Durham University

Durham E-Theses

Stratigraphy and sedimentation of the Namurian strata in the Coalcleugh - Rookhope district, Northern Pennines

Ronald Pattinson

How to cite:

Pattinson, Ronald (1964) Stratigraphy and sedimentation of the Namurian strata in the Coalcleugh - Rookhope district, Northern Pennines. Doctoral thesis, Durham University.

Use policy

The full-text may be used and/or reproduced, and given to third parties in any format or medium, without prior permission or charge, for personal research or study, educational, or not-for-profit purposes provided that:

- a full bibliographic reference is made to the original source
- a https://etheses.durham.ac.uk/id/eprint/9256/ is made to the metadata record in Durham E-Theses
- the full-text is not changed in any way

The full-text must not be sold in any format or medium without the formal permission of the copyright holders.

Please consult the full Durham E-Theses policy for further details.

Academic Support Office, The Palatine Centre, Durham University, Stockton Road, Durham, DH1 3LE
e-mail: e-theses.admin@durham.ac.uk Tel: +44 0191 334 6107
https://etheses.durham.ac.uk

STRATIGRAPHY AND SEDIMENTATION OF THE NAMURIAN STRATA IN THE COALCLEUGH - ROOKHOPE DISTRICT, NORTHERN PENNINES

by

Ronald Pattinson, B.A. (Oxon.), F.G.S.

A thesis submitted to the
Faculty of Science in the University of Durham
for the degree of Doctor of Philosophy

March, 1964.

Grey College

Durham

DURHAM UNIVERSITY
SCIENCE
12 JUN 1964
LIBRARY

ABSTRACT

Carboniferous Upper Limestone Group strata of Namurian age have been investigated in an area of 45 square miles in the Northern Pennines, with a view to establishing a rational stratigraphy and determining their depositional environment. Several cyclothems, comprising a coarsening-upward sequence of clastic sediments, have been recognised and named by the prominent marine bands taken as the base of each. The marine band may either be a widely distributed limestone or a more impersistent ironstone. A complex series of channel sandstones, shell beds and fine clastics, which does not conform to the cyclothemic concept , is grouped together as the Slate Sills Formation. Strata above the Grindstone Sill, the topmost member of the Upper Limestone Group, are poorly exposed, and are grouped together as the Rowton Well Formation.

By comparative correlations, largely outside the research area, it is known that the Upper Limestone Group is wholly of <u>Eumorphoceras</u> age, and it is suggested that the E_1/E_2 boundary lies in the vicinity of the Upper Rookhope Ironstone. The Rowton Well Sill (or "First Grit") is known to be of R_1 age, but no evidence of H zone strata has yet been found.

The petrography of the sandstones in the area is discussed and details of the main types are given. The petrography and mineralogy of the Knucton Ironstone, a sandy, sideritic chamosite oolite, are also presented. The chamosite has a 14 Å orthohexagonal structure and is diagenetic, at least in part.

Evidence is presented which shows that the Upper Limestone Group cyclothems possess all the sedimentary features of a deltaic sequence. The rocks are subdivided into eight lithological facies, and the sedimentological properties of these are given and discussed in terms of possible depositional environment. The detailed study strongly supports the general impression that the Upper Limestone Group is essentially a marine sequence in which the dominant sedimentological control was of deltaic type, with occasional episodes of dominantly fluvial sedimentation.

ACKNOWLEDGEMENTS

The author would like to express his gratitude to Professor K.C. Dunham for introducing him to the area studied and to Dr. G.A.L. Johnson for his help and encouragement in supervising the research and for critically reading the manuscript.

Sincere thanks are also due to the following :-

Prof. K.C. Dunham, for allowing the author to use his maps to obtain the details of the faults and veins of the area as well as the "outcrop" of the Great Limestone below the thick drift cover in East Allendale.

Mr. R. Philips, for demonstrating the use of the X-ray apparatus and for helpful advice on the subject of chamosite.

Messrs. B.L. Hodge and C.R. Rowley, for useful discussions on stratigraphy and sedimentology.

The Geological Survey of Great Britain, in particular, Messrs. J.H. Hull and I.C. Burgess, for allowing the author to quote unpublished information, and for discussions on the question of regional correlation.

Mrs. Maureen Kaye, for identifying by X-ray analysis certain carbonate minerals.

Mr. C. Chaplin and his technical staff, for preparing many thin-sections, photographs, and illustrations for the thesis, as well as the author's geological map of the area.

Mr. G. Dresser deserves special mention for his invaluable co-operation in producing illustrations in the closing stages of thesis production.

Miss Barbara P. Dodd, who has conscientiously typed the thesis at short notice and often at great personal inconvenience, for which the author is extremely grateful.

The Department of Scientific and Industrial Research, for financial support during the period of the research.

To any one else who has in any way contributed to this thesis the author extends his grateful thanks.

C O N T E N T S

LIST OF TEXT-FIGURES

LIST OF PLATES

32. Sublitharenite, showing rounded clay pellets, "marginal facies", Low Grit Sill.

33. Sublitharenite, "marginal facies", Low Grit Sill.

34. Litharenite, showing angular siderite fragments.

35. Chamosite oolith, showing structureless core and coarse crystallisation of rims.

36. Chamosite oolith, showing development of authigenic chamosite in core, fine crystallisation of rims, and partial opalisation.

37. As above, under crossed nicols.

38. Crystal of authigenic chamosite just occupying the core of the oolith.

39. Large crystal of authigenic chamosite in elongate oolith showing impinging quartz grain.

40. Authigenic chamosite almost completely occupying oolith.

41. Authigenic chamosite almost completely occupying oolith and showing replacive relationship.

42. Quartz, siderite, and ooliths showing different orientations of authigenic chamosite.

43. Authigenic chamosite forming with basal cleavage at right angles to long axis of oolith. Note "accordian-structure".

44. "Accordian-structure" in authigenic chamosite.

44a. Chamosite ooliths marginally invaded by siderite.

45. Shell bed at base of Crag Limestone, Nookton Burn.

46. Irregular dolomitic stringers in Lower Felltop Limestone, Beldon Burn.

47. Sandstone-siltstone intercalations in base of Hipple Sill, North Grain, Rookhope Burn.

64. "Pencil ganister" above Hipple Sill, Black Sike, Rookhope.
65. Poorly sorted conglomeratic sandstone, Low Grit Sill, Beldon Burn.
66. Relatively well-sorted granule conglomerate, Firestone Sill, River West Allen.
67. Association of large scale trough cross-stratification and planar cross-stratification, Upper Limestone Group, near Howick, Northumberland.
68. Planar cross-stratification, Rowton Well Sill, Bolt's Law, Rookhope.
69. Random section through large scale trough cross-stratified sandstone, Low Slate Sill, Hawk Sike.
70. Large scale trough cross-stratification, High Slate Sill, Beldon Burn.
71. Large scale trough cross-stratification, High Slate Sill, Beldon Burn.
72. Large scale trough cross-stratification, Upper Limestone Group, near Howick, Northumberland.
73. Longitudinal section through large scale trough cross-stratification, Grindstone Sill, White Edge, Rookhope.
74. Large scale trough structure in Coalcleugh Transgression Beds, Sipton Cleugh.
75. As above, camera angle moved to the right.
76. "Marginal facies" on south-west side of trough structure in Coalcleugh Transgression Beds.
77. Allochthenous coal and "disconformable" relationship with overlying sandstone, base of Coalcleugh Transgression Beds, Sipton Cleugh.

LIST OF TABLES

P A R T I

S T R A T I G R A P H Y

CHAPTER 1

GENERAL INTRODUCTION

I Regional setting

Research into the stratigraphy and sedimentology of the Carboniferous Upper Limestone Group was carried out in an area of 45 square miles in the northern Pennines on the borders of Northumberland and County Durham. The research area is some 20 miles west of Durham City (see inset, Fig. 1.1), extending northwards from upper Weardale as far as Beldon, Sipton, and Swinhope Burns, and in an east-west direction ranges from Hunstanworth and Rookhope in the east to Coalcleugh in the west.

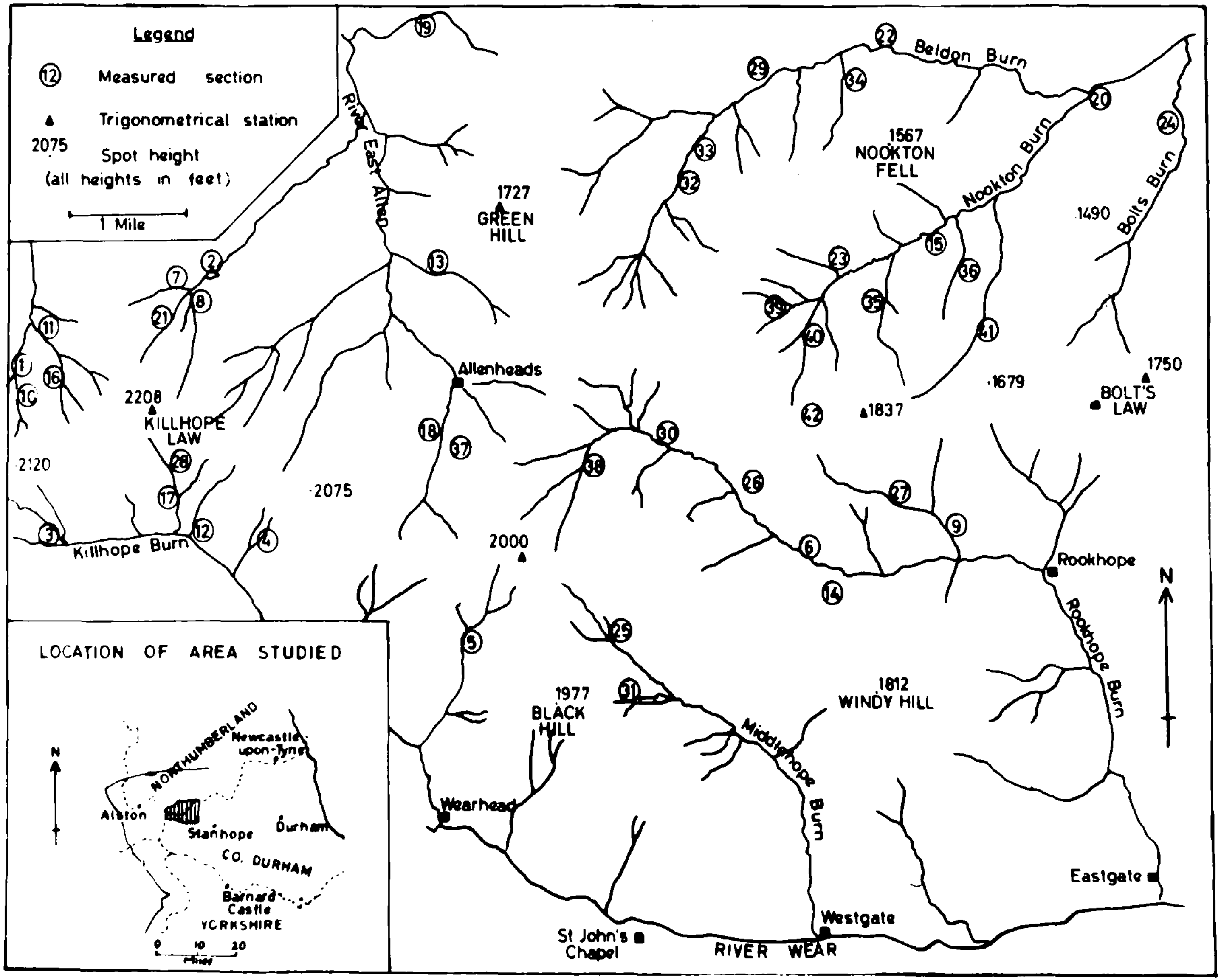
A geological map of the area is located in the pocket at the back of this volume.

