkby Stephen, a seam up to 3 inches thick occurs about 4 feet above the Great (= Main) Limestone top; this seam probably correlates with the one just above the Great Limestone on the Alston Block. At a higher level a seam is found which is almost certainly at the horizon of the High Coal Sill coal. It is represented by 2 inches of soft coal immediately above the washout channel in Hargill Beck (Pl. IV, 80), on the north side of the Cotherstone Syncline, and it is probably present on the south side of the syncline in Blue Cap Sike and Sleightholme Beck, but is not well exposed. At other localities, for example, the Rowton Sike boreholes (Pl. IV, 81) and the Selset Reservoir boreholes (Pl. IV, 79), no coal was recovered at this horizon although a sandstone with rootlets is present. The only other area where the equivalent of the High Coal Sill coal is developed is the Baugh Fell region where an 8 inch thick seam overlies the whole area covered by the washout-channel infilled with coarse sandstone, as, for example, in Round Ing Gill (Pl. IV, 89). Apparently, the coal only extends over the region embraced by the infilled channel and it presumably owes its presence so far south to the channel which probably facilitated the strong-growth of vegetation along its infilled top. Coal at the top of the cyclothem separating the two components of the White Hazle has only been seen in the northern part of the region in the Rowton Sike borehole

cores (Pl. IV, 81), and even then it is only a smut. From the above information it can be seen how rare coal is in the Cotherstone Syncline and, more particularly, on the Askrigg Block as compared with the Alston Block.

Whereas coals are much rarer in this region than on the Alston Block, strata containing marine fossils are more common. For instance, on the Alston Block in the four Swinhope boreholes (Pl. IV, 53, 54, 55 and 56) an average of 23 per cent (ranging between 15 and 28 per cent) of the Coal Sills Group strata contain marine fossils, whilst in the Rowton Sike boreholes (Pl. IV, 81), on the north side of the Cotherstone Syncline, 37 per cent of the equivalent strata are marine. The average proportion of strata bearing marine fossils in the Coal Sills sequence of the Alston Block is somewhat lower than that found in the Swinhope boreholes, however, so that the actual southward increase is even greater than is apparent from the above example. This increase southwards is not surprising when it is recalled that still farther south the Group is wholly represented by marine cherty beds and sometimes shale. Although distinct marine bands rich in fossils are developed, the other strata of the sequence often contain marine fossils also. The shale immediately above the Main Limestone and that above the Main Chert, if the latter is present, invariably contains fossils. Fossils are also present in shale in other parts of the sequence, for example, in the Rowton Sike boreholes (Pl. IV, 81), and they may even persist where the shale becomes silty or sandy, as in Hargill Beck (Pl. IV, 80). Some of the sandstones have also been found to contain marine fossils. In particular, where three sandstones are developed, the middle one is frequently fossiliferous in part, as in the Rowton Sike area (Pl. IV, 81) and Needlehouse Gill (Pl. IV, 91); hence its correlation with the fossiliferous sandstone above the High Coal Sill on the Alston Block. The upper sandstone, which is equivalent to the White Hazle, may also be fossiliferous, for example, in Faraday Gill (Pl. IV, 85), although in some cases this may be due to its coalescence with the middle sandstone. Where the sandstones are fossiliferous they may also be calcareous, but sometimes they are calcareous when unfossiliferous. Discrete marine bands of a completely different lithology than the beds with which they are associated are also quite common. They usually occur in shale but have been found to be present at the top or base of sandstones, in which case

they are similar to the fossiliferous sandstone type of marine horizon such as is developed in Needlehouse Gill (Pl. IV, 91). The largest number of bands discovered in any one section is three, these having been found by Dr. H. G. Reading (Reading, 1954 and 1957) in the cores of boreholes drilled at the site of Selsset Reservoir (Pl. IV, 79) on the north flank of the Cotherstone Syncline; two bands are found in a number of sections, however. The thickness of the bands rarely exceeds 2 feet and is often less than this; even so individual horizons can be traced over distances of up to four miles before they eventually lens out. Also, a wide variation of lithologies is exhibited by these marine bands, ranging through limestone, silty or sandy limestone, calcareous sandstone, sandstone and shaly sandstone, the passage from one lithology to another sometimes being traceable, as, for example, in the Bowes region where a limestone passes into fossiliferous sandstone. The bands are often extremely rich in fossils but sometimes they are virtually barren. Rowell and Scanlon (1957a) considered the fauna of all the marine horizons to be indigenous since many of the brachiopods have both valves articulated and the presence of long spines on one of the productids would appear to discount any suggestion that the shells may have been transported into the area. Faunal lists for these horizons are to be found in the various works on this region listed in the key to Fig. 2.

THE NORTHUMBRIAN TROUGH

Introduction

For the purpose of this account the Northumbrian Trough is defined as the whole area lying between the northern margin of the Alston Block and the southern margin of the stable Southern Uplands Massif, as in George (1958). A sub-division of this region into the Mid-Northumbrian Trough to the south, the Cheviot "Block" (comprising the Cheviot massif and the area to the east of it) in the centre and the Berwick Trough to the north is possible, but is of little significance here, as will be seen later. Although the Canonbie district is really situated within the Trough, it is dealt with separately below because of its marked detachment from the area of main outcrops of the Great Cyclothem in the Trough.

In the Northumbrian Trough the essentially non-calcareous part of the Great Cyclothem, to which no specific name is applicable, consists mainly

of shale and sandstone, but prominent coal seams are frequently present in the upper part of the sequence over much of the region and marine horizons are not uncommon, one being especially prominent in the south. Sections for the southern, central and northern parts of the region, which are given in Fig. 30, show that in general the sequence is considerably thicker than the equivalent on the Alston Block. The succession is not directly comparable with the Coal Sills Group type of sequence of the Alston Block, despite the presence of prominent sandstones and coals in it, since the required intimate sandstone-coal relationship is never properly developed. However, the upper part of the sequence above the Snope Burn Band in the south-western part of the Trough has been referred to as "Coal Sills" (Trotter and Hollingworth, 1927) because of the presence of coal seams, but the analogy is somewhat contentious.

Information regarding the detailed stratigraphy of the complete succession is unevenly distributed and on the whole rather scanty, mainly because of poor exposure. In some places, however, sections have become available from boring programmes, such as that carried out in the region to the west and north-west of Amble by the Co-operative Wholesale Society to explore the extent of the Shilbottle coal which underlies the Great Limestone. Mine workings for coal, witherite and galena at Fallowfield have also provided useful stratigraphical details. In addition, much is known about the upper part of the succession where it has been worked extensively for coal in the southern and northern parts of the region. Much of the above information with additional field observations have been embodied in the Summaries of Progress of the Geological Survey (1920 to 1931), the Survey Memoirs (Fowler, 1926; Carruthers et al., 1927; Carruthers et al., 1930; Fowler, 1936; Trotter and Hollingworth, 1932; Dunham, 1948), Smith (1912), Hedley and Waite (1928) and Johnson (1959). At a few localities a certain amount of original field-work has been carried out and, in addition, the author assisted in the logging of boreholes drilled during the re-opening of Fallowfield Witherite Mine in 1959. All these sources have been used to compile the synthesis which follows.

Thickness Variation

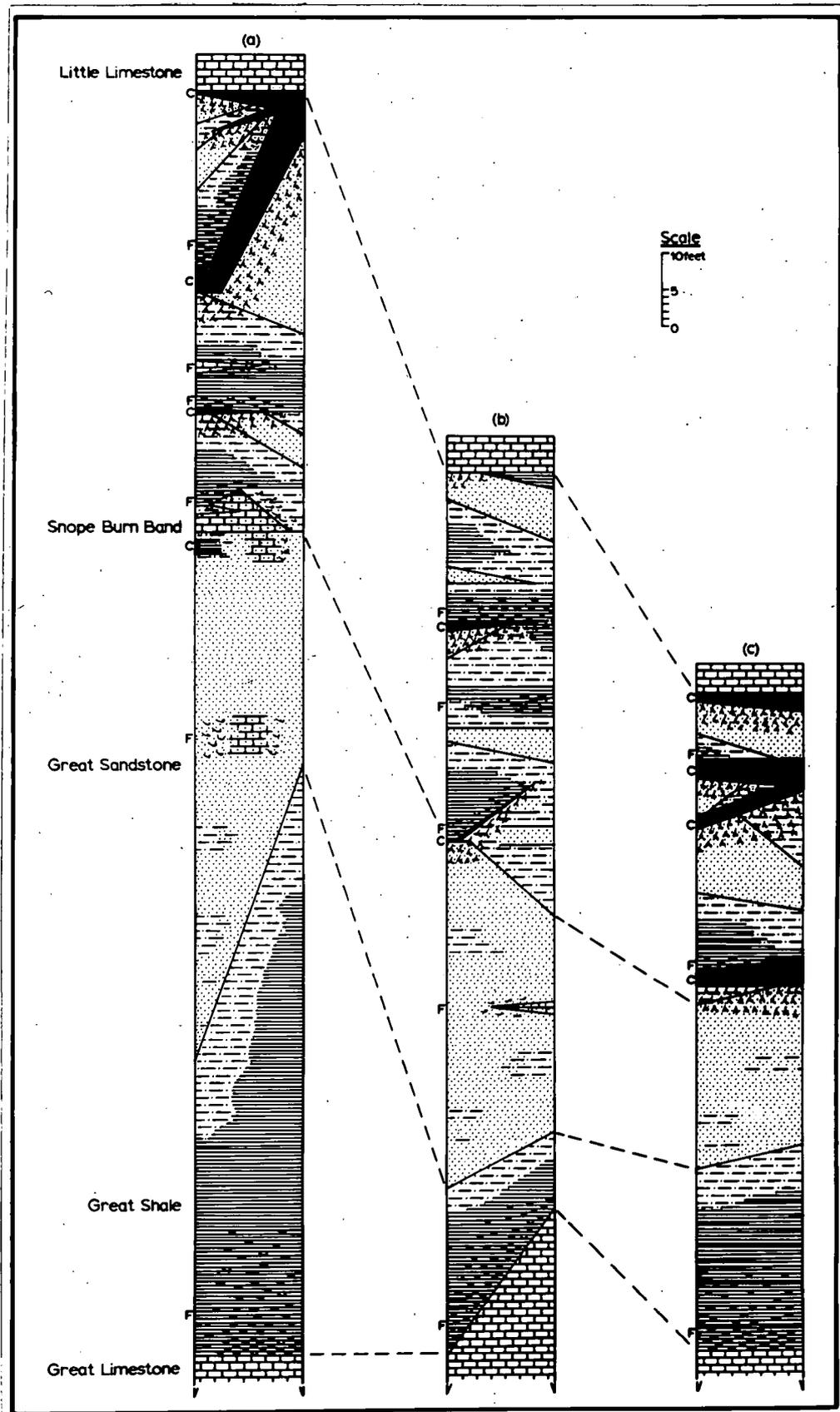
The rapid thickening of the beds passing from the northern part of the Alston Block into the southern part of the Northumbrian Trough is illustrated on Plate III. Thus, in a distance of between five and ten miles

Fig. 30.

Generalized sections of the Great Cyclothem sequence above the basal limestone in the Northumbrian Trough. Legend as Fig. 19.

- (a) Southern region.
- (b) Central region.
- (c) Northern region.

Fig. 30.



across the Stublick Faults, there is a northward thickening from 75 feet on the Block to at least 200 feet in the Trough. North-north-east of Fallowfield, which lies in the southern part of the Trough, no information regarding the full thickness of the beds exists until the Brinkburn Estate flanking the River Coquet is reached. Here, a general section, probably taken from one of the Chirm pits, gives a thickness of 180 feet for the succession. However, in the region to the north of the River Coquet, between Hazon and Alnmouth, several borehole sections indicate that there is a distinct thinning of the sequence as compared with that found farther south in the Trough. In this region north of the Coquet a Tumbler Bed lithology often replaces a considerable proportion of the lower part of the thick shale at the base of the sequence (see Great Limestone chapter), but even if the Tumbler Beds are counted as part of the sequence under consideration some thinning is still apparent. If the Tumbler Beds are considered as part of this succession there is a variation in thickness of between 134 feet and 175 feet. On the other hand, if the Tumbler Beds are taken as part of the Great Limestone, which is more correct, the succession varies in thickness between 84 feet and 134 feet, with an average of 99 feet. Slightly farther north in Howick Burn, west of Howick, a similar situation to the above exists, the respective thicknesses being 159 feet (counting the Tumbler Beds in this sequence) and 126 feet (counting the Tumbler Beds as part of the Great Limestone). Thus, in the region north of the Coquet, although there is an irregular and considerable variation in the thickness of the sequence, it is definitely thinner overall than farther south. It seems apparent, therefore, that after the initial rapid thickening in the southern part of the Trough there is a northward thinning from somewhere north of Fallowfield towards the region between the Rivers Coquet and Aln. Whether the thinning is gradual or irregular cannot be ascertained from existing information, but the effect seems to continue northwards since in the Lowick area, towards the northern extremity of the Northumbrian Trough close to the Southern Uplands Massif, the sequence is only 92 feet thick.

The borehole sections from between Hazon and Alnmouth illustrate that there can be a considerable local variation in the thickness of the sequence. However, the variation here is caused to some extent by the variable development of the Tumbler Beds, whereas in the Fallowfield Mine workings a vari-

ation in thickness of between 158 feet and 248 feet within less than one mile has been proved where the above factor is not operative. Local variation in thickness similar to the above probably takes place over the whole area but it has not become evident because of the paucity of detailed information. In such circumstances the isopachytes drawn on Plate III for the southern part of the Trough must be considerably idealized.

Important factors pertaining to the regional thickness variation in the Trough are as follows:-

(i) The Stublick Fault System, which forms the boundary between the northern margin of the Alston Block and the southern part of the Northumbrian Trough, must have acted as a contemporaneous hinge-line separating an area of thin sedimentation on the Block from a basin of thick sedimentation in the southern part of the Trough. Thus, greater subsidence must have been possible in the Trough allowing the accumulation of strata which compacted are three times as thick as their equivalents on the adjacent Block. Here, it might be mentioned that the increase in thickness of uncompacted sediments would have been even greater than three-fold due to the presence of greater thicknesses of coal and shale (with high compaction factors for their original constituents) in the Trough succession as compared with that of the Block. Passing from the region of rapid thickening of the sediments in the southern part of the Trough there appears to be a general northward thinning towards the Southern Uplands Massif which survived as a positive belt throughout Carboniferous times. Complete details of this thinning are not available, but from the evidence at hand it seems to be relatively uncomplicated and unaffected by the tectonic sub-divisions of the Trough (Mid-Northumbrian Trough, Cheviot "Block" and Berwick Trough) mentioned previously, whereas Carboniferous sediments earlier than the Scremerston Coal Group are.

(ii) A contributory factor in the thickening across the Stublick Faults is the progressive northward replacement of the Great Limestone top by shale passing from Block to Trough, as shown in Fig. 13. This involves the upper 20 to 30 feet

of the Great Limestone on the Block being represented by shale in the southern part of the Trough. As a result, the Tumbler Beds of the Block disappear, but a similar lithology is developed at a lower horizon in the upper part of the limestone of the Trough (see Fig. 13). Thus, in the southern part of the Trough the sequence gains some 20 to 30 feet in thickness at the expense of the Great Limestone. However, farther north, in the region between the River Wansbeck and Beadnell, the position is reversed since the lower part of the shale above the normal limestone top contains lenticular Tumbler Bed developments which reduce the thickness of the sequence by a maximum of 66 feet (see Great Limestone chapter for details). This replacement by Tumbler Beds of the lower part of the shale above the normal Great Limestone top causes an irregular thinning of the sequence which is greatest in magnitude and irregularity in the area between the River Coquet and Howick. However, even if the Tumbler Beds were not present there would still be a general thinning of the sequence northwards, as has been shown above, so that all the presence of this lithology serves to do is emphasize the thinning and introduce greater irregularity to the thickness variation.

(iii) It has already been shown how, passing from the Block into the Trough, the equivalent of the Low Coal Sill splits into two components and expands very considerably in thickness (see Alston Block section). The lower component consists of sandstone which is generally capped by the Snope Burn Marine Band; above this up to the equivalent of the Low Coal Sill coal the beds are generally comprised of sandy shale. Below the Low Coal Sill horizon the Great Shale also thickens appreciably, partly by replacing the Great Limestone top and also by an overall sedimentological increase. These expansions in thickness have the effect of considerably increasing the proportion of the complete sequence formed by the beds between the Great Limestone top and the Low Coal Sill coal or its equivalent in the Trough as compared with

the Alston Block, since there is no great difference in the thickness of the part of the sequence above the latter horizon in either region. However, it must be noted that in the Trough it is sometimes impossible to exactly divide the sequence as above because of the absence or non-exposure of the Low Coal Sill coal equivalent. Nevertheless, in such circumstances the approximate proportion of the complete sequence formed by the beds between the above horizons can be obtained by reasonable interpolation. A summary of the various proportions on the Alston Block and in the Northumbrian Trough is given in Table VI.

Table VI

Proportions of the complete sequence formed by the beds between the Great Limestone top and the Low Coal Sill coal or its equivalent in the various parts of the Alston Block and the Northumbrian Trough.

Region	Range in proportion (per cent)	Average Proportion (per cent)
<u>Alston Block</u>		
Major part	23-55	35
North-west part	58-79	68
<u>Northumbrian Trough</u>		
Between Brampton and Haydon Bridge	69-76	73
Fallowfield District	-	86
Howick District	56-69	61
Lowick District	-	61

Table VI illustrates the markedly increased proportion of the complete sequence formed by the lower beds in the Trough as compared with the major part of the Block, the north-west extremity of the Block being more comparable with the Trough, however. The highest overall proportion is found in the southern part of the Trough, the maximum proportion being attained in the Fallowfield district. Beyond this there appears to be a northward decrease in the proportion which

accompanies the northward thinning of the complete sequence. However, nowhere in the Trough does the proportion fall as low as that on the major part of the Alston Block.

In the above respect, the history of the essentially non-calcareous part of the cyclothem indirectly reflects the history of the complete period of Lower Carboniferous sedimentation as far as the Northumbrian Trough and the Alston Block are concerned, since during early Viséan times (from C_2 , S_1 times onwards) a great thickness of sediment was laid down in the Trough whereas the Block only received a thin veneer (if any) of sediment, something approaching an equilibrium only being attained some time after the Block was completely submerged in later Viséan times (towards the close of S_2 times). It is only an indirect reflection, however, since the similarities were not derived in exactly the same way.

Stratigraphy

The base of the succession is formed by the diachronous top of the Great Limestone, the latter being known as the Dryburn Limestone at the northern extremity of the region in the Lowick district. In the southern part of the region the top of the sequence is defined by the base of the Upper Little Limestone. Farther north, between the River Coquet and Beadnell, this limestone is represented by the thin Cushat Limestone (Summ. Prog. G.S.G.B., 1923). However, in the detached Lowick district, even farther north, there appears to be some confusion regarding the representative of the Cushat Limestone since, on the basis of lithology and a faunas fauna, it has been stated (Summ. Prog. G.S.G.B., 1923) that the Lickar Limestone of the Lowick area, which lies only 92 feet above the Dryburn (= Great) Limestone, is equivalent to the Lickar Limestone of the Howick district, which lies some 480 feet above the Great Limestone. Consequently, it seems very likely that this is a mis-correlation and that the Cushat Limestone, which lies a considerable distance below the Lickar Limestone of the Howick district, is represented by the so-called Lickar Limestone in the Lowick region, as originally postulated by Stanley Smith (1912).

The key to the correlation of the south Northumbrian Trough succession with that found on the Alston Block has already been stressed. It

lies in the splitting of the Low Coal Sill of the Alston Block into two components in the Trough. The lower component is a thick sandstone which is capped by the Snope Burn Marine Band, whilst the upper one is comprised of the beds between the marine band and the Low Coal Sill coal representative, the latter only being impersistently developed, however, so that delimitation is frequently impossible.

The sequence begins with a thick shale succession known as the Great Shale. Regionally this shale is thickest in the southern part of the Trough and it thins northward; however, the northward regional thinning is complicated and emphasized in the area between the River Coquet and Beadnell since the lower part of the shale is extensively replaced by Tumbler Beds which are developed above the normal Great Limestone top. Over much of the region the lower part of the shale is richly fossiliferous, but there are places where it is virtually barren, and in the area where the abnormal development of Tumbler Beds is present the lower part of the shale is not fossiliferous since the Tumbler Beds probably represent the fossiliferous phase of the shale. In its upper part the shale becomes sandy and invariably it grades into the overlying sandstone.

This sandstone, which is well developed throughout the region, is known as the Great Sandstone. It is thickest in the area around Fallowfield in the southern part of the Trough but, like the Great Shale and the complete sequence, after maintaining its thickness for some distance it thins progressively northwards; also, in the area to the west-southwest of Fallowfield the sandstone is persistent but not nearly so thick overall. Everywhere it has a gradational base and can be classed as a sheet sandstone. At the base it is fine grained and may be shaly, but it loses this character and becomes medium or medium to coarse grained upwards; however, at the very top it tends to become fine grained again. Usually the sandstone is most massive where it is thickest and elsewhere it has a variable flaggy to massive character. Cross-bedding, ripple-markings (causing curly bedding), slump structures and occasional load-cast structures have all been observed in the sandstone, the first two most commonly. In addition, a thin interbedded coal-shale sequence has been proved close to the top of the sandstone at one locality in the southern part of the Trough, and at a few isolated localities lenticular fossiliferous and/or limy horizons have been found within it.

In the southern part of the Trough the sandstone is often immediately overlain by the Snope Burn Marine Band into which it grades; north of Kirkheaton the Snope Burn Band is not developed however, and the sandstone usually grades imperceptibly into the overlying shale, sandstone and coal sequence. As mentioned above, the Snope Burn Marine Band overlies the Great Sandstone in the southern part of the Trough but it is not known north of Kirkheaton. Although it has been recorded at many localities in the southern part of the Trough the band would nevertheless appear to be somewhat lenticular. Generally it is comprised of sparsely crinoidal sandy limestone, but it may be represented by ferruginous clay apparently, and where it is thickest in the Fallowfield region it really becomes a marine series with considerable lateral and vertical variation in lithology.

The remainder of the sequence up to the Little (= Cushat = Lickar) Limestone is made up of a variable series comprised of repeated or modified rhythms of shale, sandy shale, shaly sandstone, sandstone, the occasional marine band, rare fireclays and coal, with much lateral passage from one to another of the first four named lithologies. There is a slight regional thinning of this part of the sequence northwards, but it is not marked, and the minimum thickness is found in the Fallowfield region in the southern part of the Trough. The shale components are quite normal and grade upwards or pass laterally by way of sandy shale and shaly sandstone into sandstone. Ironstone nodules are common in the shales of the central region but are only scattered elsewhere. The sandstones are generally of the sheet type grading up from the underlying shale by way of shaly sandstone to a fine grained lithology and then to a fine to medium or medium grained lithology. However, these sheet sandstones are generally quite lenticular and they do not have the extensive spread of the Alston Block sheet sandstones; nevertheless, there is a relatively persistent sandstone immediately underlying the High Coal Sill coal equivalent in the southern part of the Trough. Not all the sandstones are of the sheet type since very occasionally washouts have been recorded. However, these washouts have not been traced for any distance because of poor exposure. Some of the washouts are probably at the same horizon as those of the channel system on the Block; on the other hand, one of the washouts is definitely at a higher horizon than the above. That marine or quasi-marine conditions

prevailed at least in places some time during the formation of this part of the sequence is illustrated by the presence of rare thin limestone bands and fossiliferous shale, the latter being especially found immediately or closely overlying the High Coal Sill coal equivalent. Horizons with plant rootlets in situ, usually at the top of sandstones but also in shale, are not uncommon; fireclay is also developed occasionally. Both of the above are indicative of previous plant growth and often, though not invariably, are overlain or intimately associated with a coal seam. Coal seams are the most important components of the sequence both stratigraphically and economically since they are developed over the whole region and are generally thick, there being a regional thickening of the coals passing from the Block into the Trough. The seams are best developed in the southern and northern parts of the region whilst they are less prominent in the central area. Plate V illustrates the above points and also shows that over most of the region the number of seams varies from one to three, except in the Lowick district where there may be four. This variation in the number of seams arises from splitting or coalescence and attenuation or "putting in" of individual seams; obviously such phenomena also affect the thickness of the seams since where two coalesce a thicker composite seam will obviously result and vice versa. Previously the coals were known collectively as the Little Limestone coals in the southern part of the Trough and the Lickar coals in the Lowick district, no attempt to correlate the seams with the Low Coal Sill, High Coal Sill and White Hazle or Little Limestone coals of the Alston Block having been made; such a correlation is attempted on Plate V which is self-explanatory. Plate V also shows the thickness and relative positions of the seams in the sequence and, as can be seen, the High Coal Sill coal equivalent is generally the most prominent and persistent, although the other seams are sometimes important locally. Thin bands of impurity, usually of shale but occasionally sandstone, are often present in the seams, but the main part of them is generally composed of good quality bituminous coal. Because of their thickness, coupled with their quality, the seams have been extensively wrought in former times, particularly in the South Tyne Valley and the Lowick district.

Further details of the complete succession are given below in order to expand the above summary.

The Great Shale.- The shale sequence so named by Trotter and Holling-

worth (1927 and 1932) immediately overlies the Great Limestone. In the southern part of the region it varies between a thickness of 30 feet recorded in the Howard Pit Borehole (Pl. IV, 101) and the 94 feet thickness proved in Chineley Burn (Pl. IV, 104). Normally the thickness does not fall below 55 feet in this area and the average is of the order of 74 feet. North of Fallowfield, there is no information available regarding the thickness of the beds until the Brinkburn Priory area where the shale has been recorded as 60 feet thick (Pl. IV, 109); it would thus seem reasonable to assume that a large thickness is maintained northward from the southern part of the Trough as far as the above locality. However, beyond the River Coquet as far north as Beadnell, the lower part of the Great Shale is extensively replaced by Tumbler Beds. As a result of this, the shale varies from nil to 30 feet in thickness, the minimum thickness occurring in the Broomhill Deep Borehole (Pl. IV, 110), where the shale is completely replaced by Tumbler Beds, and the maximum in Shilbottle Colliery Borehole No. 4 (Pl. IV, 114), where no Tumbler Beds of consequence are developed. The average thickness of the shale in this region is around 8 feet, as in the Hazon Lee Water Borehole (Pl. IV, 111), the abnormally high and low thicknesses apparently being local developments. North of Beadnell in the Lowick district, the exact thickness of the shale sequence is not known but it is probably around 25 feet, no thick Tumbler Beds being present. Thus, the shale is thickest in the southern part of the region and there is a progressive regional thinning northwards which is complicated and emphasized by the abnormal development of Tumbler Beds in the area between the River Coquet and Beadnell.

The lower part of the thick shale succession in the southern part of the Trough is richly fossiliferous in many cases. This is not surprising since it is this part of the sequence which is almost certainly equivalent to the upper part of the Great Limestone of the Block and the thick Tumbler Bed sequence at the top of the Great Limestone of the area to the north of the River Coquet. There are some places in the southern region where the lower part of the thick shale succession is virtually barren, however. This might be taken to indicate that there were different local environmental conditions in force during the formation of the shale, possibly largely influenced by current activity which could account for such a distribution of the fossils alone. Johnson (1953) found that the follow-

ing forms were common and persistent members of the fauna in the southern part of the Trough:-

Chonetes hardrensis group Phillips, Eomarginifera lobatus (J. Sowerby), Dictyoclostus pugilis (Phillips), Rhipidomella michelini (Leveille), Leptaena analoga Phillips, mucronate trilobites, crinoid ossicles.

The richly fossiliferous nature of the lower part of the shale succession is known to persist as far north as a short distance beyond Greenleighton where, near Low Hesleyhurst, the following fauna has been recorded:-

Spirifer bisulcatus J. de C. Sowerby group, Spirifer trigonalis (Martin), Spiriferellina octoplicata (J. de C. Sowerby), Pinna flabelliformis (Martin), Athyris sp., Pustula sp., Productus sp., Fenestella sp.

The fauna from the shale above the Great Limestone in Greenleighton Quarry has already been mentioned in Chapter II. For the area beyond this, little information is at hand. However, it seems likely that in the area to the north of the River Coquet the Tumbler Beds represent the fossiliferous phase of the shale. On the other hand, the shale immediately above the Dryburn (= Great) Limestone in the Lowick district is fossiliferous apparently.

Upwards, the shale becomes distinctly micaceous and often it contains ironstone nodules to a greater or less extent. A sandy nature is gradually developed in the upper part and there is a gradation by way of sandy shale, grey beds and flags into the sandstone which invariably overlies the Great Shale.

The Great Sandstone.- The sandstone succeeding the Great Shale has been particularized as above since it is an important member of the Great Cyclothem of this region, especially in the south where it frequently forms prominent topographic features. In the North Tyne district it has also been named the Black Pasture Sill (or Stone) after a locality where it was formerly quarried as a building stone (Lebour, 1874; Hedley and Waite 1928). In the southern part of the Trough the sandstone top is delimited by the Snope Burn Band which immediately overlies it. Unfortunately, the Snope Burn Band only persists a short distance north of the latitude of Kirkheaton, so that farther north the top of the sandstone is not clearly defined. Nevertheless, the prominent sandstone lying immediately above

the Great Shale farther north can be reasonably satisfactorily correlated with the sandstone of the south.

In the southern part of the Trough the Great Sandstone normally varies in thickness between a minimum of 11 feet found at Reaygarth Colliery (Pl. IV, 103), and a maximum of 37 feet encountered in the Denton Fell Borehole (Pl. IV, 102), the average thickness being about 22 feet. However, in the Fallowfield region there is a considerable increase in thickness to a maximum of 114 feet (Pl. IV, 106), the minimum being 59 feet (Pl. IV, 107). In some cases the low thicknesses of the sandstone in the southern part of the Trough appear to be developed at the expense of the underlying shale which becomes correspondingly thicker. On the other hand, the converse does not explain the thickening of the sandstone in the Fallowfield region since the underlying shale maintains its large thickness; the probable explanation of this thickening would seem to lie in greater subsidence allowing a thicker accumulation of sandy sediment in the Fallowfield area since the latter region is situated somewhat farther into the Trough than the rest of the southern area. Whether the large thickness of the Fallowfield area is persistently maintained for any distance north is not known for certain, but it seems likely since the sandstone has been recorded as 72 feet thick in the vicinity of Brinkburn Priory (Pl. IV, 109) and it is known to form prominent features at places between the two localities. Northwards from Brinkburn Priory there is a thinning of the sandstone since in the area between the River Coquet and Beadnell it varies between a thickness of 20 feet proved in Shilbottle Colliery Borehole No. 5 (Pl. IV, 115) and a thickness of 53 feet encountered in Shilbottle Colliery Borehole No. 4 (Pl. IV, 114), the average thickness being around 33 feet, as found in the Hazon Borehole (Pl. IV, 112). Some of this thickness variation could be apparent due to the sandstone top not being definitely delimited; however, the relatively constant thickness of the beds between the horizon taken as the sandstone top and the Cusat (= Little) Limestone base, which only vary between 51 feet and 60 feet in thickness, would not support such a postulate; on the other hand, if the thin and sporadically developed coal seams below the main coal of this region are correlatable, as seems very likely, they indicate some diachronism of the Great Sandstone top which has simply been taken to lie at the top of the first massive sandstone in the absence of any more definite

delimitation. The exact thickness of the sandstone in the Lowick district is unknown but it certainly does not exceed the average thickness for the River Coquet - Beadnell region and is probably about 20 feet thick. From the above it can be seen that the thickest development of the sandstone is in the Fallowfield region; in the remainder of the southern part of the Trough to the west-south-west of this the sandstone is persistently and well developed but not nearly as prominent. North of Fallowfield the thickness appears to persist for some distance and then there is a progressive regional thinning of it.

It would appear that the Great Sandstone has a gradational base everywhere and, therefore, it can be classed as a sheet sandstone as opposed to a washout sandstone, despite its great thickness in the area around Fallowfield. A coarse grained quartzose grit which overlies the Great Limestone in the region to the south and east of Harlaw Hill, west of Long Houghton, could be a washout sandstone, but it is probably related to a higher horizon than the Great Sandstone and will be mentioned later.

In its lower part the sandstone is fine grained with a tendency to be shaly, often being partly comprised of sandy grey beds. Upwards, the grain size increases and the shaly character virtually disappears, the main body of the sandstone generally being medium grained and sometimes medium to coarse grained. Where best developed, especially in the vicinity of Fallowfield where it was formerly worked as a building stone, this main part of the sandstone is massive and only broken up by occasional thin, very micaceous shaly partings; elsewhere, it tends to be more flaggy, often contains more prominent shaly bands and is, therefore, only partly massive. The upper-most part of the sandstone is often fine grained, tends to be flaggy and in some cases is formed partly of grey beds. In the Brokenheugh Borehole (Pl. IV, 105) a 2 feet 4 inches thick shaly sequence containing thin layers of coal was proved 3 feet 6 inches below the sandstone top. This occurrence of coal within the sandstone appears to be an isolated one but a 2 inches thick coal seam immediately overlies the top of the 53 feet thick sandstone in Shilbottle Colliery Borehole No. 4 (Pl. IV, 114). However, in this latter case the position of the coal is probably due to a diachronic nature of the sandstone top, since in the adjacent Shilbottle Colliery Borehole No. 5 (Pl. IV, 115) and other boreholes the probable equivalent of the thin coal lies some distance above the massive sandstone

top, the two being separated by interbedded sandstones and shales. The thin coal seam is thus a component of the overlying series of beds; also, the top of the massive sandstone in Shilbottle Colliery Borehole No. 4 should probably be considered as part of the overlying succession since it represents beds which are so grouped at other localities.

The sandstone is often cross-bedded, especially in the more massive middle part, but individual units are thin. Curly bedding caused by interfering ripples is also a reasonably common feature, particularly in the lower part of the sandstone. In addition, occasional ball slump structures are present towards the base of the sandstone where there is a tendency towards a shaly nature. Such structures are also found in the Fallowfield region towards the top of the sandstone where the latter is grading upwards into the Snope Burn Band. Small load-cast structures also occasionally occur in places where the sandstone has a shaly character.

Close to Brunton Bank Quarry, north of Fallowfield, a prominent fossiliferous band occurs in the middle of the sandstone. This band contains Schellwienella rotundata I. Thomas in profusion and numerous crinoid ossicles of various sizes; it is probably equivalent to the 9 feet thick limestone band recorded in the Fallowfield Sinking (Pl. IV, 106). The band is obviously lenticular since it has not been recorded over a wide region and, in point of fact, was not encountered in the recent Fallowfield drilling programme (Pl. IV, 108). However, a thin limy band was proved within the sandstone in two of the nine boreholes (Pl. IV, 110 and 113) put down in the central region of the Trough.

The sandstone almost invariably grades upwards into the overlying beds and in the southern part of the Trough it tends to become calcareous in passing into the Snope Burn Band. Farther north, where the latter is not developed, the massive sandstone usually grades imperceptibly into the overlying interbedded shale, sandy shale, sandstone and coal sequence. However, in Shilbottle Colliery Borehole No. 4 (Pl. IV, 114) the sandstone might be taken as having a sharp top since massive sandstone is immediately overlain by a thin coal seam, but, as already pointed out, some of the massive sandstone below the seam is really equivalent to interbedded shale and sandstone elsewhere.

The Snope Burn Band.- This marine band was so named by Trotter and Hollingworth (1927 and 1932) since it is well developed as a sandy lime-

stone in Snope Burn, a tributary of the River South Tyne in the north-west part of the Alston Block which has been described earlier. The relatively persistent development in the north-west part of the Block appears to continue into the Trough since the band has been recorded at several localities passing from west-south-west to east-north-east between Talkin and Matfen in the southern part of the Trough; it also persists a short distance north of Matfen since it has been recorded as far as a point slightly north of the latitude of Kirkheaton, but farther north there is no trace of the band whatsoever.

Although the band has been recorded at several localities in the southern part of the Trough, there are some sections in which it has not been proved. Thus, it would appear to be somewhat lenticular, although in some cases its absence may only be apparent due to poor exposure or failure to recognize it.

Between Talkin and the River North Tyne the band varies in thickness between 1 foot 6 inches and 4 feet (Pl. IV, 100 and 105), the average being approximately 2 feet 6 inches. However, in the Fallowfield region it expands considerably in thickness and attains a maximum thickness of 22 feet with a minimum of 11 feet. The minimum thickness was encountered only a short distance from the maximum and it would appear that the maximum thickness arises from local expansion of marine strata at the expense of the beds above and below. In fact, normally its thickness does not exceed 15 feet, the average being about 13 feet. Northwards from Fallowfield there is a thinning of the band since near Kirkheaton it has been proved to be 5 feet 6 inches thick at one locality and it is known to wedge out a short distance farther north.

Lithologically, the band is generally a sparsely crinoidal dark sandy limestone, but Trotter and Hollingworth (1932) have shown that it may be represented laterally by ferruginous or ochreous clay in the south-west part of the Trough. In the Fallowfield region, where it is thickest, it exhibits a considerable variation in lithology and really becomes a marine series, as illustrated by the following generalized section:-

Fine grained slumped sandstone with <u>Camarotoechia</u> and <u>Schellwienella</u> .	4'6"
Medium grained sandstone.	2'6"
Sandy fossiliferous limestone.	2'0"

Slumped shale and grey beds.	1'3"
Fine to medium grained carbonaceous sandstone with a few shells.	3'6"
Slumped limy sandstone with shells.	4'3"
Crinoidal limestone.	9"
Limy sandstone with stylolites.	1'0"

Apart from the vertical variation in lithology indicated above, there is also marked lateral variation, the band being made up of various permutations of the above lithologies. In addition to the above, plant fragments are sometimes present and pyrite is occasionally found in small clots or disseminated. Often the shells and crinoid ossicles are whole, but in some cases they are fragmented, probably due to local current activity. At Kirkheaton the band was recorded in old borer's records as being composed of sandstone, limestone and whin, the latter being a term previously used to denote any hard stone which in many cases can be shown to be limestone. On the Geological Survey New Series 1" Sheet 14, Morpeth, 1955, the band is mapped as a thin limestone to the east and south-east of Kirkheaton.

Strata up to the Little Limestone.- The sequence which overlies the Snope Burn Band in the south of the region and the Great Sandstone top in the rest of the area is a variable series essentially comprised of shale, sandy shale, shaly sandstone, sandstone and coal, with occasional thin lenticular marine bands and sometimes fireclay. A rhythmic succession of the above lithologies can often be made out, and although the rhythmic units are sometimes imperfect or modified, it can usually be recognized that the whole sequence is formed by repetition of a number of them. Johnson (1959) named these units minor rhythms, they being distinguishable in many sections, as, for example, in the Brokenheugh Boring (Pl. IV, 105). The complete sequence above the Snope Burn Band in the south-west part of the Trough was referred to by Trotter and Hollingworth (1927) as "Coal Sills" but, although prominent coal seams are a component of it, the intimate sandstone-coal relationship is not considered to be sufficiently well developed to warrant the name "Coal Sills". As already mentioned, this part of the complete sequence represents the upper half of the Low Coal Sill and all the beds above it of the Alston Block succession.

The thickness of the sequence varies between 28 feet and 86 feet in the southern part of the Trough, the average being approximately 59 feet.

The minimum thickness is found in the Fallowfield area (Pl. IV, 108) whilst the maximum occurs in the Havannah and Blacksike Collieries (Pl. IV, 100) which lie between one and two miles east-south-east of Talkin. To the north at Brinkburn Priory (Pl. IV, 109) a thickness of 49 feet has been reported, whilst farther north in the central region of the Trough the succession has a reasonably uniform thickness and only varies between the 52 feet of Shilbottle Colliery Borehole No. 4 (Pl. IV, 114) and the 60 feet of the Broomhill Borehole (Pl. IV, 110), the average being approximately 55 feet. In the Lowick district the exact thickness is not known but it is probably about 40 to 45 feet. Thus, it can be seen that there is a slight regional thinning of the sequence northwards.