Topographically, the research area forms an upland plateau which is gently inclined to the north and north-east, and which is deeply dissected by an almost radial drainage system. The region lies on the watershed between the Tyne and Wear catchment areas, and the highest ground lies on the north side of Weardale, where heights of about 2,000 feet are common (Killhope Law, 2208 feet; Black Hill, 1977 feet). Summit heights gradually become lower to the north-east where, around Hunstanworth, 1500 feet is typical (Nookton Fell, 1567 feet; Cocklake, 1490 feet). The upland parts of the area

DURHAM UNIVERSITY SCIENCE 12 JUN 1964 LIBRARY

Figure 1.1

LOCATION OF MEASURED SECTIONS



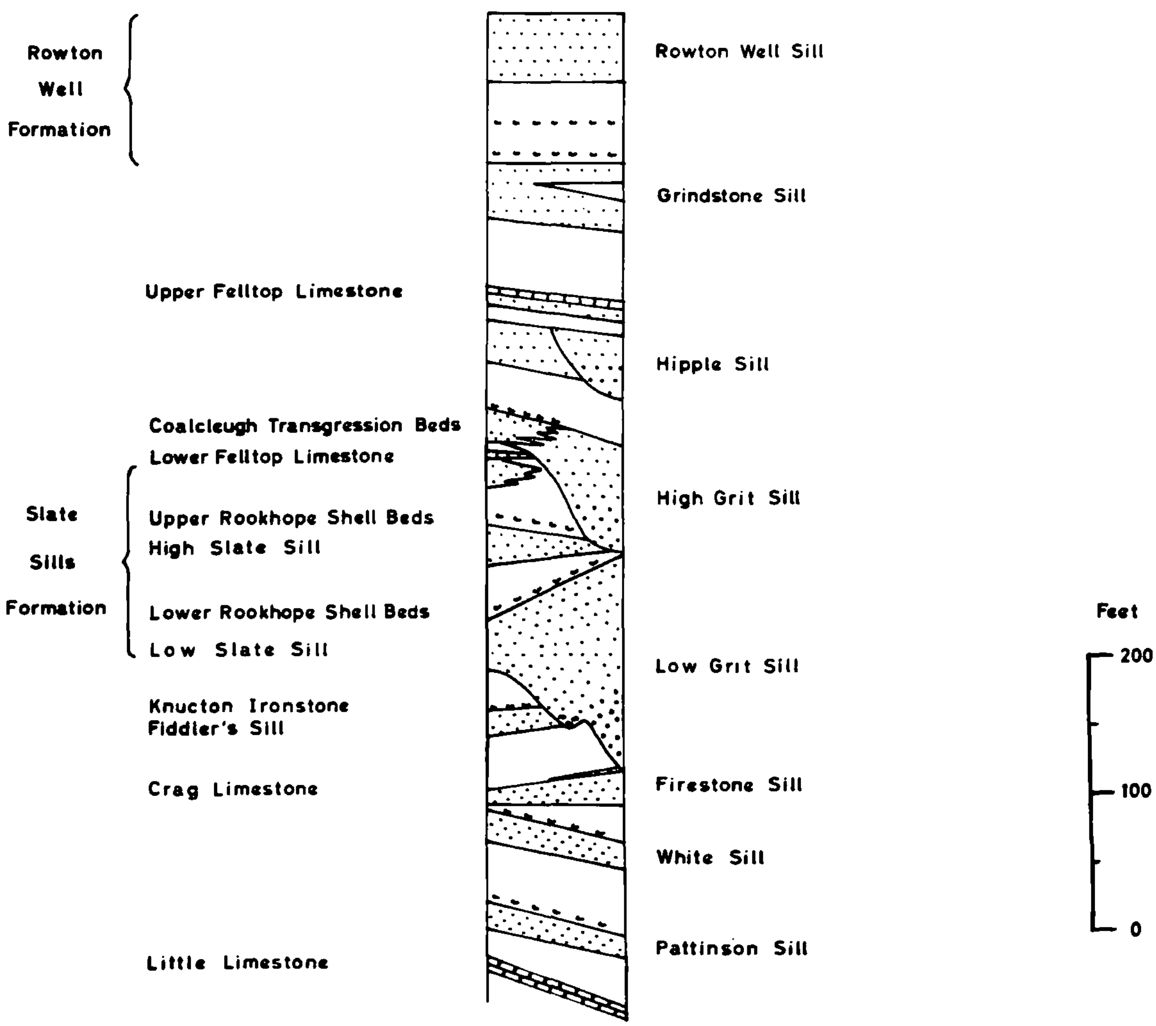
are covered by thick blanket peat, whilst boulder clay coats the lower parts of the valley sides; alluvial deposits occupy the recent flood plains of all the rivers and streams.

Settlement is generally restricted to the larger dales and very few villages occur actually on the area, although nearby Weardale is relatively well-populated. The bulk of the population is situated around the old lead mining centres, some of which still actively produce fluorspar. Dairy-farming is a common pursuit in the larger dales such as East Allendale and Weardale, whilst sheep-farming forms the main livelihood of the scattered hill farms. Most of the district, except for the headwaters of the River Derwent is well-served by roads.

The Carboniferous rocks of the northern Pennines were laid down on a surface of varying relief comprising Skiddaw Slates (Johnson, 1961) and the "Weardale granite" (Dunham et al., 1961) of Middle or late Devonian age (Dodson and Moorbath, 1961). The whole of the Carboniferous succession appears to represent a gradual transition from a marine environment, represented by the Lower Limestone Group, to a terrestrial/fresh water environment represented by the Coal Measures. Information on the Lower and Middle Limestone Groups may be found in Dunham (1948), Rayner (1953), George (1958), to name but a few, and on the Coal Measures see Trueman (1953), Magraw et al. (1963). The stratigraphy of

Figure 1.2

SCHEMATIC SECTION OF THE STRATA BETWEEN THE LITTLE LIMESTONE AND THE ROWTON WELL SILL OF THE TYNE-WEAR WATERSHED



the Upper Limestone Group in the research area is summarised in Figure 1.2.

The area represents a small part of the Alston Block, which was a relatively stable area throughout Carboniferous times. The Block is bounded on the north and south by the relatively rapidly subsiding Northumberland Trough and the Cotherstone Syncline respectively. Recent work by Mr. C. R. Rowley (personal communication, 1964) has revealed no western limit to the "Block facies" of the Carboniferous strata, but in practice, the Pennine Fault System is regarded as the western limit to the Alston Block: the eastern margin may occur some 15 miles off the Durham coast (Bott, 1961, p. 11).

Knowledge of the structure of the Alston Block is mainly due to Dunham (1948, 1958) who demonstrated the half-dome nature of the Carboniferous rocks (1948, Plate I, p. 65). Faulting has a dominant trend of NW-SE, with subordinate modes in an E-W and an ENE-WSW direction (ibid., p. 66); many of the faults are mineralised. The N-S trending monocline known as the Burtreeford Disturbance crosses the area, and on Burtree Fell produces dips up to 30 degrees. The monocline produces a displacement of some 200 feet, down to the east, but in the north, an associated fault produces a final displacement to the west (Dunham, 1948, p. 65).

II Aims of the research

The Upper Limestone Group of the Carboniferous System on the Alston Block is a complex series of sandstones, shales, limestones, and ironstones of Lower Namurian (Eumorphoceras) age, which is subject to rapid lateral variations in facies. The presence of erosive washouts aggravate the problem of correlation, which is further hampered by the often poorly exposed and faulted nature of the research area. Previous workers have suggested correlations which often prove to be of doubtful accuracy, and the stratigraphy of the Upper Limestone Group is consequently poorly known. The present writer believes that a rational stratigraphy of such a series is best obtained by application of sedimentological as well as palaeontological criteria. It is considered unreasonable to propose correlations of the various members of the Group without attempting to reconstruct the nature of their depositional environment; unlikely correlations could easily result. Thus, in attempting to deduce in detail the environments represented by the rocks, the stratigraphy of the strata becomes a necessary corollary. Furthermore, although many authors refer to the "Yoredale delta" and the "Yoredale environment", little systematic sedimentological research has been attempted on this problem. Analogies with the Mississippi delta are all too easy to make, in view of the wealth of information obtained from the many studies of it, but the writer believes that the importance of this "bird-foot delta" has been over-exaggerated in the past. The present study of Upper Limestone Group sediments represents only a small fraction of what could be done, but it is hoped that the conclusions and hypotheses presented will stimulate further work into this interesting subject.

III Previous research

Many of the names of rock units within the Carboniferous of the Alston Block are the result of the classic work of Westgarth Forster, who published the first edition of his "Treatise" in 1809, and a second edition in 1821. Additional data were later supplied by T. Sopwith (1833), Wallace (1861), and Lebour (1886). The work of Wallace is outstanding for this period. His correlation of the beds above the Great Limestone in Northumberland (the present-day Upper Limestone Group), with the Millstone Grit of Derbyshire, shows great geological perception. The Geoligical Survey produced a series of Vertical Sections through many of the mine shafts in the Alston district in the years 1877 to 1878 (V. S. Sheets 62, 63, 66), and in 1883 published the One-inch map of the area (Alston, Sheet 102, N.E.). Within the present research area they mapped two limestones above the Great Limestone, the Little and the Upper Felltop, and locally indicated a third, the Lower Felltop Limestone. The Firestone and Grindstone Sills were the only sandstone horizons mapped in the Upper Limestone Group, and, unfortunately, no accompanying Memoir was published.