The marked stratigraphical variation of the sequence would seem to indicate that a great deal of lateral passage from one lithology to another takes place. Consequently, no detailed correlation of individual beds can be made over a wide area apart from the coal seams.

The shale components of the sequence are quite normal in being relatively non-sandy in their lower parts and grading upwards or laterally by way of sandy shale and shaly sandstone into sandstone. Sometimes the shale may be fossiliferous, especially immediately above the coal seams, but this feature is not commonly seen. In the area between the River Coquet and Beadnell ironstone nodules are commonly found in the shale, whereas it appears that such nodules only have a scattered distribution elsewhere.

In general, the sandstone members of the sequence are lenticular and cannot be traced over any great distance, as can the relatively persistent sheet sandstones of the Alston Block. However, in the southern part of the Trough a relatively persistent sandstone immediately underlies the coal seam which is considered to be equivalent to the High Coal Sill coal. Normally the sandstones have gradational bases and they grade up from the shale below them by way of sandy shale. Thus, they are closely related to sheet sandstones, but in general do not have the persistent and extensive spread of the latter since they frequently die out and pass laterally into sandy shale. It would appear that all the sandstones do not have gradational bases, however, since washouts cutting out coal have been recorded. One such washout was encountered in the region between half a mile and one mile due south of Roachburn in the south-western part of the Trough, whilst another was proved in the Lowick district in the vicinity of Lickar. The

exact character of these washouts is unknown, but the one close to Roachburn cuts out the seam which is considered to be equivalent to the High Coal Sill coal and is, therefore, at a higher horizon than the washouts proved to exist on the Alston Block. The seam cut out at Lickar is the Lickar Main coal which is considered to be equivalent to the Low Coal Sill coal; thus, this washout is probably at the same horizon as the system proved below the High Coal Sill coal on the Alston Block with which it presumably links up. That the Alston Block washout system mentioned above continues northward from the Block into the Trough towards the source area of sediment cannot really be reasonably doubted, but the poor exposure in the region of the Trough does not allow its accurate delimitation. However, a coarse grained quartzose sandstone or grit exposed above the Great Limestone in the region of Harlaw Hill, which lies about two miles west of Long Houghton, could be the fill material of the continuation of the major channel. Lithologically the normal sandstones of the sequence are fine grained at the base, becoming fine to medium or medium grained upwards. In some cases they are quite hard and massive, but in many cases they are flaggy and have shale or shaly partings interbedded, the shaly nature presumably increasing in the direction of lateral passage into shaly sandstone and sandy shale.

Limestone bands and fossiliferous shale have been recorded from this sequence in only a few places in the southern and central parts of the Trough. However, they could be much more common and widespread than the number of reported finds would indicate since their discovery is greatly hindered by the poor exposure of the beds in the Trough. Limestone has not been found at surface and has only been recorded from two borings, one at Brokenheugh (Pl. IV, 105) in the southern part of the Trough, one and a half miles north-east of Haydon Bridge, and the other at Broomhill (Pl. IV, 110) in the central part of the Trough, about two and a half miles south-east of Amble. In the Brokenheugh Boring a 1 foot thick limestone occurs a little below the middle of the sequence between the High and Low Coal Sill coal equivalents, whilst in the Broomhill Deep Borehole a 2 feet 3 inches thick limestone lies in the middle of the sequence between the Great Sandstone and the Cushat (= Little) Limestone which contains no coal whatsoever. The fact that some of the shale in the sequence may be fossiliferous has been mentioned incidentally above, and at those places where a fauna has

been recorded it would appear that the fossiliferous shale immediately or closely overlies the High Coal Sill coal equivalent. In Howick Burn, one mile south-west of Howick, the shale immediately above a 7 inches thick coal contains Naiadites-like lamellibranchs, whilst the shale in a similar position in the Hazon Lee Water Borehole, which was drilled a quarter of a mile south-west of Hazon, contains Carbonicola-like shells (which have been doubtfully referred to Edmondia) and associated Lingula. In the region a mile or so to the north-east and south-west of Chirm a marine fauna has been collected from the waste heaps of shale derived from above the Chirm coal (the High Coal Sill coal equivalent), the latter having been extensively worked by adits and shafts along its outcrop. The fauna consists of brachiopods, lamellibranchs, gastropods and crinoid ossicles, among which are included the following forms:-

Eomarginifera c.f. longispina (J. Sowerby), Martinia sp.,
Lingula squamiformis Phillips, Lingula sp., Sanguinolites sp.,
Pterinopecten sp., Ctenodonta sp., Posidonomya corrugata
R. Etheridge jun., Bellerophon sp.

Horizons with plant rootlets in situ are not uncommon within the sequence and in some places even fireclay is developed. Both occurrences indicate previous growth of plants and such horizons are usually overlain or intimately associated with a coal seam, although not invariably so. Most often plant rootlets are found in the tops of sandstones, but they are also present in shale which is then known as seggar clay. Fireclay has been recorded both from immediately below and immediately above coal seams, but it does not appear to be of widespread occurrence. However, it does attain a maximum thickness of 6 feet on the Brinkburn Estate (Pl. IV, 109), where it lies between the Little Limestone coal and the Little Limestone, but usually it is thinner than this and may be only a few inches thick, as in Reaygarth Colliery John Pit where 8 inches of fireclay immediately underlies the 10 inch thick coal seam beneath the Little Limestone. These beds with plant rootlets and the fireclays are the old soils upon which vegetation grew to form the peat from which the prominent coal seams within the sequence were developed. As pointed out above, such horizons are not always associated with coal seams, however.

Coal seams are the most important components of the succession, both stratigraphically and economically, since they are developed over the whole

region at particular horizons and in most parts they are usually thick, as shown on Plate V. It can be seen from Plate V that, due to factors which will be dealt with below, the number of seams at any one point normally varies from one to three, although at one locality in the Lowick district four seams are present. Plate V also illustrates the overall regional thickening of the coals which takes place in the passage from Block to Trough; in addition, the variation in thickness of the seams within the Trough is apparent from the diagram.

The overall regional thickening of the coals passing from Block to Trough was originally demonstrated by Trotter and Hollingworth (1932, Fig. 9, p. 75) in the Brampton district. To explain the thickening it was suggested that during the formation of the peat from which the coals were formed regional subsidence did not cease completely. Consequently, the accumulation of peat would tend to keep pace with the subsidence and, since the latter was more rapid in the Trough than on the Block, thicker coals would result in the former region. However, there is some variation in the thickness of the coals within the Trough as a whole, the seams being best developed in the southern part of the region south of Chirm, particularly in the South Tyne valley and the Brampton district; in addition, the seams are also prominent in the northern part of the Trough in the Lowick district. In the region between these two areas the coals are not so prominent, possibly because subsidence was not so great due to the region being situated on the Cheviot "Block". Alternatively, plant growth may not have been so great due to this region being situated closer to the sea than the areas where the seams are thicker; some weight is added to the latter suggestion because there are no coal seams at all in the Broomhill Deep Borehole section (Pl. IV, 110), the borehole having been drilled well to the south-east of all the other sources of information for this region and, therefore, even closer to the interpolated position of the Carboniferous period sea.

The coals have previously been referred to collectively as the Little Limestone coals in the southern part of the Trough and the Lickar coals in the Lowick district. The only particularization of individual seams which has been made in the southern part of the Trough is that the worked seam (the thickest seam, which does vary in horizon to some extent) is referred to as the Little Limestone coal and locally as the Fallowfield seam, the

Chirm coal or the Rothley coal. In the Lowick district the seams are known in ascending order as the Lickar Main coal, the Rough coal (which locally splits into the Rough or Lady coal and the Parrot coal) and the Limestone coal, the latter immediately underlying the Lickar Limestone. However, no previous attempt to correlate the seams with the Low Coal Sill coal, the High Coal Sill coal and the White Hazle or Little Limestone coal of the Alston Block has been made, but this is done on Plate V which is self-explanatory. The correlation in the southern part of the Trough is reasonably certain but farther north in the Lowick district, although the correlation seems reasonable, it could be considered more contentious because of the distance and separation from the parent area.

From Plate V it will be apparent that the variation in the number of seams arises from splitting or coalescence coupled with the "putting in" or attenuation of individual seams. The splitting and coalescence also affects the thickness of seams since where two come together a thicker seam will obviously result and vice versa.

With the above in view, it is considered more reasonable to ascribe the sporadic occurrence of the separate Low Coal Sill coal equivalent in the southern and central parts of the Trough to "putting in" and attenuation of the seam, rather than coalescence with the High Coal Sill coal equivalent such as is postulated by Trotter and Hollingworth (1932). In fact, the markedly sporadic development of the seam may only be apparent to some extent since exploration for coal would be halted once the thick High Coal Sill coal equivalent above it was proved. However, the seam is definitely known to be absent in this region in some sections and it never exceeds a thickness of 9 inches in the southern part of the region and 4 inches in the central part. The section proved by the Hazon borehole in the central part of the Trough suggests that, in this rare instance, the seam splits into two very thin components. In the Lowick district the Low Coal Sill coal is considered to be represented by the prominent and persistent Lickar Main coal which varies between 2 feet 2 inches and 4 feet 6 inches in thickness.

The High Coal Sill coal equivalent is the most prominent of the seams and it persists throughout the region, usually as a separate and single horizon, but occasionally it coalesces with the Little Limestone coal to form one thick composite seam which has a maximum thickness of 6 feet 2

inches in Byron Pit; also, very rarely it splits into two distinct seams, as in the Lickar Pit of the Lowick district. In the southern part of the Trough, where it is a separate horizon, the seam usually has a thickness in excess of 3 feet, the maximum recorded thickness of 5 feet 11 inches being attained in Tynedale Colliery, Acomb. The above order of thickness with only a rare fall below 2 feet is maintained as far north as Capheaton, beyond which there is a thinning to an average of around 2 feet thick until north of Chirm where, in the central region of the Trough, the seam is usually very much thinner than its maximum recorded thickness of 1 foot 5 inches. The High Coal Sill coal equivalent in the Lowick district, the Rough coal, tends to split into two components (the Rough or Lady coal and the Parrot coal), but as a single seam it varies between 2 feet and 6 feet 2 inches in thickness.

The Little Limestone coal equivalent, which lies immediately beneath and/or (and, where the seam is split into two components) a short distance below the Little Limestone and its equivalents, is not completely persistent or very prominent usually. However, despite its impersistence it does have a widespread development and it is especially well represented in the Lowick district. Occasionally, it coalesces with the High Coal Sill coal equivalent to form a composite thick seam immediately below the limestone, and in some cases it splits into two components. In the southern part of the Trough the seam has a maximum thickness of 2 feet 9 inches where it is a single horizon in the Greenwood Borehole at South Tyne Colliery, but usually it is much thinner than this, often being only a few inches thick; where it is split into two components, neither component is ever very thick. In the central part of the Trough, north of Cambo, the seam has not been proved at any locality. However, it is well developed in the Lowick district where it is a persistent horizon immediately underlying the Lickar Limestone with a thickness varying between 1 foot 3 inches and 2 feet 6 inches.

The seams often contain thin bands of impurity, especially where they are thickest. A typical section of the High Coal Sill coal equivalent from Tynedale Colliery, Acomb, is given below:-

	feet	inches
Coal	2	2
Shale		10
Coal	1	0

	feet	inches
Shale		$\frac{1}{2}$
Coal		3
Shale		$\frac{1}{2}$
Coal	1	7
	<hr/>	
	5	11

Normally, the bands of impurity are composed of shale as above, but occasionally there are thin bands of sandstone also. Except where affected by igneous intrusion, all the seams in the Trough are bituminous in rank, as opposed to the semi-anthracitic nature of the coals on the Alston Block. This feature will be dealt with more fully elsewhere, however.

In former times coal was wrought very extensively in each of the regions of thick development by means of both adits and shafts. In the southern part of the Trough, because of their thickness and quality, it was either the High Coal Sill coal equivalent or the combined High Coal Sill coal - Little Limestone coal equivalent which was worked. In the Lowick district all the seams were worked since all are of a reasonable thickness and quality. Now, the only large operation is that carried on by the National Coal Board at Bardon Mill where the High Coal Sill coal equivalent is worked. In addition, there are one or two small workings of the same seam in the Brampton district.

THE CANONBIE DISTRICT

Introduction

The Great Cyclothem is only present in this region in a small detached area of Carboniferous Limestone Series rocks straddling the Anglo-Scottish border about two miles east of Canonbie (Fig. 1) which is situated towards the north side of the Northumbrian Trough. Over the whole area the beds are very poorly exposed and faulted, however, and the detailed succession of the Great Cyclothem is only known from the Catsbit (Peach and Horne, 1903) and Archerbeck (Lumsden and Wilson, 1961) boreholes, both of which proved very similar sequences (Fig. 31). Although this region lies about fifteen miles north-west of the Brampton district, where the nearest sections of the Great Cyclothem are to be found, there is a striking stratigraphical

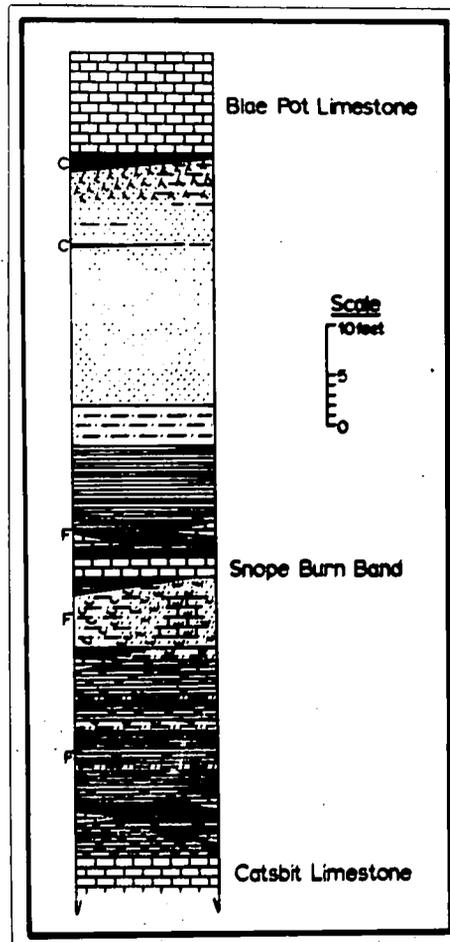


Fig. 31. Section of the Great Cyclothem sequence above the basal limestone in the Canonbie district derived from the Archerbeck and Catsbit boreholes. Legend as Fig. 19.

comparison of the sequences above the basal limestone (Great = Catsbit) apart from the Canonbie succession being considerably thinner than that of the Brampton district (compare Figs. 30a and 31). As in the Brampton region, the succession proved in the Canonbie district is not directly comparable with the Coal Sills Group of the Alston Block even though coals are present in it.

Thickness Variation

From the information available, there does not appear to be a great deal of thickness variation of the sequence in this small region since the Catsbit and Archerbeck boreholes, whose sites were not all that close together, proved thicknesses for the complete succession of 71 feet 9 inches and 68 feet 9 inches respectively. However, there is a considerable variation from the thickness of about 200 feet which is attained by the sequence in the Brampton district to the south-east. This marked thinning is probably accounted for by two factors, as follows:-

(i) The Great Shale equivalent in the Canonbie district is very much reduced in thickness as compared with the Great Shale of the Brampton district, its lower part being replaced by massive limestone which contains thin mudstone bands. As a result of this the Catsbit (= Great) Limestone of the Canonbie district is very much thicker than the Great Limestone of the Brampton district. This thinning of the shale also reduces the proportion of the complete sequence formed by the lower beds to a figure (around 50 per cent) intermediate between those for the Alston Block and the Northumbrian Trough.

(ii) The Canonbie district lies towards the north side of the Northumbrian Trough close to the stable Southern Uplands Massif. Consequently, subsidence in this area would probably be less than near to the centre of the Trough. This would then account for the overall thinning of the sequence in the Canonbie district as compared with the Brampton district since the thickness of deposition would be controlled to a large extent by the amount of subsidence taking place at the time of sedimentation.

Stratigraphy

The base of the sequence is formed by the Catsbit (= Great) Limestone and the top is delimited by the Blae Pot (= Upper Little) Limestone. Nowhere is the succession well exposed and detailed information regarding it is only available from the records of the Catsbit and Archerbeck boreholes, the latter being most useful since the borehole was logged in some detail.

It will be seen from below and Fig. 31 that stratigraphically the succession is closely comparable with that of the Brampton district despite the marked discrepancy in thickness and, in fact, it is possible to subdivide the successions in a similar manner for descriptive purposes. However, the lower half of the Canonbie succession contains indications that the whole of it was deposited under marine conditions whereas that of the Brampton region only has indications that part was formed under such an environment.

The Great Shale equivalent.- This component varies between 18 feet 10 inches (C.B.)¹ and 20 feet 6 inches (A.B.)¹ in thickness and is composed of mudstone and shale which is fossiliferous to some extent throughout. Thin limestone bands have been proved in its lower and upper parts and ironstone nodules and bands are also present except in its upper few feet. In addition there are sandy bands in the upper part of it.

Because of the thin limestone bands in this component it could possibly be classed as Tumbler Beds. However, the limestone bands are markedly subsidiary so that a classification as Tumbler Beds is not considered to be justified.

The Great Sandstone equivalent.- The sandstone, which apparently grades up from the shale below, varies between 6 feet (A.B.) and 9 feet 6 inches (C.B.) in thickness. It is fine grained and often contains thin shaly bands, although it may be completely shaly to some extent also. In addition, it is slightly calcareous and fossiliferous.

The Snope Burn Band equivalent.- The band is represented in both boreholes by limestone which is grey, compact and fossiliferous and

1: Thicknesses proved in the Catsbit (C.B.) and Archerbeck (A.B.) boreholes.

varies between 1 foot 9 inches (A.B.) and 2 feet 8 inches (C.B.) in thickness. In the Catsbit borehole the band immediately overlies the Great Sandstone equivalent but in the Archerbeck borehole 6 inches of calcareous, fossiliferous shale with coaly plant stems separates the two.

Strata up to the Blae Pot Limestone.- This sequence is relatively simple stratigraphically, no variations such as those encountered in the Brampton district having been proved by the two borehole sections. Little thickness variation was proved by the boreholes either since one proved a thickness of 40 feet (A.B.) and the other 40 feet 9 inches (C.B.).

The Snope Burn Band is immediately overlain by 9 feet 7 inches (A.B.) to 9 feet 8 inches (C.B.) of shale which is micaceous and fossiliferous and contains thin limestone bands and ironstone nodules. This shale grades upwards into sandstone which forms the rest of the sequence apart from either one or two coal seams. The sandstone is fine grained and pure overall but it tends to be shaly at the base. It also contains silty bands in its lower part and there are micaceous laminae throughout. In the upper few feet plant rootlets in situ are found and the sandstone has a tendency to be shaly in this part also.

In the Catsbit borehole only one coal seam was proved; this immediately underlies the Blae Pot Limestone at the very top of the sequence and it is 6 inches thick. A seam of hard, dull and bright coal was proved in a similar position overlying the rooty sandstone top in the Archerbeck borehole but it is 1 foot 9 inches thick. This variation in the thickness of the seam could be apparent and due to better core recovery being attained in the more recent Archerbeck borehole because of superior boring techniques. A similar explanation could also account for the absence from the Catsbit borehole of the 1 inch thick hard, bright coal proved 9 feet 6 inches below the Blae Pot Limestone in the Archerbeck borehole. However, there is no reason why such a thin seam should be impersistent either. As far as correlation of the seams is concerned, it would appear that the thick seam at the top of the sequence is the equivalent of the Little Limestone coal of the area to the south and east and that the thin impersistent seam may be the High Coal Sill coal equivalent.

THE EAST AND NORTH RIM OF THE LAKE DISTRICT

Introduction

The outcrop of the Great Cyclothem in this region stretches north-west from approximately two miles west of Appleby, through Penrith, to a point some two and a half miles north-east of Caldbeck, from whence it trends due west to some seven miles west of Caldbeck where the beds are faulted out and not exposed again until Gilcrux in West Cumberland is reached some six miles farther west (Fig. 1). Between Appleby and Penrith the outcrop is relatively little disturbed by faulting, but to the north-west of Penrith faulting at right angles to the strike occurs and it increases and becomes more complex in the area to the east and west of Caldbeck. Throughout the area the beds are poorly exposed, especially in the Eden valley where they are particularly badly masked by glacial deposits. The base of the sequence is formed by the Great Strickland (= Kings Meaburn, Main or Great) Limestone which is only intermittently exposed. The top of the sequence is not even as well defined as this, however, except in the area around Caldbeck where the equivalent of the Upper Little Limestone has been recognized and named (Summ. Prog. G.S.G.B., 1931; Geological Survey New Series 1" Sheet 23, Cockermouth, 1959). Elsewhere in this region no top to the Great Cyclothem appears to have been defined, though suggestions have been made as to possible equivalents of the Upper Little Limestone. For instance, the Bewley Castle Limestone, which is found in Teas Gill some two and a half miles west-north-west of Appleby, has been correlated with the Upper Little Limestone by Versey (1960), whereas Goodchild (in Dakyns et al., 1897) compared it with the "Red Beds" of Swaledale, whilst Tiddeman (in Dakyns et al., op. cit.) considered it to be more like "a thin limestone found on top of Mallerstang above the higher Eden valley" and Miller and Turner (1931) correlated it with the Crow Limestone. Thus, all these suggestions, apart from that of Versey, put the Bewley Castle Limestone higher in the sequence than the Upper Little Limestone. Consequently, no specific horizon can be definitely attached to the limestone of Teas Gill as yet, but it is almost certainly above that of the Upper Little Limestone. A 4 feet thick limestone recorded 35 feet above the Great Strickland Limestone in the River Lowther some three miles south-south-east of Penrith has also been correlated with the Upper Little Limestone by Miller and Turner (op. cit.); such a correlation could be correct, but the extremely thin sequence so derived between the Great Strickland Limestone and the supposed Upper Little Limestone equivalent does not bear this out, and it seems more likely that the

thin limestone is a marine band within the Great Cyclothem. Everywhere within this region the beds above the basal limestone appear to consist of shale and sandstone, but only in the Caldbeck region has coal been recorded in association with them. However, even where coal is present the sequence does not warrant the name Coal Sills Group.

Thickness Variation

Owing to the lack of exposure and the consequent poor delimitation of the equivalent strata, it is impossible to ascertain whether the Coal Sills Group strata of the Alston Block do actually thicken in this area to the west of the Pennine Fault System. Thus, evidence is not available as to whether the Pennine Fault System acted as a contemporaneous hinge line during deposition of these beds. However, Mr. C. Rowley (personal communication) has found that in the area to the east of Appleby the strata below the Coal Sills Group equivalents are not significantly thicker than their equivalents on the Alston Block. In the region at the north end of the Lake District around Caldbeck the beds equivalent to the Coal Sills Group have a thickness of the order of 90 to 100 feet. Since this thickness is in excess of the average for the Alston Block but less than that for the Northumbrian Trough, it could be taken as indicating a northward thickening towards the western continuation of the Northumbrian Trough, the westward continuation of the latter having been postulated by Smith (1927) and Trotter and Hollingworth (1927) and substantiated by Eastwood (1930) and George (1958). Further detailed information is required to clarify the situation, however, but the position at the northern end of the Lake District could be similar to that in the north-west part of the Alston Block where it would appear that sagging of the Block in sympathy with the adjacent Northumbrian Trough allowed thick sedimentation.

Stratigraphy

The poor exposure of the beds above the basal limestone to the east of the Lake District on the south-west side of the Vale of Eden does not allow clarification of the detailed stratigraphy, there being only intermittent exposures of sandstone and shale at various localities, as recorded by Dakyns et al. (1897); also present apparently are marine bands, but no coal at all has been found in association with the beds. Thus, it can only be said in general terms that the sequence consists of shales and sandstones

with marine bands. At the north end of the Lake District around Caldbeck the stratigraphical situation is somewhat clearer since the Upper Little Limestone has been recognized to delimit the top of the sequence. The available details pertaining to the stratigraphy are to be found in articles by Eastwood (in Summ. Prog. G.S.G.B., 1931) and Trotter (in Trueman, 1954) and on the Geological Survey New Series 1" Sheet 23, Cockermouth, 1959. From these sources it can be construed that above the basal limestone the sequence is 90 to 100 feet thick and consists of shale and sandstone with at least one coal seam associated. The lower half of the sequence is dominated by either one or two sandstone horizons, there being a thin shale separating the sandstones where two are developed. Even where two sandstones are developed they are grouped together and named the Hensingham Grit, presumably by analogy with the development in West Cumberland where the Hensingham Grit immediately or very closely overlies the First (= Great) Limestone. The upper part of the sequence consists essentially of shale but the most important horizon present is a prominent coal seam which occurs some 35 feet or so below the Upper Little Limestone. Trotter (op. cit.) insinuates that more than one coal is present but states that only one seam attains a workable thickness. These coals were known locally as the Warnell Fell Coals because the prominent seam referred to above was worked in former times, particularly on Warnell Fell about one and a half miles north-east of Caldbeck. The seam attains a maximum thickness of 2 feet 6 inches according to Trotter (op. cit.). Therefore, it is considerably thicker than any of the seams on the Alston Block, except those developed in the north-western part, and its thickness is more in line with seam thicknesses in the Northumbrian Trough. Consequently, the earlier suggestion of this area lying to the south of but adjacent to the westward continuation of the Northumbrian Trough does not seem unreasonable. The worked seam has been arbitrarily referred to as the Little Limestone Coal on the Cockermouth sheet (Geological Survey New Series 1" Sheet 23, 1959), whereas, by analogy with the Alston Block and the Northumbrian Trough, its position in the sequence and its thickness suggest that it is most likely the equivalent of the High Coal Sill coal of the Alston Block. According to Eastwood (in Summ. Prog. G.S.G.B., 1931), in general a similar stratigraphy to that of the Caldbeck area persists to the west of the limit of outcrop of the Great Cyclothem as far as Aspatria where a number of boreholes were drilled in former times. To the west and

south-west of Aspatria, which lies some three miles north-east of Gilcrux, the situation is considerably changed since above the basal limestone member of the cyclothem the beds, which are known collectively as the Hensingham Group, are subject to lateral and vertical changes and completely lack definition in terms of cyclical sedimentation; this situation will be discussed more fully in the relevant section dealing with West Cumberland below.

THE WEST RIM OF THE LAKE DISTRICT

Introduction

In this region, which comprises West Cumberland, the main outcrop of the beds equivalent to the Great Cyclothem stretches from Gilcrux south-south-westwards to Egremont where younger rocks mask any further outcrop to the south (Fig. 1). To the west of the main outcrop the beds are also exposed in two inliers, one around Hensingham, one mile south-east of Whitehaven, and the other around Distington, four miles north-north-east of Whitehaven (Fig. 1). Information pertaining to the beds is also available from mine workings and boreholes to the west of the main outcrop and to the north-east and north-west of the northern limit of outcrop. Thus, although the exposure of the beds is generally not good, the available information is by no means scanty because of the mine workings and boreholes; all this information has been documented in the Geological Survey Memoirs for the Maryport district (Eastwood, 1930) and the Whitehaven and Workington district (Eastwood et al. 1931). Forming the base of the beds representing the Great Cyclothem is the First (= Great) Limestone. Above this is the Hensingham Group which extends upwards to the horizon of the Udale Coal where dark shales have yielded Gastrioceras cumbriense Bisat; the Group has the Hensingham Grit at or close to its base and the remainder of it consists essentially of sandstones and shales. Unfortunately the Hensingham Group completely lacks definition in terms of cyclical sedimentation, none of the marker limestone equivalents of the Upper Limestone Group to the east being recognizable; consequently, it is impossible to accurately define the beds equivalent to the Great Cyclothem apart from the basal limestone. In fact, all that can be said is that the lower part of the Hensingham Group probably represents the beds of the Great Cyclothem above the basal limestone. These beds of the Hensingham Group do not in any way resemble the type Coal Sills Group succession.

Thickness Variation

Because of the impossibility of accurately defining what part of the Hensingham Group represents the beds of the Great Cyclothem above the basal limestone, it is obviously not possible to enter into any detailed discussion relating to thickness variation. Nevertheless, the considerable thickness variation of the Hensingham Group as a whole illustrated by Eastwood (1930) and Eastwood et al. (1931) gives some guide to what happens. It must be pointed out, however, that this thickness variation of the whole Group may not be entirely due to sedimentation, but to some extent the result of an unconformity of unknown magnitude at the top of the Group. In the southern-most outcrops the Group is only about 80 feet thick in places, increasing northwards to about 150 feet around Hensingham. Passing farther north the Group thickens to about 400 feet around the latitude of Workington, some eight miles north of Hensingham; this thickening is not simple, however, because there are local variations, as at Lamplugh, some seven miles north-east of Hensingham, where the Group appears to be only about 60 feet thick. In the next eight miles or so north the thickening is even more pronounced, reaching around 1,600 feet in boreholes at Bank End, one and a quarter miles north-east of Maryport, and Bluedial, three and a half miles north-east of Maryport. The manner of thickening in this northern region appears to be somewhat complicated since in boreholes near Crosby, two and a half miles east-north-east of Maryport, and Aspatria, three miles north-east of Gilcrux, the Group is only about 400 feet thick, whereas to the south of this at Bullgill, one and a quarter miles west of Gilcrux, and Tallentire, two miles south-south-west of Gilcrux, Eastwood (1930) considered the Group again to be of the order of 1,600 feet thick. Thus, there is a zone between Crosby and Aspatria where the Group is thin, separating two areas where the Group is very much thicker. Eastwood (1930) suggested that the northward thickening of the Hensingham Group, as well as the intercalation of non-calcareous sediments in the Main Limestone Group below it, could be explained by the existence of the westward continuation of the Northumbrian Trough to the north of Workington; the complication introduced by the thinning of the Group between Crosby and Aspatria was taken to indicate that the Trough was not a simple depression, but one having a low ridge in it.

Stratigraphy

As stated previously, it seems most likely that the lower part of the

Hensingham Group represents the beds of the Great Cyclothem above the basal limestone, but, because the Hensingham Group lacks definition in terms of cyclical sedimentation, it is impossible to be very much more specific than this. On the other hand, because at or close to the base of the Hensingham Group the prominent Hensingham Grit is known to occasionally have an erosive base, one might be tempted to postulate the presence of an unconformity at the base of the Grit cutting out the beds representing the Great Cyclothem above the basal limestone. However, this latter postulate is almost certainly not correct since, although there are occasional minor inequalities where the Hensingham Grit cuts into the First (= Great) Limestone, over most of West Cumberland the Grit occurs at about the same position with respect to particular beds of the First Limestone. Thus, accepting the original suggestion, either part of the Hensingham Grit or the whole of it and some of the beds of the Hensingham Group above it represent the beds of the Great Cyclothem above the basal limestone.

Immediately above the First (= Great) Limestone there is frequently a development of shale which varies between a few inches and about 12 feet in thickness. The shale is usually barren, but this is not always so since fossils have been found in it occasionally. In some cases the shale becomes sandy upwards and grades into the overlying Hensingham Grit. In other cases, however, the overlying Hensingham Grit has a sharply defined erosive base and the shale between the Grit and the First Limestone is cut out partly or completely, the Grit actually cutting the upper part of the First Limestone at a few localities.

The so-called Hensingham Grit is rather arbitrarily defined since its upper limit is not clearly marked and, therefore, it is impossible to be certain that the same horizon is taken as its top in every case. The deposit apparently varies in thickness between about 18 feet and 100 feet, being thinnest overall in the southern part of the region, as might be expected; however, in the northern part of the region there are occasional places where it is also poorly represented. The deposit referred to as the Hensingham Grit may consist entirely of arenaceous material, but in many cases it consists of arenaceous material divided by a band or bands of shale. The arenaceous material comprising the Grit varies from fairly coarse grained grit to moderately fine grained sandstone, with quartz as the main constituent; no fresh feldspar has been noticed, but the rock is

sometimes richly micaceous, especially where it is coarse grained and thin bedded. Occasionally the arenaceous material is partly calcareous and, also, cross-bedding has been noted as a feature of the arenaceous components at some localities. At a few isolated localities part of the arenaceous portion of the Grit has been found to be fossiliferous and contain brachiopods and lemellibranchs; normally, however, the only fossil material in it consists of plant remains which sometimes manifest themselves as chips of coal. The band or bands of shale within the Grit may be very thin or quite prominent. Within one such prominent band of shale a thin coal has been found, and, elsewhere, a thin or lenticular limestone has been recorded within a shale parting. In addition, the shale partings have been found to be fossiliferous in a number of cases.

The remainder of the Hensingham Group above the Hensingham Grit is comprised mainly of shale with subsidiary sandstones, such limestones and coals as are present being thin and poor. Within this sequence, which, as stated above, completely lacks definition in terms of cyclical sedimentation, lithological changes, both lateral and vertical, occur with such rapidity that in sections less than a mile apart it is impossible to attempt more than a broad correlation of belts of strata. The shales are dark and often they are fossiliferous, especially where they are limy. A thin bedded character is generally a feature of the sandstones which also frequently contain abundant plant rootlets in situ in their upper parts; in addition, the sandstones are occasionally limy and fossiliferous. The limestones are lenticular and seldom exceed 2 feet in thickness; they are generally of a dark colour and are impure, but usually they are reasonably fossiliferous; in some cases the limestones pass laterally into clay ironstone, whilst in other cases the limestones are partly silicified. Coals are never well developed within the sequence and, in fact, are rarely seen.

The above type of lithology for the Hensingham Group persists as far south as Egremont where the beds disappear beneath younger rocks. Somewhere beneath this cover of younger rocks there is a marked facies change, however, since in the Furness District of South Cumberland at least part of the Hensingham Group, as well as the Main Limestone Group (including the First Limestone) below it, is probably represented by part of the predominantly shaly Gleaston Group.

THE KIRKBY LONSDALE AREA

Introduction

In this area the outcrop of the Great Cyclothem, which is not very extensive, stretches to the east and west of Whittington, the latter being situated about one and a half miles south-south-west of Kirkby Lonsdale (Fig. 1). Although the outcrop appears to be uncomplicated structurally, the beds are not well exposed and Hicks (1958), the most recent worker on the area, did not find it possible to interpret what exposures there are above the Main (= Great) Limestone with certainty. The Main Limestone, which is about 15 feet thick throughout the area, is reasonably well defined at the base of the sequence, and can be traced from east to west across the area from the River Lune to half a mile south of Hutton Roof where it turns to run south-south-west until it abuts the fault separating it from older beds. Unfortunately, nowhere in the area has an equivalent of the Upper Little Limestone been recognized to delimit the top of the cyclothem. Nevertheless, Hicks (op. cit.) considered an appreciable thickness of the shale and sandstone sequence above the Main Limestone to be the equivalent of the Coal Sills Group elsewhere. The stratigraphy of these beds does not compare closely with that of the type Coal Sills succession, however, no coals being developed.

Thickness Variation

As stated above, Hicks (1958) believed that a considerable thickness (shown as approximately 175 feet plus on a generalized section) of the strata above the Main Limestone in this area was equivalent to the thinner Coal Sills Group succession of the Askrigg Block. If this is so, as seems reasonably probable, the Kirkby Lonsdale area must be situated within a basin of deposition which is probably the southern prolongation of the Ravenstonedale Gulf. Such a thickening of the beds is not entirely unexpected since, as pointed out previously, in passing from east to west the equivalent strata on the Askrigg Block thicken towards the Dent Fault System, the latter presumably having acted as a contemporaneous hinge-line during deposition, with thick sedimentation in an area of subsidence to the west of it and thinner sedimentation to the east of it in a more stable area. Furthermore, Miller and Turner (1931) recorded that the Yoredale beds south of Kirkby Lonsdale are over 2,000 feet thick and, therefore, twice as thick

as they are to the east of the Dent Fault System.

Stratigraphy

According to Hicks (1958) the beds immediately above the Main Limestone consist of shale and flaggy shale (shown as approximately 100 feet thick on the generalized section) with a flaggy sandstone above this, no coal at all having been discovered. Associated with the flaggy sandstone around Whittington is a 2 feet thick medium to coarse grained sandstone which is crowded with shale pebbles up to 1 foot long. This particular horizon is somewhat impersistent around Whittington. Nevertheless, it appears to correlate with a sandstone to the east of Whittington, and to the west it develops to at least 15 feet thick in Town's Quarry, about three quarters of a mile west-north-west of Whittington. A further three quarters of a mile to the west-north-west, in the Hutton Roof Quarries, the equivalent appears to be over 100 feet thick and it consists of two main sandstone components separated by a thickness of at least 20 feet of laminated silty mudstone with lenses of sandstone. South-west of the Hutton Roof Quarries the horizon has not been recognized and the sandstone is probably very much attenuated. The manner in which this sandstone rapidly thickens and thins suggests that it occupies a washout-channel; thus, it is tempting to relate it directly to the coarse grained channel-fill sandstone of Baugh Fell, but without more definite evidence it is impossible to be categorical on this point.

Summarizing, it can be seen from the above that in this area the beds of the Great Cyclothem above the basal limestone appear to be thicker than their equivalents on the adjacent Askrigg Block. They consist of shale and sandstone, but no coal has been discovered; the most prominent sandstone horizon is possibly a sandstone-filled washout-channel.

THE ISLE OF MAN

Rocks of Carboniferous age are known in three areas of the Isle of Man, one towards the southern tip of the island around Castletown, one on the west coast around Peel and the other at the northern end of the island. Only at the northern tip of the island are beds of equivalent age to the Great Cyclothem preserved, however, and these are only known from one deep borehole which was recorded by Smith (1927). Considered overall, the lower

part of the sequence proved by the borehole is comparable with that of West Cumberland up to what is taken as the equivalent of the Great (= First) Limestone, but above this the beds are more like those above the Great Limestone in North-east Cumberland than the Hensingham Group of West Cumberland.

In the borehole, Smith (1927) considered the Great Limestone to be represented by 25 feet of massive grey limestone, but, in addition, above the massive limestone the 15 feet of fossiliferous shale followed by 2 to 3 feet of shale and limestone should probably be considered as the Tumbler Beds component of the Great Limestone by analogy with other areas. Overlying these beds in the borehole a 65 to 67 feet thickness of shale was proved and this was followed by a sandstone-shale sequence consisting of 3 feet of sandstone at the base overlain by 15 feet of shale and 18 feet of interbedded sandstone, calcareous grit and shale. Within the thick shale a 9 inches thick coal seam was found 20 to 22 feet above what has been taken as the top of Great Limestone Tumbler Beds. By analogy with the sequence of North-east Cumberland, Smith (op. cit.) considered this coal to be the equivalent of the so-called Little Limestone coal, the sandstone-shale sequence above the thick shale being taken as the representative of the Firestone Sill. Thus, if Smith's suggestions, which seem reasonable enough, are accepted, there is no equivalent of the Little Limestone developed and, therefore, the upper limit of the sequence equivalent to the Great Cyclothem is not accurately defined. Nevertheless, the limit must lie somewhere in the shale a short distance above the 9 inches thick coal seam and, consequently, the beds representing the upper part of the Great Cyclothem above the basal limestone are relatively thin and they consist entirely of shale except for the coal seam. Such a situation with thin sediments containing no sandstone is quite easily explained, since it would appear that the northern end of the Isle of Man lay towards the southern limit of the northern region of deltaic deposition during this period, similar to the southern part of the Askrigg Block which has already been described. Some confirmation that the northern part of the Isle of Man was situated in the position described above is forthcoming from the sequence at the southern tip of the island which, although it is considerably older than the Great Cyclothem, indicates that it was formed within a region of different environment to that of the northern sequence; this region was possibly the western continuation of the Bowland Trough.

THE CRAVEN DISTRICT

As far as the Great Cyclothem is concerned, across the region now occupied by the Craven Faults there was obviously a north to south change from a typical Yoredale lithology into a Bowland Shale lithology, as illustrated diagrammatically for the complete succession by Edwards and Trotter (1954, p.19, fig. 8). The actual change is never seen with respect to the Great Cyclothem, however, basically because the cyclothem as such wedges out on the Askrigg Block, and also because the unconformity at the base of the Grassington Grit cuts out beds in the critical stretch of ground in any case. On the basis of goniatite evidence, the Great Cyclothem has been shown to be of lower E_1 age (Johnson, Hodge and Fairbairn, 1962) as has the lower part of the Upper Bowland Shales which contain the Scale Haw Limestone of E_{1a} age (Hudson and Cotton, 1943). From the above information, and especially as it is reasonably certain that the Scale Haw Limestone is the representative of the Main (=Great) Limestone (Black, 1950), it becomes apparent that the Upper Bowland Shales immediately above the Scale Haw Limestone are the representatives of the part of the Great Cyclothem above the basal limestone. However, it is impossible to accurately define the upper limit of the equivalent beds since no marker horizon is present in the shales to equate with the Upper Little Limestone.

Although no specific details are known, the Boroughbridge Borehole (Hudson, 1949) proved similar basin facies sediments to those in the Craven District some fifteen miles to the east, thus indicating that the Craven Faults probably veer to the north passing eastwards, as suggested by George (1958).

THE FURNESS DISTRICT

In this region, which lies to the south of the Lake District and comprises South Cumberland, a similar situation to that in the Craven District exists. Here, the Gleaston or Yoredale Group, which is quoted as being of $D_2 - D_3$ age, consists of black shales up to 1,400 feet thick which contain thin dark cherty or coarse crinoidal limestones and thin sandstones in their lower 500 feet (Dunham and Rose, 1941; Eastwood, 1953). However, no equivalent of the Great Limestone has been found in these shales even though the First (=Great) Limestone is a prominent member of the sequence in West Cumberland only a few miles to the north. Neither does any gonia-

tite evidence exist to allow an attempt at a correlation of the Great Cyclothem with beds in this region. In fact, all that can be said is that some of the black shales in the upper part of the Gleaston Group might be equivalent to the Great Cyclothem.

The marked facies change which must take place passing north towards West Cumberland has already been mentioned, but it might be re-iterated that part of the Gleaston Group is probably equivalent to the Main Limestone Group and at least part of the overlying Hensingham Group of West Cumberland.

CHAPTER V

SANDSTONE PETROLOGY

GENERAL

The major sandstones of the Great Cyclothem have been examined in detail petrologically, essentially from the point of view of helping to assess their provenance and the conditions under which they were deposited. Obviously, the information so gained does not yield a complete answer as far as these matters are concerned and it is necessary to take into consideration the other diagnostic features of the sandstones such as their field relationships, sedimentary structures and fossil content before any satisfactory comprehensive interpretation can be made. Apart from the major sandstones, other components of the cyclothem have been examined petrologically, such investigations having been mainly for specific identification purposes, however, and the results have been embodied in the stratigraphical sections (Chapters III and IV) of this work. In particular, no detailed study of the shales was made since if it had there would have been duplication of effort because Yoredale shales were synchronously and specifically investigated by a colleague (Harbord, 1962), with whom there has been considerable mutual co-operation. Furthermore, for the purpose of this work, which has been more particularly directed towards the Coal Sills Group and its equivalents rather than the basal limestone of the cyclothem, it was considered that the sandstones presented more numerous and reliably interpreted features than the shales, the latter presenting an involved problem in themselves since they require subtle techniques of investigation and, in addition, are particularly susceptible to marked change from their original state caused by such agents as diagen^esis, mineralization and weathering. Also, conclusions derived from a study of the sandstones have a bearing on the shales because of the frequent intimate association of the two lithologies. The failure to investigate all the lithologies in detail in the present work obviously does not mean that in the final analysis all are not taken into consideration because the assessment would be incomplete otherwise. In this context it might be mentioned that, although it is not fully comprehensive, some detailed petrological information relating to other

lithologies involved in the cyclothem is available apart from that of Harbord (op. cit.) on the shales, for example, the work of Wells (1955a and 1955b) on the Main Chert.

The majority of the sandstones examined were from the Alston Block, but to broaden the field and correlate with existing observations, samples from other areas have been investigated; in addition, all the information accumulated by other workers has been utilized. The method of study involved the techniques enumerated below:-

(i) . The standard examination of thin sections using a petrological microscope for the determination of the various constituents of each sandstone. Identification of most of the minerals was made by means of their optical properties. One refinement was introduced, however, in that selected thin sections were stained with sodium cobaltonitrite solution after etching the thin section surface with hydrofluoric acid; this technique serves to pin-point any potash feldspar by staining it yellow if it is present. The proportions of the various constituents were estimated visually using charts designed for the purpose; more refined methods were not used because the sandstones are comprised essentially of quartz in the majority of cases. The microscope was fitted with a micrometer-eyepiece for measuring grain sizes and the variation of the same (to assess the degree of sorting) in each thin section; it is accepted that such a method for investigating grain sizes and their variation is not the ideal one since it has very definite limitations, but in such a study as this on indurated rocks with a dominant silica cement, even less satisfactory results would arise if attempts were made to disaggregate the sandstones in order to carry out sieve analyses on them. All grain size determinations have been related to the Wentworth grade scale (Wentworth, 1922), the pertinent part of which is summarized in Table VII. As far as grain shape (degree of roundness and sphericity) is concerned, visual estimates were made from the thin sections using charts designed for the purpose.

Table VII

Part of the Wentworth grade scale

<u>Grain size (mm.)</u>	<u>Designation</u>
4 - 64	Pebbles.
2 - 4	Granules.
1 - 2	Very coarse grained sand.
0.5 - 1	Coarse grained sand.
0.25 - 0.5	Medium grained sand.
0.125 - 0.25	Fine grained sand.
0.625 - 0.125	Very fine grained sand.
0.004 - 0.125	Silt.
Less than 0.004	Clay.

(ii) Apart from their investigation in thin section, the heavy minerals of selected sandstones have been studied further after separating them from crushed samples, this operation being carried out initially by panning and finally by using bromoform as the media^m in the standard manner; the process of panning was checked and found to be a satisfactory technique for making a primary concentrate, thus speeding up the overall separation process considerably. Sandstones from a known constant horizon and from random horizons have been considered in order to determine whether there is any lateral and vertical variation in the heavy mineral assemblage.

(iii) In a few cases either X-ray powder photography or differential thermal analysis was used for the determination of interstitial clay minerals and cements which could not be identified satisfactorily by optical methods.

(iv) Occasional sulphide-bearing sandstones have been investigated by means of polished sections in order to positively identify the sulphide as pyrite. Here, it might be mentioned that several sulphide-bearing ironstone nodules, shales and coals have also been examined by means of polished sections for a similar reason and all, including the coals, proved to contain no other sulphide but pyrite. In the case of the sandstones

the pyrite appears to be essentially secondary since it can frequently be seen replacing quartz grains; however, in the other lithologies the pyrite is probably primary in most cases, its formation being attributable to the former existence of reducing conditions.

The major parts of all the sandstones are predominantly composed of quartz grains, the other components, apart from the clay minerals and micas, only being minor constituents generally. The proportion of clay minerals rises considerably where the sandstones are shaly, especially in the sheet sandstones where they grade up from the underlying shale; however, in many thin sections of massive sandstone examined the clay content is low. Mica can also be common, particularly where the sandstones are shaly and also in thin bands along many bedding planes, but normally in the main body of the sandstones mica is only a minor constituent. No very marked difference in the mineralogy of the sheet sandstones and the washout-channel sandstones is apparent, although the major washout-channel sandstone does contain more feldspar in its lower part than any of the other sandstones. However, the two types of sandstone do vary somewhat in grain size, the washout-channel sandstones being significantly coarser grained in their lower parts when compared with the overall grain size of the sheet sandstones. The various aspects of the sandstones are dealt with in more detail below.

FIELD APPEARANCE

The general character of the bedding in the individual sandstones has already been mentioned in the stratigraphical section (Chapter IV) of this work, as have the sedimentary structures; in addition, the latter features are to be dealt with more fully in Chapter VI. Consequently, no further details will be given here since reference may be made to the pertinent chapters for information. Suffice is to say that the sandstones are often massive, but they may be flaggy and in a number of cases they are soft and shaly to some extent. All the major sandstone bodies are well lithified apart from where they are distinctly shaly or where there is an occasional band of soft uncemented sand grade material. In most cases the sandstones are orange, brown or buff in colour at surface owing to the oxidation of their original iron content and the introduction of

other iron oxide by the weathering processes. An interesting feature connected with this point is the common occurrence of a zoned colour variation, a development probably attributable to a Liesgang ring effect. Where the sandstones are unweathered, as in fresh underground exposures, they are usually grey to blue-grey in colour.

TEXTURE

Introduction

The texture of the sandstones has been investigated as far as the grain size, sorting, grain shape and cementation are concerned and it has been found that the major difference lies in the washout-channel sandstones being significantly coarser grained and less well sorted in their lower parts when compared with the other sandstones. The various features are discussed in more detail below, the grain size and sorting together because of their obvious inter-relationship, and the grain shape and cementation together because of the effect which the latter has had on the former.

Grain Size and Sorting

The major parts of the sheet sandstones are essentially composed of very fine to fine, fine, fine to medium or medium (lower part of the range) grain sized material (all grain sizes are referable to the Wentworth grade scale given in Table VII). However, locally, as well as in passing up from the underlying shale and where they are wedging out (locally and regionally) by passing laterally into shale, the sandstones are much finer grained overall with material as fine as silt grade and even clay grade forming a prominent component. On the other hand, the sheet sandstones do sometimes contain an admixture of coarse grained, granule and fine pebbly material, as in the upper part of the prominent fossiliferous sandstone of Teesdale; in addition, they may locally consist of such material overall with pebbles up to 7 mm. diameter; however, it must be stressed that such occurrences are not very common. In spite of the variation in overall grain size the material comprising any particular part of a sandstone is usually well sorted and sometimes very well sorted (Fig. 32), the grain size variation in general being within the range of one or two classes of the Wentworth grade scale. However, there are exceptions to this rule

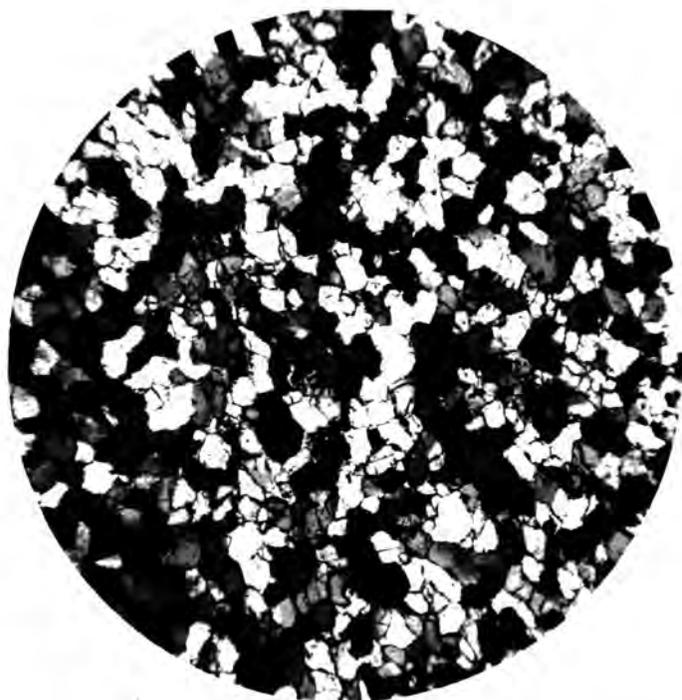


Fig. 32. Well sorted fine to medium grained sandstone with some secondary overgrowths; High Coal Sill, Redmires Quarry, near Stanhope. Crossed nicols, x 27.

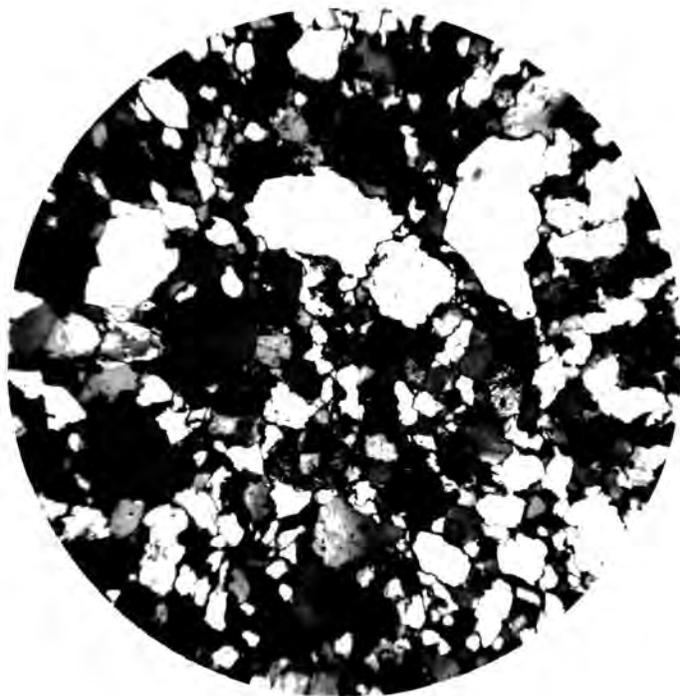


Fig. 33. Poorly sorted very fine to coarse grained sandstone with a small amount of interstitial calcite; Upper White Hazle, Linzgarth Cleugh, near Rookhope. Crossed nicols, x 27.

and occasional patches of poorly sorted material are present, particularly where the sandstones are coarsest. Such occurrences usually appear to be local, but it has been found that the upper component of the White Hazle is persistently relatively poorly sorted, as illustrated in Fig. 33; as mentioned in the stratigraphical section of this work, this sandstone component is strictly the basal member of the overlying Little Cyclothem, however.

The main body of the sandstone filling the contemporaneous "channel" shown on Plate III and described in Chapter IV is similar to that of the sheet sandstones and it is composed predominantly of fine, fine to medium and medium grained material with reasonably good sorting, but it does appear to contain rather more common coarse grained lenses. As opposed to the washout-channel sandstones, the contemporaneous "channel" sandstone almost invariably has a gradational base passing up from the underlying shale, the lower part of it being comprised of silt grade and very fine to fine grained sandy material.

The washout-channel sandstones, which have been described in Chapter IV and delimited on Plate III, are characterized by invariably having a sharp erosive base with no gradation up from the underlying sediments. The fill material at the base of the major channel is essentially of very coarse to coarse grain size (Figs. 34 and 35) with occasional grains of granule size and rare pebbles up to 20 mm. diameter; despite their general rarity, Hicks (1958) has shown that granules and pebbles of up to 20 mm. diameter are reasonably common in the washout-channel sandstone of the Baugh Fell region in the south-west part of the Askrigg Block, that is to say, at what appears to be the seaward end of the major washout-channel; granules and pebbles up to 13 mm. diameter are also a prominent component in the lower 18 feet of the major washout-channel sandstone on Mickle Fell. In addition, the sandstone contains a minor fraction of material which in places is as small as very fine grain size but usually considerably larger. Some differentiation of the various grain sizes has been effected since in places there are thin lenses of very coarse grained or even pebbly material amongst somewhat finer material; in the field such lenses often appear coarser than they are because of their porosity and they may be colloquially termed grit without any of the specific implications of that name. Even where differentiation has not taken place the material comprising



Fig. 34. Moderately sorted coarse to very coarse grained sandstone with polycrystalline grains and secondary overgrowths; High Coal Sill major washout-channel sandstone base, Sunny Brow Mine Quarry, near St. John's Chapel. Crossed nicols, x 27.

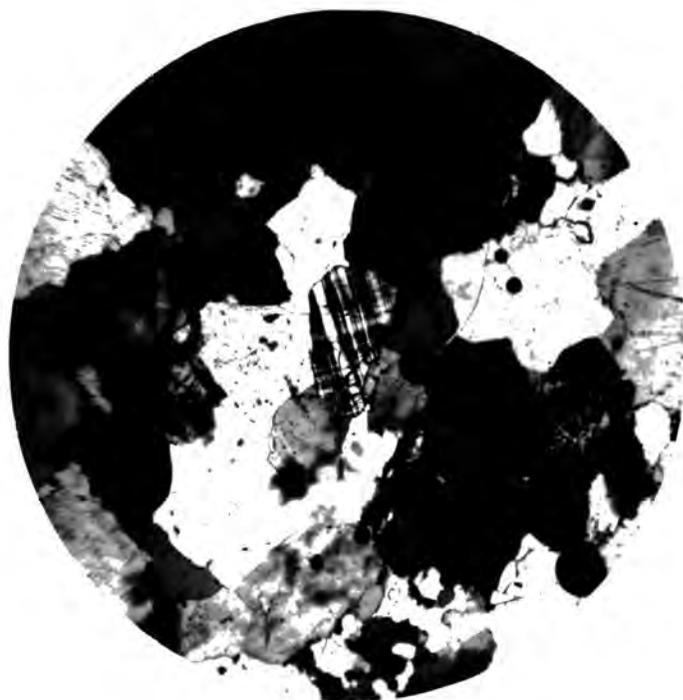


Fig. 35. Moderately sorted coarse grained sandstone with fresh microcline; same locality as Fig. 34. Crossed nicols, x 27.

the sandstone is not too badly sorted overall and it may be described as moderately sorted (Figs. 34 and 35) as opposed to the generally well sorted material of the sheet sandstones; this does not mean to say that there are not some poorly sorted patches, however. The coarse grained nature of the sandstone persists upwards for approximately half its total thickness, this being a maximum of about 40 feet. The material becomes less coarse grained upwards and eventually above the half way mark passes into a lithology comprised of either medium, medium to fine or fine grained sand which is reasonably well sorted generally (similar to that forming the upper parts of the subsidiary washout-channel sandstones, as illustrated in Fig. 38). In fact, in places the very top of the major washout-channel is filled with silt and clay grade material containing only a very fine grained sand admixture and discrete thin bands of fine grained sand. The very basal parts of the sandstones filling the subsidiary channels are essentially of coarse grain size (Fig. 36) with a little very coarse grained material associated (Fig. 37); abnormally and very rarely there are grains of granule and pebble size up to 9 mm. diameter present also. In addition, there is a subsidiary admixture of finer grained material, particularly of medium grain size (Figs. 36 and 37). Nevertheless, the sandstones are not too badly sorted overall, very poorly sorted material only being of local extent. In general the coarse grained nature only persists for the lower 5 feet or so of the sandstones, there being only rare exceptions to this rule. Above their basal parts the sandstones are comprised of medium, medium to fine or fine grained well sorted material (Fig. 38), into which the coarser grained lithology grades. As in the case of the major channel the very top of the subsidiary channels may be filled with material of silt and clay grade.

The bulk of the material comprising the various sandstones conforms to the grain size limits specified above, but there are notable exceptions to this general rule. In particular, the heavy minerals are almost invariably of a common grain size in what ever type of sandstone they occur, the grains generally being no larger than fine grained (Fig. 40) with only rare occurrences of medium grained material even in the coarsest lithologies. Hicks (1958) has brought to light one exception to this rule, however, in discovering corroded garnets, which were originally up to 1.4 mm. long, in the very coarse grained pebbly washout-channel sandstone of the Baugh

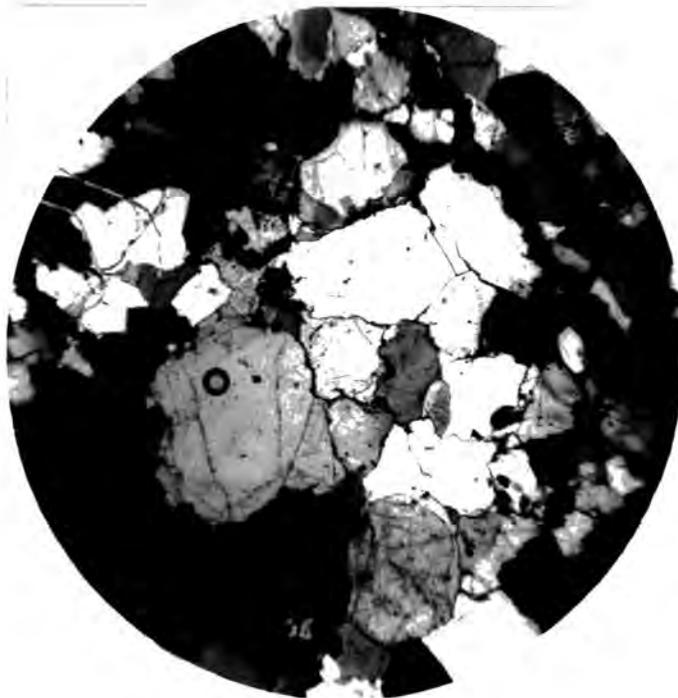


Fig. 36. Reasonably well sorted medium to coarse grained sandstone with obvious secondary overgrowths; High Coal Sill subsidiary washout-channel sandstone base, Rogerley Quarry, near Frosterley. Crossed nicols, x 27.

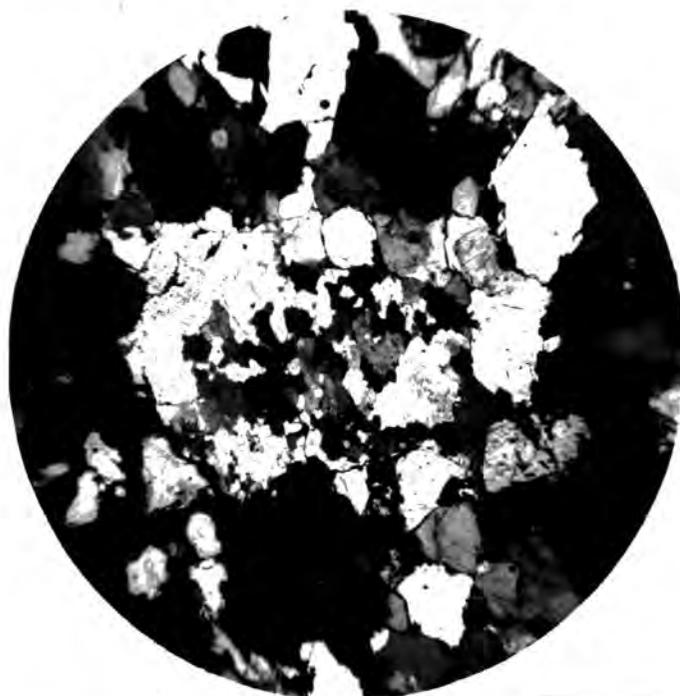


Fig. 37. Very coarse grained polycrystalline quartz grain in otherwise reasonably well sorted medium to coarse grained sandstone; same locality as Fig. 36. Crossed nicols, x 27.

Fell region on the Askrigg Block. Obviously the fact that the heavies are generally of smaller grain size than the rock in which they occur could be partly attributable to their high specific gravity, the transporting agent being able to carry larger grains of the other sandstone components further because of their lower specific gravities. However, this does not explain the approximate common grain size of the heavies in sandstones of varying coarseness; it would, therefore, appear reasonable to assume that the heavy minerals available in the source material of the sandstones were originally of small grain size in general. In addition to the above it has also been found that in the finer grained lithologies the heavy minerals are often concentrated into streaks which are also rich in mica and carbon, such a feature being indicative of extensive sorting by winnowing action. In direct contrast to the heavies, the micas generally tend to occur in flakes with lengths somewhat larger than the average grain size of the sediments of which they form a component, except the coarsest lithologies. This feature is presumably attributable to the property of the micas of splitting into thin flakes longer than other component grains of the sandstones of similar weight since this would enable the flakes to be transported further than the other components of similar grain size.

Grain Shape and Cementation

These two features are taken together because it is obvious that the original shape of the quartz grains, as far as the degree of roundness is concerned, has often, if not invariably, been markedly modified by cementation processes, the angularity of the grains being significantly increased when compared with their original shape. In this context the most important cementing agent is silica, there being numerous examples of original sub-rounded or rounded quartz grains outlined by a thin layer of dust with partial secondary overgrowths of silica in optical continuity around the parent grains, the overgrowths interlocking with adjacent grains to form a mosaic with an essentially sub-angular grain shape (Figs. 32, 34, 36 and 38). Interpenetration of adjacent grains by solution of silica at the original quartz grain contacts has also obviously taken place frequently, presumably complementary to the above, thus providing at least some, if not all of the silica for the secondary overgrowths; this also

serves to reduce the roundness of the individual grains with a consequent increase in angularity. It must be admitted that by no means all the grains exhibit an original sub-rounded or rounded centre with a secondary overgrowth of silica and, in fact, a large proportion of the grains in any one sandstone occur with a predominant sub-angular shape in an interlocking mosaic with no evidence of secondary overgrowth. However, the very nature of the interlocking sutured mosaic demands modification of the original grain shape as an explanation of its formation since the grains could not be so intimately related otherwise; therefore, the above process of interpenetration and probably secondary overgrowth was probably operative even though specific evidence for secondary overgrowth is often lacking. This does not necessarily mean that the original grains were sub-rounded or rounded as in the case of those whose original shape is at least partially preserved by the secondary overgrowths. However, it is most significant that only rare original sub-angular to sub-rounded grains are found with secondary overgrowths of silica, the majority of grain centres with overgrowths being sub-rounded or rounded. Therefore, in the absence of other evidence it must be construed that those grains with their original shape preserved represent the overall original character of the sediment deposited. The present angularity of the grains is also emphasized in places due to the quartz being attacked and partly replaced where it is in contact with clay mineral; this is a significant point which must be taken into consideration in interpreting the shaly sandstones (generally fine grained) which tend to exhibit more angular grains than the less shaly sandstones where obvious modification of the quartz grains has been able to take place. In addition, distinct corrosion of the quartz grains appears to have occurred where they are associated with calcite, and the resultant grains are often markedly angular, although the roundness of some grains appears to have been improved in the process also (Fig. 39).

Thus, as far as the grain shape is concerned the majority of the sandstones now have angular, sub-angular, sub-angular to sub-rounded or occasionally rounded quartz grains (the latter generally in the case of the coarser lithologies), all of which are bound together into a more or less continuous interlocking sutured mosaic depending upon the amount of other original interstitial cement present; the most common shape is sub-angular. However, the evidence cited above indicates that when deposited the quartz



Fig. 38. Well sorted medium to fine grained sandstone with fresh plagioclase and secondary overgrowths; 6 feet above subsidiary washout-channel sandstone base, Rogerley Quarry, near Frosterley. Crossed nicols, x 27.

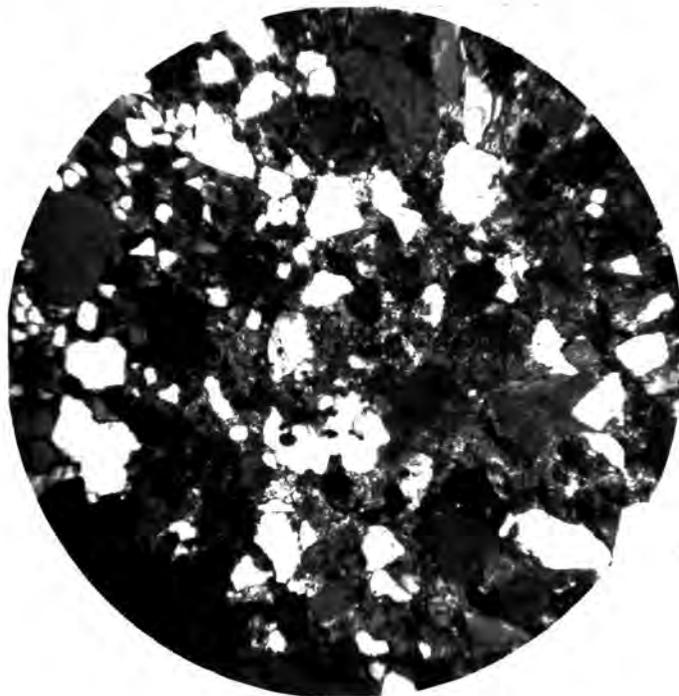


Fig. 39. Poorly sorted very fine to medium grained calcareous sandstone with quartz grains corroded by carbonate; Upper White Hazle top, Linzgarth Cleugh, near Rookhope. Crossed nicols, x 27.

grains were predominantly sub-rounded and rounded, although in the finer grain sizes there does appear to have been some sub-angular material in the original deposit, but there is no evidence to suggest that such material was predominant. In particular, the larger grains were invariably well rounded, a feature which has tended to persist even where the grains have been involved in the cementation process. It is probably significant to note that there is no marked difference apparent in the roundness of any of the material which is considered to exhibit its original shape in both the washout-channel sandstones and the sheet sandstones. This could be taken to indicate that the source material of the sandstones had a reasonable degree of roundness such as that which could be present in pre-existing sediments. If the source material had not been of such a kind as the latter it could be reasonably expected that the different types of sandstones within the Great Cyclothem would exhibit some difference in their degrees of roundness because of their differing environments of deposition.

In addition to their roundness a large proportion of the quartz grains comprising the sandstones have a high sphericity, but there is a small proportion which have a low sphericity, that is to say, they are elongate. Such elongate grains generally occur with a sub-parallel orientation in relation to each other, the micas and the bedding of the sandstones, particularly in the sheet sandstones, as mentioned below.

The subsidiary granular detrital components of the sandstones in general appear to exhibit a similar original grain shape to the quartz, and, in particular, the heavy minerals are predominantly well rounded, though not invariably (Fig. 40). The feldspars also generally show a good degree of rounding and, since in a number of cases the grains have been unaffected by authigenesis and weathering, they, along with the heavies, present further evidence of the better rounding of the original sediment than is generally apparent from the indurated sandstones. However, the micas invariably occur in elongate laths or plates which in most cases are orientated parallel or sub-parallel to each other and the bedding, in common with the occasional elongate quartz grains. This parallel alignment of the micas is particularly common and well developed in the sheet sandstones and it is best seen along the bedding planes where micas tend to be concentrated. Where the sheet sandstones contain plant rootlets in situ, how-

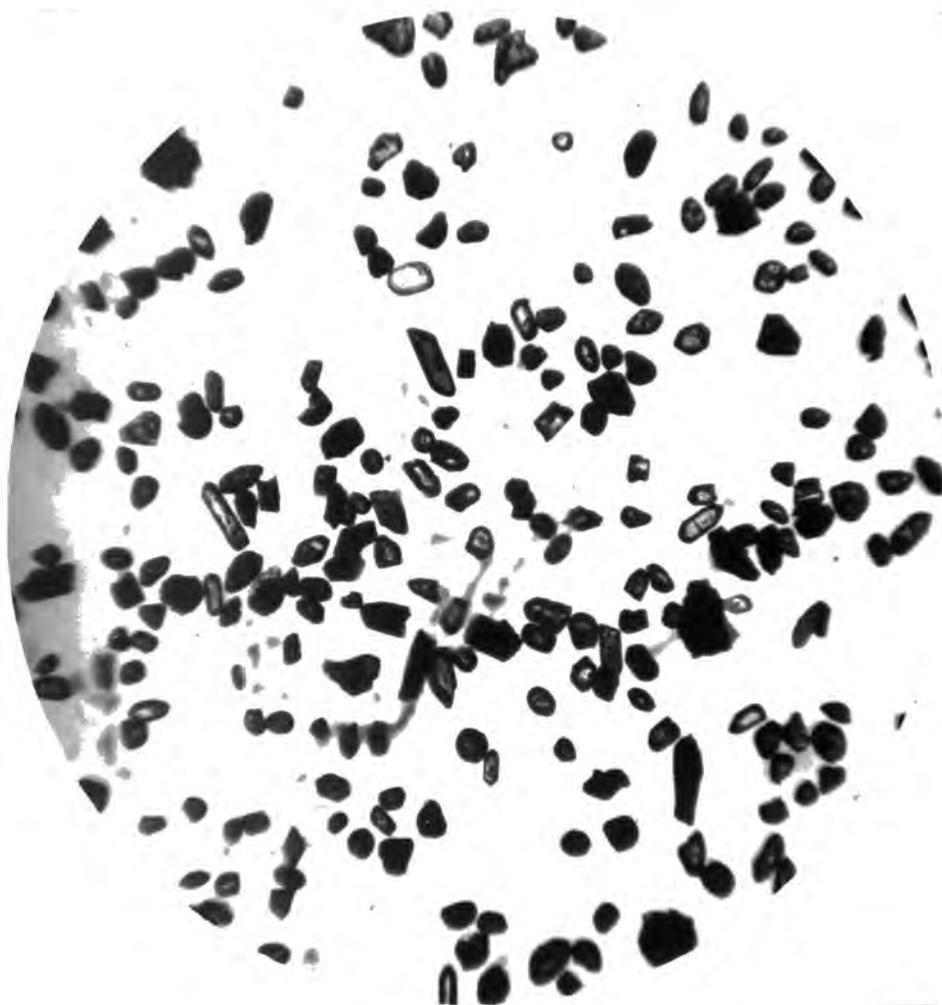


Fig. 40. Typical heavy mineral separation mainly of rutile and zircon;
Great Sandstone, Brunton Bank Quarry, near Fallowfield.
Ordinary light, x 40.

ever, no preferred orientation exists, the micas having a hap-hazard relationship to each other owing to the disturbance after deposition caused by the growth of the plants. The micas in the lower parts of the washout-channel sandstones do not exhibit very marked preferred orientation but it is not completely lacking; higher in the channel sandstones, as in the contemporaneous "channel" sandstone, the micas show a definite tendency to sub-parallel orientation which is well developed along the bedding planes.

As pointed out above, the main cementation process affecting the majority of the sandstones has involved the interpenetration of adjacent quartz grains by solution of the silica at their contacts and the complementary deposition of silica in the original interstices between the grains. The secondary silica has generally grown around the original grains in optical continuity, the original boundaries of the parent grains being outlined by a layer of dust in many cases; also, it can occasionally be seen that in the overgrowth process efforts have been made to develop crystal faces. Very few grains have been observed with overgrowths completely around them, most grains being partly interpenetrant. In addition to the silica of the secondary overgrowths there are occasional interstitial patches of microcrystalline and cryptocrystalline silica which were probably derived by some of the redistributed silica being deposited in pore spaces without growing in optical continuity with adjacent grains or itself.

As mentioned previously also, by no means all of the grains within the sandstones have obvious secondary overgrowths, but the process of interpenetration and probably secondary overgrowth must have taken place, even where it is not obvious, in order to produce the closely welded character which is a prominent feature of the majority of the sandstones. Thus, the above cementation process has given rise to a more or less continuous interlocking mosaic of essentially sub-angular grains (Figs. 32, 36 and 38). It is envisaged that the process of solution of silica at grain contacts and the deposition in interstices between the grains was promoted by the load of super-incumbent strata once the deposits were buried, the silica being redistributed with the aid of connate water. A contributory factor in the redistribution may be the solid (plastic) flow of quartz grains at pressure points, a process claimed by Taylor (1950) to have been operative

in some sandstones; such a process has been shown to occur experimentally but the extent of its effect in the sandstones would be difficult to define. No external source of silica for the secondary overgrowths seems necessary because the amount required would be provided in the complementary part of the process, that is, the solution of silica at the grain contacts. It might be pointed out that Greensmith (1957) did not consider this to be the case as far as the Millstone Grit and Coal Measure sandstones which he worked on were concerned since he postulated the separate precipitation of a silica (or calcite) cement at or soon after the time of deposition of the sandstones. Such a process appears inconsistent with the present observations since the sandstones of the Great Cyclothem exhibit compaction features (a large number of contacts per grain in the overall sutured mosaic and buckled micas) which would not be present if cementation by the precipitation of silica had taken place at or soon after deposition. It might be specifically mentioned here that of necessity the redistribution of the silica must involve some compaction with a consequent decrease in the original thickness of the sandstone deposited.

As noted previously, the above cementation process has apparently markedly affected the grain shape of the sandstones. On the other hand, there is no evidence to suggest that it has significantly altered the grain size and sorting of the sandstones even though it has been kept in mind that Goldstein (1949), working on the Dakota sandstones of the Colorado Front Range, claimed that the finer constituents of the sands had been completely dissolved and redeposited as cement.

It has already been stated that the redistribution of silica acted as the main cementing process in the sandstones and generally it has resulted in a well lithified rock. There is some variation in the extent of such cementation, however, which would appear to have been controlled largely by the amount of interstitial material originally present in the sediment, the redistribution of silica having been inhibited by such material. The interstitial material generally consists of clay minerals but carbonate is sometimes present, and both materials must be regarded as cementing agents in themselves. Where no such material, or very little was present, the sandstones have often been rendered siliceous and highly compact by silica cementation; such rocks are not very common, however, but where they do occur they may contain the remains of plant rootlets, in which case they

are known as ganisters or pencil ganisters if the plant rootlets are very abundant; it might be added that the name ganister has also been given to some siliceous sandstones which contain no plant rootlets. In most of the sandstones there is at least a small percentage of interstitial detrital clay mineral present, although some of the clay mineral is obviously secondary and derived by the degradation of the micas and feldspars. Such material acts as a cement by packing the pore spaces between the quartz grains. However, because of its character the clay mineral does not act as a very strong cement and, consequently, the more shaly sandstones, with clay mineral often completely surrounding many of the quartz grains, tend to be rather soft and not particularly well lithified. Furthermore, the nature of the clay mineral cement allows it to be removed easily by weathering agents, thus resulting in an increased porosity of the sandstones in surface exposures; such a porosity would probably not have been present if the pore spaces had been open whilst the redistribution of silica was going on. Where a carbonate cement is present it is generally calcite, although occasionally it is siderite. Occurrences of carbonate in surface exposures of sandstones are not very common, however, but when it is present the carbonate usually forms a fair proportion of the rock and constitutes quite a tough cement. The rarity of sandstones at surface containing small amounts of carbonate cement would appear to be due to weathering processes having leached out the material which was originally present, because in a fair proportion of sandstone samples from underground (from mine exposures and borehole cores) a small percentage of interstitial calcite has often been detected. Thus, in surface exposures the porosity of the sandstones is probably partly accounted for by removal of carbonate from the rock since, as in the case of removal of clay minerals, the porosity would not be as high if the redistribution of silica had not been inhibited by the original interstices between the grains being filled with carbonate. Where it has been completely removed from surface exposures of the sandstones it is impossible to determine the original presence of calcite. Furthermore, where it is present it is by no means certain that the calcite is an original constituent of the sandstone because it could have been so easily introduced by carbonate-rich ground waters or during authigenesis. Thus, unless it is associated with fossils, calcite is not a reliable indicator that the sandstone was formed under marine or near

marine conditions.

MINERALOGICAL COMPOSITION

Introduction

The mineralogy of the various sandstones is basically similar as far as the mineral species present are concerned, apart from the local relative abundance of potash feldspar whose distribution appears to be restricted to the base of the major washout-channel sandstone. The main variation really only involves the differing proportions of quartz, clay minerals and sometimes micas, so that all the sandstones may be considered together as far as their mineralogy is concerned. The following constituents have been identified in the sandstones, quartz being by far the most common in the main body of the sandstones:- quartz, chert, feldspars, micas, clay minerals, carbonates, heavy minerals, carbon, rock fragments, pyrite and limonite. These are considered specifically and in more detail below.