An intensification in the study of problems in the Carboniferous in general, and the Namurian in particular, did not really take place until the latter half of the

Twentieth Century. Most of the work up to this period was done by the Geological Survey. Trotter and Hollingworth produced a Memoir on the Brampton District (Sheet 18) in 1932, in which they suggest correlations across the Alston Block. Many of these, however, have subsequently been revised. Carruthers classic "Adventure in Stratigraphy" (1938) covered a considerable thickness of the Upper Limestone Group over a vast area. In view of the short time in which this was accomplished and the lack of detailed mapping, it is almost inevitable that errors in correlation should appear. Carruthers did, however, introduce several new names, and brought out the essentially variable and often erosive nature of the deposits. Dunham's all-embracing reconnaissance of the Northern Pennine Orefield (1948) is a masterly compilation and condensation of data. Part of it was discussed with special reference to cyclic sedimentation at the 1948 International Geological Congress (Dunham, 1950), and Dunham's revision of the Alston Sheet (25) is due to be published in the near future (G. S. Summ. Prog., 1961). Trotter in 1952, produced a very interesting review of the Namurian in the north of England, concentrating to a large extent on sedimentation facies and the distribution of the several Stages. Modification of some of his correlations seems justified in the light of subsequent work.

Rayner's review of the Lower Carboniferous in

Northern England (1953) was quickly followed by a series of doctoral studies on the strata of the Alston Block and adjacent areas. Two exist only in thesis form; Green (1954) attempted to correlate Namurian strata from the Block to the Northumberland Trough, and Jones (1956) studied the Namurian in an area to the south, between Middleton-in-Teesdale and Woodland, Co. Durham. An important contribution was published by Reading (1957) who established a correlation between the Alston and Askrigg Blocks, much of which is still accepted. The chert facies associated with the Main, Little, and Crow Limestones has been adequately covered by Wells (1955) and Hey (1956). The Geological Survey brought out a new provisional edition of the Hexham One-inch Sheet (19) in 1956, but the map is considerably modified by the writer in Beldon Burn. Invaluable work on the Askrigg Block, which has application to the writer's researches on the Alston Block has been presented by Rowell and Scanlon (1957, a,b,), Wilson and Thompson (1959), and Wilson (1960 a, b). Since 1960 the Geological Survey has been revising the Cotherstone district on the Brough and Barnard Castle Sheets (31, 32), but so far no details have been published. Rather more directly concerned with the author's area of research is the work of Dunham and Johnson (1962) on boreholes near Allenheads, Northumberland, and Johnson et al (1962) on the base of the Namurian and "Millstone Grit". A useful account of the Upper Limestone Group in the vicinity of Cross Fell, Westmorland, is included in the Memoir on the Moor House Nature Reserve (Johnson and Dunham, 1963).

IV The use of the term "cyclothem" in stratigraphy

The considerable variation of rock types in the Upper Limestone Group renders a unique definition of a cyclothem within this series impossible. A cyclothem is essentially a sedimentological concept, and as such should have a sedimentological basis; it can be used as a time unit only with great discretion. In the Middle Limestone Group, a cyclothem is generally defined as the suite of rocks between the base of one major limestone and the base of the succeeding major limestone. This boundary is chosen because it marks the position of the greatest sedimentological break, namely, between terrestrial coal swamp conditions and fully marine limestone conditions. In the Upper Limestone Group, however, the sedimentological environment has undergone some changes, and the Middle Limestone Group type of cyclothem is not always observable. Thus, a re-assessment of the status of the term "cyclothem" appears to be desirable.

The following criteria are used in the writer's definition of a cyclothem in the Upper Limestone Group:-

1) the boundaries should be at the horizon of greatest change of sedimentological environment

2) the included sediments should generally coarsen upwards, although erosive channel sediments which fine upwards may also be common.

This definition does not invalidate any Middle Limestone Group cyclothem or any other, in which a coal/marine bed junction is used as a boundary, but the problem is complicated in the many Upper Limestone Group cyclothems which are wholly marine or quasi-marine; this particularly affects those cyclothems which culminate in a shell bed.

The principal shell beds in the Upper Limestone Group strata studied are the Pattinson Band, the White Band, and the Knucton Shell Beds. The Rookhope Shell Beds are, in general, too variable to be included here, and are regarded as part of a new stratigraphical unit, the Slate Sills Formation. Although the shell beds in the Upper Limestone Group are often regarded as the analogues of the limestones in the Middle Limestone Group it is impracticable to use the base of the shell bed sequence as the boundary of a cyclothem. The reasons for this are:-

1) the underlying sandstone often contains thin shell beds or scattered shells, and there is no sharply defined beginning to marine-fossiliferous conditions

2) the lowermost shell beds occur at different positions in different areas, and are not correlatable
3) it is demonstrable (p. 195) that the non-erosive sandstones and shell beds belong to intimately associated facies, and there is no sedimentological break between them.

It is noteworthy that all the major shell beds culminate in an ironstone, either a sideritic ironstone or a sideritic chamosite oolite; this is believed to represent a shallow water coastal lagoon environment (p. 214). As the ironstone is usually followed by black marine shale of deeper open water origin (p. 187), then the junction between the ironstone and the shale represents the greatest sedimentological change, and should mark the boundary of a cyclothem of this type, according to the writer's definition.

Another factor which must be introduced here is that of "historical precedence". It is accepted as standard that a cyclothem in the Carboniferous is named by the prominant marine member occurring at its base. A cyclothem of the type envisaged would have this marine bed at the top, and nomenclature problems are immediately introduced. Furthermore, naming of some cyclothems in the Upper Limestone Group has already taken place (Dunham and Johnson, 1962, p. 250), and to propose a further nomenclature would result in great confusion. In order to maintain some degree of uniformity in terminology, it is proposed that in a shell bed sequence the ironstone forming the uppermost bed be regarded as the basal member of the succeeding cyclothem, despite the fact that the sedimentological boundaries of the cyclothem would be slightly different. At best this is rather unsatisfactory, but, short of an ex cathedra proclamation, there is no immediate alternative.

CHAPTER 2

LITTLE LIMESTONE CYCLOTHEM

This cyclothem comprises strata between the base of the Little Limestone and the top of the Pattinson Sill (Fig. 2.1). It has been suggested by Dunham (1948, p.31) that the Pattinson Sill is not a unique horizon, but a series of lenticular sandstones. If this is so then the Pattinson Sill is not a good horizon upon which to base a stratigraphical unit. However, it cannot be proved absent over any of the area mapped, and, in view of this, and its apparently uniform lithology, it is concluded that the Pattinson Sill may legitimately be employed in this way. Considerable confusion has existed in the past concerning the correlation and nomenclature of this sandstone. Forster (1821, p.100) first recorded it as a 12 foot hazle (fine grained sandstone) occurring 18 feet above the Little Limestone. Wallace (1861, plate I, p.17) continued to use the term in the originally defined sense, but the Geological Survey, in publishing their Vertical Sections (Sheets 62 and 63, 1877, 1878) did not adopt a standard procedure. In the Allenheads Mine Section (V.S. Sheet 62) the sequence Little Limestone, Pattinson Sill, White Sill is recorded (Fig. 2.2). But in the Derwent Mine, Taylor's Shaft (V.S. Sheet 63) the White Sill is recorded between the Little Limestone and the Pattinson Sill. The general practice of the Primary Surveyors is, therefore, that the first <u>major</u> sandstone above the Little Limestone is termed the Pattinson Sill.