Detailed Mineralogy

Quartz.- In most of the sandstones at least 90 per cent and often over 95 per cent is composed of various varieties of quartz grains. However, the proportion can be much lower than this, particularly where the sandstones are shaly, in which case the proportion of clay mineral and sometimes micas rises at the expense of the quartz; the situations where the sandstones become shaly have already been specified. The presence of carbonate also involves a considerable reduction in the proportion of quartz occasionally. Three detrital varieties of quartz have been recognized, as follows:-

- (i) Monocrystalline grains with no profound undulose (strained shadow) extinction. These features are indicative of original derivation from an igneous source, but such grains are certainly not dominant in the sandstones.
- (ii) Monocrystalline grains with marked undulose extinction to a greater or lesser extent, sometimes showing a tendency towards the development of polycrystallinity (mosaic straining) in the extreme cases. Undulose extinction of this type is generally accepted as indicating a metamorphic derivation, but it is possible that some undulose extinction is generated

during cementation after the grains have been deposited due to pressures developed in the sediment. It would also appear that some strained quartz can occur in igneous rocks, particularly the plutonic ones. Thus, the presence of marked strain shadows is not an absolutely definitive criterion indicating a metamorphic derivation, although it is a useful means of classification. Grains of this type are by far the most common in the sandstones.

(iii) Polycrystalline grains with sutured boundaries between the individual anhedral crystals making up the grains (Figs. 34 and 37). This type of grain is never very common, but even so it can almost be described as a ubiquitous component of the sandstones. Such grains are generally of a reasonably large size and thus more common in the coarser sandstones. However, much of the finer monocrystalline material could have been derived by the break-up of such grains. The milky coloured granule and pebble grade material in the sandstones, generally referred to as vein quartz, as well as some less coarse material has this polycrystalline character which is regarded as that of metamorphic quartzite.

In addition to the above detrital varieties of quartz there is often a varying but usually small amount of interstitial microcrystalline or cryptocrystalline quartz. Such material is considered to have been derived during the quartz redistribution process, as mentioned earlier.

Apart from the dust outlining the original grains where they are surrounded by secondary overgrowths, numerous small inclusions within the quartz grains have been noted, but they have never been observed in abundance in any one thin section of sandstone. They consist of recognizable muscovite, biotite, apatite, zircon, tourmaline, rutile and indeterminate acicular crystals which are also probably rutile; occasional fluid inclusions have also been observed but only rarely do they contain gas bubbles. It might be noted that the observed predominance of regular inclusions as opposed to irregular ones does not agree with the findings of Butterfield (1940) who investigated selected Yoredale sandstones collected from between the Great Scar Limestone and the Undersett Limestone of the Ask-rigg Block. Interpreted in the light of Mackie's (1897) findings the

observed inclusions indicate that the quartz was originally derived predominantly from metamorphic rocks with a subsidiary amount from igneous rocks, thus confirming the conclusions derived from the varieties of quartz present in the sandstones.

Chert.- Rare rounded detrital grains of chert are present in the sandstones, only the odd grain having been detected in any one thin section.

Feldspars.- Some variation in the feldspar content of the sandstones is in evidence since the sheet sandstones, the contemporaneous "channel" sandstone, the subsidiary washout-channel sandstones and the upper part of the major washout-channel sandstone generally contain less than 1 per cent, whereas the coarse grained base of the major washout-channel sandstone has been found to contain up to 3.5 per cent and the presence of crystalline kaolinite, sometimes with remnants of feldspar in it, indicates that there was more than this present originally (Hicks, 1958). The higher proportion of feldspar in the coarser grained sandstones was also noted in those rocks studied by Gilligan (1920) and Butterfield (1940). The varieties of feldspar present and their distribution in the sandstones is dealt with below:-

(i) Plagioclase in fresh rounded grains with distinct albite twinning (Fig. 38), suitably orientated grains always having extinction angles of less than 20 degrees indicating a soda-rich composition in the albite-oligoclase range. This type of feldspar almost invariably occurs in extremely fresh grains with virtually no alteration, the freshness presumably being due to the known stability of the albite-rich feldspars under widely varying conditions. All of the sandstones have been found to contain this variety of feldspar.

(ii) Plagioclase in untwinned grains which almost invariably exhibit alteration to a greater or lesser extent, the alteration product generally being illitic in character, although some kaolinite may be present occasionally. This type of feldspar has been identified as plagioclase rather than potash feldspar principally by carrying out the staining technique mentioned earlier and obtaining negative results; in addition, in the few cases where it has proved possible to obtain interference figures they have proved to be biaxial positive. The

composition within the plagioclase range has not been determined specifically but it is probably more anorthitic than the unaltered twinned type of feldspar, the more calcium-rich plagioclases tending to decompose rather more easily than the soda-rich ones. This variety of feldspar has also been found to occur in all the sandstones.

(iii) Microcline and microcline-microperthite grains which usually exhibit typical cross-hatched twinning (Fig. 35) and a variable degree of alteration. Some grains are remarkably fresh with only a small amount of alteration to illitic material around the edges and along cracks, whereas other grains are almost completely or completely altered to clay mineral which can be illitic but is often mainly kaolinite; the ultimate in the latter case has been noted by Hicks (1958) in the sandstone from the base of the major washout-channel in the Baugh Fell region which in places contains about 12 per cent kaolinite with little or no feldspar remaining unaltered. The alteration of the feldspar to kaolinite is almost certainly at least partly due to relatively recent weathering, the reasonably unaltered grains occurring where they are protected by being surrounded with an intergrown mosaic of quartz (Fig. 35). This type of feldspar has only been found in the sandstone filling the lower part of the major washout-channel, where it occurs in relatively large grains. Its restriction to the major washout-channel sandstone probably reflects the more rapid deposition which took place in the channel, the potash feldspar presumably surviving there because it was not subjected to the same degree of winnowing and hence destructive action which was involved in the formation of the other sandstones; its larger grain size as a component of the material at the base of the major washout-channel probably contributed to its survival also.

The significance of the feldspars lies principally in the occurrence of microcline and microcline-microperthite adding to the evidence that the original source of the sandstones consisted of granitic rocks to some extent. Much of the alteration of the feldspars to clay minerals is post-

depositional since the intimate relationship of the clay minerals with the remnants of the parent grains would not have survived otherwise; in this context, the delicate vermiculitic books of kaolinite, which are presumably derived from feldspar, could not have survived the rigours of transport. In fact, alteration of the feldspars is almost certainly being effected by the weathering agents at the present time.

Micas.- In the main body of the sandstones the micas generally comprise no more than 2 per cent of the rock and often considerably less. However, there are concentrations of mica along bedding planes where the proportion rises considerably; also, locally and in the lower parts of the sandstones where they are shaly, micas are much more common and may comprise at least 10 per cent and often more of the rock. Both muscovite and biotite are present in the sandstones, the material identified as muscovite generally being markedly predominant; the two micas are dealt with separately below:-

(i) Muscovite is generally by far the commonest of the micas and in some cases it appears to be the only mica present in the sandstones. However, it is possible that some of the material identified as muscovite is actually completely or very nearly completely bleached biotite; there is no critical evidence to fully substantiate such a hypothesis except the slight pleochroism of some of the almost colourless laths, and, consequently, it is impossible to satisfactorily differentiate such material from muscovite. Previously, Lewis and Rees (1926) also suggested that some of the mica which appeared as muscovite in sandstones from the Coal Measures had such an origin. The muscovite occurs in virtually colourless elongate plates and laths, the plates and laths very frequently having frayed edges where the muscovite is degraded to sericitic or illitic material; the sericitic material consists of an aggregate of minute micaceous flakes whilst the illitic material is similar but considerably finer grained. Many examples of buckled muscovite flakes occur where they have been affected by compaction; on the other hand in places it can be observed that the mica plates have arrested the authigenic growth of quartz.

(ii) Biotite and its derivatives are generally much less common overall than muscovite, but in the shaly parts of the sandstones the position may be reversed. The biotite occurs in plates and laths which tend to be somewhat smaller and less elongate than those of muscovite. Only very rare laths of relatively unaltered, brown, markedly pleochroic biotite occur, but it is possible, as stated above, that an indeterminate amount of the mica identified as muscovite may be bleached biotite. Laths of material with a micaceous habit, pale brown to colourless pleochroism and obvious expanded cleavage bear close affinity to biotite and have been identified as hydrobiotite; they are reasonably common. Another alteration product of biotite retaining the micaceous habit consists of colourless chlorite intimately associated with a variable amount of finely disseminated opaque material which has a high reflectance and is presumably an iron mineral thrown out of an iron-rich biotite during the alteration to chlorite; such flakes are not common but they are present in many of the sandstones. The occasional flakes of apple-green pleochroic chlorite present in the sandstones are also probably derived from biotite since in one case a single flake has been observed composed of interdigitating green chlorite and brown biotite with the alteration to chlorite taking place along the cleavage planes of the original biotite flake. The partial or complete destruction of the biotite has resulted in the production of aggregates of very fine micaceous flakes generally referred to as illitic, but which probably contain some chloritic material also; in fact, there are some aggregates of material which are probably more correctly identified as predominantly chloritic. Where complete destruction of the biotite flakes has taken place it is obviously impossible to determine whether the clay minerals have been derived from such a source or whether they were original detrital components of the sandstones deposited in the interstices between sand grains; therefore, as in the case of muscovite, the only clay mineral which can be safely attributed to derivation from biotite is that which is assoc-

iated with remnants of the parent mineral.

The two types of mica and their derivatives often tend to occur concentrated together in bands with the flakes in a preferred orientation sub-parallel to the bedding. Scattered flakes which may or may not have a preferred orientation do occur as well, however. It might be mentioned that much of the alteration of the micas, particularly the alteration to clay minerals associated with remnants of the parent flakes, must have taken place subsequent to deposition since the delicate material would not have survived in such a form during transport. In fact, some of the alteration has probably been brought about by weathering and is probably going on at the present time; in this context it might be mentioned that the degraded biotite, particularly the hydrobiotite, tends to break down to limonite under the effect of weathering.

Clay Minerals.- The normal sandstones may contain up to 10 per cent of interstitial clay mineral but the proportion is often considerably less than this, and in some instances a negligible amount of clay mineral is present, in which case the sandstones are usually markedly siliceous, as mentioned previously. On the other hand, where the sandstones become shaly locally and where they are grading up from the shales below them, they contain a considerably larger proportion of clay mineral than 10 per cent in accordance with their degree of shaliness.

All the clay mineral in the normal sandstones is interstitial occurring in pockets of variable size and narrow bands between the sand grains; however, there is some evidence indicating that illitic material has attacked and developed at the expense of some of the quartz grains, particularly where "floating" grains of quartz are present in the centre of a mass of illite; this feature is particularly evident in the more shaly sandstones which contain abundant "floating" quartz grains. A fair proportion of the clay mineral is presumably detrital, but it has already been shown that some is secondary where it has developed at the expense of feldspars and micas; however, it is impossible to differentiate between the primary detrital clay mineral and the secondary material unless the latter is associated with its parent mineral or the kaolinite is of the delicate crystalline variety which could not possibly have been transported.

In thin section the clay minerals are not particularly easy to identify

but it would appear that sericitic and illitic material, which occur as fine and very fine grained micaceous matted aggregates respectively, are the predominant clay minerals. However, some kaolinite may occur intercalated with the flakes of illite; this is not particularly evident from thin sections but the presence of a 7 \AA line on X-ray photographs of some clay minerals confirms the presence of kaolinite. A little kaolinite may occur discretely in fine mosaic-like masses, but the most obvious occurrence is in the coarse grained major washout-channel where it is the alteration product of potash feldspar and is in the form of vermiculitic books; kaolinite is rarely common, however, except in the latter situation. Occasional very fine grained aggregates of colourless to very pale green, slightly pleochroic material, identified as chloritic, may also be present in the sandstones too.

Carbonates.- The sandstones by no means invariably contain carbonate as one of their constituents and, in fact, there are only a few instances where it occurs in small amount (less than 5 per cent) in surface exposures; however, there is some evidence from unweathered samples obtained from boreholes and mine workings to indicate that small amounts of carbonate were probably present in many more of the sandstones before they were subjected to surface weathering. Where it is present in the sandstones, the carbonate is usually abundant, but such occurrences are generally isolated, for example, the large fossiliferous concretions rich in carbonate (up to 65 per cent) in the Low Coal Sill of Sally Grain and Scraith Burn, upper Weardale; it might be added that the occurrences of carbonate are not all quite as restricted as the above, but, nevertheless, they are not very widespread usually. However, the upper component of the White Hazle is frequently calcareous with the carbonate becoming more abundant upwards as it grades into the Little Limestone, Fig. 33 illustrating the sandstone where it contains only a small amount of carbonate whilst Fig. 39 illustrates a part much richer in carbonate from a higher horizon; the fact that this sandstone is really the basal component of the overlying Little Cyclothem has already been mentioned. Probably the most persistent and frequent occurrence of carbonate is in the sandy marine bands, but even here the proportion of carbonate present is very variable laterally and it is not invariably present by any manner of means; the Snope Burn Band is the most obvious example of this type of occurrence. All the carbonate obser-

ved occurs interstitially as a cement, no definite detrital grains having been discovered. A particular feature of the sandstones where a calcite cement is present is the apparent corrosion of the quartz grains by the calcite (Fig. 39).

Most of the carbonate found in the sandstones consists basically of calcite, although the brown iron-rich weathering shells on some of the calcareous sandstones, such as those on the concretions in Scraith Burn and Sally Grain, indicate that a certain proportion of iron carbonate may be associated with the calcite. Very occasionally the carbonate has been found to be basically siderite, such occurrences usually being found in the rather carbonaceous shaly basal parts of the sandstones. One abnormal occurrence of siderite discovered is in small nodules in the upper part of the Low Coal Sill of Snodberry Cleugh, upper Weardale, the sandstone being otherwise devoid of carbonate. The frequent limonite-stained character of the sandstones at surface could possibly be partly attributed to the former presence of small amounts of siderite since, because of its susceptibility to oxidation, the mineral is readily altered to limonite at outcrop; however, it could not be claimed that all the limonite was derived from such a source because there are other means by which it could be introduced into or formed in the sandstones. Where there are fossils present in the sandstones they often occur as casts which frequently contain powdery aggregates of brown limonite; this could be taken to indicate that the fossils were preserved in iron-rich carbonate immediately prior to weathering.

Because of their susceptibility to alteration and redistribution during diagenesis and weathering the carbonates alone are generally not reliable indicators of the environment of deposition. However, where there are marine fossils associated with the carbonate the obvious conclusions derived are much more reliable.

Heavy Minerals.- Only a small quantitative portion of any of the sandstones is comprised of heavy minerals, the average amount present generally being less than 0.1 per cent and often considerably less, contents as low as 0.002 per cent by weight having been recorded. Abnormally there may be an appreciably higher proportion than this present, such as the 1.4 per cent recorded by Hicks (1958) from the major washout-channel sandstone of the Baugh Fell region, but such occurrences appear to be very rare. In fact, in general the heavy minerals appear to be most abundant

in the finer grained sandstones, as also noted by Butterfield (1940) in Yoredale sandstones from between the Great Scar Limestone and the Undersett Limestone of the Askrigg Block. Because of the low proportion of the sandstones they usually comprise, the heavy minerals are only occasionally seen in thin sections; nevertheless, in the finer grained sandstones they sometimes tend to be concentrated into streaks which are generally rich in mica also. Because of their sparsity the heavy minerals have to be concentrated, as described previously, in order to study them satisfactorily. A typical mount made from a heavy mineral separation is illustrated in Fig. 40.

The species of heavy minerals discovered in the sandstones, in their relative order of abundance, are as follows:- zircon (colourless, dusky and pink varieties), rutile (brown, foxy-red and golden-yellow varieties), opaques (mainly leucoxene after ilmenite with white surface reflection, but also a little magnetite with steel-black reflection), tourmaline (variations between olive-green, emerald-green, brown and golden varieties, all of which are markedly pleochroic), apatite (colourless to very pale green), garnet (colourless and isotropic), anatase (yellowish-green and tabular) and brookite (yellow, tabular and striated); the latter two only occur very rarely, probably as an alteration product of ilmenite. Because of its known presence in the Millstone Grit from the work of Gilligan (1920), monazite has been specifically looked for but none was found; in particular, with the object in view of discovering this mineral the heavy mineral separations were tested for radio-activity but with negative results. Zircon is by far the most abundant of the heavy minerals in general, the following proportions, based on a count of approximately 650 grains in a heavy mineral separation from one of the sandstones, giving the general picture:- zircon 76 per cent, rutile 11 per cent, opaques 9 per cent, tourmaline 2 per cent, apatite 1 per cent, others 1 per cent. Although only rarely seen elsewhere, garnet is a relatively prominent constituent forming 0.8 per cent of the major washout-channel sandstone of the Baugh Fell region in which, needless to say, it dominates the overall heavy mineral assemblage. In this particular sandstone the garnet occurs as partly replaced skeletal remains of original grains which were up to 1.4 mm. long. The other occurrences of garnet are as small scattered grains which comprise very much less than 1 per cent of the heavy mineral assem-

blage of the sandstone they occur in. Opaque heavies are occasionally prominent and may sometimes dominate the assemblage or at least be more abundant than rutile.

No marked vertical or lateral variation involving the incoming or outgoing of species in the heavy mineral assemblage within the Great Cyclothem sandstones has been discovered, except the relative abundance of garnet in the major washout-channel sandstone of the Baugh Fell region, the mineral being rare elsewhere even in the major washout-channel sandstone. A possible explanation of this restriction of abundant garnet to one particular part of the major washout-channel sandstone has already been postulated in Chapter IV. As far as the normal heavy mineral suite of the sandstones is concerned there appears to be some lateral and vertical variation in the inter-specific ratios of the species present; however, this has not been fully investigated, but the variation, rather than being a regional one, may be related in some way to the grain size variation of the sandstones. Even though there does appear to be such a variation, zircon is almost invariably the dominant component of the heavy mineral suite by a very considerable margin. It might be noted that the overall heavy mineral assemblage of the Great Cyclothem is similar in terms of the species present and their relative proportions to that for the majority of the remainder of the Upper Limestone Group according to Mr. C. G. Godwin (personal communication); the heavy mineral assemblage of Yoredale sandstones (collected from between the Great Scar Limestone and the Undersett Limestone of the Askrigg Block) investigated by Butterfield (1940) is also very similar to that of the Great Cyclothem sandstones. These assemblages contrast markedly with that of the Millstone Grit which is rich in garnet and also contains monazite (Gilligan, 1920).

From the above it can be seen that basically the heavy mineral assemblage of the Great Cyclothem sandstones consists of a small number of the most stable and ubiquitous mineral species, the anatase and brookite being regarded as authigenic. Such a situation is indicative either of derivation from pre-existing sediments with an already depleted heavy mineral assemblage, or derivation from a primary crystalline source with much abrasion and destruction of the less stable mineral species before deposition; it might be added that there is no obvious reason for suspecting intrastratal solution as being a significant contributor in the depletion

of the heavy mineral assemblage. The weight of the evidence from the 'heavies' would appear to support derivation mainly from pre-existing sediments, especially as a large proportion of the grains are rounded or well rounded. However, there is a subsidiary admixture of virtually euhedral and also angular grains (the latter could be partly derived due to breakage during disaggregation of the sandstones, but the existence of some angular grains in the rocks has been confirmed from thin sections) which could indicate that some of the sediment came from a primary crystalline source; on the other hand, such grains could have been preserved in pre-existing sediments which were further broken down, thus liberating the less maturely shaped heavies, during the Great Cyclothem sedimentation cycle. Even if the sandstones were mainly derived from pre-existing sediments, the predominance of zircon, although somewhat emphasized due to the mineral's resistance to destruction, indicates a substantial original contribution from an acid igneous source, thus enlarging on the conclusion based on the occurrence of potash feldspar. Broadly generalizing, the rutile, apatite and leucoxene (derived from ilmenite probably) are also primarily indicative of an original igneous (acid and basic) source, whereas the tourmaline and garnet are most likely to have been derived from metamorphic rocks.

Carbon.- Most of the sandstones contain a certain amount of carbon, but it is rarely a very prominent constituent. In general, detrital carbon is most abundant in the shaly lower parts of the sandstones, there being only a small amount in the main body of the sandstones usually. However, those sandstones which contain Stigmaria and plant rootlets in situ naturally have a certain amount of carbon associated, but even in such circumstances, although the carbon is very obvious, it is not particularly abundant. In addition, the bases of the washout-channel sandstones, particularly the subsidiary ones, often contain reasonably common quite large derived fragments of vegetation whose outlines and sometimes the ornamentation are picked out by a thin film of coal or a concentrated layer of disseminated carbon. Derived angular coal fragments also occur sometimes, particularly in the channel sandstones, but not usually in abundance; however, as mentioned in Chapter IV, the upper component of the White Hazle frequently contains coal fragments, particularly at its base, the fragments having been derived by the erosion of the thin coal seam which separates the two components of the White Hazle.

In thin section the carbon appears totally black in transmitted light whilst under reflected light it is also predominantly black but within it pin-points of white reflection appear from isolated points. In the normal detrital type of occurrence the carbon appears as rounded grains, irregular ragged fragments and also in a finely disseminated state; such material often occurs concentrated and associated with richly micaceous bands, but it also occurs discretely and scattered too. Where it is present in intimate association with plant rootlets in situ the carbon appears as concentrations of disseminated material and irregularly shaped fragments; the Stigmaria with which the rootlets are generally associated may also have a similar occurrence of concentrated disseminated material along them, but in many cases there is a distinct thin film of coal outlining them. In addition, the derived large fragments of vegetation found in the lower parts of the washout-channel sandstones exhibit similar features, thin coal films often being present. The derived coal fragments are generally angular and of considerably larger size than the average grain size of the sediments which contain them, as opposed to the normal detrital carbon which tends to be of a similar grain size to the sandstones which contain it.

Thus, there are various modes of origin for the carbon within the sandstones, some of the carbon having been derived and some formed in situ. Nevertheless, all occurrences are related to plants and indicate the growth of such somewhere within the environment, thus reflecting the existence of swamp or terrestrial conditions during and subsequent to the formation of the sandstones. Obviously, the coals which frequently overlie the sandstones confirm such conclusions. The derived carbon fragments represent comminuted plant debris, some of which has been worn into rounded grains; the other occurrences and their derivations are self-explanatory.

Rock Fragments.- The sandstones have no very predictable distribution of rock fragments, nor any great variety in the types. However, irregular shale fragments up to 10 cm. long are generally quite common in the lower parts of the washout-channel sandstones. Shale also occurs in the other sandstones in occasional lenticular bands of irregularly shaped small fragments; in addition, galls of clay ironstone are sometimes associated with the shale fragments. The angular coal fragments mentioned above are

also really rock fragments and, therefore, warrant mention here. Both the shale and coal fragments are considered to have been derived locally within the environment of deposition. They, therefore, indicate the existence of a certain amount of penecontemporaneous erosion even though deposition was the main activity; one way which this can take place is well illustrated by the washout-channels whose courses cut into the underlying shales and coals, thus resulting in their sandstone fillings being the most prolific in fragments. The survival of the shale and coal as fragments must be taken to indicate at least their early partial lithification.

Since the major washout-channel sandstone cuts into the Great Limestone it might be expected that limestone fragments would be present in the sandstone-fill at the base of the channel. No such fragments have been discovered, however, although Hicks (1958) noticed that the washout-channel sandstone of the Baugh Fell region contained occasional voids which he thought may have been due to the solution of limestone pebbles; it might be pointed out that this observation was made before the present work had shown that the major washout-channel did actually cut into the Great Limestone on the Alston Block.

Pyrite. - Only rare occurrences of pyrite within the sandstones have been noticed and invariably the mineral has proved to be of secondary origin, this being obvious from the cross-cutting relationships which the pyrite grains and euhedra have with the other constituents of the sandstones.

Limonite. - This mineral is certainly of secondary origin, but in surface exposures of the sandstones it is almost invariably present to a greater or lesser extent imparting to the rocks an orange, brown or buff colour. However, as mentioned above, it is generally absent from the sandstones where they have not been subjected to weathering. Thus, its occurrence is directly attributable to weathering, the limonite being derived by the oxidation of some of the original iron-bearing minerals of the sandstones and the introduction of other iron oxide by the weathering processes. The limonite generally occurs staining the clay minerals to varying degrees, but it is also present in discrete concentrations as clots and thin films around the quartz grains, as well as occasional concretions.

Some of the limonite has undoubtedly been derived by the weathering of siderite and probably calcite which has some iron carbonate intimately associated with it. Another probable source is hydrobiotite which is unstable, breaking down to limonite, when subjected to weathering. The other obvious source of limonite from within the sandstones is the pyrite which tends to break down when weathered. Introduction of limonite has undoubtedly been effected to some extent by iron-rich surface waters.

CONCLUSIONS

From the point of view of provenance, the overall maturity in grain shape and sorting and the marked maturity in mineral composition are all indicative of the sandstones being predominantly derived from pre-existing sediments, but there is some evidence to suggest that a subsidiary amount of material was derived from primary crystalline rocks also. Even though the material for the sandstones was probably largely derived from pre-existing sediments, the mineralogy indicates that the original source of the pre-existing sediments was primary metamorphic and igneous rocks, the evidence suggesting that metamorphic rocks were the dominant contributors.

As far as the conditions of deposition are concerned the overall evidence from the sandstones and the associated sediments indicates that the material forming them was transported by and deposited in water. Basically the material forming the major parts of the sheet sandstones, the contemporaneous "channel" sandstone and the upper parts of the washout-channel sandstones would appear to have been transported by and deposited in water where similar conditions of current strength, abrasion and winnowing action prevailed since, in general, all exhibit similar overall grain sizes, sorting, degrees of roundness and mineral compositions. The general maturity of the sandstones in all these aspects suggests that, apart from being derived from pre-existing sediments, a fair amount of abrasion took place during transport; also it would appear that after deposition active winnowing was able to take place in reasonably shallow water in many cases, deposition not being too rapid to inhibit it; needless to say, it is impossible to assess the exact extent of such activity because this would depend upon knowing the maturity of the source sediments. Where the sandstones locally become somewhat shaly the winnowing action was obviously less effective, the finer clay fraction not

having been removed; in the case of the vertical (particularly where the sheet sandstones grade up from the underlying shale) and lateral regional passage to a more shaly character, however, the change is probably largely attributable to the feed of material being predominantly of clay grade due to a weakening of the transporting agent rather than failure of the sorting related to less active winnowing. The local poorly sorted parts of the sandstones, which are frequently coarse grained, presumably arose due to local increases in strength of the transporting agent and/or failure of the winnowing action to be fully efficient, the latter possibly being due to more rapid local deposition. Such occurrences of poorly sorted coarse grained material amongst well sorted finer material, along with the local shaly occurrences, indicate that the conditions of deposition were not absolutely uniform; this situation is not entirely unexpected in a natural environment. The basal parts of the washout-channel sandstones differ from the other sandstones in being considerably coarser grained and less mature with their poorer sorting and slightly different mineralogical composition; these features are obviously indicative of somewhat different conditions of deposition as compared with those of the other sandstones. The coarser grain size reflects the greater strength of the transporting current, such a feature fitting in well with the strength of the agent, that is to say, the rivers, required to initially cut the channels containing the sandstones. Thus, the coarser grained sands with their moderate sorting represent the initial deposits laid down when the material being transported was deposited due to slackening of the current, the indication from the poorer sorting being that deposition was more rapid than in the case of the other sandstones. Confirmation of the more rapid deposition and the consequent reduced winnowing action appears to be present as far as the major washout-channel sandstone is concerned, since the survival of microcline and microcline-microperthite can probably be attributed to relatively rapid deposition, the similar feldspars having been destroyed in the other sandstones due to greater winnowing action. The lack of any significant difference in the rounding of the components of the basal parts of the washout-channel sandstones and the other sandstones could be taken to indicate that the bulk of the material forming the sandstones was derived from pre-existing sediments with good rounding, because if this were not so there would be

some difference in the degree of rounding of the components of the different sandstones relating to the differing conditions of deposition. However, it could be that, at least to some extent, the basal parts of the washout-channel sandstones possess as high a degree of rounding as the other sandstones because of their coarser grain size, the rounding effected by rolling during transport of the coarser grained material offsetting the rounding attained later due to winnowing by the material forming the other sandstones; in this context it might be mentioned that this latter material would be moved mainly by saltation because of its finer grain size and hence it would not suffer so much rounding during transport.

In some instances the cements of sandstones have been utilized as indicators of the depositional environment. As far as the Great Cyclothem sandstones are concerned the main cementation has arisen, as described previously, by the redistribution of silica derived from the constituent detrital quartz grains of the sandstones, no other source of silica appearing to be required. Thus, there is no evidence to support the existence of the process suggested by Greensmith (1957) for the cementation of Millstone Grit and Coal Measure sandstones which involves the precipitation of silica from acid waters such as those found in a delta under fluvial influence. Therefore, the main cementing agent does not offer any definite indication of the depositional environment of the sandstones even though it seems likely on the basis of other evidence that at least parts of the sandstones were laid down in a deltaic environment under fluvial influence. As mentioned previously, because of their susceptibility to alteration and redistribution during diagenesis and weathering the carbonates alone are generally not reliable indicators of the depositional environment; where there is association with marine fossils the situation is clarified somewhat, however. The implications of the presence of a prominent clay fraction in the sandstones has already been dealt with above as far as the environment of deposition is concerned.

Within relatively recent years numerous different sandstone classifications have been erected, the multiplicity being attributable to the very variable mineralogy of the sandstones and the different emphasis placed on various features and requirements by the different workers. The most important of these classifications have been published by the following authors:- Krynine (1948), Pettijohn (1948, 1954 and 1957),

Tallman (1949), Rodgers (1950), Dapples, Krumbein and Sloss (1953), Folk (1954 and 1956), Packham (1954), Gilbert in Williams, Turner and Gilbert (1954) and Bokman (1955). All these classifications have their different merits but none are entirely satisfactory. In fact, confusion has arisen because there has been no standardization on terminology or class limits, various authors having used different names for the same sandstone types in some cases, whilst in other instances the same name has been used for different sandstone types; for example, as pointed out by Potter and Glass (1958), the terms orthoquartzite (Krynine, 1954; Pettijohn, 1948, 1954 and 1957; Folk, 1954), quartzose sandstone (Dapples et al., 1953) and quartz arenite (Gilbert in Williams et al., 1954) all basically describe the same type of quartz-rich sandstone. Fortunately, the complexities of these different classifications do not fully concern this work since the Great Cyclothem sandstones are basically mature quartz-rich deposits which may be described as orthoquartzitic, the major parts being true orthoquartzites; thus, the sandstones are members of a division of many of the different classifications about which there is general agreement as far as its compositional limits are concerned, despite it having been named differently by various authors, as mentioned above. However, on the basis of some of the classifications the more shaly or argillaceous sandstones should be designated subgraywackés solely because of their high clay content. Such a designation is not considered valid since the sandstones do not contain the requisite components, particularly the necessary proportion of rock fragments, to be related to a graywacké as originally defined by Naumann (1858); also, the term graywacké holds implications of derivation by vigorous tectonic activity with deposition in a geosyncline, conditions which certainly can not be associated with the formation of the Great Cyclothem sandstones. It was because such difficulties arose by including detrital clays in the classifications that Folk (1954) completely disregarded them. Because of their general intimate association with the mature quartz-rich sandstones, the argillaceous sandstones may also be described as orthoquartzitic, although they are not true orthoquartzites. In order to overcome this difficulty in classification, Harbord (1962) erected an orthoquartzite series of sandstones (along with an arkose series and a graywacké series) and gave the sandstones the general name arenite with descriptive prefixes;

thus, the true mature quartz-rich orthoquartzites are described as quartz arenites and the more argillaceous sediments with orthoquartzitic affinities are known as impure quartz arenites or argillaceous arenites. The above discourse covers most of the sandstone members of the Great Cyclothem but those sandstones containing a carbonate cement also need classifying. In view of their framework fraction consisting dominantly of quartz they may be termed calcareous or sideritic orthoquartzites. However, where the carbonate (usually calcite) becomes dominant the rock must be classified as an arenaceous limestone.

CHAPTER VI

SEDIMENTARY STRUCTURES

GENERAL

Those sedimentary structures considered in detail below are the more prominent ones which generally have field relationships and sizes that render them best studied in the field rather than the laboratory; however, some of the structures are best exhibited in borehole cores, although they are usually observable in the field too. They largely occur above the basal limestone in the essentially non-calcareous beds which form the upper part of the cyclothem over a large proportion of the area, and furthermore, they are particularly prominent in the sandstone and shaly sandstone components of these beds to which many of them are virtually confined. Probably of most importance within the arenaceous lithologies are the useful directional structures which manifest themselves as cross-bedding and ripple-marks. In addition, however, load-casts, slump structures, animal traces, graded bedding and stylolites have been noted in the sandstones and related sediments; in general, the latter group of structures are by no means as common or as obvious as the directional structures, cross-bedding and ripple-marks being almost ubiquitous features of the sandy beds to a greater or less extent. Structures such as current lineations, drag grooves and current fluting have not been recognized in the sandstones. In the other lithologies, nodules of various types occur, particularly in the shales, and in the basal limestone of the cyclothem beautifully displayed stylolites are especially prominent.

The main purpose of considering the sedimentary structures has been to assess the bearing which they have upon the provenance and conditions of deposition of the sediments which contain them; in addition, however, the implication of the occurrence of stylolites has also been looked into. With the above in view, the sedimentary structures have been studied in specific detail in the development of the Great Cyclothem on the Alston Block and in adjacent areas, the latter having been done in order to correlate with other workers' observations in the remainder of Northern England. With respect to the remainder of Northern England, as in other parts of this work, where they are available the published observations of other workers have been taken into consideration in compiling this account.

DIRECTIONAL STRUCTURES

Introduction

The sedimentary structures considered under this heading are those which elsewhere have previously been found to be useful for determining direction of current flow as well as indicating other environmental conditions. Of this type of sedimentary structure, cross-bedding, ripple-marks, current lineation, current fluting, load casts, drag grooves and slump structures have all been used successfully, either in combination or singly, for determining local and/or regional direction of sediment transport. However, of these structures only cross-bedding and ripple-marks have been found to be present in sufficient abundance with the necessary widespread distribution within the rocks under consideration to attract a study of them as current flow direction indicators. Other structures used elsewhere as direction indicators are also present in the rocks, but they are not useful from this point of view in the present case since they do not possess the necessary requirements of abundance, widespread distribution and ease of measurement. Such a situation with one or two structures dominant and the others subsidiary or completely absent is not entirely unexpected since the formation of the different structures depends on differing depositional environments. Even though they are present in reasonable abundance with a widespread distribution the cross-bedding and ripple-marks are of limited use as direction indicators for various reasons, as will be seen below.

Cross-bedding

Cross-bedding, the most prominent of the sedimentary structures within the Great Cyclothem, is present to a greater or less extent in the majority of sandstones of sheet, contemporaneous "channel" and washout-channel types. However, to a large extent it depends upon the lithification and weathering of the sandstones as to whether the structure is obvious or not, there being a number of cases where a sandstone is cross-bedded without the feature being readily detectable. In a few cases the sandstones are almost or completely cross-bedded throughout, but more normally the structure only occurs commonly in specific parts of the sandstones; this does not mean that it is necessarily completely absent from other parts of the sandstones, however. In the sheet sandstones it is most often found in the middle portion,

whilst in the contemporaneous "channel" and washout-channel sandstones cross-bedding occurs in the basal and middle parts most commonly. It is significant to note that the fossiliferous sandstones and sandy marine bands contain no obvious cross-bedding, although their lateral representatives may; thus, the marine or quasi-marine environment would appear to have been unsuitable for at least the preservation if not the formation of the structure.

Although exposures of the sandstones are often obviously cross-bedded, it is frequently difficult to accurately measure the dip directions of the cross-bedding laminae because of the nature of the outcrop, such a situation being the rule rather than the exception. Thus, at most localities it is completely impossible to obtain sufficient measurements to carry out a separate analysis even if the apparent variation is such as to warrant this. Consequently, all measurements taken on the Alston Block have been grouped together for the purpose of this consideration.

The cross-bedding most often appears in units ranging from 3 inches to 2 feet thick, although occasionally they are thicker. These units, which in general are only traceable laterally for a few feet, are made up of individual laminae varying in thickness between $\frac{1}{4}$ inch and 6 inches, with an average of 1 inch or so, the variation in general being directly related to the overall size of the units. These laminae are generally slightly curved (concave upwards), but the curvature is not usually very marked and may be so slight as to make the laminae appear straight. Those laminae making up a unit generally have a unidirectional dip which varies between 10 degrees and 25 degrees, the most normal angle being between 15 degrees and 20 degrees. Thus, the individual laminae may be termed foresets within the generally accepted terminology of cross-bedding, but no associated bottomset or topset beds have ever been noted with them. The above-mentioned features of the cross-bedding are illustrated in Figs. 41, 42 and 43. The individual foresets appear to be homogeneous throughout, there being no accumulation of coarser grained material at the foot of them, as would be expected in the case of classical delta foresets. Where individual cross-bedded units are superimposed, as is frequently the case, each succeeding unit generally truncates the underlying one to a greater or less extent; in fact, even where cross-bedded units are overlain by sandstone which is not cross-bedded, the tops of the units usually appear



Fig. 41. Typical cross-bedding; High Coal Sill subsidiary washout-channel sandstone, Ashes East Quarry, near Stanhope.



Fig. 42. Typical cross-bedding with distinct curved laminae; White Hazle, Blagill Burn, Blagill.



Fig. 43. Typical cross-bedding dip slope; White Hazle, Blagill Burn, Blagill.



Fig. 44. Typical cross-bedded unit overlain and truncated by non-cross-bedded material; High Coal Sill major washout-channel sandstone, Sunny Brow Mine Quarry, near St. John's Chapel.

to be truncated (Fig. 44). Individual superimposed units usually vary in their direction of dip, the variation often being considerable; even in the same unit, where the dip is generally unidirectional, as stated above, a slight swing in the direction of dip of the laminae is sometimes apparent as the unit is traced laterally.

Intimately associated and interspersed with the above type of cross-bedding is a subsidiary form in which in the ideal case the sand infills obvious troughs so that two sets of curved cross-bedding laminae dip into the centres of the troughs, one from each side, there being a third dip component parallel to the axes of the troughs. These infilled troughs, which are only occasionally perfectly preserved, vary in cross sectional width between 6 inches and 10 feet with the majority having a width nearer the maximum; the maximum depth of the troughs, and hence the thickness of the units contained, is of the order of 2 feet, the thickness being directly proportional to the width and hence considerably less than 2 feet in the case of the narrower troughs; unfortunately, exposure does not allow the lengths of the troughs to be determined. An almost invariable feature of the troughs is their erosive bases. This type of cross-bedding has been frequently recognized in various formations since it was first described from the Casper formation of the Laramie basin and named festoon cross-bedding by Knight (1929). An example of a perfect unit from a sandstone of the Great Cyclothem is illustrated in Fig. 45.

From the above it is obvious that in some cases the essentially unidirectional dipping cross-bedding units may simply be the exposed half of a complete festoon cross-bedded unit, the other half being obscured due to the character of the exposure. In other cases, unidirectional units can arise due to the imperfect preservation of festoon cross-bedded units, as illustrated in Fig. 46 (taken from Potter and Glass, 1958) which thus demonstrates how a large proportion, if not all of the cross-bedding described above can be referred to under the broad term of festoon cross-bedding.

As far as its derivation is concerned, cross-bedding can obviously be formed wherever sediment is laid down at an appreciable angle to horizontal, there being several agencies in differing environments by which this can be effected. In a sub-aqueous environment such bedding may be formed in miniature deltas by the classical method of sediment tumbling down a delta front slope to form characteristic foresets; it can also be formed



Fig. 45. Complete festoon cross-bedded unit; White Hazle, Blagill Burn, Blagill.

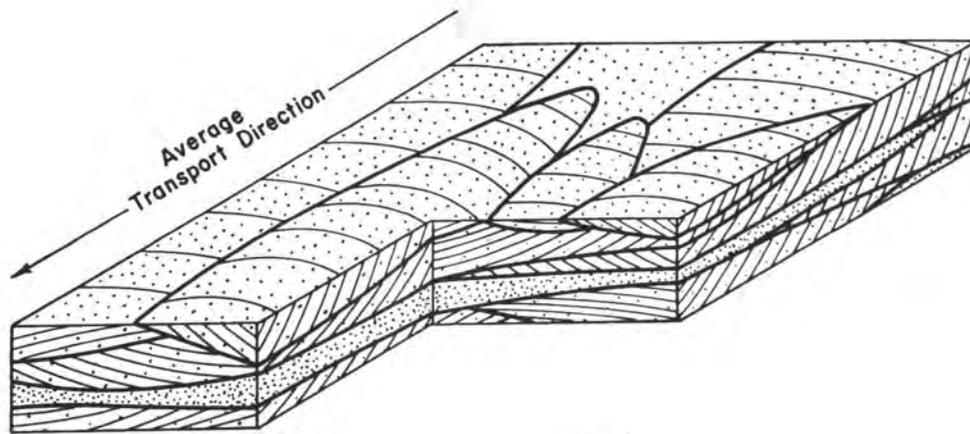


Fig. 46. Block diagram illustrating a typical markedly cross-bedded sandstone of the Great Cyclothem (after Potter and Glass, 1958).

in a braided river system on point bars, channel bars and even on the beds of the streams; in addition, ripples on a large and small scale can give rise to cross-bedding by their migration; furthermore, deposition on the sides of beach gulleys, in beach cusps and on bars and spits can produce forms of cross-bedding, whilst changes in beach profile result in very low angle cross-bedding. Cross-bedding can also be formed under sub-aerial conditions and is known as aeolian; it differs from sub-aqueous cross-bedding in having a generally confused appearance and, as can be seen from the above description, can be ruled out of this consideration. Despite the open-minded work of geologists before his time, the works of Sorby in the 1850's (1852, 1856, 1859a and 1859b) appear to have influenced many, but not all, subsequent workers who have frequently assumed that one mechanism, that is to say, deposition on the sloping surface of miniature deltas, is adequate to explain all sub-aqueous cross-bedding. The features of the cross-bedding in the Great Cyclothem sandstones are not consistent with such a derivation for various reasons. In particular, it is difficult to envisage how the complete festoon cross-bedded units could be formed in such an environment and the repetition of units is atypical of miniature delta cross-bedding; neither are the variable and often low dips of the frequently curved laminae like the reasonably high constant dips of true foresets which are comprised of straight laminae; also, in miniature delta cross-bedding the coarsest sand grains aggregate at the foot of the delta slope, a feature which is not apparent in the relatively homogeneous cross-bedding laminae under consideration; furthermore, cross-bedding formed in a miniature delta sometimes has bottomset beds, if not topsets associated with the foresets, whereas in the present case no such features have been discovered. Thus, from the foregoing it can be seen that there is considerable evidence against the cross-bedding in the Great Cyclothem having been formed in the most generally accepted environment, that is to say, miniature deltas. Of the other environments mentioned above, the most likely one in which the described cross-bedding could have been formed is a complex fluvial one comprised of essentially shallow, but occasionally markedly incised, braided and meandering streams on an extensive and developing flat low-lying coastal plain in a deltaic setting. In this setting, as the streams migrated laterally sediment would be laid down at an angle to horizontal on point bars (at the insides

of bends) and channel bars (in mid-channel), the cross-bedding extending in the direction of movement with the longest cross-bedded units being formed in the most markedly meandering streams. It has been shown that in such an environment to the above, the most rapid accretion takes place in a flood stage and under such conditions deposition occurs on the floor of the channels in troughs and hollows, thus giving rise to perfect festoon cross-bedded units. The above is obviously a simplification of the process involved in the formation of the cross-bedding, but it is the most feasible one since objections can be raised against all the other processes mentioned previously.

If the above mode of formation is accepted it can be seen that in the majority of cases the cross-bedding will be formed with the dip of the laminae at right angles to the current flow at any particular point, the only major departure from this general rule being in the case of the festoon cross-bedded units which have one dip component parallel to the axis of the unit and hence the current direction. In view of the character of the environment postulated for the formation of the cross-bedding with its streams of variable direction and probably meandering nature, an analysis of cross-bedding directions should be characterized by a more or less random scatter with little or no direct indication of the direction of the sediment source. Reference to the Schmidt rose diagram (Fig. 47), which takes into consideration the 258 accurately measurable cross-bedding unit directions available in the area studied in detail, illustrates that this is the case, there being only a faint indication of a peak in a south-south-east direction indicative of a north-north-west source for the sediments; it might be mentioned that regional lithological variations and the overall wedging out of the sediments on the Askrigg Block also indicate such a north-north-west derivation, however. A separate analysis (Fig. 48) of the cross-bedding measurements from a section of the contemporaneous "channel" in the Bollihope valley, Weardale, where the "channel" course can be shown to run from east-north-east to west-south-west (Plate III), clearly illustrates the formation of cross-bedding at right angles to the overall current flow. Thus, the cross-bedding is not a clear-cut direct indicator of the regional sediment source since its formation was controlled by local phenomena.

In addition to the cross-bedding described above, there is a very

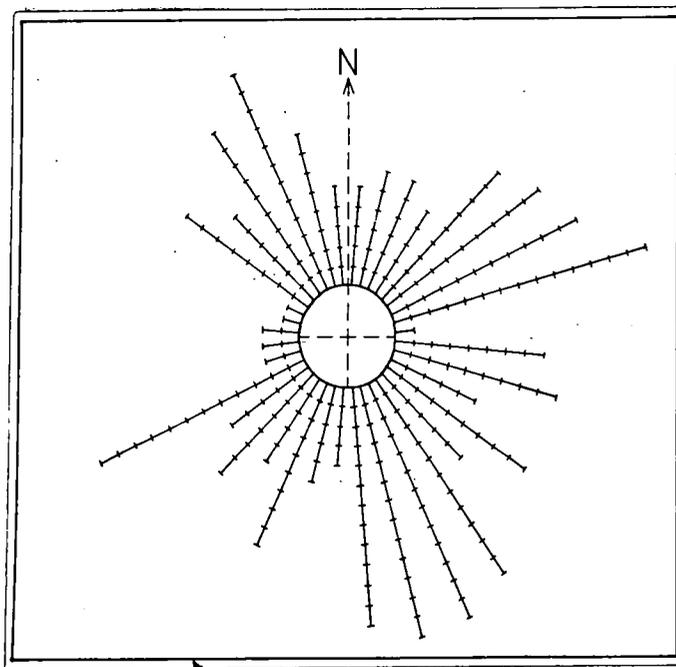


Fig. 47. Schmidt rose diagram based on 258 cross-bedding unit dip directions from the Great Cyclothem sandstones of the Alston Block. The class interval is 10 degrees and each unit length represents a single observation.

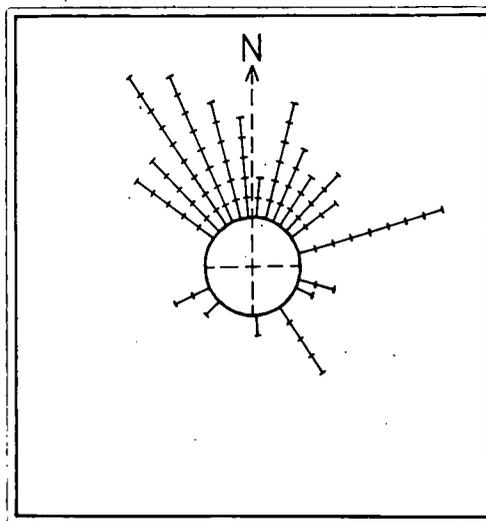


Fig. 48. Schmidt rose diagram based on 79 cross-bedding unit dip directions from a section of the contemporaneous "channel" sandstone in the Bollihope valley, off Weardale. Plotted as Fig. 47.

much larger scale form which is of limited occurrence. This form has already been described in Chapter IV and is illustrated in Fig. 26. It is restricted to the washout-channels and consists of wedges of interbedded sand and silt with an inclination parallel to the edges of the channels and a dip into the centre of them; the individual lenses of sand are generally cross-bedded themselves on a small scale similar to that described above. This large scale wedge or cross-bedding would appear to owe its formation to the intermittent deposition of streaks of sand and silt on one side of each deeply trenched washout-channel whilst the other side was being eroded during lateral migration, the erosion side being eventually plugged with a mass of sand when the erosive power was lost. Thus, the large scale cross-bedding is related to the small scale type in its mode of formation, both being formed in channels of varying size more or less at right angles to the current flow.

Ripple-Marks

In the sandstones of the Great Cyclothem ripple-marks are not as prominent as cross-bedding, but they are probably as abundant if not more so. They tend to occur most commonly in the lower parts of the sheet sandstones and are even abundant in the lowest shaly parts; in fact, in their lower parts the sheet sandstones can often be described as "ripplestones" because of the profusion of ripples. However, ripples-marks do also occur in the upper parts of the sheet sandstones as well as in various parts of the contemporaneous "channel" and washout-channel sandstones, there being a fairly common intimate association with cross-bedding. Despite their abundance, ripple-marks are only rarely well exposed in situ, except perhaps the interference type (see below), and they are usually best seen on the surfaces of blocks detached from the parent outcrops. Obviously, such a situation markedly detracts from the use of the ripple-marks as current direction indicators because of the impossibility of measuring the required orientation in most cases.

Three different types of ripple-marks have been recognized in the sandstones; these are the asymmetrical type, the symmetrical type and the interference type. Although it is possible to classify the three different types as above, there appears to be gradations between them, particularly between the asymmetrical and symmetrical forms. Because of this it is

sometimes necessary to make a very careful examination of the ripples before it is possible to classify them specifically. In spite of there being different types of ripples developed, there is no apparent order to their distribution, this being quite arbitrary.

Of the two distinct and generally clear-cut types, that is to say, the asymmetrical and symmetrical forms, asymmetrical ripples are the most common, but, as pointed out above, they are only occasionally exposed in situ. In fact, if the number of observed occurrences of them in situ were taken as an indication of their abundance they would be regarded as rare. The finding of such ripples in detached sandstone blocks modifies this assessment, but, nevertheless, asymmetrical ripples are by no means very common. In plan the ripples appear as a number of essentially parallel, more or less equidistant ridges (the ripple crests) trending in straight or gently curved lines. The wavelength, that is to say, the distance between each ripple crest, normally varies between $1\frac{1}{2}$ inches and 4 inches with an average around 2 inches to 3 inches. In cross section the ripples are asymmetrical, as the name suggests, with an amplitude of around $\frac{1}{2}$ inch or less. The above features are illustrated in Fig. 49 which actually shows the ripples in situ. In the ideal cases the asymmetry of the ripples is marked, there being distinct gentle and steep slopes developed; however, as mentioned above, in some cases there does appear to be a gradation between the asymmetrical type and the symmetrical type of ripple so that the asymmetry is not always marked. The asymmetrical type of ripple is known to be produced by a current of air or water flowing over sandy material at a critical velocity, the gentle slope of each ripple being formed on the up-current side whilst the steep slope is formed on the lee-ward side. Thus, the resulting ripple crests trend at right angles to the producing current and, therefore, their orientation can be used for deducing the direction of current flow. The few exposures of asymmetrical ripples which are suitable for measuring their orientation indicate a range between north-east and north-west for the origin of the current. It is of interest to note that this range embraces and therefore confirms the faintly indicated north-north-west current source derived from a study of the cross-bedding.

Symmetrical ripples have only occasionally been seen in situ, but they do occur in detached blocks (Fig. 50) somewhat more commonly. How-



Fig. 49. Asymmetrical ripples in situ; High Coal Sill, Broperygill Sike, Flushie Mere, Teesdale.



Fig. 50. Normal-sized symmetrical ripples in a detached block; Parson Byers Quarry, near Stanhope.

ever, they are certainly much less common overall than the asymmetrical type of ripple. In plan they appear similar to the asymmetrical ripples and they are generally similar in size with a 2 inch to 3 inch wavelength and an amplitude of around $\frac{1}{2}$ inch or less (Fig. 50). A larger form with a wavelength of approximately 1 foot 6 inches and an amplitude of 2 inches to $2\frac{1}{2}$ inches has been recognized, however, in detached blocks at one locality (Fig. 51). In cross section the ripples are obviously symmetrical, but they have broad crests (Fig. 50) rather than the sharp crests which are a normal characteristic of wave generated or oscillation ripple marks. Nevertheless, they probably owe their formation to the to-and-fro movement of a standing body of water agitated by waves rather than to current actions. The few symmetrical ripples observed in situ have an orientation range similar to that of the asymmetrical ripples.

Interference ripples are by far the most common of the three types and they are frequently seen in situ (Fig. 52) or in detached blocks. This type of rippling is particularly common in the lower parts of the sheet sandstones where a considerable thickness of the rock is frequently rippled and as a result is often quite friable; such rippling does occur in various other situations as well, however. Interference rippling imparts a typical "curly bedding" to the sandstones which is particularly obvious in cross section; another name which the interference ripples have acquired is "tadpole nests", presumably from the numerous separate small hollows (Fig. 52) which the sandstone contains when rippled in such a manner. Interference ripples were almost certainly produced in some instances by the superimposition of at least two sets of ripples with different trends, presumably in a situation where the conditions and hence the currents varied considerably. In addition, it may be that in some cases distinct asymmetrical and symmetrical ripples were never formed due to rapid fluctuations in the producing agent, such as would be experienced in a zone of breakers where vortices and such-like phenomena would be prevalent causing the sandy material to take up the form of interference ripples. It would also seem likely that the simple partial destruction of asymmetrical or symmetrical ripples by subsequent current activity outside the critical velocity for ripple formation could give rise to interference ripples. From the above it can be seen that the interference type of ripples are of no use whatsoever as current direction indicators.



Fig. 51. Large-scale symmetrical ripples in a detached block; Parson Byers Quarry, near Stanhope.



Fig. 52. Interference ripples in situ; High Coal Sill, Claypit Burn tributary, Swinhope, Weardale.

Thus, overall the ripple-marks within the sandy sediments of the Great Cyclothem are of very limited use as current direction indicators, partly because of the limited exposure of the most useful ripple type, and partly because of the predominance of interference ripples which are useless as current direction indicators. From a general environmental point of view the asymmetric ripples could be produced in both air and water currents of the critical velocity. However, it is doubtful if the aeolian type would be preserved so that the ripples must indicate a sub-aqueous environment which is confirmed by the association with the other type of ripples which are undoubtedly formed in an aqueous environment. Many of the ripple features can be closely paralleled on modern coastal flats which are under tidal influence; some are also visible in shallow sandy bottomed streams. These analogies give an important guide to the environment which prevailed during the main period of ripple formation, that is to say, whilst the lower parts of the sheet sandstones were being formed. The environment envisaged consists of an extensive deltaic coastal flat which was under tidal influence and intermittently crossed by shallow streams. Such an environment fits in well with that in which it is considered most of the cross-bedding in the sandstones was formed since at any one time the coastal flat under tidal influence would be at the seaward extremity of a fluvially influenced flat low-lying coastal plain, the latter eventually transgressing upon the former as deltaic conditions advanced seawards, thus accounting for the ripple-marks occurring in the lower parts of the sheet sandstones with cross-bedding being predominant in the overlying beds in the middle of the sheet sandstones. The later sporadic formation of ripple-marks and hence their association with cross-bedding is not surprising since no doubt conditions suitable for the formation of ripples prevailed at least locally in the environment where cross-bedding was predominantly formed.

OTHER STRUCTURES

Introduction

Of the remaining structures discovered, load-casts, slumping and stylolites are best seen in borehole cores, although they are usually observable at outcrop to a greater or less extent also. Animal traces, graded bedding and nodules are generally more clearly exhibited at out-

crop, although they are usually discernible in borehole cores too. Only the nodules in the shales, the stylolites in the basal limestone and perhaps the animal traces in the sandstones are particularly common, the others being distinctly subsidiary. Of the structures, load-casts and slumping have been found useful as direction indicators in other situations, but those in the Great Cyclothem are of no use in this context. However, all the structures have certain implications which will be systematically discussed below.

Load-Casts

These structures are best developed in the lower parts of the sheet sandstones where the latter are shaly, the best load-casts occurring along sandstone-shale contacts; load-casts do occur in other parts of the sandstones where a shaly character is developed, however. As mentioned previously, the structures are best exhibited in borehole cores, but they have been recorded in the field also; nevertheless, it can not be claimed that they are particularly obvious or common. The load-casts appear as mushroom-shaped penetrations of one lithology into the other, the size being of the order of 1 inch laterally and vertically. The structures are an example of soft sediment deformation and arise from the mechanical protrusion of one lithology into the other prior to lithification, the process presumably being activated by the load of superincumbent strata.

Slump Structures

Slump structures have not been found very commonly; when present they are confined to the sandstone beds and usually to the basal parts of the sheet sandstones, although not invariably. Borehole cores exhibit the occasional slump structures best and they have only been noted rarely at outcrop; the latter fact does not necessarily preclude the structures from being more common than would appear since their character is not one which makes them easy to recognize at outcrop. The most distinct form of slump structure observed is a type which has approximately the shape of a ball, up to 1 foot diameter, the internal structure being defined by contorted carbonaceous or shaly layers of varying intensity. These are named ball slump structures and probably owe their formation to the local piling up of sediment into an unstable position which finally collapsed and att-

ained a more stable position by rolling into a ball. This type of slumping is probably a local feature caused by the above process and not due to the overall slope of the sedimentation surface being steep; if the latter were the cause the structures would be much more common than they appear to be. The disturbed bedding which is also occasionally seen in zones up to 1 foot thick could also be related to minor slumping. However, its mode of formation could also be attributed to animal activity or to deposition on subsequently compacted plant debris or to mechanical distortion before lithification induced by the weight of superincumbent strata. In fact, all the processes could have been effective although the lack of plant remains in association with the disturbed bedding does not support such a derivation, whereas the presence of animal traces does lend some support to that mode of origin.

Graded Bedding

Graded bedding in the generally accepted sense is not a common feature of the sandstones, to which it is restricted if present. This is not surprising in view of the orthoquartzitic nature of the sandstones, graded bedding being a more normal feature of greywackés. That which occurs obviously is in very small units which are only of local extent and no more than a few inches thick. It has been noted in the sheet sandstones occasionally, but is more common in the coarser parts of the washout-channel sandstones where a very coarse grained fraction forms the base of the units which gradually decrease in grain size upwards. Such units almost certainly owe their formation to a winnowing action rather than to direct deposition in a graded sequence.

Another form of graded bedding on a large scale is that involved in the gradation upwards of the sheet and contemporaneous "channel" sandstones from the underlying shales. This is a reversed form of the normal type of graded bedding since it involves a gradation up from the finer grained shale to the coarser grained sandstone. On the other hand, the washout-channel sandstones exhibit a normal type of graded bedding on a large scale. In the former case the derivation is attributable to an increase in the carrying capacity or strength of the sediment transporting agent, whereas the reverse is obviously so for the washout-channel sandstones.

Animal Traces

Like a number of the other structures, the traces of animal activity in the form of castings, trails and borings are most abundant in the lower parts of the sheet sandstones; they do occur in other parts of the sandstones occasionally, however, but are by no means common generally. Nevertheless, on the Askrigg Block in the area to the north of Dale Head in Arkengarthdale, and to the south-west of Bowes, the White Hazle equivalent contains so-called "annelid tracks" (named fucoid markings by Dakyns et al., 1891) in profusion, thus giving rise to the term "wormy grits". The traces most commonly seen are castings and trails, borings only being found occasionally. In general the castings and trails are exhibited best in loose blocks of sandstone, but they have been noted in situ in a number of cases.

Castings, which are formed of material which has apparently passed through the gut of an animal, are often characterized by the lithology in which they are preserved being paler than the host material, particularly in dark richly organic sediment, because of the animal having removed the organic matter from it as food. By far the most common casting is that known as Crossopodia. This appears as a sinuous and elongate flattened ridge whose ends are rarely seen; in cross section it is of the order of 10 mm. to 20 mm. wide and 5 mm. thick. In detail the flattened ridge often has a subsidiary median ridge along its length, and faint transverse striae dividing it up into short lengths of 1 mm. or so are generally present also. Any one such casting is generally confined to the same bedding plane. Another type of casting occasionally seen on bedding planes is a simple sinuous cylindrical (occasionally somewhat oval because of flattening due to compaction) form with a diameter of around 5 mm.; the ends of this casting have not been observed. A distinctly segmented casting has also been found but it is only of rare occurrence; this form is made up of an overlapping linked series of slightly elongate dome shaped prominences each with a length of around 10 mm., a width of 8 mm. and a maximum height of 3 mm. to 4 mm. It occurs on bedding planes but is not found sufficiently often to determine its degree of continuity.

The actual trails present in the rocks are generally seen as casts on the sole of the overlying layer in blocks broken away from the parent outcrop; the trails are, therefore, groove trails, but are best seen in

relief. By far the most common trail sole-mark in the sandstones consists of numerous separate ridges of variable size with a width between 1 mm. and 10 mm., a height of 2 mm. to 5 mm. and a length ranging from a few centimetres to at least 1 foot; in fact, the width of an individual trail sometimes varies considerably and where the trails die out they do so by narrowing and shallowing. The individual trails are often straight or only slightly curved, but they have a random orientation and are generally scattered in profusion over the bedding planes, adjacent trails touching or crossing. No ornament of any kind is visible on the casts of the trails.

Borings have only occasionally been recognized, but they could be more common than is apparent because they are not easily located. Those borings seen are around 10 mm. in diameter and at least 10 cm. long. Usually they are vertical or only slightly inclined and the laminae within the sandstone containing them are generally downwarped somewhat immediately adjacent to the borings.

The significance of the various castings, trails and borings is somewhat tenuous since there is no absolutely critical evidence as to the type of animals which formed them, and in certain cases there is some question as to whether they have an organic association at all. However, the castings, trails and borings are frequently referred to colloquially as "annelid or worm tracks and borings" and, in fact, there is no evidence against formation by worms, although it must be admitted that there is no critical evidence supporting such a derivation either. Nevertheless, the total absence of any fossil remains intimately associated with the traces does suggest formation by soft bodied organisms such as worms; this is particularly so in the case of the castings which are comparable to some extent with worm tracks observable on modern beaches. There is a possibility that the supposed trails do not have an organic origin since they could represent rolled accumulations of sand and mucilaginous material such as are seen on modern beaches. However, the preferred orientation which might be expected in such circumstances is not a feature of the trails which are randomly orientated, as described above. Furthermore, the frequent association of the trails with bedding planes containing a layer of dark carbonaceous material is suggestive of derivation by animal activity, the organic material having provided a source of food originally. Thus, the trails could have been formed by browsing animals such as gas-

tropods and lamellibranchs; however, the total absence of gastropod and lamellibranch shells in most of the sandstones does not support such a postulate. Apart from an origin due to animal activity, the so-called borings could be variously ascribed to rain pitting, ascending air bubbles and ascending water currents. Thus, it must be admitted that there is no absolutely critical evidence as to the mode of origin of any of the structures and they may have a combined organic and inorganic derivation; it seems undoubted that some, if not all, are of organic origin, however. Therefore, the only really definite indication that the traces yield regarding the environment in which they were formed is that the physical conditions and food supply were suitable for animal life.

Nodules

Various different types and sub-types of nodular structures are present within the different lithologies comprising the Great Cyclothem, and their distribution has been dealt with in Chapters III and IV.

By far the most common nodules are those of ironstone which occur in the shales and sandy shales; normally such nodules are not developed in the lower parts of the shales where the latter are fossiliferous, but this general rule is not always the case. As well as being present in the shaly beds referred to above, that is to say, those underlying and grading up into or representing the sheet sandstones, ironstone nodules are also found in the shaly upper parts of the material infilling the washout-channels. The regional distribution within all of these beds appears to be quite arbitrary since nodules may be present in abundance at one locality and be absent at another. The nodules are hard and stand out from the surface of any outcrop where they can frequently be seen to lie in bands; in fact, the ironstone material itself may form bands or lenses in places. In form the nodules may be rounded or nearly so, but more often they are elongate and flattened to a greater or less extent; in addition, they may have a somewhat irregular outline because of rounded undulations on the surface of them. Some peculiar shapes are also developed such as the bell-shaped nodules, locally known as "cat-heads", from the shale immediately above the Great Limestone in the area to the north of Alston. The nodules vary in size considerably and may be only a fraction of an inch in diameter or at least 1 foot in diameter. In

composition they are basically made up of siderite and they represent aggregations of iron carbonate subsequent to the formation of the shale containing them since the remnant bedding of the shale passing straight through them can be made out in a number of cases, particularly on polished surfaces. Many of the nodules are totally composed of siderite, but quite a number contain pyrite either in small clots, very narrow veinlets or in a disseminated state; the pyrite generally comprises only a small proportion of the nodules, but in a few cases disseminated pyrite has been found to be abundant. Occasionally the nodules contain fossils where they occur in association with fossiliferous shale, but where nodules are present fossils are usually least abundant in the shale. In some cases the nodules prove to be septarian and contain a radiating and concentric series of calcite veinlets; such types have been noted particularly in the region around Alston, many of the "cat-heads" being septarian. The siderite of the nodules is indicative of reducing conditions which may have been fairly weak (Krumbein and Garrels, 1952; Teodorovich in Chilingar, 1955), particularly where pyrite is not associated with the siderite. However, such conditions need not necessarily have prevailed during deposition; this is almost certainly the case since the reducing environment is more likely to have developed within the sediment after deposition, perhaps just below the sediment-water interface, due to the presence of organic matter such as plant fragments whose remains do occur commonly in association with the nodules.

Another form of nodule which occurs in the shaly beds, but much less commonly than the ironstone nodules in most cases, is the type composed entirely of pyrite. Such nodules occur with much the same distribution as the ironstone nodules, but occasionally, as in Redmires Quarry, near Stanhope in Weardale, they are abundant in the fossiliferous shale almost immediately above the Great Limestone where they contain beautifully preserved fossils. The pyrite nodules are rarely above 3 inches in diameter and are often smaller than this. They are sometimes rounded, but more often are somewhat irregular in shape although they preserve an overall rounded shape. As mentioned above, the nodules are entirely composed of pyrite and some have cubic crystal faces developed on the outside of them. The pyrite is indicative of formation in reducing conditions which may have been strong (Krumbein and Garrels, 1952; Teodorovich in Chilingar, 1955).

Conditions such as this probably prevailed after deposition due to entombed plant and animal material putrifying within the sediment.

Discrete nodules of iron sulphide are also present within the coal seams, but they are not very abundant except at certain localities such as Barhaugh Pit and Flow Edge, near Alston, where the worked High Coal Sill seam contains prominent nodules. Normally the nodules are only an inch or so in diameter, but those found around Alston are quite large and up to at least 6 inches in diameter. The small nodules are usually rounded, whereas the larger forms tend to be flattened and disc-shaped. Examination in polished section of the iron sulphide forming the nodules has proved it to be pyrite rather than marcasite which is reportedly (Pettijohn, 1957) more typical of the iron sulphide in coal seams. The pyrite is indicative of the reducing conditions which prevailed during the coalification process of the plant debris from which the coal seams are formed.

Within the sandstones proper, nodules have only been found rarely and these have been discussed in Chapters IV and V. Of very restricted occurrence are the small siderite-sand nodules in the upper rooty part of the Low Coal Sill of Snodberry Cleugh, upper Weardale; these were probably formed under mild reducing conditions subsequent to the deposition of the sandstone, the sand grains being subsequently corroded by the carbonate. Also within the Low Coal Sill are the large fossiliferous calcareous concretions of Sally Grain and Scraith Burn in upper Weardale; these are not nodules in the strict sense of the term, but they are related phenomena. The concretions have been described and discussed fully in Chapters IV and V, and suffice is to mention that it seems possible that they are the remnants of a more extensive lens or lenses of similar material which was formed under marine or quasi-marine conditions. The 1 foot diameter pockets of concentrated limonitic material discovered in the fossiliferous part of the thick development of the Lower White Hazle in Howden Burn, Bollihope, are probably similar developments to the above on a smaller scale, the carbonate presumably having been subsequently altered to limonite. In some cases the limonite pockets or bullions are hollow to a varying extent.

Within the Great Limestone and its equivalents sporadic occurrences of chert nodules have been recorded from a number of localities, but nodules are rarely common and are often totally absent. However, it would appear that they are common in the north-east part of the Askrigg Block

(Wells, 1955a and 1957) where the main bulk of the limestone has a striking silica content, shown by analyses to be as high as 10 per cent (Wells, op. cit.), a figure which is surprisingly high in view of the fact that silica is very rarely seen in thin sections. Thus, the nodules in this area probably arose due to the subsequent segregation of the silica into nodules following the primary precipitation of it in a cryptocrystalline relationship with the carbonate of the limestone. The area in the north-east part of the Askrigg Block where the limestone contains common chert nodules and has an overall relatively high silica content coincides with that where the limestone is overlain by the Main Chert; thus, it would appear that even during deposition of the limestone the area was under the influence of the agent, that is to say, the river carrying silica-laden water, and the conditions which resulted in the formation of the overlying chert. The subsidiary but interesting bands of chert-dolomite nodules discovered at a reasonably constant horizon in the lower part of the Great Limestone over the major part of the Alston Block have already been described in detail in Chapter III and illustrated on Fig. 10.

Stylolites

As in the majority of limestones, stylolites are a ubiquitous feature of the Great Limestone and its equivalents. They occur commonly throughout the thickness of the limestone either singly or in groups forming a plexus. They are best exhibited in borehole cores, but can also be easily observed at outcrop. The stylolites appear as zig-zag sutures with serrated teeth-like projections, known as keystone offsets, the projection of one side fitting into sockets of like dimensions on the other side; the structures have an average amplitude of around 1 cm., but they can be considerably larger or smaller than this. Generally the stylolites have a film of black carbonaceous shaly material along them which varies in thickness but is rarely more than 1 mm. to 2 mm. thick and often less. Most commonly the stylolites lie approximately horizontal and parallel to the bedding, but inclined and even vertical ones do occur reasonably often. It is now certain that stylolites are solution-pressure phenomena and that their formation post-dates rock induration, as shown by various workers such as Stockdale (1926 and 1943) and Dunnington (1954). The entirely different theory of contraction-pressure formation prior to

rock consolidation postulated by Shaub (1949) appears to be ill-founded, as shown by Dunnington (op. cit.). The solution-pressure process of formation of the stylolites has obviously resulted in a thickness reduction of the Great Limestone and its equivalents. Stockdale (1926) considered that in limestone the reduction could be as much as 40 per cent of the original thickness. In the present case the amount of reduction has not been determined, but undoubtedly it is not inconsiderable. Evidence of it having taken place is to be seen where truncated fossils abut the stylolitic sutures; also, the films of carbonaceous material along the stylolites represent the insoluble residue remaining after solution of the limestone.

Very occasional stylolites of small amplitude have been recognized in borehole cores through the sandstones, but they are certainly not common apparently. Thus, in the present case there is no support for the suggestion of Heald (1953 and 1955) relating to the cementation of sandstones being due to total solution of sand grains along stylolitic sutures with precipitation elsewhere in the rock. It would appear that solution took place at all points of contact of the sand grains, as postulated in Chapter V.

CHAPTER VII

PALAEONTOLOGY

The distribution of fossils within the beds comprising the Great Cyclothem has been comprehensively dealt with in Chapters II, III and IV; consequently, it is not intended to go into this any further, but the significance of the fossils will be discussed below. Apart from those fossils specifically mentioned in the text of this work, lists of fossils relating to the cyclothem have been presented by many authors. Their various works are dealt with in Chapter I and listed in the key to Fig. 2; in addition, a series of works containing specific reference to the fauna of the Great Limestone are enumerated at the end of Chapter III. Those fossils collected during the present work from the Coal Sills Group of the Alston Block and immediately adjacent areas are listed in Appendix II.

The majority of the fossils present in the cyclothem are of little use for correlation purposes, both on a regional and zonal basis, since they usually belong to facies faunas, particularly in the Coal Sills Group and its equivalents. However, the mere presence of fossils has proved to be useful in some cases for clarifying local detailed correlation problems. The most important fossil discoveries relating to this work are those of the goniatites from just above the Great Limestone at Greenleighton, Northumberland, and a short distance above the Little Limestone in Swinhope Burn, East Allendale; as shown in Chapter II, these finds, when considered with others, have allowed the Viséan-Namurian junction to be fixed at the base of the Great Limestone, the Great Cyclothem forming the lowest beds of the Namurian succession in Northern England.

Apart from the reasonably prolific scattered fauna within the Great Limestone and its equivalents, there are three prominent biostromes and a series of crinoid bioherms in various parts of the limestone, all of which are described and discussed in Chapter III. The biostromes and bioherms presumably indicate colonization of the Great Limestone sea-floor by their various components due to the widespread favourable environmental conditions prevailing at certain periods. In addition to the above, from a general environmental point of view, the fossils comprising the scattered fauna, the biostromes and the bioherms often indicate that a

certain amount of current activity was a feature of the sea in which the limestone was formed.

Within the sediments of the Coal Sills Group and its equivalents marine fossils often occur in reasonably distinct marine bands or scattered within the shales and sandstones. In a number of cases the marine fossils in these situations are considered to be indigenous, but in other cases they are derived; in the former case the fossils are indicative of a true marine environment whilst in the latter case the fossils at least indicate the proximity to marine conditions. Thus, the occurrence of marine fossils associated with the terrigenous sediments, which are often calcareous where fossiliferous, is indicative of marine incursions into the deltaic sedimentation environment. It has been shown that the marine horizons are most abundant in the terrigenous sediments of the southern part of the region with an overall decrease northwards; this, along with evidence of marine conditions persisting throughout the formation of the cyclothem in the extreme south and south-east of the area under consideration, confirms that marine incursions came from a southerly direction, but that in many cases they were not of sufficient magnitude to penetrate too far north towards the land from which the sediments were derived.

As far as plant fossils are concerned, these are confined to the sediments of the Coal Sills Group and its equivalents. Apart from the common Stigmara and associated plant rootlets in situ, very few specifically identifiable specimens of plant remains have been found. However, the occasional specimens of Lepidodendron and rare Cordaites have been recovered from the coal seams and as isolated fragments from the base of the subsidiary washout-channel sandstones. Of the indeterminate material, comminuted plant debris is common in various situations whose distribution has been dealt with in Chapter IV; such material would appear to indicate prolific plant growth in the source area of the sediments and probably parts of the area of deposition too. Probably the most important of the plant remains are the Stigmara and associated plant rootlets in situ whose distribution, particularly where they occur in the tops of the sheet sandstones, has also been dealt with in Chapter IV. Such remains are so important because they directly indicate previous plant growth at certain specific intervals, presumably under terrestrial marsh or swamp conditions, this plant growth often having resulted in the formation of peat from which

the coal seams of the cyclothem were formed. The Stigmaria and plant rootlets in situ, frequently with the associated coal seams overlying the beds the plants occur in, are prominent and of widespread occurrence in the northern part of the region. Their development southwards becomes progressively weaker overall and to the south of the Cotherstone Syncline both plant remains in situ and coal seams are virtually absent; there is one exception to this general rule, however, because the top of the major washout-channel sandstone on the Askrigg Block contains plant rootlets in situ and is overlain by a thin coal seam. Thus, plant growth was most prolific in the northern part of the region closer to true terrestrial conditions, whilst it became weaker southwards and east-south-eastwards towards the sea until it died out almost completely except where local conditions in the form of the washout-channel sandstone top allowed it to extend considerably farther south than normal. The intimately associated coals exhibit a similar distribution to the above, as might be expected, the coal seams being thickest, most persistent and numerous in the northern part of the region with a gradual but marked decrease in thickness, persistence and number southwards and east-south-eastwards.

CHAPTER VIII

PALAEOGEOGRAPHICAL SYNTHESIS

GENERAL

The main purpose of this investigation has been to trace and evaluate in detail the character and variations of the sediments forming the Great Cyclothem in Northern England in order to reconstruct the cyclothem's depositional history and the broad palaeogeography of the area in which it was formed. The detailed information relating to this investigation has been set out in the foregoing chapters along with detailed conclusions derived from a consideration of the evidence presented by the various features. These conclusions have been synthesized and the broad picture of the setting under which the Great Cyclothem was formed is to be presented briefly below.

DELIMITATION AND STRUCTURAL SETTING OF THE DEPOSITIONAL ENVIRONMENT

The area of Northern England in which the Great Cyclothem and its equivalents are developed stretches from the Craven Faults and their western projection in the south to the Southern Uplands and their western extension in the north. As far as the latter boundary is concerned, however, there are sediments related to those of the cyclothem in the Midland Valley of Scotland to the north of the Southern Uplands, the true northern limit of deposition of sediments closely related to the Great Cyclothem, and probably the source of the terrigenous sediments themselves, being the postulated Highland - "Atlantean" Massif of George (1958) which lies north of the Midland Valley Trough. Nevertheless, the Southern Uplands Massif, which acted as a rigid block during deposition of the cyclothem, is taken as the boundary of the area to be considered here; because of the rigid nature of the Southern Uplands Massif during deposition the Great Cyclothem sediments in Northern England thin towards it. In detail the southern limit of the area lies along an east-west line following the present-day Craven Faults and extending through the southern end of the Lake District to the north of the Furness region and thence through the centre of the

Isle of Man. It would appear that during sedimentation an elongate positive ridge extended along this line which could quite possibly have been land during formation of the Great Cyclothem, as postulated by Trotter (1952) for E_{1a-b} times; this ridge was probably derived due to the late P_2 uplift which Hudson (1933) has shown took place along the line of the Middle Craven Fault. The uplifted ridge formed an effective divide separating the Bowland Trough and related areas to the south of it from the region to the north which is under consideration here. Apart from the ridge separating two areas of completely different sedimentation, considerable evidence exists, as set out in Chapters III and IV, to show that on the north side of it beds of the Great Cyclothem, particularly the basal limestone, wedge out at least partly if not completely against the uplifted ground; evidence has also been presented to show how components of the Bowland Shales, particularly the Scale Haw (=Great) Limestone, wedge out northwards against the south side of this uplifted ground.

During the formation of the Great Cyclothem, as well as before and after, the area between the Southern Uplands Massif and the land ridge to the south along the line of the Craven Faults was complicated by rigid blocks and subsiding troughs. The Northumbrian Fault-Block and the Lake District Massif with troughs between them and to the north dominate this picture, the trough to the north being the Northumbrian Trough, its northern limit being formed by the stable Southern Uplands Massif (Fig. 2); an interesting feature as far as the troughs are concerned is the discovery that the Cotherstone Syncline, which divides the Alston and Askrigg Block components of the Northumbrian Fault-Block, actually acted as a subsiding area during formation of the Great Cyclothem, as shown on Plate III. These various block and trough features had a considerable effect on the thickness of sedimentation, particularly of the terrigenous sediments, the thicker sedimentation taking place in the subsiding troughs which were divided from the rigid blocks by contemporaneous hinge lines, the latter now being represented by faults usually. Details of the thickness variations of the terrigenous sediments caused by these various features have been enumerated in Chapter IV and largely illustrated on Plate III. It might be mentioned that the Great Limestone and its equivalents do not appear to be markedly affected by the tectonic sub-divisions except for

the regional thinning towards the uplifted ground at the southern limit of the area; the thickness variation is apparently more closely controlled by the relative time of on-set of the subsequent deltaic deposition.

Apart from markedly affecting the thickness variation of the terrigenous sediments, the structure of the area appears to have affected their stratigraphy to some extent; for instance, the thick coal seams of the Northumbrian Trough are partly ascribed to relatively rapid subsidence encouraging the necessary plant growth and the consequent thick accumulation of peat. The complication of the Northumbrian Trough sequence, apart from its general overall thickening, by the development of more numerous minor rhythms in the upper part of any one cyclothem as described by Trotter and Hollingworth (1932), does not appear to apply in any great degree to the Great Cyclothem now that the correlation of its stratigraphy is more fully understood; however, the sequence is complicated to some extent by the splitting and thickening involved in the cycle containing the Low Coal Sill representative in the Northumbrian Trough, as described in Chapter IV, the other cycles comprising the Great Cyclothem above this basal one having a much more comparable thickness in the Northumbrian Trough and on the adjacent Alston Block.