Figure 2.1A

LEGEND USED IN MEASURED SECTIONS

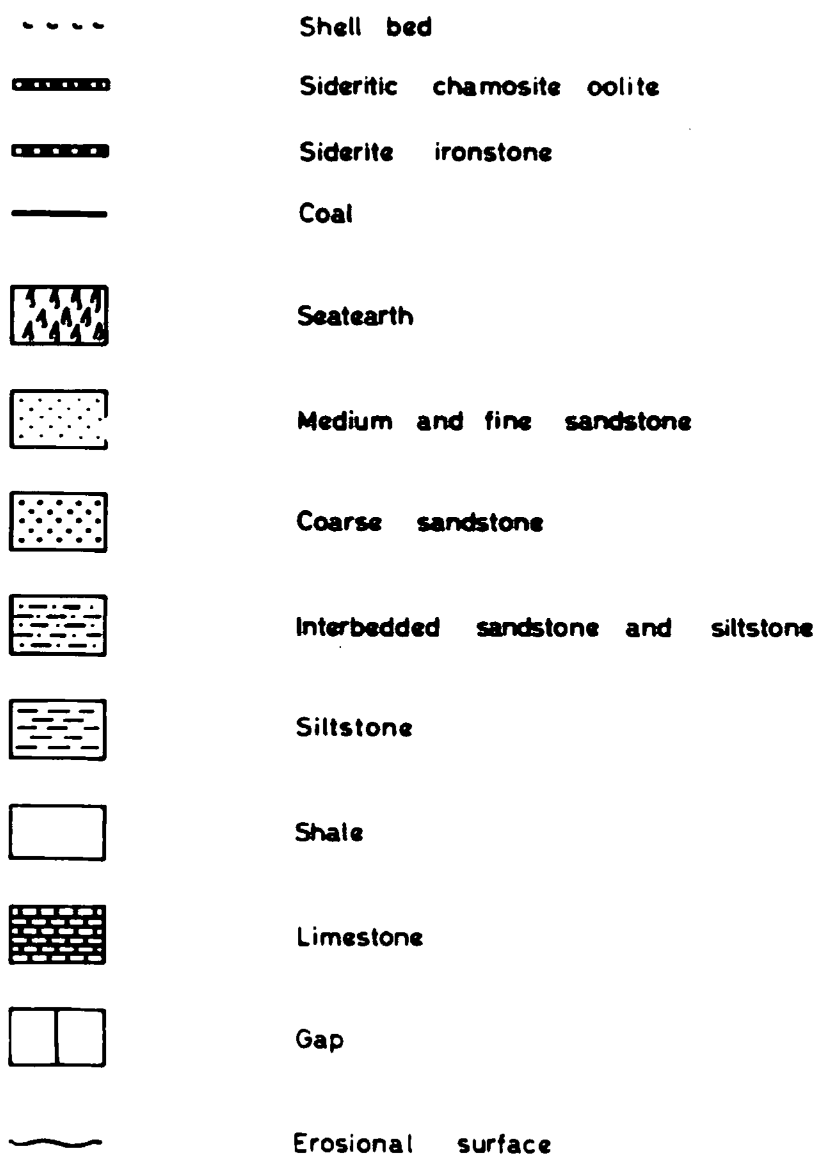


Figure 2.1

MEASURED SECTIONS IN THE LITTLE LIMESTONE CYCLOTHEM

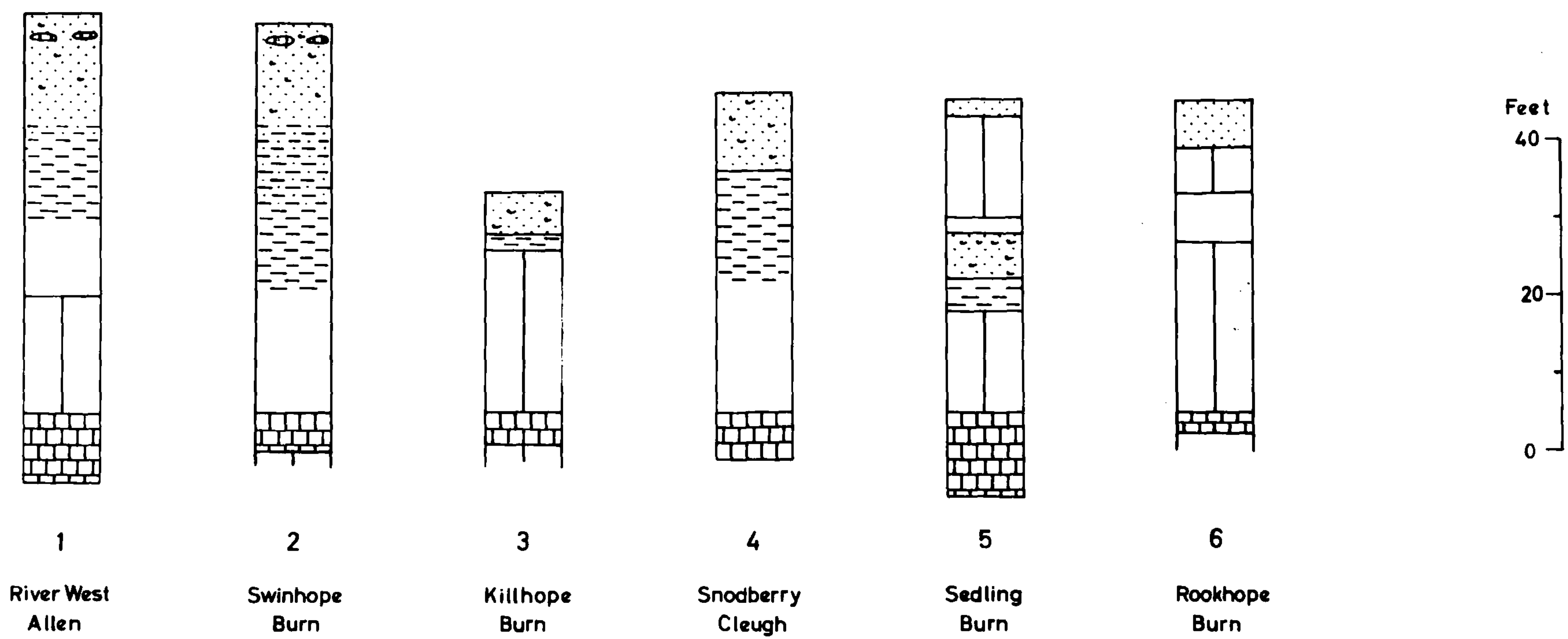


PLATE 1. Little Limestone in River West Allen.

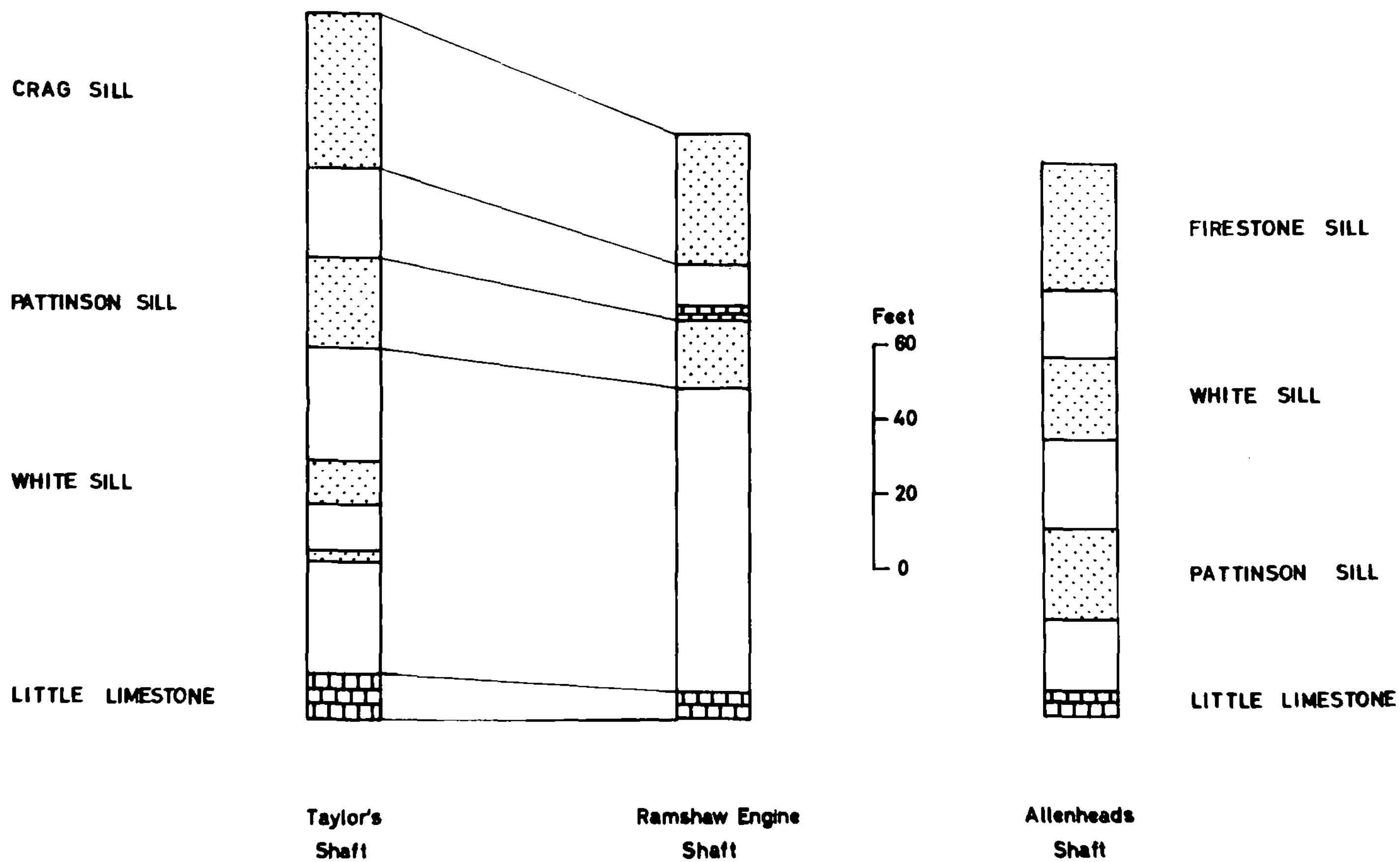
PLATE 2. Snodberry Cleugh, showing sequence from Little Limestone to Pattinson Sill.

They were undoubtedly influenced in their decision by the apparent disappearance of their "White Sill" of Taylor's Shaft in nearby Ramshaw Engine Shaft (Fig.2.2). This question is further discussed on page 22.

Little Limestone. The Little Limestone was first named by Forster in 1809 and has subsequently been widely recognised by other geologists because of its proximity to the easily mapped Great Limestone. It may sometimes be referred to as the Upper Little Limestone to distinguish it from a limestone in the Middle Limestone Group known as "The Lower Little". The Little Limestone is not exposed in the north-east of the area because the regional dip in this direction carries it below the surface. However, it has been recorded in mine shafts around Ramshaw and Blanchland. The best exposures occur at Coalcleugh in West Allendale (Plate 1) and in the several tributaries of Killhope Burn (Plate 2). In Weardale east of Sedling Burn evidence of its persistence is gained only by the presence of loose blocks of limestone, although better exposures are found in Rookhope Burn. Complete sections through the Little Limestone are not common, but the greatest measured thickness is 13 feet in Sedling Burn, and the least is 6 feet from Snodberry Cleugh. Similar thicknesses have been recorded by the Geological Survey in mine shafts throughout the area. Dunham quotes the average thickness as less than 10 feet (1948, p.31). The Little Limestone can apparently undergo quite rapid changes in thickness. In the Derwent Mine Shafts (V.S. Sheet 63) it decreases from 11 feet (Jeffrey's Shaft) to 7 feet (Ramshaw Engine Shaft) within just over half a mile.

Figure 2.2

INCONSISTENCIES IN NOMENCLATURE AS QUOTED BY THE GEOLOGICAL SURVEY IN THE LATE 19TH CENTURY



The Little Limestone is dark grey in colour and highly crinoidal, with only small amounts of fine-grained calcite matrix. Macrofossils are not abundant but the following have been recorded during the survey:-

Chaetetes sp.

Lonsdaleia floriformis (Martin)

Zaphrentid

"*caudagalli*"

Chonetes sp.

Gasteropods indet.

Dunham and Johnson (1962, p.243) obtained a more comprehensive fauna from a number of highly fossiliferous bands in borings near Allenheads.

The Little Limestone contains a puzzling structure which is believed to have a primary sedimentological origin, but whose precise genesis is uncertain. The structure is composed of light grey, coarsely crystalline dolomite ~~(?)~~ whose shape is subject to considerable variation but is generally saucer-shaped (see p. 175 and Fig. A.1). It has been found widely over the western part of the area, and the fact that it is restricted to the Little Limestone strongly suggests a primary origin.

Fine Clastics. The Pattinson Sill sandstone is separated from the Little Limestone by a varying thickness of shale and siltstone with occasional thin beds of sandstone. In the area surveyed the thickness of this unit only varies between 30 and 40 feet. According to the Geological Survey (V.S. Sheets 62, 63), the supposed equivalents of the Pattinson Sill may occur 8 to 55 feet above the Little Limestone.

The shale above the Little Limestone is black or dark grey and slightly micaceous. It contains a fauna of lamellibranchs, crinoids, ostracods, and, occasionally, Orbiculoidea nitida and Lingula sp. The shale often contains siderite concretions, and in Swinhope Burn it has small weathered pyritic segregations. This occurs at the locality at which Cravenoceras aff. malhamense, indicative of the E_1 zone, was found by Hodge and Johnson (see Johnson, Hodge and Fairbairn, 1962). The stratigraphical significance of this discovery is discussed elsewhere (p. 97).