DEPOSITIONAL SETTING AND HISTORY

The broad general sequence involved in the formation of the Great Cyclothem began with the laying down of the thick basal limestone over a prolonged period in a shallow clear sea following the rapid and widespread invasion by the sea which took place from the south and east-south-east over an extensive flat low-lying area subsequent to the deltaic deposition of the underlying Four Fathom Cyclothem. Following the long period of limestone deposition this sea was eventually encroached upon by deltaic conditions extending from the land to the north and north-west, the deltaic deposits consisting essentially of clay, sand and peat which are now represented by shale, sandstone and coal. Such conditions virtually persisted throughout the formation of the remainder of the cyclothem, there being local and regional regressions of deltaic conditions at times with complementary marine incursions, however, which resulted in the composite nature of the cyclothem. Although they persisted throughout the formation of the remainder of the cyclothem, deltaic conditions never reached the

extreme south-east of the area, so that marine conditions prevailed there throughout the period during which the essentially non-marine beds of the cyclothem were formed elsewhere. It might be mentioned that the term deltaic conditions used here simply refers to an environment in which continental and marine deposition are both possible, the continental phase of the delta merely being an extension out from the land of the flood and coast plain areas of the fluvial environment. No direct comparison with the Mississippi delta is considered possible despite the large amount of published information available regarding this delta, such as that of Fisk et al. (1954). This latter situation has encouraged some recent workers on the Yoredales, such as Moore (1955 and 1958), to closely relate the specific sedimentary environments of the modern Mississippi delta with the Yoredales even though the Mississippi delta is well known to be one of the most atypical of deltas with its bird's foot structure. A closer comparison of the deltaic environment of the Great Cyclothem would appear to be with such deltas as those of the Rhône, the Niger or even the Wadden Sea area of Holland.

As pointed out above the Great Cyclothem began with the formation of the basal limestone in a clear shallow sea following a widespread invasion of the area by this sea from the south and east-south-east. The base of the limestone is generally quite sharp, although there may be a gradation up from the underlying deltaic sediments in places; nevertheless, it would appear that the incursion of the sea over the whole area was rapid. The relative constancy of the limestone in lithology indicates the broadly similar conditions prevailing over the whole area. Its considerable though variable thickness, apart from where it thins markedly against the uplifted ground in the south, also indicates the widespread nature of the marine conditions which persisted for a long period. In the sea marine life was common at all times, but at certain periods conditions were so suitable over wide areas that the marine life proliferated to such an extent that the bioherms and widespread biostromes were formed. Although conditions were favourable to marine life, there is evidence in the form of rolled and eroded fossils of some current activity over the whole area during limestone formation, thus indicating the shallow nature of the sea. In addition, it would appear that the sea in north-east part of the Askrigg Block was under the influence of an agent

delivering silica-rich waters, as well as the calcium-rich waters from which the limestone was formed, because in that area the limestone is relatively rich in silica. Otherwise, during the formation of the major part of the limestone the whole area was under the influence of incoming calcium-rich waters, the transporting agents carrying no other terrigenous material of consequence apart from the fine grained carbon which largely contributes to the pigmentation of the limestone. However, after a considerable thickness of limestone had been formed, the limestone sea was invaded by waves of muddy sediment derived from the land to the north and north-west, the muddy material being transported into the sea by the rivers from the land which had previously only carried calcium-rich waters, the change in the character of their load perhaps being caused by uplift in the source area with the consequent rejuvenation of the rivers. Such conditions gave rise to the alternating limestone-shale sequence of the so-called Tumbler Beds which form the top of the basal limestone of the cyclothem in the bulk of the northern part of the area. These waves of muddy sediment, which herald the full on-set of deltaic conditions, reached the majority of the northern part of the area earliest because of their derivation from the north and, in fact, muddy sediments only locally reached farther south than the latitude of the Cotherstone Syncline before the full on-set of deltaic conditions. This is indicated by the virtual restriction of well developed Tumbler Beds at the top of the limestone to the area north of the Cotherstone Syncline, the Tumbler Beds of the north being developed at a lower horizon than those to the south, the most southerly Tumbler Beds being represented wholly by shale in the north; thus, the basal limestone has a markedly diachronous top which contrasts with its base whose formation is ascribed to a widespread marine transgression at one particular point in time.

Immediately or closely following the deposition of limestone and perhaps even concurrently with the later stages of its formation in places, over a large area in the north-east part of the Askrigg Block and adjacent smaller areas to the north and south of this, the material now represented by primary chert was formed under marine conditions by the deposition of colloidal silica from silica-laden waters transported into the area by a river whose essentially sandstone-filled contemporaneous "channel" is preserved within the deltaic sediments to the north of the main area of

chert; the course of this "channel" is delimited on Plate III and its relations with the surrounding sediments are described in Chapter IV. The main area of chert coincides with the area on the Askrigg Block in which the underlying limestone is relatively rich in silica and it seems reasonable to assume that to some extent the silica-laden river waters even influenced this area during deposition of the limestone, as mentioned earlier. This chert deposition took place whilst the deltaic deposition of terrigenous sediments occurred concurrently and laterally to it, the formation of chert only ceasing when the area was overcome by the deltaic sediments. In the extreme southern part of the area, where the deltaic sediments and the chert for that matter are wedging out, this overriding never took place and, consequently, the whole of the beds of the cyclothem above the basal limestone consist of chert in places.

As far as the deltaic conditions are concerned, these extended out from the land situated to the north and north-west of the area of deposition by the system of rivers which fed the environment building out terrigenous sediments into the shallow sea, the extremely shallow nature of this sea being indicated by the local establishment of plant life with the consequent formation of coal at occasional widespread localities shortly after the termination of limestone deposition. Initially muddy clay grade sediments were built out into the sea, these muddy sediments eventually overwhelming the marine organisms thus causing fossils to be concentrated immediately above the basal limestone. As the muddy sediments were built farther out into the sea those already deposited nearer the shore were overlain by sediments which increased in grain size upwards eventually attaining sand grade; these coarser sediments could not be transported farther because of the streams carrying them only having sufficient power to carry the finer grained sediments farther south at any one time. From this it can be seen that the deltaic conditions built outwards by a "carpet-rolling" effect, the initial layer consisting of clay grade material followed by layers of increasing grain size as the delta grew. The sand grade or laterally equivalent material built up in very shallow water to form an extension of the coastal plain with low relief at or near to sea-level, and in the process was subjected at various stages to wave and current action, "annelid" activity, minor stream channelling and winnowing. Thus, a sequence was eventually built up which increased in grain size upwards,

the uppermost sand grade material comprising the sheet sandstone of the sequence. Variations from this sequence can arise, generally due to local or regional failure of the sheet sandstone, although in some cases the variation is caused by one sheet sandstone coalescing with another or even the splitting of a sheet sandstone into more than one component, as in the case of the Low Coal Sill equivalent in the southern part of the North-umbrian Trough. The local failure of the sheet sandstone can probably be attributed to the local failure of the transporting agent due to loss of power, perhaps related to blockage by plant growth or a sand bar; local diversion of the transporting streams could also lead to similar results. On the other hand, when the mode of formation is considered it can easily be seen how on a regional scale the sandstone component of the cyclothem becomes impersistent and eventually wedges out to the south and south-east before the shale of any one cycle. Once the deltaic sediments had built up to or close to sea-level to form a low-lying extension of the coastal plain, they were gradually colonized by vegetation growing out from the land to the north. This vegetation eventually resulted in the accumulation of peat from which the coal overlying the sheet sandstone or its representative was formed; the fact that any one coal is generally thickest and most persistent in the northern and north-western parts of the area is to be expected since the growth of vegetation was bound to decrease and eventually die out southwards towards the sea. • Apart from the major widespread developments of coal described above, there are occasional local developments of coal, or at least plant rootlets in situ, at other horizons marking the local growth of plants in the environment, thus giving a further indication of its general situation close to sea-level. Undoubtedly there would be major rivers feeding the terrigenous sediments to the deltaic environment by way of shallow distributaries, the latter giving rise to the cross-bedding in the sheet sandstones, as described in Chapter VI. The courses of these major rivers normally lay well to the north of the deltaic environment, but at least at one period, possibly due to uplift of the land to the north markedly rejuvenating the rivers, a major channel with subsidiary associated channels transgressed over the area cutting deeply into the underlying sediments; once the rivers lost their cutting power these channels were alluviated, initially with very coarse grained pebbly material followed by material gradually becoming finer grained upwards. The courses of these

channels where they can be traced on the Northumbrian Fault-Block are shown on Plate III. It has been shown previously in Chapter IV that the channels transgressed on to the area following the formation of the High Coal Sill sheet sandstone but prior to the colonization of the area by vegetation from which the High Coal Sill coal was formed. The possibility of similar washout-channels occurring at another horizon in the Northumbrian Trough has been mentioned in Chapter IV. The development of the somewhat different sandstone-filled contemporaneous "channel" which fed the silica-rich water to the area of chert in the north-west part of the Askrigg Block has already been dealt with. It could be that the anomalous Hensingham Grit sequence of West Cumberland also represents the beds formed in a similar situation to the latter "channel" because the strata in West Cumberland which are considered to be equivalent to the deltaic sequence of the cyclothem are by no means a normal development.

Apart from the marked thickness variations and the stratigraphical complexities introduced by the structural setting, the formation of the beds of the cyclothem overlying the basal limestone was not a simple one involving a single phase of delta building, but a multiple one marked by regional and local regressions of the delta, three major advances of the deltaic conditions as described above being recognizable; consequently, the Great Cyclothem is a composite one and not a simple limestone-shale-sandstone-coal rhythm. The regressions of deltaic conditions were marked by complementary encroachments of marine conditions from the south and east-south-east. Thus, following each phase of delta building and plant growth there was an encroachment of marine conditions over the majority of the deltaic area. These encroachments were of variable magnitude but generally resulted in the establishment of at least quasi-marine conditions which are represented in numerous places by marine fossils in the shales overlying the coal seams. However, in some places distinct calcareous marine bands with indigenous fossils were formed, thus indicating the temporary establishment of true marine conditions which were eventually overcome by the re-advance of the delta. During the actual building out of the delta local marine incursions were able to take place at various horizons with the establishment of true marine or quasi-marine conditions; these incursions were of variable extent, but a prominent marine horizon developed in such a manner is the Snope Burn Band. In this context it might be mentioned

that during the infilling of the upper parts of the washout-channels local marine incursions were able to take place along them apparently; similarly, the contemporaneous "channel" appears to have facilitated local marine incursions. Such a situation as described above indicates the close inter-play between the two environments. As might be expected with deltaic conditions advancing from the north and north-west on to the sea in the south and east-south-east, the marine horizons within the essentially deltaic beds, particularly the true and distinct marine bands, are most common in the south with a decrease northwards; this does not mean to say that there are not prominent and reasonably widespread marine horizons in the northern part of the area, however, the Snope Burn Band being a good example of such a horizon.

Deltaic conditions at one time or another spread over the bulk of the area under consideration, but there is a regional southward thinning of the terrigenous sediments so derived until they eventually wedge out completely in the extreme south-east part of the Askrigg Block, as shown on Plate III which includes the chert with the other sediments above the basal limestone. The character of this wedging out with isolated small thin patches of shale and chert to the south of the main line of wedging out has been discussed in Chapter IV. It is not surprising in view of the mode of formation that the sheet sandstones wedge out completely before and to the north and north-west of the shales, the latter persisting farthest south-east along with the chert. As far as the sheet sandstones are concerned, in general the lowest one in the sequence, the Low Coal Sill and its equivalents, reaches least farthest south whilst the uppermost one, the White Hazle and its equivalents, extends farthest south; obviously, this represents a progressive southward advance of the delta following each regression during the formation of the Great Cyclothem. The complete and partial wedging out of terrigenous sediments to the south-east and south due to the failure of the delta to invade farther in these directions is obviously a phenomenon to be expected as the distance from land increased; however, the failure may be to some extent due to the uplifted ground along the line of the Craven Faults and their extension causing "backing-up" of sediment as a result of the change of regional slope affecting the carrying power of the agents transporting the sediments. Thus, in the extreme south-east there was continuous limestone deposition whilst the deltaic beds of the cyclothem were formed elsewhere, there being no intervening

beds or widespread obvious break between the basal limestone of the Great Cyclothem and the overlying Little Limestone. Such a situation would be expected to give rise to a thicker limestone in the south-east than elsewhere; the thickening is not at all spectacular, however, probably because of the marked thinning which takes place against the uplifted ground along the line of the Craven Faults. It was from this region of continuous limestone deposition that the marine incursions into the deltaic environment took place to give rise to the marine horizons. The major marine transgression which terminated the Great Cyclothem and gave rise to the Little Limestone and equivalents would also take place from this region; this transgression does not appear to have been as widespread as the one which resulted in the formation of the Great Limestone and equivalents because no recognizable Little Limestone is developed in West Cumberland and the Isle of Man.

MECHANISM OF CYCLIC SEDIMENTATION

The mechanism which resulted in the formation of the Great Cyclothem and similar cyclothem or rhythmic deposits has invited much comment and speculation. It is undoubted that such sedimentation involves oscillations in the influence of marine and deltaic conditions over the area, the cause of the recessions and advances so arising being the moot point, however. The several different theories put forward to explain the above have recently been considered in detail by Wells (1960) and, consequently, it is only intended to give a brief consideration of them here.

Control of the mechanism solely involving various forms of cyclical climatic variation has been postulated by Brough (1928) and Wanless and Sheppard (1936), but such theories do not have any strong tangible evidence to support them, as mentioned by R.C. Moore (1950) with particular reference to the Wanless and Sheppard idea of cyclical glacial control. Furthermore, it is unlikely that plant growth could completely interrupt the supply of sediment to the area, as postulated by Robertson (1948 and 1952), thus resulting in the overall control of the cyclic sedimentation; however, plant growth could be responsible for local blockages which would explain to some extent lateral variations in the sediments such as the local failure of sheet sandstones and the local marine horizons. In a similar manner the periodic formation of sand bars would locally impede the flow

of sediment, but not give rise to major cyclic features. Moore (1955, 1958 and 1959) suggested that each cessation of deltaic sedimentation was due to the feeding river being diverted elsewhere, thus allowing the delta to be overcome by the sea as regional subsidence progressed. The diversion of the feeding river was ascribed to crevassing, by analogy with conditions in the modern Mississippi delta. This mechanism presents a problem as to where the river was diverted to because it is reasonable to assume that it continued to deposit sediment in the form of a delta elsewhere. Moore (op. cit.) tentatively suggested that the site of this second area of deltaic deposition was situated in the area of the present North Sea, despite the fact that all the deep boreholes drilled to the east of the Northumbrian Fault-Block have indicated that the Yoredale beds exhibit an increase in the number and proportion of marine horizons in this direction. Furthermore, it is difficult to envisage how the diversion mechanism could effect such a complete cessation of terrigenous sedimentation required to fully account for the cyclic sedimentation since it is probably not a single river which is involved but a system of rivers. Nevertheless, this novel idea of Moore's can not be completely disregarded since it presents another means of explaining the local variations in the sequence mentioned above.

The remaining theories (Hudson, 1924 and 1933; Weller, 1930, 1931, 1956 and 1958; Weller et al., 1958; Wheeler and Murray, 1957; R.C. Moore, 1936 and 1950; Dunham, 1950) all involve tectonic control as the mechanism for producing the cyclic sedimentation. As far as this is concerned, all consider that cyclical uplift in the sediment source area took place to initiate the phases of terrigenous sedimentation, each uplift being followed by progressive denudation towards base level. Such a process conveniently explains the general upward increase in grain size of each cycle of terrigenous sediments, the fine grained sediments which would eventually be derived towards the end of this process as rejuvenation gave way to maturity being mainly deposited towards the "feather edge" of the delta, the objection of Dunham (op. cit.) to the process thus being covered when the full regional spread of the sediments is considered rather than a restricted area by vertical sections. Most of the above workers consider that the marine incursion at the end of each phase of deltaic sedimentation was due to normal subsidence of the area; compaction of

the accumulated sediments would also facilitate influx of the sea, as mentioned by Van der Heide (1950). Perhaps this was so as far as the majority of the marine horizons overlying the coal seams and some of the more local ones within the Great Cyclothem are concerned. However, it is not considered to be a satisfactory explanation of the marine incursions which resulted in the formation of the thick major limestones of the Yoredales, of which the Great Limestone and its equivalents are the thickest. Such incursions are more likely attributable to active tectonic subsidence because of the widespread and rapid influx involved even when the flat low-lying relief of the area to be transgressed over is taken into consideration. Tectonic subsidence in the area of deposition as well as uplift in the sediment source area was initially suggested by Weller (op. cit.). R.C. Moore (1950) and Moore (1958) consider this diastrophic rise and fall in the areas of erosion and deposition too mechanical to be likely, but it might be pointed out that all the other suggested modes of formation involve repetition too. In support of his contention that tectonic activity played no part in the mechanism of Yoredale cyclic sedimentation, Moore (op. cit.) mentions that uplift along the Middle Craven Fault, less than 20 miles south of Wensleydale, during the time the Yoredales were being deposited had no known effect in the area he studied; however, it has been shown in the present work that the uplifted ground did exert some influence during formation of the Great Cyclothem, though not directly towards producing the cyclic deposition. In strong support of the tectonic control it can be pointed out that the pulsating movements of the Sudetic period heralding the Hercynian orogeny were taking place during the time of Yoredale deposition, and it is this kind of regional movement which would be required to produce the cyclic sedimentation rather than the relatively local movement cited by Moore (op. cit.) above. The reason that the area under consideration in which the Yoredale rocks were formed was affected by the pulsating movements and other areas such as the adjacent Bowland Trough were not is probably due to the former never being under very deep water and, consequently, it was in a critical situation to be affected by even small scale tectonic activity of a regional nature.

PROVENANCE

Here it is intended to deal with the location of the source area of

sediments and the composition of the source rocks before transport to the delta. In addition, comment will be made upon observations relating to the climatic and tectonic condition of the source area.

As far as the location of the sediment source area is concerned, various features indicate that it lay to the north and north-west of the area of sedimentation under consideration, and it was almost certainly the Highland - "Atlantean" Massif which George (1958) has shown was situated some way to the north and north-west of the Midland Valley of Scotland. The various features on which such a conclusion is based are as follows:-

(i) The general sedimentary situation of the Great Cyclothem with terrigenous sediments thinning or dying out completely to the south and south-east, a complementary thickening taking place to the north and north-west, and there being continuous marine conditions throughout the formation of the cyclothem in the extreme south-east part of the area.

(ii) The directional sedimentary structures in the sandstones in the form of cross-bedding and ripple-marks; these have been discussed in detail in Chapter VI and shown to have considerable limitations.

(iii) The coal seams with the maximum number, maximum thickness and greatest persistence in the north followed by a decrease in number, thickness and persistence east-south-eastwards and southwards, the seams eventually dying out completely in these latter directions.

(iv) The marine bands and/or horizons which are most common in the south decreasing northwards.

(v) The overall channel directions, particularly those of the washout-channels.

Thus, the material forming the deltaic sediments was transported from land to the north and north-west of the area of sedimentation in a dominant south to south-east direction.

Presumably, during the formation of the basal limestone of the cyclothem the source area only supplied calcium-rich waters with a variable content of dissolved silica to the area of deposition, no significant erosion taking place in the source area to produce the deltaic sediments, the only activity being leaching of calcium and variable amounts of silica

from the rocks in the source area. Thus, the source area at least contributed in part to the material forming the basal limestone of the cyclothem, but the type of rocks being leached can not be adjudged and evidence from the deltaic sediments must be used to determine this. It has already been shown in Chapter V that various features of the sandstones indicate the source rocks to be largely relatively mature pre-existing sediments with only a subsidiary admixture derived from primary crystalline igneous and metamorphic rocks. Furthermore, it would appear that the pre-existing sediments in the source area were originally derived from primary metamorphic and igneous crystalline rocks with the metamorphic contribution being predominant. These source sediments could have been of Old Red Sandstone age, but they themselves may have been derived from pre-existing sediments formed during an even earlier period. If the source sediments were of the above age they were probably part of the Upper Old Red Sandstone sequence since it is known from the work of Mackie (1897) that the heavy minerals of these beds are dominant in zircon and tourmaline with only subsidiary garnet, whereas the Lower Old Red Sandstone beds contain dominant garnet with subsidiary zircon and tourmaline. Thus, during Lower Carboniferous times probably only the Upper Old Red Sandstone beds were being eroded and supplying detritus to the deltaic environment; this would mean that the Lower Old Red Sandstone sediments were not exposed to erosion until a later period, this later period probably being during Millstone Grit times, the Millstone Grit being rich in garnet.

From the point of view of climate there is some evidence to suggest that the source area was under the influence of tropical conditions. For instance, the leaching of calcium from the rocks which took place during limestone formation is known to be active under tropical conditions, and the most favourable environment for limestone formation is a relatively warm sea. Furthermore, silica-laden waters which would be required to form the prominent chert developments of the cyclothem are known to be derivable from tropical regions. The luxuriant vegetation growth required for the formation of the coals as well as the abundant fragmentary plant material found in some of the sediments is also suggestive of tropical conditions, although it does not present absolutely categorical evidence on this point.

As far as the tectonic condition of the source area is concerned

the mechanism envisaged for the formation of the cyclothemtic deposits demands cyclic uplift of it, each uplift being followed by progressive denudation to base level. Thus, the source area was subjected to cyclic increases of orographic relief followed by a reduction of this relief by erosion. Obviously, the magnitude of the uplifts can not be quantitatively assessed, but they were probably not large in view of the character of the movements promoting them.

Summarizing, it can be seen that the sediment source area lay to the north and north-west of the area of deposition, the material fed to the marine and deltaic environments being respectively leached and eroded predominantly from pre-existing sediments. The source area was apparently influenced by tropical climatic conditions and subject to cyclical uplift and denudation causing variation in relief.

APPENDIX I

COAL RANK ON THE ALSTON BLOCK AND IN ADJACENT AREAS

GENERAL

As will be gathered from Chapter IV, the coal seams of the Great Cyclothem on the Alston Block and in adjacent areas are, in general, so well developed from the point of view of thickness and lateral persistence that they lend themselves to detailed study; this is particularly the case as far as the High Coal Sill coal and equivalents are concerned. Consequently, the seams have been examined from the point of view of their rank, the High Coal Sill coal and equivalents having been studied in most detail, but, in addition, the other coals of the cyclothem have been considered, as well as seams in the underlying (the Boredale coal) and overlying (the Firestone coal) strata where necessary. As far as utilizing the seams at various horizons is concerned it might be mentioned that no significant vertical variation in rank has been noted, the seams in the strata above and below the cyclothem simply having been used in order to assess the regional variation in rank where the coals of the cyclothem are not exposed. The results of this work and the conclusions derived there from are briefly summarized below.

REGIONAL VARIATION OF RANK

Previous to this work Trotter and Hollingworth (1932) had shown that in passing southward from Haltwhistle in the Northumbrian Trough to Alston on the Alston Block, there is a progressive change in the coals from a bituminous nature with a 30 to 40 per cent dry-ash-free volatile content at the former locality to a semi-anthracitic character with a 10 to 14 per cent dry-ash-free volatile content around Alston. In order to obtain a regional picture of the full extent of this devolatilization, all the available analyses relating to the area and seams in question have been gathered together and several new analyses carried out, the new analyses having been kindly done by the National Coal Board North-eastern Division Scientific Department (Coal Survey). Including those previously to hand and those carried out during the present work, there are now some 60

analyses available of the seams under consideration, the coal samples analysed being fairly evenly spread over the area of their outcrop on the Alston Block and the immediately adjacent areas in the Tyne Valley to the north and the Cotherstone Syncline to the south. These analyses show that in general over the major part of the Alston Block where the seams outcrop they are of a similar semi-anthracitic character to those around Alston, there being an increase of volatile content in the seams towards the northern and south-western extremities of the Block. In a northerly direction the seams eventually become completely bituminous in the Northumbrian Trough where there is a widespread similarity to the character noted around Haltwhistle by Trotter and Hollingworth (op. cit.). Apart from the south-westerly increase of volatiles mentioned above, there is also evidence to show that the seams increase in volatile content to the south of the Alston Block on the north side of the Cotherstone Syncline, but further work is needed to fully clarify the situation there.

In addition to the devolatilization of the Viséan and Namurian coals dealt with above, Trotter (1954) has shown that the Westphalian coals of the Durham Coalfield exhibit a progressive decrease in volatile content to the west, north-west and south-west towards the region of extremely low volatile content on the Alston Block already dealt with, there being two specific areas where the coals are even lower in volatile content than those of the adjacent area in the vicinity of Burnopfield and Cornsay. This progressive change of the Coal Measure seams is specifically illustrated by the variation in the Victoria seam of the Lower Coal Measures, the information quoted having been kindly supplied by the National Coal Board Durham and Northern (N & C) Divisions Scientific Department (Coal Survey). Adjacent to the Durham coast this seam has a dry-ash-free volatile content of the order of 34 per cent which decreases to a minimum 23 per cent dry-ash-free volatile content westwards, the local decreases of some 2 per cent dry-ash-free volatile matter below the regional average around Cornsay and Burnopfield being quite distinct.

Thus, it can be seen that there is a very definite progressive devolatilization of all the seams considered towards the centre of the Alston Block, there being a large area at the centre of the Block where no marked regional variation in the volatile content of the highest rank

semi-anthracitic coals can be made out.

EFFECTS AND CAUSE OF DEVOLATILIZATION

Where the semi-anthracitic seams are not too badly weathered the coal forming them breaks into small fragments, the individual fragments tending to have a conchoidal fracture when broken further; such a feature is typical of anthracitic coal. In addition to this general feature, at one locality, in Parson Byers Quarry, near Stanhope, within the area of semi-anthracite, variable sized roughly ovoidal bodies (Fig. 54) of coal occur within the High Coal Sill seam on surfaces approximately parallel to the bedding, the maximum diameter of these bodies being around 25 mm. In some cases numerous small individuals are crowded together (Fig. 53), whilst in other cases the larger bodies occur separately (Fig. 54). These structures have not been reported from any coal in Great Britain previously, but by analogy with similar structures from Alaska, the coal-fields of Washington State and the Walsenburg district of Colorado in the United States, the Newcastle district of Australia (Moore, 1950, pp. 247-249) and the Permian coals of India (Francis, 1961, p. 578), they are identified as niggerheads. No other occurrences of these structures have been discovered on the Alston Block apart from those in the High Coal Sill seam at Parson Byers Quarry; the reason for this restriction is not fully understood and, in fact, it may be only apparent.

As far as the formation of niggerheads is concerned, Moore (1950) has attributed it to heat alteration of the coal. This suggestion has been investigated further during the present work in conjunction with Dr. D. Chandra, formerly of the National Coal Board North-eastern Division Scientific Department (Coal Survey), and it has proved possible to show that the coal forming the niggerheads and the semi-anthracitic coals associated with them, both locally and regionally, are of a similar abnormal chemical composition, the analyses falling outside the band for normal coals on Seyler's Chart when plotted. Furthermore, the reflectance values of the niggerheads and associated coals have all been found to be abnormal when compared with normal coals, the closer comparison in reflectance values being with laboratory carbonized coals (Chandra and Bond, 1956) and known thermally metamorphosed coals from the Wilsontown Main seam and the Antarctic (Brown and Taylor, 1961).

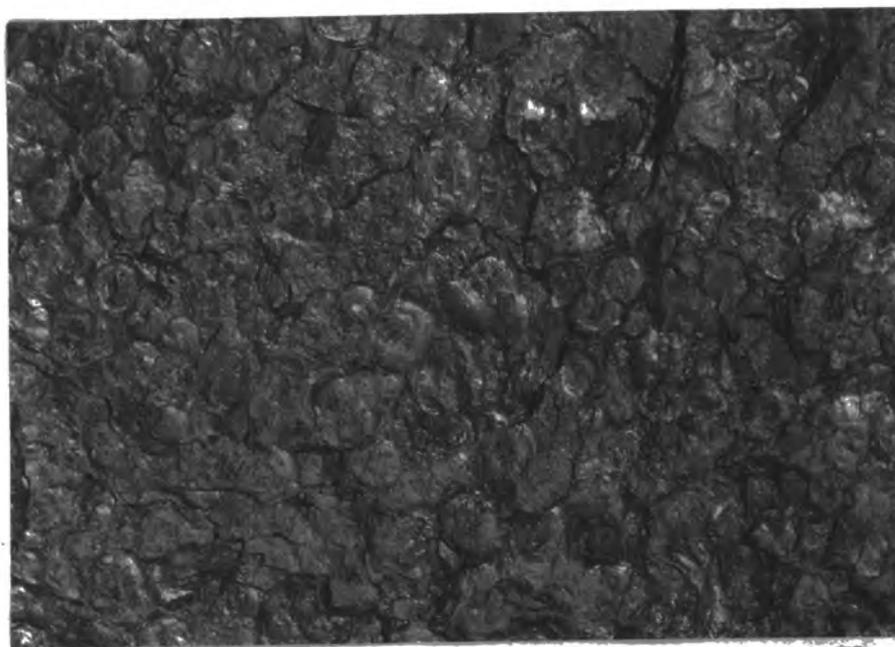


Fig. 53. Impressions of numerous small niggerheads; High Coal Sill coal, Parson Byers Quarry, near Stanhope. x 2.

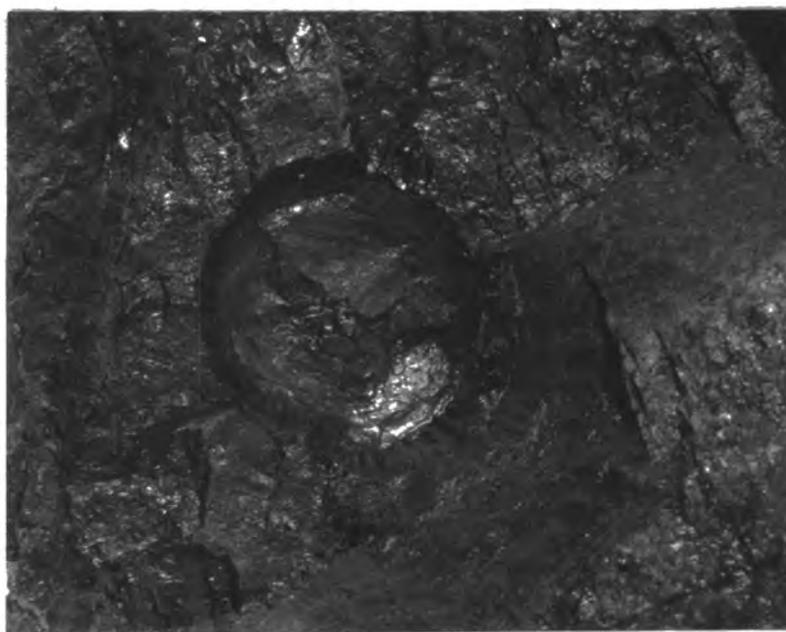


Fig. 54. Large solitary niggerhead; same locality as Fig. 53. x 2.

Thus, there is considerable evidence to indicate that the semi-anthracites and the associated niggerheads of the Alston Block, along with the higher volatile but somewhat devolatilized coals in the surrounding area, have been produced by heat alteration, the source of heat having been nearest to the semi-anthracites with a progressively decreasing overall effect away from this central zone.

SOURCE OF HEAT

From the foregoing it can be seen that there is little reason to invoke variation in load metamorphism due to depth of burial (Hilt's Law) as the cause of the regional rank variation described above, since it has been shown on the basis of chemical and optical data that some source of heat is required and not pressure. As far as pressure related to tectonic activity is concerned, it would appear that the over-thrusting developed along the Pennine Faults did not significantly affect the coals because there is evidence to suggest that the rank decreases in a south-westerly direction towards the Pennine Faults; also, in the tectonically complex area to the west of the Cotherstone Syncline the coals are of a normal bituminous variety. Thus, there is no strong evidence to support the view of Trotter (1954) that the devolatilization of the seams in the western part of the Alston Block was affected by the overthrusting associated with the Pennine Faults.

No local phenomena such as igneous dykes or even the Little Whin Sill can be seriously considered as the required source of heat because of the widespread nature of the devolatilization. The Great Whin Sill is of widespread development but it normally lies at considerable depth beneath the coals and even in the rocks closely adjacent to it into which it is intruded the metamorphic effects are not very widespread. Furthermore, the sill is present in just as close proximity to the bituminous coals of the Northumbrian Trough as it is to the semi-anthracites of the Alston Block. Thus, the Great Whin Sill can be discounted as the heat source which effected the variable regional devolatilization.

The only remaining possible source of heat is the "Weardale granite" which was proved to underlie the Alston Block in the Rookhope Borehole (Dunham et al., 1961; Dunham et al., in press, 1965) following the work of Bott and Masson-Smith (1957) who predicted its presence subsequent

to defining a widespread low gravity anomaly over the Alston Block. Unfortunately the granite is pre-Carboniferous in age and, consequently, no thermal metamorphic effects in Carboniferous rocks can be directly ascribed to it. However, greater than normal heat-flow from or facilitated by the granite could possibly have caused the devolatilization of the coals by a process of prolonged low temperature heating, coal being a very sensitive metamorphic rock. In support of heat-flow from the granite as an explanation of the regional variation in rank of the coals, it can be pointed out that the region of maximum devolatilization tallies with the area in which the granite is nearest to surface, the latter being indicated by the gravity anomaly being at its greatest; thus, the coals are most affected where the granite lies closest to them. As the gravity anomaly decreases away from the centre of the Alston Block, thus indicating that the granite lies correspondingly deeper below surface, so does the volatile content of the coals rise. However, there is a distinct local fall in the volatile content of the Coal Measure seams where the gravity anomaly indicates that the granite locally approaches nearer to surface around Cornsay and Burnopfield, both localities lying to the east of the main granite prominence (Bott and Masson-Smith, *op. cit.*).

Thus, although the devolatilization of the coals can not be ascribed to conventional thermal metamorphism related to intrusion of the "Weardale granite" because of the latter's pre-Carboniferous age, there is clear evidence from the correlation of the granite's gravity anomaly with the regional variation in rank to suggest an intimate association which is here considered to be related to somewhat greater than normal heat-flow permitted by the granite. This suggestion awaits confirmation by the thermal conductivity work at present being carried out in the Rookhope Borehole by the Geophysics Section of the University of Durham Department of Geology.

APPENDIX II

LIST OF FOSSILS

As pointed out in Chapter VII, in a number of cases specific mention of the cyclothem's fossil content has been made in the text of this work and, in addition, various works have been enumerated in which lists of fossils relating to the cyclothem have been presented. The fossils listed in detail below are those collected and identified during the present work from the Coal Sills Group of the Alston Block and immediately adjacent areas; no details of the fauna of the Great Limestone on the Alston Block are given here since this has been dealt with at considerable length in Chapter III. The fossils are listed in related groups for the purpose of clear presentation.

Cordaites sp.; Lepidodendron sp.; Stigmaria sp.; Plant debris indet.;
Plant rootlets indet.

Sponge indet.; Sponge spicules indet.

Zaphrentids indet.

"Annelid" tracks; "Annelid" boring tubes; Crossopodia sp.; ?C. sp.;
Serpula sp.

Archaeocidarid inter-ambulacral plates; Archaeocidarid spines; Crinoid calyx plates indet.; Crinoid ossicles from less than 1 mm. to 13 mm. in diameter, generally separate but some articulated lengths; ?Platycrinus sp.

Fenestella sp.; Penniretepora sp.; Rhabdomeson sp.

Actinoconchus planosulcata (Phillips); Athyris sp.; Buxtonia scabricula (Martin); Camarotoechia pleurodon (Phillips); Chonetes hardrensis (Phillips) group; C. speciosus Cope group; C. sp.; Dictyoclostus sp.; ?D. sp.; Echinoconchus sp.; ?E. sp.; Eomarginifera lobata (J. Sowerby); E. longispina (J. Sowerby); ?E. sp.; Gigantoproductus latissimus (J. Sowerby) group; G. group; Lingula mytilloides J. Sowerby; Orbiculoidea sp.; Orthotetids indet.; ?Overtonia fimbriata (J. de C. Sowerby); ?O. sp.; Phricodothyris sp.; ?P. sp.; Productus concinnus J. Sowerby; P. ?concinnus J. Sowerby; c.f. P. concinnus J. Sowerby; P. c.f. productus (Martin); P. spp.; Productid spines indet.; Schellwienella crenistria (Phillips);

S. rotundata I. Thomas; Spirifer c.f. bisulcatus J. de C. Sowerby group; S. striatus (Martin) group; S. trigonalis (Martin); S. sp.; Smooth Spirifers indet.

Allorisma sulcata (Fleming); Amusium c.f. planicostatum (M'Coy); A. c.f. tenue (de Köninck); Aviculopecten dissimilis (Fleming); A. c.f. perradiatus (de Köninck); A. sp.; ?Cypricardiella concentrica (Hind); Edmondia c.f. arcuata (Phillips); E. c.f. expansa (Hind); ?E. laminata Phillips; ?E. c.f. transversa Hind; E. sp.; Juvenile Lamellibranchs; Nuculana attenuata (Fleming); N. ?attenuata (Fleming); N. laevistriata Meek and Worthen; N. c.f. laevistriata Meek and Worthen; N. c.f. stilla (M'Coy); Nuculids indet.; Nuculopsis gibbosa (Fleming); Pectenids indet., Posidoniella sp.; Protoschizodus sp.; Pterinopecten c.f. granosus (J. Sowerby); Sanguinolites plicatus (Portlock); Solenomorpha sp.

Aclisina sp.; Bellerophon sp.; Bucaniopsis sp.; Coleolus sp.; ?C. sp.; Dentalium sp.; Euphemites urei (Fleming); E. sp.; ?E. sp.; Glabrocingulum sp.; Loxonema sp.; ?L. sp.; Murchisonia sp.; ?M. sp.; Naticopsis sp.; ?N. sp.; Straparollus sp.; Turreted Gastropods indet.

?Coelonautilus sp.; Cycloceras sp.; Orthoconic Nautiloids indet., Pseudorthoceras sp.; Stroboceras sulcatum (J. de C. Sowerby).

Trilobites indet. (pygidia); Weberides mucronatus (M'Coy).

Ostracods.

Bradydont crushing plates; Fish bone fragments indet.

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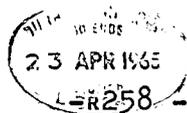
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THE DISTRIBUTION OF THE GREAT CYCLOTHEM ON THE ALSTON BLOCK AND IN ADJACENT AREAS

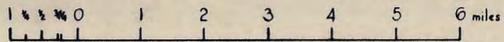
PLATE IA



LEGEND

- Little Limestone
- Great Limestone } Great Cyclothem
- - - Faults

- ④ Nos. indicate positions of sections on Plate IV
- ② Nos. indicate positions of sections on Plate V



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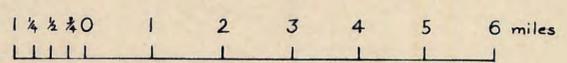
THE DISTRIBUTION OF THE GREAT CYCLOTHEM ON THE ASKRIGG BLOCK

PLATE IB



LEGEND

- Little Limestone
 - Main (Great) Limestone
 - Grassington Grit unconformity
 - Permian
 - Faults
- ① Nos. indicate positions of sections on Plate IV



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THE DISTRIBUTION OF THE GREAT CYCLOTHEM IN NORTHUMBERLAND

PLATE IC

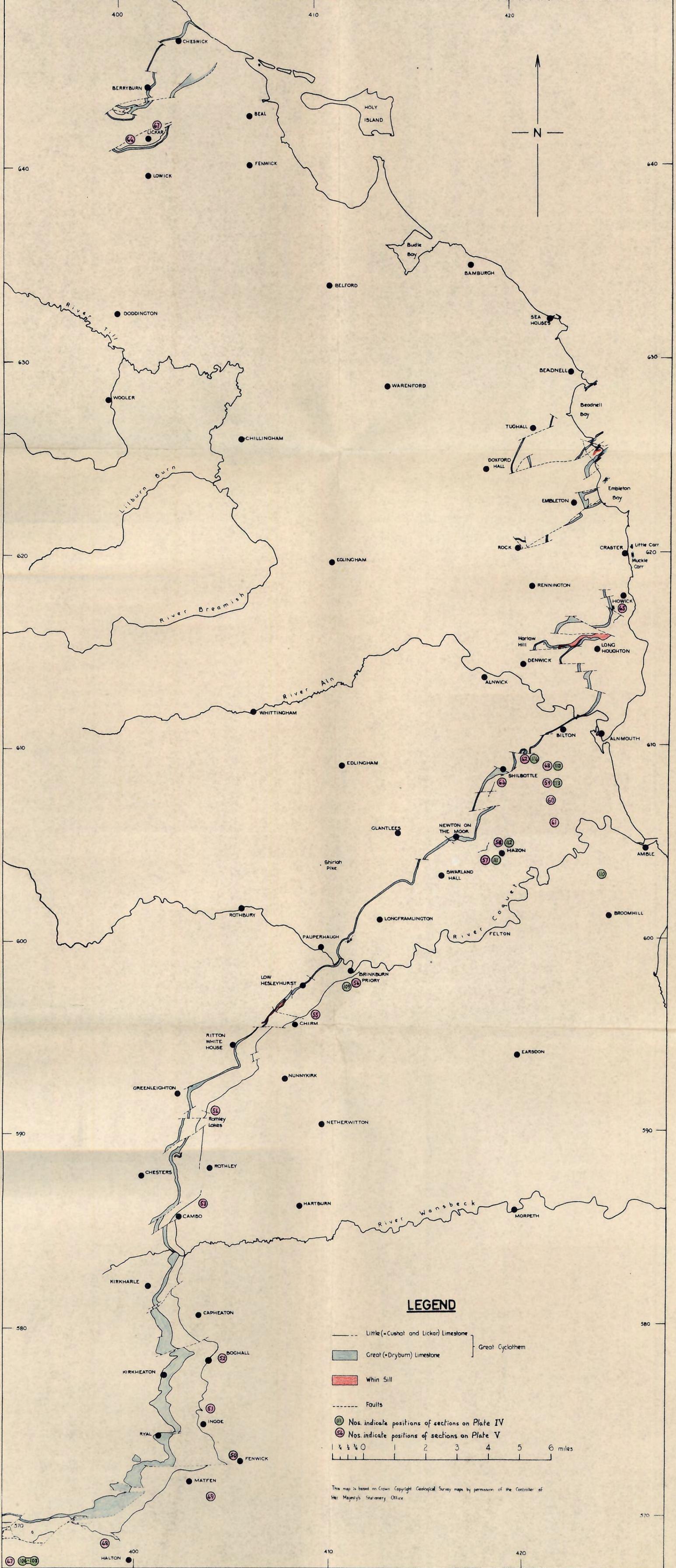
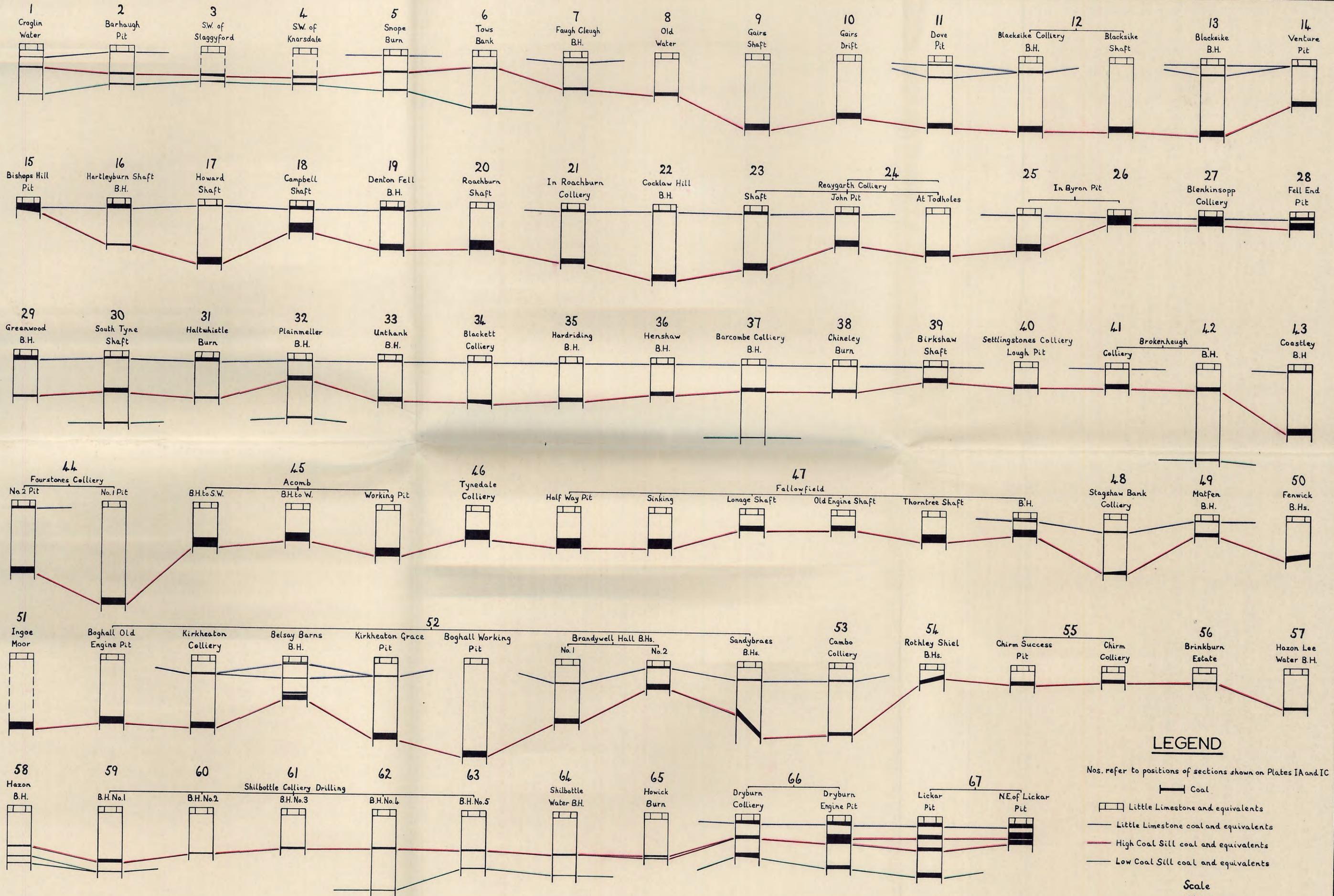


PLATE V. SECTIONS SHOWING THE DEVELOPMENT OF THE GREAT CYCLOTHEM COALS IN THE NORTHUMBRIAN TROUGH AND ADJACENT AREAS



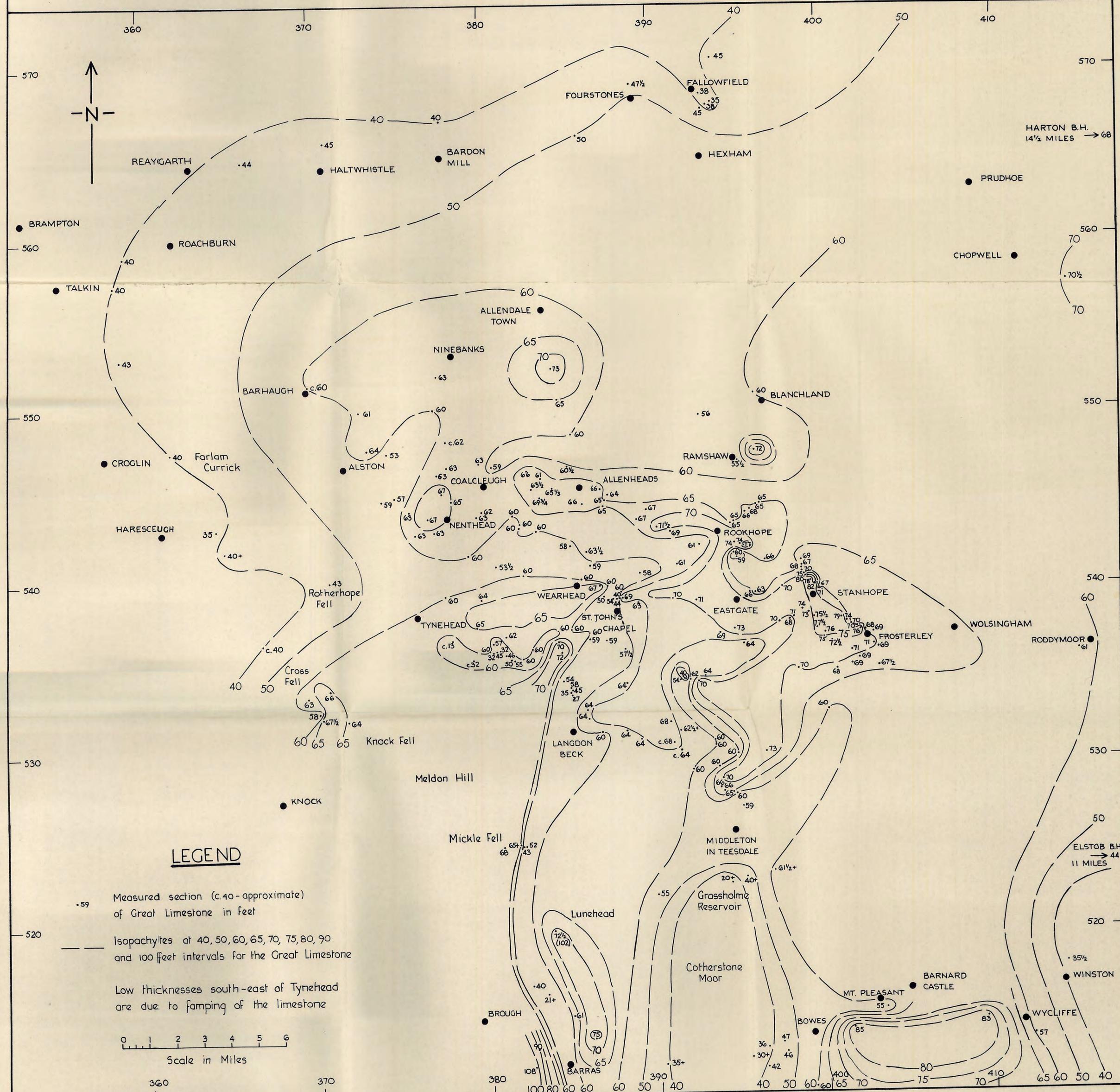
LEGEND

Nos. refer to positions of sections shown on Plates IA and IC

- Coal
- Little Limestone and equivalents
- Little Limestone coal and equivalents
- High Coal Sill coal and equivalents
- Low Coal Sill coal and equivalents

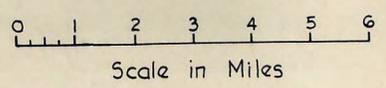
Scale
20 feet
0

PLATE II THICKNESS VARIATION OF THE GREAT LIMESTONE ON THE ALSTON BLOCK AND IN ADJACENT AREAS

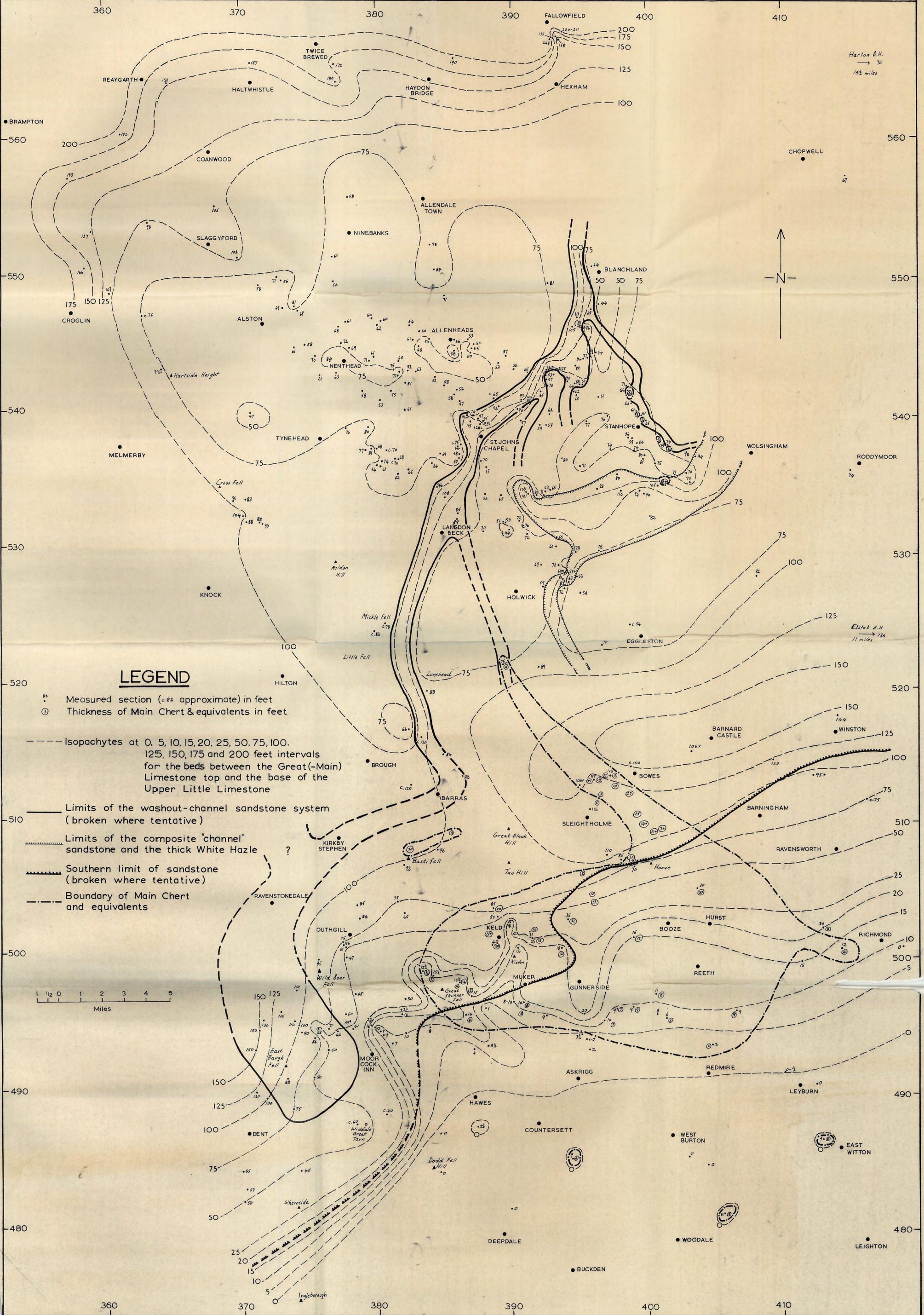


LEGEND

.59 Measured section (c.40-approximate) of Great Limestone in feet
 - - - Isopachytes at 40, 50, 60, 65, 70, 75, 80, 90 and 100 feet intervals for the Great Limestone
 Low thicknesses south-east of Tynehead are due to fanning of the limestone



DETAILS OF THE UPPER PART OF THE GREAT CYCLOTHEM IN THE NORTHERN PENNINES



LEGEND

- Measured section (c. 82 approximate) in feet
- ⊙ Thickness of Main Chert & equivalents in feet

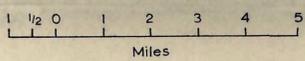
--- Isopachytes at 0, 5, 10, 15, 20, 25, 50, 75, 100, 125, 150, 175 and 200 feet intervals for the beds between the Great (=Main) Limestone top and the base of the Upper Little Limestone

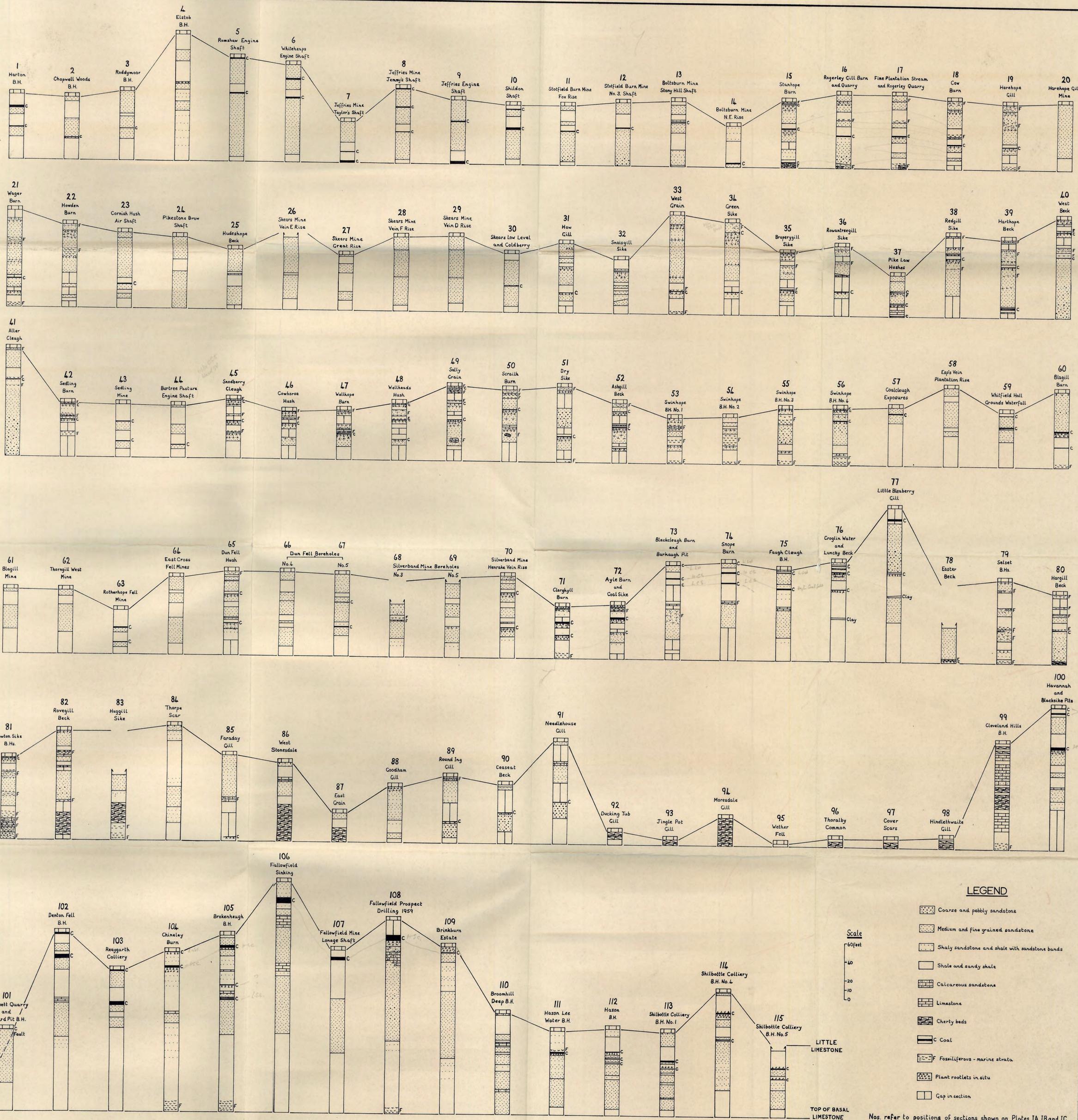
— Limits of the washout-channel sandstone system (broken where tentative)

— Limits of the composite "channel" sandstone and the thick White Hazle

— Southern limit of sandstone (broken where tentative)

— Boundary of Main Chert and equivalents





Granite beneath the Northern Pennines

A FULLY cored borehole sited at Rookhope (NY35/937,428), West Durham, has proved the existence of granite at 1,281 ft. depth directly beneath Lower Carboniferous (Viséan) strata. The drilling, which is still in progress, is financed by the Department of Scientific and Industrial Research, and forms part of a programme of geological and geophysical investigation by the Durham Colleges Geology Department.

The background of the operation is as follows. The lead-zinc-fluorine-barium deposits, which occur as veins and replacements in the Carboniferous rocks of the northern Pennines, were shown by K. C. Dunham^{1,2} to exhibit a concentric pattern of regional mineral zones, suggesting that mineralization was due to heated solutions, rising at a limited number of centres, and thereafter distributed laterally along channels conditioned by hard beds in the Yoredale sequence. Acid magmatic activity at depth was considered to be a possible source of the solutions. Later on, M. H. P. Bott and D. Masson-Smith³, following up a strong negative Bouguer anomaly, first noticed during a traverse by J. Hospers and P. L. Willmore⁴, made a detailed gravimeter survey of the region. This revealed a negative gravity anomaly of 35 milligals amplitude closely similar in character to the gravity field over exposed granitic batholiths with roof cupolas, such as the Cornubian batholith. Furthermore, certain features of the anomaly were considered to be inconsistent with interpretation as a sedimentary basin. Under the Alston Block, the cupolas indicated by the gravity survey correspond exactly with the postulated emanative centres of the mineralization. When the gravity survey was published, it was suggested that the most probable explanation was that a granite of Permo-Carboniferous age underlay the area, and that it not only supplied the mineralization, but also contributed to the devolatilization of the coal seams in the area. Using a method of calculation devised in collaboration with R. A. Smith, Bott³ showed from the magnitude of the second derivative of the anomaly that the top surface could not be deeper than 3,500 ft. below Weardale. No upper limit to the depth can be placed from the gravity data, but having regard to the fact that no contact metamorphism is seen in the exposed

Carboniferous rocks except near the Whin Sill, he concluded that the probable depth was between 2,000 and 3,000 ft. The postulated granite has become known as the 'Weardale granite'.

The borehole commenced near the top of the Great Limestone, 350 ft. from the surface position of the hanging wall of the Red Vein, one of the most powerful W.N.W. channels of mineralization in the district, with a yield so far of 460,000 tons of fluor spar and 48,000 tons of galena. The collar of the boring is also 500 ft. from the hanging wall of the E.N.E. Boltsburn Vein, a weak but very persistent fracture, which has yielded 143,000 tons of galena, mainly from associated replacements. Both veins dip towards the boring, which was sited so as to pass through them at depth. Below the Great Limestone, the base of which is taken as the Viséan-Namurian boundary in northern England, a normal Middle Limestone Group succession was encountered. Two quartz-dolerite sills were proved in these beds; the Little Whin Sill, 6 ft. thick, is intruded into the Three Yard Limestone, and the Great Whin Sill, 200 ft. thick, lies beneath the Jew Limestone. The base of the Middle Limestone Group remains to be defined exactly when the faunal study of the cores has been carried out, but the expected change from dark blue-grey limestone to pale grey limestone shows the approximate position of this boundary. The Lower Limestone Group is represented by an alternation of light grey limestones, shales and sandstones; no massive Melmerby Scar Limestone such as is present below Cross Fell is developed; but the typical 'pseudo-breccia' lithology characteristic of this limestone is present in some of the bands. Beneath these light-coloured limestones, black shale with very thin quartz- and feldspar-bearing conglomerate beds rest directly on weathered granite which in a few feet gives place to fresh, well-foliated microcline-quartz-muscovite-oligoclase rock. The foliation is nearly horizontal, and aplite and pegmatite bands occur at various angles.

So far, ten intersections of metalliferous mineralization have been made. Of eight in the Carboniferous, three are horizontal replacements in limestone and one of these is 16 ft. thick, rich in green fluorite and sphalerite. Two typical Pennine Zone I veins, carrying pyrrhotite, fluorite, quartz, have been intersected within the granite at 1,349-1,363 ft. and at 1,585-1,656 ft., the latter being accompanied by extreme alteration of the granite.

Two definite conclusions may be drawn at this stage: (1) the granite so far proved is of pre-Carboniferous age; (2) the mineral veins were fed from some

source beneath that part of the granite so far drilled. To these may be added the suggestion that the buried pre-Carboniferous cupolas served to localize the upward flow of mineralizing fluids into the Carboniferous rocks.

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Isotopic Ages of the Weardale Granite

AGE determinations have been carried out on muscovite from the Weardale Granite¹ by both the rubidium-strontium and potassium-argon methods. One specimen from a depth of 1,396 ft. in the borehole was measured by both methods, while another from 1,314 ft. was measured by the potassium-argon method only.

Isotopic dilution techniques were employed for the determination of rubidium, strontium and argon. A flame photometric method was employed to determine potassium. The results for the rubidium-strontium method are given in Table 1, and those for the potassium-argon method in Table 2.

All the results agree within the limits of error. Agreement between the two methods makes it highly probable that the weighted mean of the four figures

Table 1. RUBIDIUM-STRONTIUM DETERMINATIONS ON MUSCOVITE

Depth of sample (ft.)	Rubidium (p.p.m.)	Normal strontium (p.p.m.)	Radiogenic strontium (p.p.m.)	Age (m.yr.)
1,396	762	19.4	1.15	360 ± 12
1,396	757	19.6	1.15	365 ± 12

Decay constant of rubidium-87 = 0.1475×10^{-10} yr.⁻¹

Table 2. POTASSIUM-ARGON DETERMINATIONS ON MUSCOVITE

Depth of sample (ft.)	K ₂ O (per cent)*	Weight fused (gm.)	Radiogenic argon (p.p.m.)	Atmospheric argon (per cent)	Age (m.yr.)
1,396	10.01	2.034	0.240	17.4	370 ± 10
1,314	10.26	3.291	0.239	24	356 ± 12

Decay constants of potassium-40: $\lambda_{\alpha} = 0.584 \times 10^{-10}$ yr.⁻¹
 $\lambda_{\beta} = 4.72 \times 10^{-10}$ yr.⁻¹

Isotopic abundance of potassium-40 = 0.0119 atom per cent

* Potassium analyses by Dr. N. J. Snelling.

is close to the true age of emplacement of the granite.

The following points may be noted: (i) The weighted mean of 362 ± 6 million years corresponds to a Middle or Late Devonian age of emplacement, according to the latest time-scales^{2,3}. The isotopic results therefore agree with the borehole evidence for the pre-Carboniferous age of the granite. (ii) The age of the Northern Pennine mineralization from the field evidence⁴ is undoubtedly post-Carboniferous and probably pre-Tertiary. From lead isotope measurements by Moorbath⁵ the mean model age of Northern Pennine galenas is 280 ± 30 million years, indicating that the mineralization is in fact of Hercynian age. Thus, from the lead isotope data and the absolute ages, as well as from the observations reported in the preceding communication, the northern Pennine mineralization is not connected with the emplacement of the Weardale granite. (iii) The weighted mean of 362 ± 6 million years for the Weardale granite is significantly younger than the dates for the Shap granite given by Kulp *et al.*⁶. These authors obtained 391 ± 7 million years by the potassium-argon method and 381 ± 7 million years by the rubidium-strontium method. Unpublished rubidium-strontium results obtained at Oxford on the Skiddaw granite suggest that the latter may be contemporaneous with the Weardale granite.

We are indebted to Prof. Dunham for supplying the material for this investigation.

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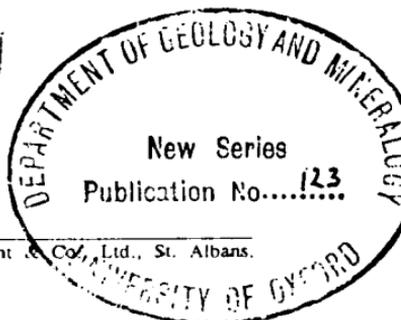
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PROCEEDINGS
OF THE
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The Base of the Namurian and
of the Millstone Grit in
north-eastern England

BY

G. A. L. JOHNSON, B. L. HODGE and
R. A. FAIRBAIRN

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THE BASE OF THE NAMURIAN AND OF THE MILLSTONE GRIT IN NORTH-EASTERN ENGLAND

BY G. A. L. JOHNSON, B. L. HODGE AND R. A. FAIRBAIRN

(Read at Sheffield, 13th January, 1962)

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SUMMARY

During the last few years evidence has been accumulating which has indicated that the junction between the Lower and Upper Carboniferous, the Viséan-Namurian junction, lies in the vicinity of the Great Limestone at the base of the Upper Limestone Group. The zonal evidence for the position of this boundary is reviewed and five new goniatite records from this part of the succession are described. Two have a direct bearing on the boundary problem—*Cravenoceras leion* Bisat, the basal goniatite of the Namurian, from the shales above the Great Limestone at Greenleighton quarry, Northumberland, and *Cravenoceras* aff. *malhamense* (Bisat) from the shales above the Little Limestone in Swinhope Burn, East Allendale. The base of the Namurian is now shown almost certainly to lie between the Four Fathom Limestone and the Great Limestone; the base of the latter is shown to be the nearest suitable mapping horizon for the base of the Millstone Grit Series.

INTRODUCTION

The position of the Viséan-Namurian junction was agreed at an international meeting shortly after the publication of Mr. W. S. Bisat's classic work on the zonal distribution of Carboniferous goniatites in the southern Pennines (Jongmans, 1928, p. XLIV; Bisat, 1924; 1928). The change in goniatite faunas, characterized by the extinction of the genus *Sudeticeras* and the incoming of the genera *Eumorphoceras* and *Cravenoceras*, is now regarded as indicative of the Namurian base and this horizon can be determined

accurately in the southern Pennine area. The boundary was chosen by Wright *et al.* (1927) as the base of the Millstone Grit and it has been used in this way by subsequent authors. It is now the general practice to identify the junction between the Millstone Grit and Carboniferous Limestone with that between the Upper and Lower Carboniferous (the Viséan–Namurian junction) though locally the stratigraphy may require a slight departure from this principle (see Earp *et al.*, 1961, p. 5).

When the Carboniferous succession is traced northwards from the southern Pennine and Craven Lowland areas, rapid facies changes occur in the vicinity of the Craven faults. In the Northern Pennines, on the other side of the fault belt, Yoredale cyclothemic deposits, in which goniatites are rare fossils, were laid down. Owing to this the exact horizon of the Namurian base and, by custom, that of the Millstone Grit, has been difficult to fix here. This is particularly true of the early period of research into these sequences when there was no sound palaeontological basis of classification and beds of various ages came to be included under the term Millstone Grit. New goniatite evidence bearing on these problems is the substance of this communication. The specimens here described or figured, with numbers prefixed GSM and GSL are in the Geological Survey collections at London and Leeds respectively; those prefixed RAF are in Mr. R. A. Fairbairn's collection at Newcastle, and the remainder, including *Cravenoceras* sp. from the Swinhope borings, are in the University Geological Department at Durham.

II. THE MILLSTONE GRIT PROBLEM IN NORTHERN ENGLAND

In the first and second editions (1809, 1821) of Westgarth Forster's treatise on the strata of the Northern Pennines the term "Millstone Grit" is used in the early sense for a particular coarse sandstone, twenty-seven feet thick, in the sequence below the Brockwell Coal. In the second edition he calls the lower part of the Carboniferous succession the "Lead Measures", with the top at the base of the sandstone next above the Grindstone Sill. This line has been taken as the base of the local Millstone Grit by subsequent workers in north-eastern England, including the primary and later surveyors of the Geological Survey.

A lithological division of the Carboniferous System into Mountain Limestone with Yoredale Series, Millstone Grit and Coal Measures was applied to the succession of north Yorkshire by Phillips (1836). This particular classification is applicable to only part of the Pennine region and attempts to use it outside this area have led to much confusion. Thus the Yoredale facies descend lower when traced from the Pennines northwards, and southwards these beds are replaced by different sedimentary facies. The Millstone Grit, so characteristic in the Pennines, loses its identity

in Northumberland owing to lithological changes and when traced south to the Midlands it dwindles and disappears.

In the Yorkshire Pennines Phillips (1836) fixed the base of his Millstone Grit at the top of the Main (= Great) Limestone, the last thick limestone band of his underlying Yoredale Series. This horizon was not easily traced outside the Northern Pennines. The Millstone Grit Series was first defined by Hull and Green (1864) in the region about the borders of Lancashire, Staffordshire and Derbyshire. They attempted to strike a parallel between the sequence there and Phillips' sequence in the Northern Pennines and limited the Millstone Grit Series to the four grits between the top of the Rough Rock and the bottom of the Kinder Scout Grit. Farther north the Millstone Grit of Northumberland and Durham was defined by Tate (1868) to include all the beds from the top of the highest limestone, with marine fossils, to the base of the Bröckwell Coal, the lowest workable seam of the Coal Measures. When the primary surveyors of the Geological Survey mapped northern England during the latter part of the last century they fully realized the confusion surrounding the strata grouped and mapped as Millstone Grit. In the Mallerstang Memoir (Dakyns *et al.*, 1891) it is stressed that the boundary between the Yoredale rocks and Millstone Grit is a disputed point, the chief difficulty arising from the changeable and impersistent character of the sandstone beds (*op. cit.*, p. 12). They point out that on their maps of northern England the base of the Millstone Grit is taken at three different stratal positions: the top of the Great (= Main) Limestone, the base of the Ingleborough Grit, and in the north, at the base of the sandstone next above the Grindstone Sill.

A new resurvey of northern England was started by the Geological Survey in the 1920's and on their initial maps the interpretation of the Millstone Grit by Tate and Westgarth Forster was used and the underlying beds were placed in the Upper, Middle and Lower Limestone Groups (Carruthers, 1924). In the revision of the geology of the Brampton district of east Cumberland (Trotter and Hollingworth, 1932) the Upper Limestone Group was taken to include all the strata up to the base of the Coal Measures and the term Millstone Grit was not used, the authors claiming rightly that there is little change in the sedimentary facies between the base of the Upper Limestone Group and the base of the Coal Measures, and that faunas of Lower Carboniferous type occur nearly to the top of the succession. Furthermore they stress the arbitrary nature of the Upper Limestone Group-Millstone Grit junction chosen by previous workers in the north of England (*op. cit.*, pp. 98-9). In the Northern Pennines Dunham (1948) retained the Westgarth Forster classification of the Carboniferous succession but stated that the "local Millstone Grit", above the Grindstone Sill sandstone, was equivalent to only part of the full Millstone Grit succession of south-east Yorkshire. He anticipated

the present findings correctly, stating that, on the evidence then available, part if not most of the Middle Limestone Group belongs to the P Zone and much of the Upper Limestone Group to the E Zone (see also Fig. 1).

The position of the Viséan–Namurian junction in the Northern Pennines remained unknown until relatively recent years. This

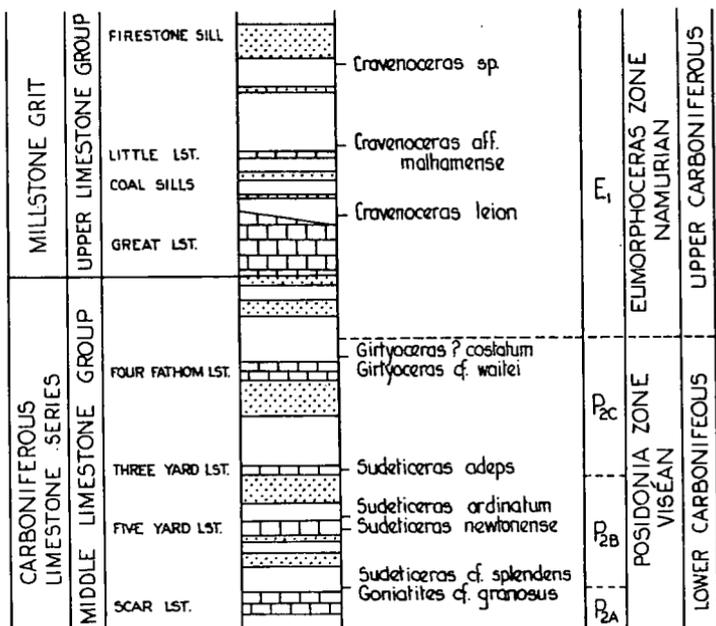


FIG. 1.—Generalized vertical section of the Carboniferous rocks above and below the Viséan–Namurian junction in north-eastern England, showing the position of the more important goniatite records.

boundary was discussed by Hudson and Cotton (1943, p. 170, footnote) who suggested that it must lie in the vicinity of the Middle (= Scar) Limestone; Trotter (1952, p. 94) agreed. New evidence in the form of goniatite records from the Northern Pennines, described by Rayner (1953, p. 286), suggested that the boundary was rather higher in the succession and the Viséan–Namurian junction was tentatively placed near the base of the Great Limestone (*op. cit.*, p. 288). In general agreement with this, George (1958, p. 297) took the Four Fathom and Undersett Limestones and their lateral correlatives as approximately defining the top of

the Viséan Stage. When the revision of the Cocker mouth district (one-inch sheet 23) was published by the Geological Survey in 1959 the base of the Millstone Grit Series was taken at the top of the Great, or First, Limestone. The base of the Namurian was taken at the base of the Great Limestone by Johnson (1958; 1959), though Trotter (1960, p. 5) took the top of this limestone for this junction in the *Lexique Stratigraphique International*. Opinion has been satisfied that the Viséan-Namurian junction lies in the vicinity of the Great Limestone. Detailed confirmation of this view required more goniatite records in or near the Great Limestone and this evidence has now been found.

III. VISÉAN-NAMURIAN JUNCTION FAUNAS

The junction between the Viséan and Namurian in Western Europe is determined by goniatite faunas and in Great Britain these are best known in the Bowland Shales, Yorkshire, and the equivalent shales of Derbyshire. At this junction the goniatite genera *Sudeticeras*, *Girtyoceras* and *Lyrogoniatites* disappear and representatives of *Eumorphoceras* and *Cravenoceras* enter. The horizon at which *Cravenoceras* enters is taken as the base of the Namurian (Bisat, 1930) and hence of the Upper Carboniferous. The general succession of faunas at this junction was described by Bisat (1950) and more recently the goniatite faunas of the Bowland Shales in the Clitheroe district have been described in detail by Ramsbottom (1961, p. 182 *et seq.*).

Though goniatites are the index fossils for determining the horizon of the base of the Namurian, certain other fossils have been found to have a limited vertical range and to be of value. Important amongst these are *Tylonautilus nodiferus* (Armstrong) and *Caneyella* [*Posidonia*] *membranacea* (M'Coy); *T. nodiferus* has a broad zonal significance in the Namurian succession. Two forms of the species have been distinguished by Stubblefield (see Trotter, 1952, p. 86) and in particular an early mutation which occurs high in the P₂ Zone and in E₁. The distribution of *T. nodiferus* on the Askrigg Block was confirmed by Rowell and Scanlon (1957, p. 3) who show that the early mutation ranges throughout E₁, and *T. nodiferus* s.s. has a limited range in the E₂ Zone. *Caneyella* [*Posidonia*] *membranacea* (M'Coy) also has a restricted range in the vicinity of the Viséan-Namurian junction and according to Parkinson (1936, p. 317) enters at about the middle of P₂ and continues upwards into the E₁ Zone; recent work in the Clitheroe district has confirmed this general distribution (Ramsbottom, 1961). Another useful fossil indicative of an Upper Viséan succession is the foraminifera, *Howchinia bradyana* (Howchin), which disappears in the upper part of the P₂ Zone but ranges downwards well into the D Zone of the Viséan (Davis, 1951, p. 248).