In Sedling Burn, a thin calcareous sandstone, $3\frac{1}{2}$ feet thick, occurring only 17 feet above the Little Limestone, should not be confused with the Pattinson Sill, which can be seen a further 15 feet above. The dark grey shales below the minor sandstone contain abundant Chonetes hardrensis group as well as Productus concinnus and occasional nuculid lamellibranchs. The top 12 inches of this shale show a rapid transition into the dark grey fine grained sandstone. It has a local calcite cement forming large concretionary structures, and siderite may also be locally abundant. The shale contains a predominantly brachiopod fauna which includes Camarotoechia pleurodon (very common), Productus concinnus, ?Phricodothyris sp., Athyrids indet., and occasional indeterminate lamellibranchs.

The top of this sandstone contains worm burrows in association with an increased siderite content. This bed has not been detected in any other part of the area.

The shale above the Little Limestone invariably becomes silty and more micaceous as the base of the Pattinson Sill is approached. In some cases, as in Swinhope Burn and West Allendale there is a complete passage from shale to medium-grained sandstone. Here, the massive Pattinson Sill has up to 15 feet of fine-grained, very micaceous, highly fissile sandstone below. In other localities (Rookhope Burn, Snodberry Cleugh) there is a relatively abrupt contact, with the medium-grained sandstone resting on dark-grey micaceous siltstone.

Pattinson Sill. The Pattinson Sill is typically a medium-grained sandstone with scattered crinoid columnals and shell fragments. It is massive weathering, and, because of the absence of argillaceous and micaceous material, has no evidence of any kind of bedding. Various worm-burrows, some of them U-shaped, are often common and contain a concentration of fine-grained detritus. In western exposures there is invariably a band of calcareous concretions up to 3 feet thick occurring a few feet below the top of the sandstone. This is not associated with a noticeable increase in the fossil content, and the possible significance of this nodular horizon is discussed elsewhere (p.195). Ganister is not developed at the top of the Pattinson Sill, but it may be considerably reworked by burrowing organisms in places. Common fossils in the Pattinson Sill include:-

"caudagalli"

Camarotoechia pleurodon (Phillips)

Productus concinnus J. Sowerby

Schellwienella rotundata I. Thomas

Spirifer bisulcatus J. de C. Sowerby group

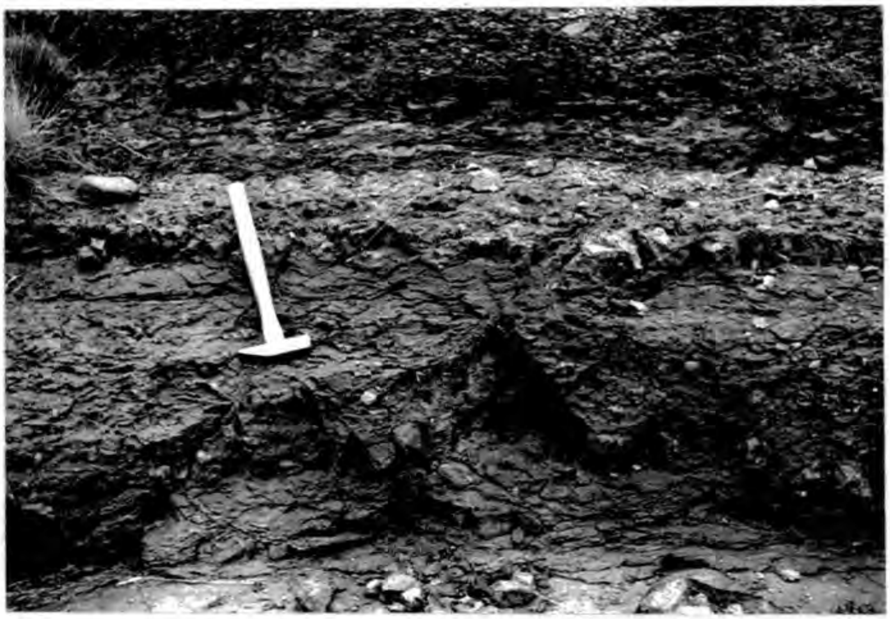


PLATE 3. Rubbly weathering of sideritic Pattinson Marine Band, Shieldrigg Burn.

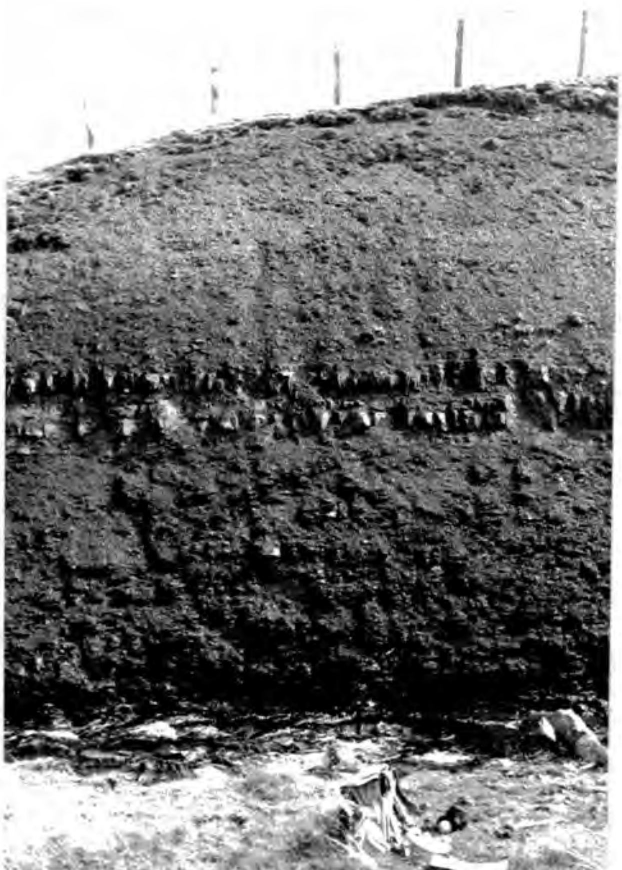


PLATE 4. Pattinson Marine Band ocurring 5 feet above the Pattinson Sill, River West Allen.

CHAPTER 3

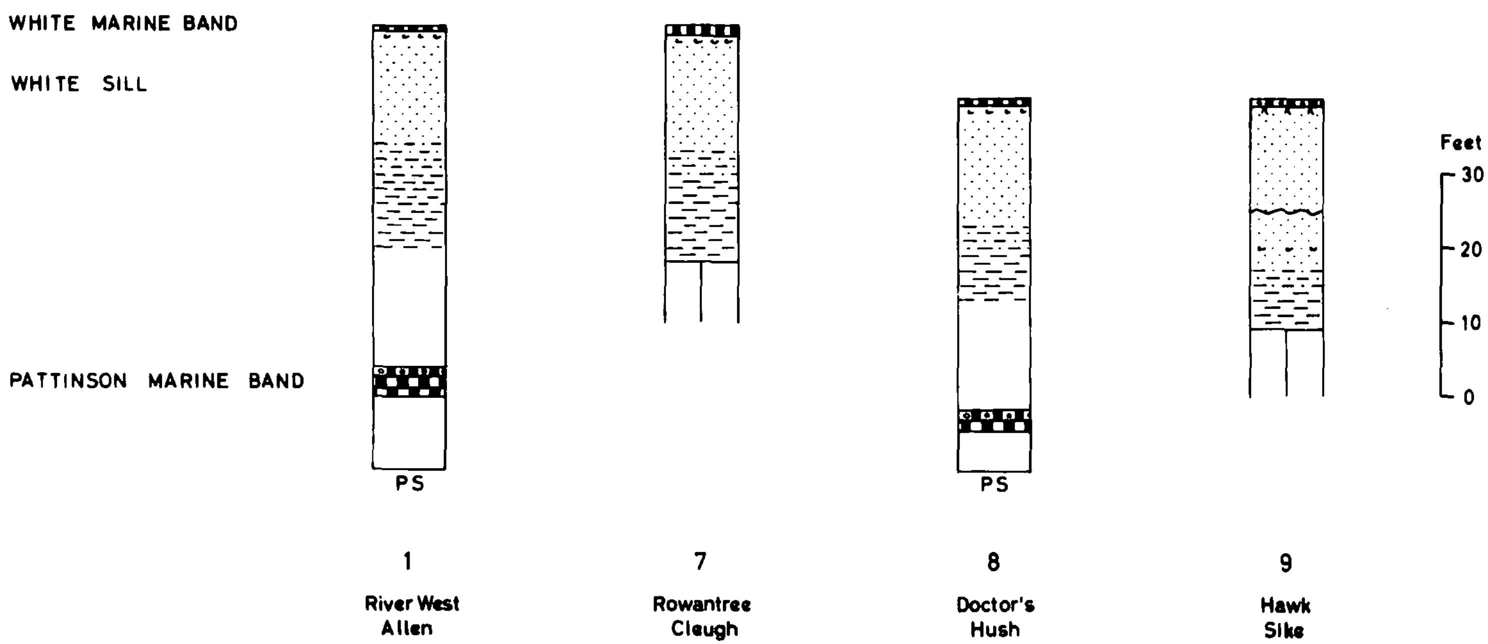
PATTINSON BAND CYCLOTHEM

The sideritic Pattinson Marine Band is taken as the base of this cyclothem (p. 13) and the White Sill forms the sandstone unit at the top (Fig.3.1). The Pattinson Band Cyclothem is not exposed anywhere in the north-east part of the area except for a small inlier at Coal Crag in Nookton Burn, where the top of the White Sill is seen. The fact that the Pattinson Marine Band is unrecorded in mine sections in the Hunstanworth district renders it almost impossible to recognise this cyclothem here. The best exposures occur in Rookhope Burn and around Coalcleugh. A number of complete sections through the Pattinson Band Cyclothem have been measured in the area and the full thickness ranges between 55 and 70 feet. The two lowest values recorded are 42 feet at Killhopehead and 45 feet in Taylor's Shaft.

Pattinson Marine Band. The Pattinson Marine Band was first recognised by Trotter and Hollingworth (1927) in the Brampton area. Whether this horizon is persistent over the whole of the Alston Block has never been ascertained, but in the area studied it has not been recognised to the east of the Burtreeford Disturbance. In Swinhope Burn and West Allendale the Pattinson Marine Band is a black, medium to fine grained sandstone with a siderite cement (Plate 3). It contains ooliths believed to be composed of chamosite, thus rendering

Figure 3.1

MEASURED SECTIONS IN THE PATTINSON BAND CYCLOTHEM



it an easily recognisable horizon. The oolitic rock is not more than one foot thick, but the whole marine band may total 4 feet in all. It occurs some 3 to 5 feet above the Pattinson Sill, being separated from it by black shale and thin sandstones colonized by burrowing organisms (Plate 4). The Pattinson Marine Band was noted by Dunham and Johnson (1962, p.244) in the Swinhope borings, where they record a dominantly molluscan fauna. At outcrop the author found mostly brachiopods, including:-

Buxtonia scrabricula (Martin)
Camarotoechia pleurodon (Phillips)
Productids
Schellwienella rotundata I. Thomas

In Weardale and Rookhope Burn the Pattinson Marine Band is not present. The black shale above the Pattinson Sill contains no sideritic development, but does have a fauna of scattered nuculid and other lamellibranchs.