A more general change in the faunas, apart from goniatites, near the base of the Namurian has been described from western Northumberland (Johnson, 1959, p. 120 *et seq.*). The change is characterized by the disappearance of certain Upper Viséan species while a few Namurian species enter. Recent work by one of us (G.A.L.J.) has shown that the range of fossils at this horizon on the Alston Block is generally similar to that which was found in western Northumberland.

IV. SUCCESSION AND INDEX FAUNAS

(a) General sequence

In northern England the succession of beds in the vicinity of the base of the Namurian lies between the Five Yard Limestone and the Great Limestone (Fig. 1). This succession forms part of a well-developed series of cyclothem which are laterally persistent throughout much of northern England (Rayner, 1953; Johnson, 1960, 1962; Johnson and Dunham, 1962). The general sequence in each consists of the following members in upward succession: limestone, marine shale, ferruginous shale, sandstone, ganister or seat earth, coal. A more detailed sequence for the standard cyclothem of the Northern Pennines will be found in Dunham (1950, p. 50) and details of those in the Wensleydale region and the Northumberland Trough are given in Hudson (1924) and Johnson (1959) respectively.

The palaeontological sequence in the cyclothem gives positive evidence of division into a lower marine series and an upper deltaic and terrestrial series. The limestones and the lower part of the shales are marine; the former are crinoidal and contain numerous brachiopods and corals. Above the shales the more coarsely clastic divisions begin with sandy-shales and sandstones before the main sandstone member. A thin coal seam resting on a seat earth or ganister is present above the sandstone in many cyclothem. The increase in grain size of the clastic sediments is a constant factor and the clay mineral fraction of the sediments also varies, illite clays being dominant in the marine beds while kandite minerals (kaolin group clays) are often present in quantity in the deltaic and terrestrial parts of the cyclothem (Johnson, 1960, p. 122).

The lateral persistence of the marine horizons is important in determining the stratigraphical position of the successions owing to the rare occurrence of the goniatites, and their scattered distribution at isolated localities spread over the region. No succession of goniatite-bearing horizons in one stratal section has been found and indeed at several localities only single specimens have been collected. Much work has been carried out on the lateral correlation of the Carboniferous succession during the last hundred years and there is agreement on the general persistence of many

of the major marine horizons. Thus the Great (= Main) Limestone can be correlated owing to the presence of a series of biostromes which are a persistent feature of this horizon from Northumberland to Yorkshire (Johnson, 1958); it is also the most important lead-zinc ore bearing horizon in the Pennine orefield and is known in great detail in many shafts and mine workings throughout the area. Using all available data the structure of the Northern Pennine orefield has been illustrated by structure-contours on the base of the Great (= Main) Limestone (Dunham, 1959, p. 124). All evidence supports the view that the Great Limestone and its lateral equivalents are persistent and recognizable throughout north-eastern England and this is equally true of the other major marine horizons.

(b) Scar Limestone Cyclothem

Several goniatites have been collected from the shales immediately above the Scar Limestone of the Alston Block. The most important came from Bowlees quarry, near Middleton-in-Teesdale, and include *Goniatites* cf. *granosus* Portlock (Rayner, 1953, p. 286) and *Sudeticeras* cf. *splendens* Bisat.¹ *G. granosus* is the index fossil of the P_{2a} Zone and *S. splendens* occurs in a band at the base of the *Neoglyphioceras subcirculare* Zone, P_{2b}; an horizon at the top of the P_{2a} Zone is indicated by these specimens. Other goniatites have been found at the same horizon on the Moor House National Nature Reserve, near Cross Fell, and include *Girtyoceras* sp. and several specimens which have been tentatively identified as either *Beyrichoceratoides* or *Anthracoceras* (Johnson and Dunham, 1962); they are not of zonal value. A lamellibranch tentatively referred to a small form of *Caneyella* [*Posidonia*] *membranacea* (M'Coy) is fairly abundant at the same horizon and is of interest as the lowest record of this species in the region. The range of *C. membranacea* in northern England is limited to high Viséan and low Namurian beds (p. 345).

(c) Five Yard Limestone Cyclothem

One of the earliest goniatite records on the Alston Block comes from the Roddymoor boring at Crook, Co. Durham. Here *Girtyoceras* sp. was obtained with other fossils from shales overlying the Five Yard Limestone of Woolacott's correlation (Woolacott, 1923; Dunham, 1948, p. 11). Another goniatite is now recorded from this horizon by one of us (G.A.L.J.), in Middle Tongue Beck, on the west side of Great Dun Fell, Westmorland (Johnson and Dunham, 1962); the specimen, *Sudeticeras newtonense* Moore, was found *in situ* in the outcrop of the Five Yard Limestone on the south side of the burn. It is well-preserved and uncrushed,

¹ Collected by Dr. G. H. Mitchell. See report of field meeting at Middleton-in-Teesdale, May 1957. *Proc. Yorks. Geol. Soc.*, 1958, 31, 326-7.

in limestone matrix, and has a maximum diameter of thirty-eight millimetres. Well-developed constrictions are visible on the shell, which is ornamented with very fine transverse and concentric striae; the suture line is clear and compares closely with *S. newtonense* from the Neilson Shell Bed figured by Currie (1954, p. 589, text-fig. 7, No. g1). The determination of the specimen, now in the Geological Survey Museum (GSM. ZI 7324), has been checked by Dr. Ramsbottom and Mr. Bisat. The type specimens of *S. newtonense* come from Newton Gill, near Long Preston, Yorkshire, where they occur with *Sudeticeras* aff. *ordinatum* Moore at twenty-five feet above the *Sudeticeras splendens* band (Moore, 1950, p. 45); the horizon is P_{2b}. *Sudeticeras ordinatum* Moore, P_{2b}, has been recorded from the shales above the Five Yard Limestone of the Coverdale district on the Askrigg Block by Wilson (1960, p. 293) and the zonal position of this limestone is thus clear.

(d) Three Yard Limestone Cyclothem

The only goniatite record from the Three Yard Limestone Cyclothem of the Northern Pennines comes from the Alston Block where a single specimen¹ was found in calcareous shale just above the limestone where it crops out on the west bank of Ireshope Burn. The goniatite is flattened on a bedding plane but a fair amount of detail is preserved. Dr. Ramsbottom reports that it partly resembles a specimen which was found in the P_{2c} Zone in the Alport boring at a depth of 1098.9 feet. The Alport specimen is in the Geological Survey Museum collection (GSM. Zf 4701-2) and was tentatively referred by Mr. Bisat (1950, p. 120) to an early form of the *Cravenoceras leion* stock. The new goniatite from the shales above the Three Yard Limestone is not the same species as the Alport specimen in Dr. Ramsbottom's opinion and at the present time it remains unidentified.

In north Northumberland *Sudeticeras adeps* Moore has been recorded from the shales above a limestone mapped as the Acre (= Three Yard) Limestone by the primary surveyors of the Geological Survey (Trotter, 1952, p. 94; Rayner, 1953, p. 286). The correlation of the Acre with the Three Yard Limestone has recently been discussed by Johnson (1959, pp. 94, 112). *S. adeps* is indicative of P_{2c} age.

(e) Four Fathom Limestone Cyclothem

The precise zonal position of the Four Fathom Limestone was proved by a goniatite fauna collected from the large diameter cores of a water boring put down near Barnard Castle, Co. Durham.

¹ Collected by Mr. R. F. Goossens. See report of field meeting at Rookhope and Weardale, May 1961. *Proc. Yorks. Geol. Soc.*, 1962, **33**, 262-4.

The boring is sited at Mount Pleasant, one and a half miles south-west of Barnard Castle on the road to Bowes (034152) and traversed 594 feet of strata including the Main (= Great) and the Undersett (= Four Fathom) limestones. The Undersett Limestone was twenty-five feet thick in the boring and was separated by twelve feet of dark, fossiliferous shales from an overlying series of calcareous cherts (Fig. 2); this succession can be seen at outcrop in the River Greta at Bowes less than three miles south-west of the borehole. The full depth of the borehole was cored and a large collection of fossils was made during the detailed examination of the cores. Eight goniatites were collected between four and six feet above the top of the Undersett Limestone, in the shales between the limestone and the chert beds. The shales are tough, black and pyritic, with ill-developed bedding and approach a mudstone. Fossils are abundant and include nautiloids, lamelli-branths including *Caneyella* [*Posidonia*] *membranacea* (M'Coy) and gastropods; rarer brachiopods are also present. The goniatites have been examined by Mr. Bisat and Dr. Stubblefield who identify some of them as follows:

Depth at which found	Museum Number	
feet 359	GSM. 85048	<i>Girtyoceras</i> cf. <i>waiteri</i> Moore or <i>G.</i> cf. <i>shorrocksii</i> Moore
359	GSM. 85049	<i>Sudeticeras</i> sp., juv.
359	GSM. 85050	<i>Girtyoceras?</i> <i>costatum</i> Ruprecht
361	GSM. 85244	<i>Girtyoceras</i> sp.
361	GSM. 85245	<i>Girtyoceras</i> sp.

The horizon of *Girtyoceras?* *costatum* is known with some certainty. This goniatite was found to be abundant in the P_{2c} Zone in the Alport boring (Hudson and Cotton, 1945) and occurs elsewhere at this horizon. Similarly all the types of *Girtyoceras shorrocksii* come from the Lower Bowland shales near Dinkley Ferry, River Ribble, Lancashire, near the top of the P_{2c} Zone (Moore, 1946, p. 413). The type specimens of *G. waiteri* Moore also come from the P_{2c} Zone at a locality near Hilly Clough Farm, Weets Hill (Ramsbottom, 1961, p. 186). The highest Viséan goniatite faunas include *Girtyoceras shorrocksii* and *Girtyoceras?* *costatum* according to Bisat (1950). *Girtyoceras waiteri* occurs slightly above *G. shorrocksii* in both the Alport boring, and the

Whinney Gill Reservoir exposure at Skipton, Yorkshire (Bisat, 1950, pp. 112-3). The goniatite fauna collected from the shales above the Four Fathom Limestone in the Mount Pleasant boring can thus be reliably assigned to the upper part of the P_{2c} Zone of the Viséan. Since the discovery of the Mount Pleasant goniatite fauna, a search has been made of outcrops of the shales above the

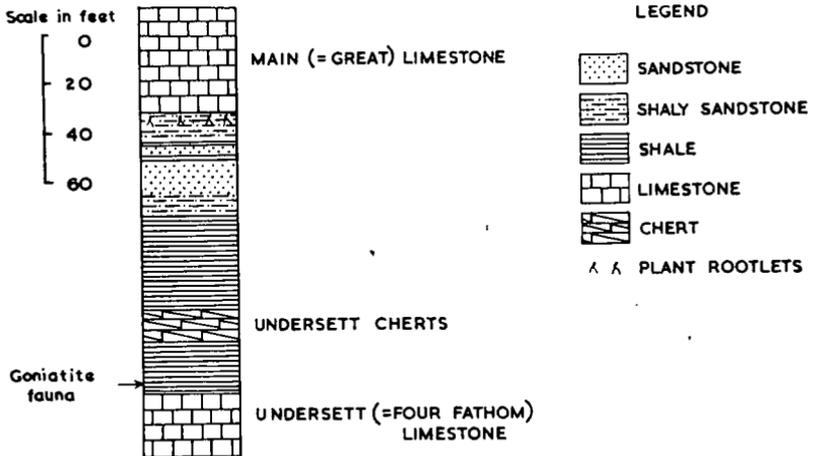


FIG. 2.—Vertical section of the Undersett (= Four Fathom) Cyclothem and the overlying Main (= Great) Limestone proved in the Mount Pleasant boring at Barnard Castle, Co. Durham, showing the position of the top Viséan, P_{2c} age, goniatite fauna. Permission to publish geological data from the Mount Pleasant borehole has been kindly granted by Barnard Castle U.D.C.

Four Fathom Limestone for further specimens. Fragmentary goniatites have been found at several localities but none has been identifiable. The lamellibranch, *Caneyella* [*Posidonia*] *membranacea* (M'Coy), which occurs with the goniatites in the Mount Pleasant boring, has been found repeatedly in the Four Fathom Limestone shales on the Alston Block and also in western Northumberland (Johnson, 1959; Johnson and Dunham, 1962). The nautiloid *Tylonautilus nodiferus* (Armstrong), early mut., first appears in the Four Fathom Limestone shales where it has been recorded in western Northumberland (Johnson, 1959, pp. 113-4).

The highest appearance of *Howchinia bradyana* (Howchin) in the microfauna of the Four Fathom Limestone is of interest. The species was recorded as ranging from P_2 down to the D Zone (Davis, 1951), and has been used in the interpretation of some Midland borings as an indicator of the proximity of D Zone massive limestones. On the Alston Block *H. bradyana* occurs for the last time in the Four Fathom Limestone and is fairly common

in the limestones below this (Johnson and Dunham, 1962). In western Northumberland it is a fairly common member of the microfauna of the limestones between the Five Yard and the Jew and makes its last appearance in the Three Yard Limestone (Johnson, 1959, p. 123).

(f) Great Limestone Cyclothem

The search for goniatites in the Great Limestone has continued for many years, since the limestone contains an abundant

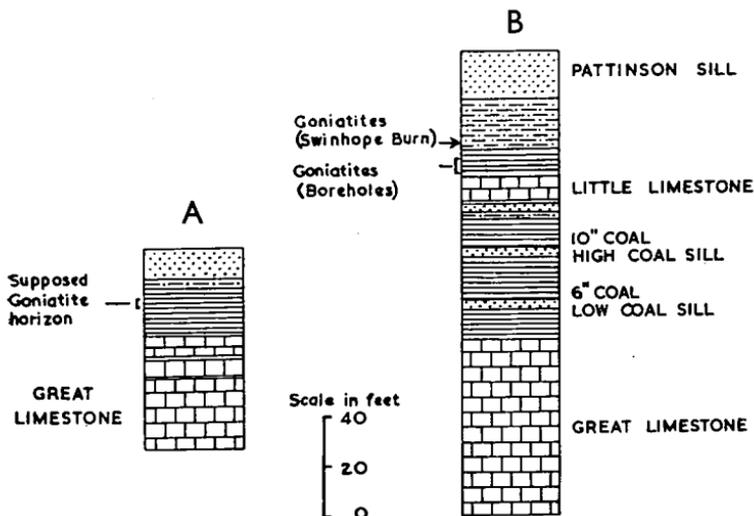


FIG. 3.—A, Vertical section of the strata exposed in Greenleighton quarry, Northumberland, showing the Great Limestone and the shale overburden with the horizon at which *Cravenoceras leion* Bisat is believed to occur.

B, Vertical section of the Great Limestone and Little Limestone Cyclothems in the Swinhopehead area, East Allendale, showing the position of the goniatite faunas in the shales above the Little Limestone. The key to the ornament is given in Fig. 2.

fauna at many places and the overlying shales are often richly fossiliferous. The limestone is the thickest and the most persistent laterally of the cyclothem strata and is worked in many large quarries throughout its outcrop. Despite this wealth of exposure no goniatites had been recorded from it or its associated shales until one of us (R.A.F.) found specimens in the tip of overburden of a quarry near Greenleighton farm, Northumberland (035916), about nine miles NNW. of Belsay and just off the Belsay-Rothbury road.

The Great Limestone is worked here in a large quarry which also exposes some thirty feet of shale and sandstone (Fig. 3A). The overburden is removed, and forms large tips at the top of the

working face. The shale and argillaceous limestone of the tips are packed with fossils which weather out beautifully on the surface, and over the last four years six specimens of goniatites have been found. They are well preserved and uncrushed, in calcareous nodules; similar nodules occur in the undisturbed shales approximately twelve feet above the top of the limestone, and this is probably the horizon of the goniatites. Unfortunately none has been found *in situ*, but in view of their rarity this is not surprising; the six known specimens have been found at different places on the tips. Other fossils in the shales include abundant brachiopods, particularly species of *Chonetes*, *Productus* and *Spirifer*, with lamellibranchs, gastropods, crinoids and polyzoa. The shales also contain occasional, impersistent, silty, calcareous bands which are often rich in well-preserved specimens of *Chonetes*. Twenty-five feet above the limestones the shales grade upwards into very flaggy sandstones.

TABLE I
Dimensions of *Cravenoceras leion* Bisat from Greenleighton quarry,
Northumberland

Specimen Number	Diameter	Thickness	Umbilicus
	<i>mm.</i>	<i>mm.</i>	<i>mm.</i>
GSL. LZ 3406	13.5	10.5	3.0
RAF/2	11.0	7.0	2.5
RAF/3	13.0	8.5	2.5
GSL. LZ 3407	11.0	8.0	2.0
RAF/5	14.0	10.5	4.0

The Greenleighton goniatites have been examined by Dr. Ramsbottom and Mr. Bisat who report that all belong to the species *Cravenoceras leion* Bisat; the horizon is E_1 (Namurian). *Cravenoceras leion* is the index fossil of the E_{1a} Zone and its entrance has been taken as the base of the Namurian (Bisat, 1930, p. 28). The specimens fit well into the *C. leion* species group and have shells of subglobose form with an open umbilicus of a width about one-fourth of the diameter of the shell. The venter and flanks are broadly rounded and nearly semicircular in outline. The dimensions of five of the specimens are given in Table I. The external ornament is well preserved in some specimens (Plate 22, figs. 11-4) and consists of closely-set, thin, non-crenulate transverse striae, emerging from the umbilicus in a slightly forward direction

and bending to form a very shallow sinus over the venter. Shallow constrictions are developed on the shells. The suture line is well displayed on some of the specimens (Plate 22, fig. 10) and shows the broadly rounded ventral saddles and narrow lateral lobes.

Tylonautilus nodiferus (Armstrong), early mut., has been

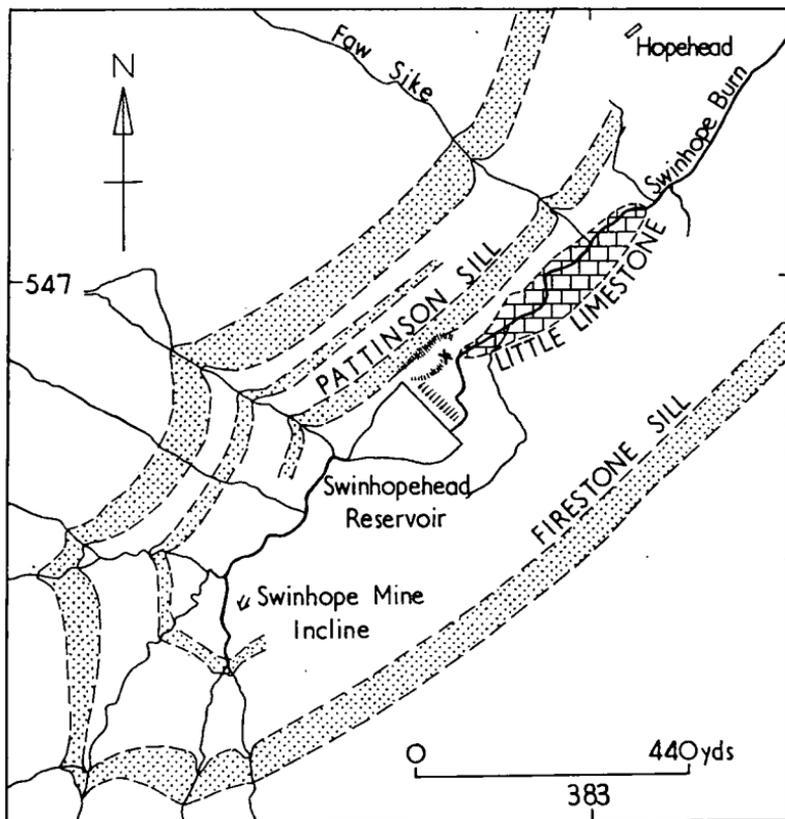


FIG. 4.—Map of the Swinhopehead area, East Allendale, showing the inlier of Little Limestone in Swinhope Burn. The locality in the shales above the Little Limestone from which *Cravenoceras* aff. *malhamense* has been recorded is marked X. The key to the ornament is given in Fig. 2.

recorded in the Great Limestone by Rhodes from the Smiddy Gill section of Swarth Fell (see Rowell and Scanlon, 1957, p. 3).

(g) Little Limestone Cyclothem

Fragmentary goniatites identified as *Cravenoceras* sp. were found in the shales above the Little Limestone in the cores of a series of borings put down near Allenheads in south Northumberland (Dunham and Johnson, 1962). They consisted of broken

fragments only (for example Plate 22, fig. 8) occurring between one foot three inches and eight feet above the top of the Little Limestone. Further investigation of the Little Limestone shales (B.L.H. and G.A.L.J.), however, was rewarded by the discovery of seven specimens, fourteen feet six inches above the limestone in Swinhope Burn, East Allendale (Fig. 4).

The locality lies about a hundred yards below Swinhopehead reservoir, where the shales above the limestone are well exposed in the sides of a small, abandoned, outlet channel (828469); the limestone here forms an inlier, and was identified by the primary surveyors as the Little Limestone, which is confirmed by the present work (Fig. 3B). The nearest exposure is in the new incline of Swinhope mine, 1550 yards to the west, where the dip is three degrees to the east; this dip carries the top of the limestone exactly to its position in Swinhope Burn.

The goniatic-bearing shale is decalcified, micaceous, slightly silty, and contains small ironstone nodules; the specimens are not abundant and appear to be confined to a single band; they are accompanied by comminuted plant debris and marine fossils, including specimens of *Chonetes*, indeterminate orthotetids and lamellibranchs. Some of the goniatices are completely decalcified and occur as hollow external moulds, others are partly decalcified and some specimens are preserved in the solid state.

TABLE II
Dimensions of *Cravenoceras* aff. *malhamense* (Bisat) from Swinhope Burn, East Allendale, Northumberland

Specimen Number	Diameter	Thickness	Umbilicus
	<i>mm.</i>	<i>mm.</i>	<i>mm.</i>
GSL. LZ 3408	4.0	3.5	1.5
GSL. LZ 3409	6.0	—	2.0
GSL. LZ 3410	5.0	4.0 ⁺	2.5
5	8.0	4.5	2.0
6	3.5	3.0	2.0
GSL. LZ 3411	3.0	2.0	1.0

The goniatices found in Swinhope Burn have been examined by Mr. Bisat and Dr. Ramsbottom and the latter reports as follows:

“These are *Cravenoceras* sp., but there are a number of unusual

features, notably the raised umbilical rim and the marked hyponomic sinus. A raised umbilical rim is known in examples of comparable size in both *C. leion* and less definitely in *C. malhamense*, but these species do not show any hyponomic sinus. The only *Cravenoceras* examples seen which show any hyponomic sinus at this size (c. 8 mm.) is *C. cowlingense* from the same erratic block in Keighley churchyard which yielded the types of *Anthracoceras cherryi* Bisat. The ornament of the specimens is, apart from the sinus, very close to that of *C. malhamense*, and *C. aff. malhamense* (Bisat) would seem to be the best name for them until more is known about the *Cravenoceras* succession in E_1 times."

Cravenoceras malhamense is the index fossil of the E_{1c} Zone (Fig. 1) and the presence of *C. aff. malhamense* in the Little Limestone shales is certainly indicative of E_1 but the age cannot be more narrowly defined. *C. malhamense* differs from *C. leion* in having a smaller umbilicus and generally coarser transverse ornament (see Plate 22). Dimensions of six of the specimens of *C. aff. malhamense* from Swinhope Burn are given in Table II. The shells are of cadicone form with wide umbilicus and broad venter (Plate 22, figs. 1-7). External ornament consists of delicate, transverse striae, non-crenulate and non-dichotomizing, with a marked hyponomic sinus on the venter (Plate 22, fig. 2). The sutures are not well shown but the general outline can be made out in some of the specimens (Plate 22, fig. 3).

Tylonautilus nodiferus (Armstrong), early mut., has been recorded from the Little Limestone by Johnson and Dunham (1962) from Middle Tongue Beck, on the west side of Great Dun Fell, Westmorland.

(h) Beds above the Little Limestone Cyclothem

Goniatite records are rare from the succession above the Little Limestone Cyclothem in Northumberland and on the Alston Block. Records of E_2 age occurring high in the Upper Limestone Group refer to a specimen identified as *Anthracoceras* sp., of the *A. discoides* Bisat group, from the Thornborough Limestone of the South Tyne section at Wydon, Northumberland (Rayner, 1953, p. 287) and to specimens of *Tylonautilus nodiferus* (Armstrong) s.s., from the Styford Shale of the Tyne Valley (Rayner, *op. cit.*). The goniatites reported by Shotton and Trotter (1936, p. 386) from a faulted block of Yoredale strata at Star Hows, Ardale Beck, below Cross Fell, have been re-examined in recent years and Mr. Bisat identifies them as *Cravenoceras* sp. nov. and *Kazakhoceras* [*Neodimorphoceras*] sp. (Johnson, 1959, p. 115, footnote); the specimens indicate an E age but the exact stratigraphical horizon of the beds is unknown. A single goniatite, identified as *Cravenoceras* sp., has been recorded from just below the Firestone Sill on Little Dun Fell, Westmorland (Johnson and Dunham, 1962).

On the Askrigg Block of the Northern Pennines two important goniatite bearing horizons have been described by Dunham and Stubblefield (1945) and Wilson and Thompson (1959). High in E_2 the Colsterdale Marine Beds contain a goniatite fauna including *Cravenoceratoides nitidus* (Phillips) and *Anthracoceras paucilobum* (Phillips), with *Tylonautilus nodiferus* s.s. Below this the Cockhill Marine Band contains *Cravenoceras cowlingense* Bisat, the index fossil for the E_{2a} Zone, and this horizon has been traced to the northern margin of the Askrigg Block where it occurs in Mirk Fell Gill and Brigstone Gill (Hudson, 1941; Wilson and Thompson, 1959, p. 54). This marine band gives some evidence of the position of the base of the E_2 succession on the Askrigg Block and according to Reading (1957, p. 31, fig. 2) this horizon (Mirk Fell Ironstone) is equivalent to the Coalcleugh Transgression Beds on the Alston Block to the north. On this evidence the E_1 Zone extends far above the top of the Little Limestone Cyclothem but the upper limit of the zone must remain uncertain until more goniatite evidence has been found in this part of the succession.

V. CORRELATION AND DISCUSSION

The new records of *Cravenoceras leion* and *C. aff. malhamense* in the succession above the Great Limestone of northern England show that the base of the Namurian must lie not far below. A highest Viséan, P_{2c} age, fauna is known from the shales slightly above the top of the underlying Four Fathom Limestone (Fig. 1). There is thus between these two goniatite horizons some hundred and thirty feet of strata within which the Viséan-Namurian junction must lie. There are two goniatite records within this series of beds—a single fragmentary specimen, identified by Dr. Ramsbottom as ?*Cravenoceras* sp. (Wilson, 1960, p. 297) in shales at about twenty feet above the Undersett (= Four Fathom) Limestone at Downs Gill, Coverhead, and *Eumorphoceras pseudo-bilingue* (Bisat), recorded from immediately below a limestone, believed to be the Main (= Great) Limestone, on Fountains Fell, Yorkshire (Hudson, 1941, p. 269; Black, 1950, p. 39; Rayner, 1953, p. 286). In both cases these goniatites indicate Namurian age. Although great reliance cannot be placed on them owing to poor preservation in the former and uncertain stratigraphical position in the latter, these goniatite records give a strong indication that the base of the Namurian lies in the clastic succession between the Great and Four Fathom Limestones (Fig. 1).

It is customary to place the junction between the Millstone Grit and the Lower Carboniferous at the base of the Namurian, that is, the junction between the Upper and Lower Carboniferous, or at the nearest mapping horizon to this (p. 345). The base of the Namurian has been shown almost certainly to lie below the Great

Limestone and thus within the underlying clastic sequence, but in this succession no suitable mapping line exists. The nearest boundary is the base of the Great Limestone (Fig. 1) which can be traced throughout northern England and is regarded as one of the least diachronous stratal lines in this part of the Carboniferous succession. But this is contrary to the original interpretation of Phillips (1836) who placed the base of his Millstone Grit Series at the top of the Main (= Great) Limestone. The top of the Great Limestone, however, is not regarded as a satisfactory stratigraphical boundary owing to the irregular development there of a limestone-shale alternation known as the Tumbler Beds. The thickness of the Great Limestone varies between about thirty-five feet in Northumberland and over eighty in Weardale. Recent detailed study of the Great Limestone Cyclothem by one of us (B.L.H.) has shown that there is considerable local variation in the thickness of the limestone owing to the development of limestone bands within the overlying shale. It seems probable that much of the highly fossiliferous shale overlying the Great Limestone in Northumberland is the lateral equivalent of the upper part of the Great Limestone of the Alston Block. In this case the *Cravenoceras leion* horizon at Greenleighton, Northumberland, may be contemporaneous with part of the Great Limestone to the south. These considerations support the view that the Great Limestone is of low Namurian age and suggest that the best mapping line for the base of the Millstone Grit Series is the base of the limestone.

VI. ACKNOWLEDGEMENTS

The writers wish to express their thanks to Mr. W. S. Bisat and Dr. W. H. C. Ramsbottom who have examined the new goniatites mentioned in this paper. Professor K. C. Dunham has kindly advised on the presentation of the work and Mrs. K. M. Fairbairn prepared the text-figures for publication. The photographs which form Plate 22 are the work of Mr. C. Chaplin and Mr. G. Dresser of the University Geological Department, Durham.

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DISCUSSION

In a written communication Professor T. S. WESTOLL expressed his regret for his unavoidable absence but wished to congratulate Dr. Johnson and his colleagues on this valuable addition to our knowledge of the zonal framework of the Limestone Group of Northumbria. This paper adds new precision to the results of Dr. Johnson's careful collecting over some dozen years. Mr. Fairbairn's success in collecting so many specimens of *Cravenoceras* at Greenleighton is also the reward of remarkably persistent and careful efforts. The writer had identified as *Cravenoceras* aff. *leion* group four of the specimens, collected by Mr. Fairbairn and now handed over to Dr. Johnson. The firm recognition of these zonal forms is of the greatest significance.

Dr. D. H. RAYNER also congratulated Dr. Johnson and his co-authors for the valuable palaeontological records that had been described—another contribution to the extensive Carboniferous studies being pursued in the Department of Geology at Durham. It was also clear that the goniatites had been found only after much patient search and this did apparently represent a real rarity of these fossils in the Yoredale facies, compared, for instance, with their local abundance at some levels in the Bowland Shales. Were there any salient characters in the accompanying fauna, or in the lithology of the goniatite-bearing rocks, that might indicate conditions of preservation, and throw light on this question of relative rarity?

Professor K. C. DUNHAM said that his suggestion in 1948 that the base of the Namurian would be found near the position of the Great Limestone was to be regarded as an expression of prejudice rather than prophecy. He was very pleased that the authors had succeeded in obtaining new critical evidence on the exact position but he wished to enquire whether the shales from which the *C. leion* came were regarded as above the Great Limestone or whether there was evidence to show that they were the equivalent of the upper part of that limestone as developed in the Northern Pennines.

Dr. J. SHIRLEY commented upon the interest of this communication to those working on the shelly faunas of this part of the Carboniferous. Thanks to the work of Dr. Johnson and his colleagues upon the goniatites it was now certain that the Great Limestone provided the earliest exactly dated Namurian brachiopod-coral fauna and, since the goniatites are so rare in this facies, close study of the fauna should provide a basis for recognition of this important horizon where the goniatites fail.

Dr. A. W. WOODLAND congratulated the authors on an invaluable compilation of all the known data relating to the Namurian-Viséan boundary in the north of England. The discovery of well-preserved specimens of *Cravenoceras leion* from a

position not far above the Great Limestone was a great step forward. This problem of the base of the Millstone Grit was one which was exercising the minds of the Geological Survey in the north of England, since work was now proceeding in areas where these rocks cropped out. It was interesting to note that as far back as 1884 J. R. Dakyns was writing from Penrith to his superiors pleading for Phillips' line at the top of the Main Limestone to be accepted as the base of the Millstone Grit on the Geological Survey's maps of northern England. This was turned down and it was not until 1959 with the publication of the Solid Edition of the Cockermouth Sheet that this boundary line was re-affirmed. In view of this the speaker wondered whether there was, at present, a clear justification for taking the base of the Great Limestone as the dividing line between the two formations. The *C. leion* at Greenleighton came from a position which may be construed as lying one or two minor cyclothem above the Great Limestone if comparison be made with other recently described sections, on the Alston Block for example, where minor cycles are present between the Great and Little limestones. Furthermore no great weight can yet be placed on the occurrence of *Cravenoceras* below the Great. The specimens collected from about twenty feet above the Undersett Limestone by Wilson (1960, p. 297) were identified as ?*Cravenoceras* and some uncertainty surrounds the exact location of those reported from Fountains Fell.

The AUTHORS in reply thanked Professor Westoll for his support for their findings. Goniatites do form a rare element in the faunas of Yoredale facies compared to other groups of marine fossils as Dr. Rayner pointed out. They are not restricted to any particular lithology and can occur in limestone, calcareous shale or ferruginous shale but seem to be most commonly present in black pyritic mudstone. Dr. Johnson stressed that the scarcity of Yoredale goniatites referred actually to specimens capable of reliable identification; fragmentary goniatites were far more common. The abundant evidence of shallow water conditions in Yoredale deposits seems to explain why fragile shells, including goniatites, are found broken and dispersed in the rock (Johnson, 1960).

With regard to the shelly faunas in the vicinity of the Great Limestone, mentioned by Dr. Shirley, extensive collections have been made from these beds. The faunas are most interesting and the authors hope that some account of them will appear in due course.

In reply to Professor Dunham and Dr. Woodland, Mr. Hodge said that he was just completing a detailed examination of the Great Limestone Cyclothem over a large part of northern England which had shown that the thickness of the Great Limestone varied considerably. In particular the top of the limestone is very

variable, owing to the development of a limestone-shale alternation. Further, it seemed clear that the upper part of the limestone in some places is equivalent laterally to calcareous shales above the limestone elsewhere. The goniatites found at Greenleighton lie within the richly fossiliferous shales, above the limestone, that are regarded as equivalent to the upper part of the Great Limestone of Weardale. Thus unfortunately the top of the Great Limestone is not a satisfactory time-line in northern England. Owing to this, and taking in account all the known goniatite evidence—albeit uncertain as Dr. Woodland stressed—the authors felt it advisable to take the base of the limestone as the base of the Millstone Grit. This is regarded as one of the least diachronous boundaries close to the base of the Namurian.

EXPLANATION OF PLATE 22

Cravenoceras aff. *malhamense* (Bisat)

Shales fourteen feet above the Little Limestone, Upper Limestone Group, Namurian, E₁ Zone. Swinhope Burn, one hundred yards downstream from Swinhopehead reservoir.

FIGS. 1, 2.—Lateral and ventral views of uncrushed specimen showing the wide umbilicus and marked hyponomic sinus, GSL. LZ 3410, × 5.

FIGS. 3, 4.—Lateral and ventral views of a latex cast made from a natural external mould showing the sutures, GSL. LZ 3408, × 5.

FIGS. 5, 6.—Oblique and ventral views of a small specimen showing the raised umbilical rim, marked constrictions and the hyponomic sinus, GSL. LZ 3411, × 5.

FIG. 7.—Lateral view showing ornament and umbilical rim, GSL. LZ 3409, × 5.

Cravenoceras sp.

Shales about three feet above the Little Limestone, Upper Limestone Group, Namurian, E₁ Zone. Swinhope mine boring No. 3 (see Dunham and Johnson, 1962, pl. 17).

FIG. 8.—Fragment of broken shell showing part of the umbilicus and flanks, × 5.

Cravenoceras leion Bisat

Shales approximately twelve feet above the top of the Great Limestone, Namurian, E₁ Zone. Greenleighton quarry, nine miles NNW. of Belsay, Northumberland.

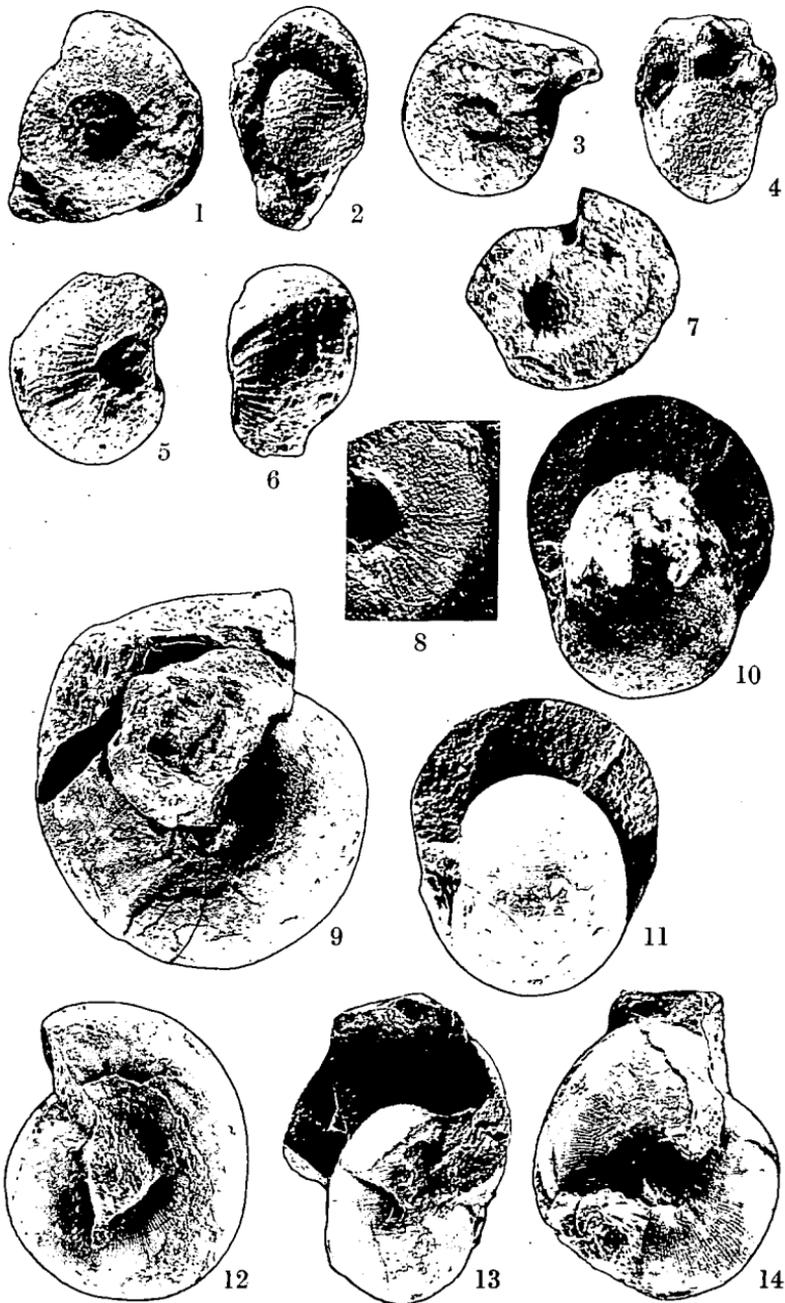
FIG. 9.—Lateral view, GSL. LZ 3406, × 3.5.

FIG. 10.—Same specimen, internal whorls photographed under liquid to show the sutures, × 3.5.

FIG. 11.—Same specimen, ventral view of internal whorls showing ornament with very slight hyponomic sinus, × 3.5.

FIG. 12.—Same specimen, lateral view of the internal whorls, × 3.5.

FIGS. 13, 14.—Ventral and lateral views of a slightly crushed specimen showing external ornament, GSL. LZ 3407, × 3.5.



CRAVENOCERAS

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A guide to the geology of the district around Alnwick, Northumberland, by T. S. Westoll, D. A. Robson and R. Green, 1955 (*Proceedings*, Vol. 30, No. 5), 40 pp., 5 pls. Price 6/- (Post-free, 6/4).

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