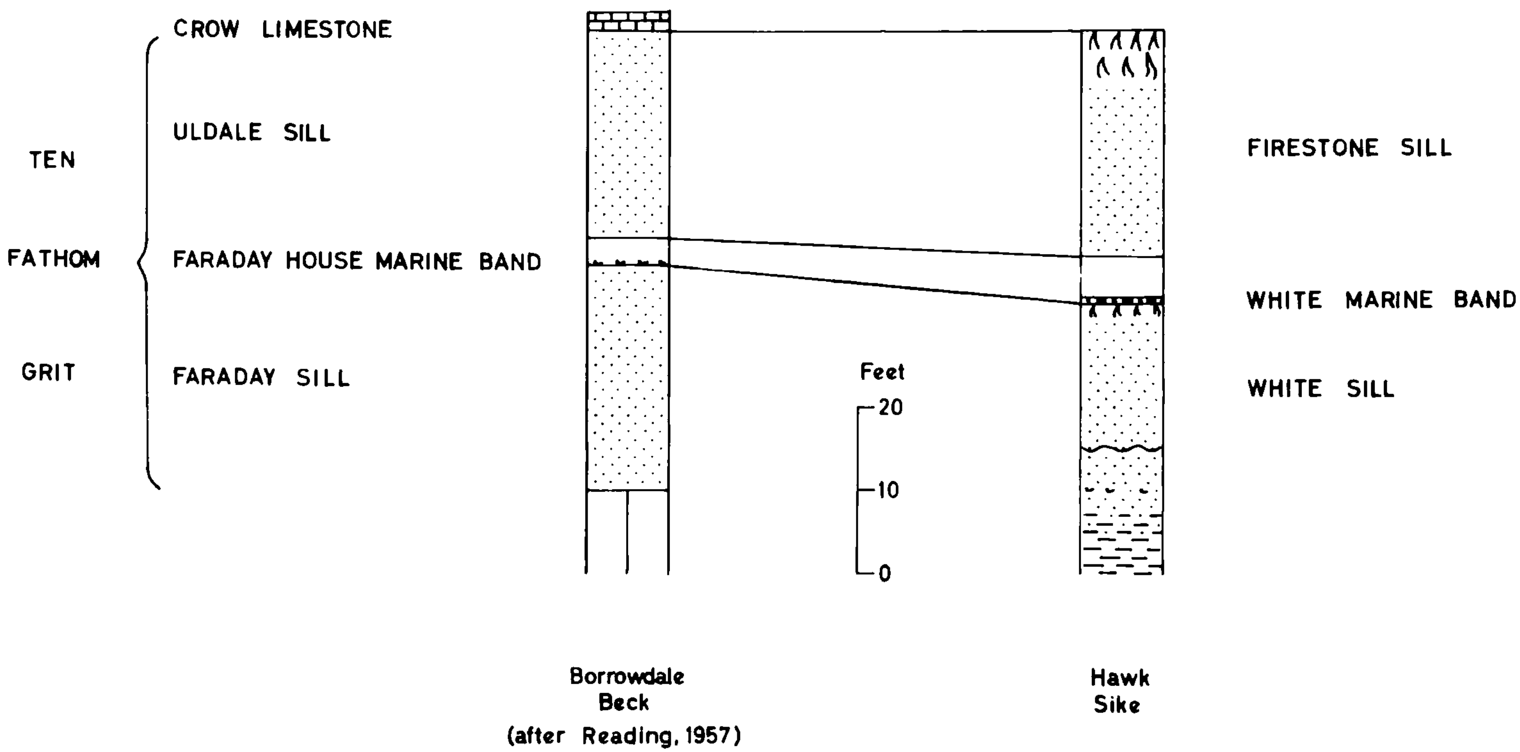
Fine Clastics. At every exposure throughout the area where the White Sill is developed there is a gradual upward passage from black shale, through silty shale with fine grained sandstone intercalations, to the fine grained and medium grained sandstone of the White Sill. There is only one variation, seen in Rookhope Burn, where an additional 5 foot medium grained sandstone containing Eomarginifera lobata, Schellwienella sp., and crinoid columnals, occurs 15 feet above the Pattinson Sill.

White Sill. The type locality of the White Sill is at Shildon, near Blanchland (Whittard and Scott Simpton, 1960 p. 348), but it was first mentioned by Winch in 1817. Little conformity has been adopted by the Geological Survey in their use of the term "White Sill" (p. 14). The confusion undoubtedly has arisen by the use of this term for both stratigraphical and lithological purposes. Stratigraphically it has been defined as a sandstone above the Venture Band of Brampton with the White Marine Band overlying it (Trotter and Hollingworth, 1932, Pl. III, p.69), and as a sandstone 20 to 40 feet above the Pattinson Sill (Dunham, 1948, p.32). On the Geological Survey Vertical Section Sheets 62 and 63, around which most of the controversy has centred, it appears that the term "White Sill" is used more with a lithological than a stratigraphical connotation. This is borne out by the use of this expression twice in the same shaft section for sandstones 200 feet apart. To use the term "White Sill" in a stratigraphical sense it is necessary to modify the Geological Survey nomenclature. In the Derwent, Shildon and Beldon mine sections (V.S. Sheets 63, 62), the sandstone denoted "Pattinson Sill" is now considered to be the equivalent of the White Sill elsewhere on the Alston Block. This is in agreement with the terminology suggested by Dunham (1948, p.31). The White Sill is believed to correlate with the lower leaf of the Ten Fathom Grit (i.e. the Faraday House Sill) of the Cotherstone area (Fig.3.2).

In the area north of Killhope Law the White Sill is 15 feet thick and comprises a medium to fine grained, fissile

Figure 3.2

SUGGESTED EQUIVALENTS OF THE TEN FATHOM GRIT OF COTHERSTONE ON THE ALSTON BLOCK



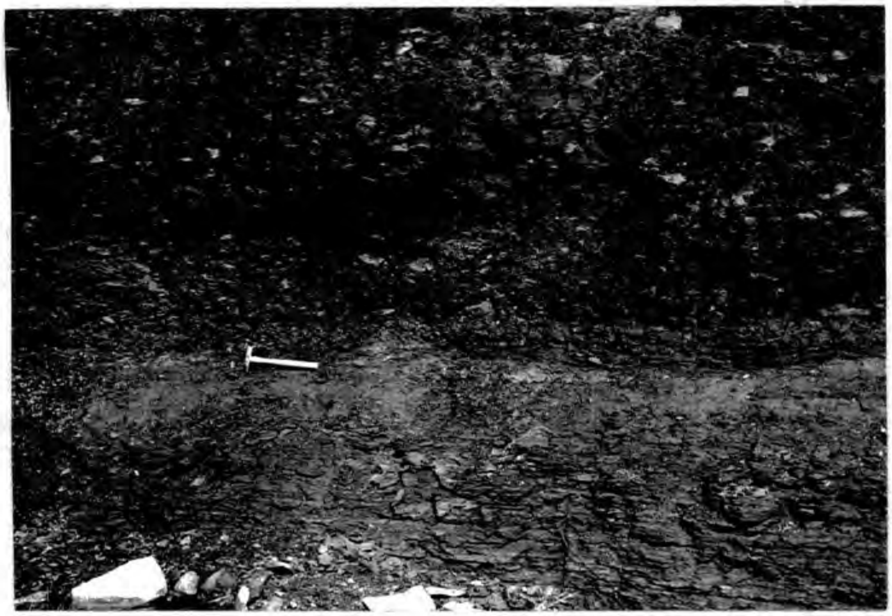


PLATE 5. Top of Pattinson Band Cyclothem, Killhopehead. Hammer at position of White Marine Band.

PLATE 6. Firestone Sill, Killhopehead, showing transitional base.

sandstone with ripple lamination. It may contain some silty bands up to one foot thick and finely comminuted carbonaceous material is common. Dunham and Johnson (1962, p.245) record ganister at the top of the White Sill in the nearby boreholes, but it has not been recorded at outcrop in this vicinity; a poorly defined seatearth does occur in Rookhope Burn.

It is interesting to record that the White Sill is scarcely developed in the northern tributaries of Killhope Burn. Only in one un-named sike are 4 feet of fine grained, fissile sandstone developed at the White Sill horizon. In Betty's Cleugh to the east of this locality, and at Killhopehead Bridge to the west, the White Sill is apparently represented by a few feet of dark grey, micaceous silty shale with occasional plant remains. It is identified as such by the overlying 3 inch ironstone band which contains brachiopods at Killhopehead Bridge, and by the fact that it is followed by a black shale with subconchoidal fracture (Plate 5). Although a rather subtle change in lithology this is considered to be important.

The White Sill is also found to have undergone a slight change in character when it is seen in Rookhope Burn. Here it is a medium grained micaceous sandstone with irregular bedding. It still has a transitional base where it contains vertical worm burrows and poorly preserved brachiopods, including:-

?Athyrids

Buxtonia sp.

Schellwienella rotundata I. Thomas

The upper part of the White Sill may also have large scale cross-stratification.

CHAPTER 4

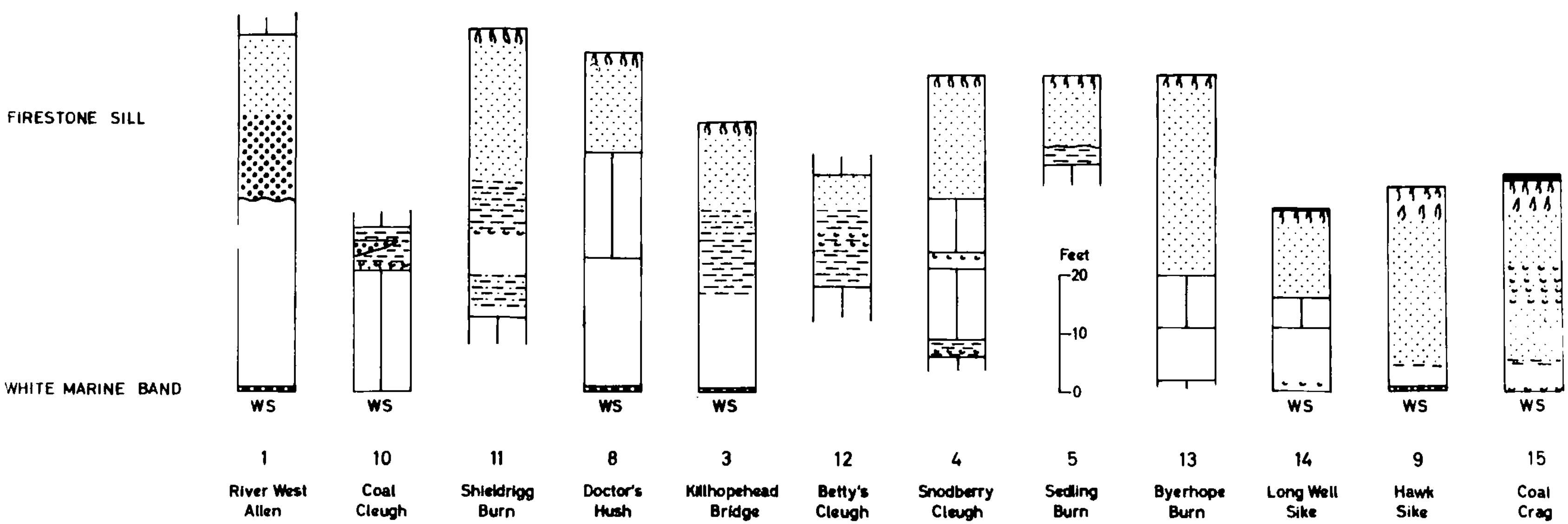
WHITE BAND CYCLOTHEM

The ferruginous marine band immediately overlying the White Sill gives its name to this cyclothem. The White Band has been widely observed at outcrop in the southern and western parts of the area. Around Hunstanworth in the north-east it is recorded as a limestone in the many shaft sections. The Firestone Sill occurs at the top of the White Band Cyclothem. Complete exposures throughout this cyclothem are common in West Allendale, Killhope and Rookhope, but it is not fully known in other districts. The total thickness of the cyclothem varies somewhat over the area, but invariably lies between 30 and 60 feet (Fig.4.1). A more striking variation, however, takes place in the proportion of shale and sandstone in the cyclothem. In Rookhope Burn and the shaft sections in upper Bolt's Burn, shale represents as little as 15 to 20% of the whole thickness, although this increases to 50% to the north-east in Shildon Mine. This contrasts markedly with the White Band Cyclothem around Killhope Law, where shale is responsible for 50 to 75% of this unit.

White Band. The White Band in the type locality near Brampton has been described by Trotter and Hollingworth (1932) as a thin, calcareous sandstone overlying the White Sill. In the area surveyed the White Band is undoubtedly best developed and best seen west of the Burtreeford Disturbance, where it is represented by a fossiliferous, sideritic ironstone, 9 to 18 inches thick. The siderite occurs as cement to a medium to

Figure 4.1

MEASURED SECTIONS IN THE WHITE BAND CYCLOTHEM



fine grained sandstone and is especially abundant in the uppermost few inches. It often exhibits evidence of having been reworked by burrowing organisms, and includes many fossils, such as Productus concinnus, lamellibranchs, bellerophontids, and bryozoa. The iron-rich character of the White Band is maintained in one of the few good exposures of this horizon in the east of the area, i.e. in Hawk Sike (Rookhope). In other respects it is quite different, however, for it is represented by a 7 inch bed of siltstone which contains scattered quartz grains, with, locally a proliferation of ooliths. The latter are pale, almost white, in colour, but are believed to be composed of chamosite. The White Band here contains Chonetes sp., Camarotoechia pleurodon, productids, lamellibranchs and crinoids. Yet another rock type occurs at Coal Crag in Nookton Burn, where the White Band is a 9 inch calcareous sandstone, containing Camarotoechia pleurodon, Schellwienella sp., and productids. The White Band is here suggested to be the equivalent of the Faraday House Marine Band in the Cotherstone area (Fig.3.2).

Fine Clastics. Throughout the area the White Band is followed by black shale, commonly with siderite nodules. Despite the considerable differences in amount of the fine clastics, the gradual passage through micaceous siltstones to fine and medium grained sandstones is almost ubiquitous. There are two instances, however, where channel erosion has taken place in the Firestone Sill, producing an abrupt contact between the sandstone and the underlying shale. In Coptcleugh Sike, the black siderite shale below the Firestone contains Euphemites urei and small pyritised nuculids. An interesting series of shell beds occurs some 5 feet below the Firestone Sill in Betty's Cleugh (Killhope) (Fig.4.1). There are at least five thin shell beds, all less than 3 inches thick, but which occupy a band 4 feet thick. Several of these have a siderite cement, and may die out laterally within a few feet. The following fossils have been obtained from this horizon:-

Buxtonia scrabricula (Martin)
Camarotoechia pleurodon (Phillips)
Eomarginifera lobata (J. Sowerby)
Orthotetids
Productus concinnus J. Sowerby
Spirifer trigonalis (Martin) group

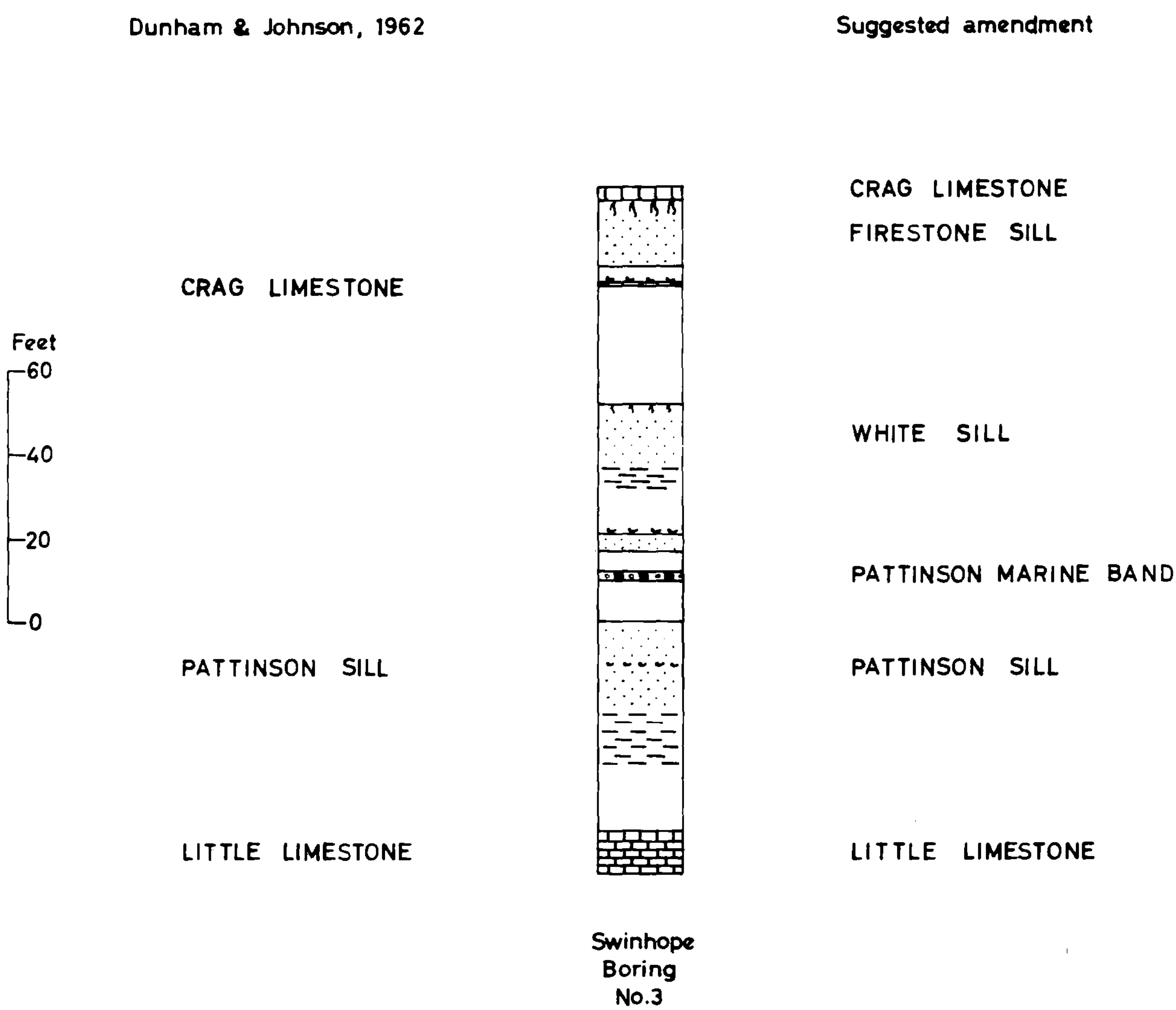
A series of calcareous concretions, up to 2 feet long and 6 inches thick, occur in the black pyritic shales above this band.

Firestone Sill. Forster (1809) provides us with the first published description of the Firestone Sill, whose present day type-area centres around Allenheads and Rookhope. Several authors have shown that the Firestone Sill may die out completely (Dunham, 1948, p.32; Jones, 1956, p.81). On the other hand, Trotter and Hollingworth (1938, p.79) report the Firestone Sill as a "remarkably persistent" horizon in the Brampton district. Similarly, Rowell and Scanlon (1957, p.12) state that the Uldale Sill exists everywhere below the Crow

Limestone in the north-west corner of the Askrigg Block. Dunham and Johnson concluded (1962, p.245) that the Firestone Sill is "poorly developed" in the area to the north of Killhope Law. They based their conclusion on the recognition of the Crag Limestone in the Swinhope borings. However, this interpretation is at variance with data obtained at outcrop during the present survey, for the writer has recognised a thick development of the Firestone Sill in the area around Killhope Law. Since the writings of Westgarth Forster there have been strong indications that the Crag Limestone is not developed as a limestone in the vicinity of Alston Moor. He records only "ironstone and coal" above the Firestone Sill (1821, p. 99). Similarly, on the Geological Survey Vertical Section Sheet 66 (1878) of the Alston District, an "ironstone", which they denote as a ferruginous sandstone, occurs in this position in a number of mine sections. It is doubtful, in fact, whether this ironstone represents the Crag Limestone in this area, because in most cases (except in Dowgang Mine) it underlies a coal. It is more likely to be the equivalent of a highly limonitic ganister seen at outcrop in East Allendale at the top of the Firestone Sill. The Allenheads Mine Section (V.S. Sheet 62) indicates no limestone in the vicinity of the Firestone Sill. Carruthers (1938, p.238) records the "Crag Lime" as a dark shelly sandstone one foot thick lying above the Crag Coal at Coalcleugh. In the Brampton District, Trotter and Hollingworth (1932, p.79) report that the Firestone Band (equivalent to the Crag horizon) is frequently represented by a ferruginous clay. There is one occurrence of a limestone

Figure 4.2

REINTERPRETATION OF THE CRAG LIMESTONE HORIZON IN THE SWINHOPE BOREHOLES

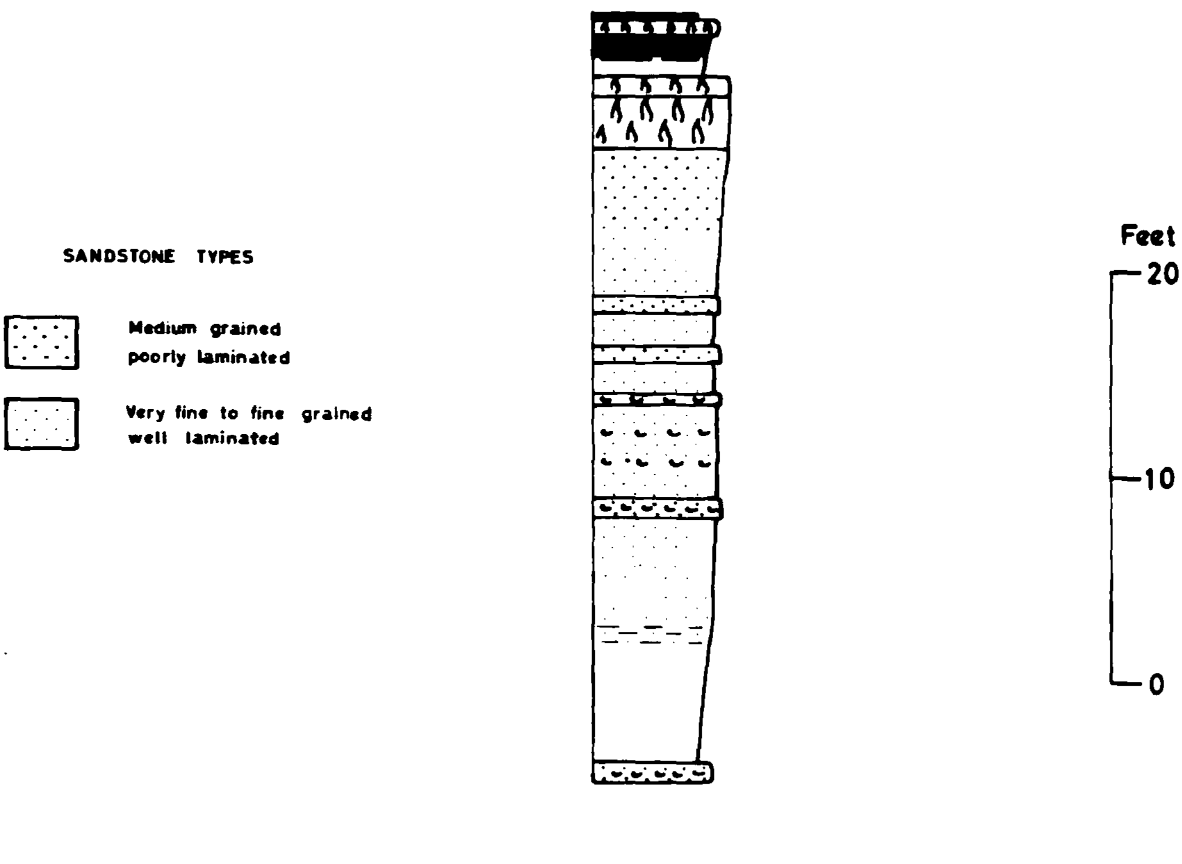


noted at this horizon in Barneycraig Mine, near Carrshield in West Allendale, but, as Dunham points out (1948, p.34), this passes into an ironstone (a ferruginous, limy sandstone with shells) to the south-west. A detailed investigation of the area has failed to reveal the Crag Limestone, and it is concluded that it is not developed as such in the Killhope Law region. Furthermore, it is considered that the beds described by Dunham and Johnson as the Crag Limestone are, in fact, those shell beds which have just been described (p. 27) from Betty's Cleugh, and which occur under the Firestone Sill (Fig. 4.1). This modified correlation (Fig.4.2) makes the previously anomalous sandstone above this marine horizon the Firestone Sill, an interpretation which accords well with information obtained at outcrop.

In the study area the Firestone Sill is present throughout, though subject to changes in lithology; the thickness ranges from 7 to 50 feet. In those parts of the area where the Firestone Sill is transitional with the shales below (Plate 6), the lithology of the sandstone is relatively constant. In Nookton Burn, where it is well-exposed, the Firestone is a medium to fine grained sandstone with abundant white mica and comminuted plant material. It has small scale cross-stratification in association with regular lamination. It may contain silty intercalations up to one foot thick, but eventually the sandstone passes up into a ganister with abundant rootlets (Fig.4.3). At Coal Crag, above the ganister, which is itself 3½ feet thick, there are 3½ feet of shale, coal, and

Figure 4.3

WHITE BAND CYCLOTHEM AT COAL CRAG IN NOOKTON BURN



highly carbonaceous ganister. In Nookton Burn, also, there are four thin shell beds within the Firestone (Fig.4.3), containing the following fossils, frequently in a fragmented condition:-

Camarotoechia pleurodon (Phillips)
Productus griffithianus de Koninck
Schellwienella sp.
Spirifer sp.

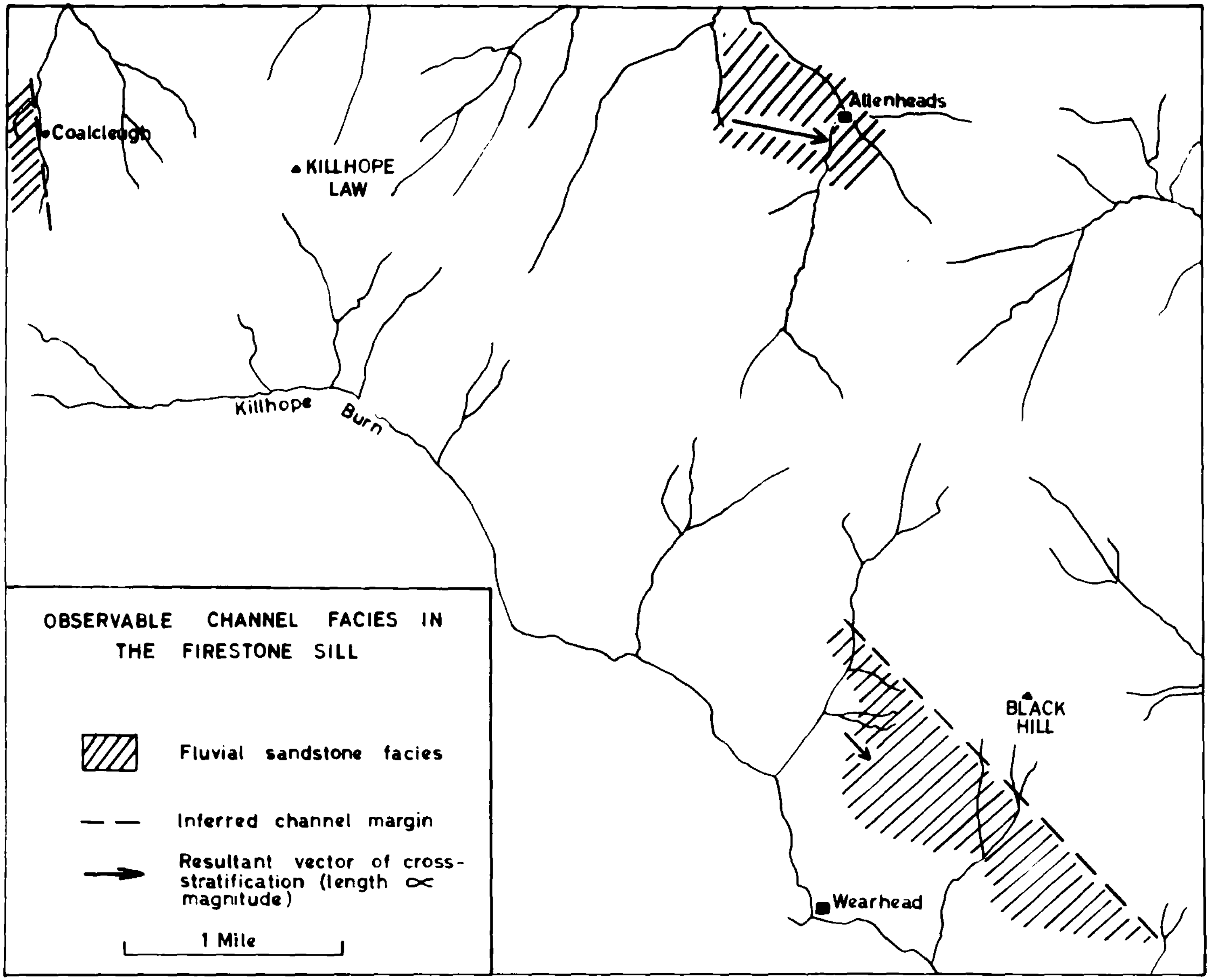
Lamellibranchs

Euphemites sp.

They also contain occasional worm borings and trails.

In Rookhope Burn the Firestone Sill exhibits little change, although it is slightly coarser in grain size, being generally a medium grained sandstone with thin intercalations of coarse sandstone. The ganister on top has been extensively quarried. The quarries and rare natural exposures on the eastern side of Allendale, north of Allenheads, reveal a more massive weathering Firestone Sill. Apart from a probable change in cementation there is no fundamental difference in lithology. The seat earth on top is, characteristically, heavily stained with limonite, and generally contains meandriform rootlets. South of Allenheads the Firestone has undergone a marked change in character. It has become a thick, coarse grained, felspathic sandstone, which eventually becomes medium to fine grained at the top. It is well cross-stratified,

Figure 4.4


Coalcleugh
KILLHOPE LAW
Allenheads
Killhope Burn
BLACK HILL
Wearhead
OBSERVABLE CHANNEL FACIES IN THE FIRESTONE SILL
Fluvial sandstone facies
Inferred channel margin
Resultant vector of cross-stratification (length ∝ magnitude)
1 Mile

and, because it is a fining upwards unit (see p. 242) it is believed to represent a channel facies of the Firestone Sill (Fig.4.4). Further evidence for this is found in Weardale, where a similar coarse, cross-stratified sandstone occurs. This horizon maps round into the Firestone and White Sill members to the east of Elmford Cleugh, where the former is represented by a ripple laminated medium grained sandstone, 7 feet thick. Apparently the channel in the Firestone Sill has cut down through most of the underlying White Sill. Channel erosion is a common feature of the Firestone Sill on the Alston Block (Jones, 1956, p.82; Reading, 1957, p.39). The channel facies is also seen in Sedling Burn, where a medium grained sandstone rests sharply on black shale with an irregular coal locally marking the contact.

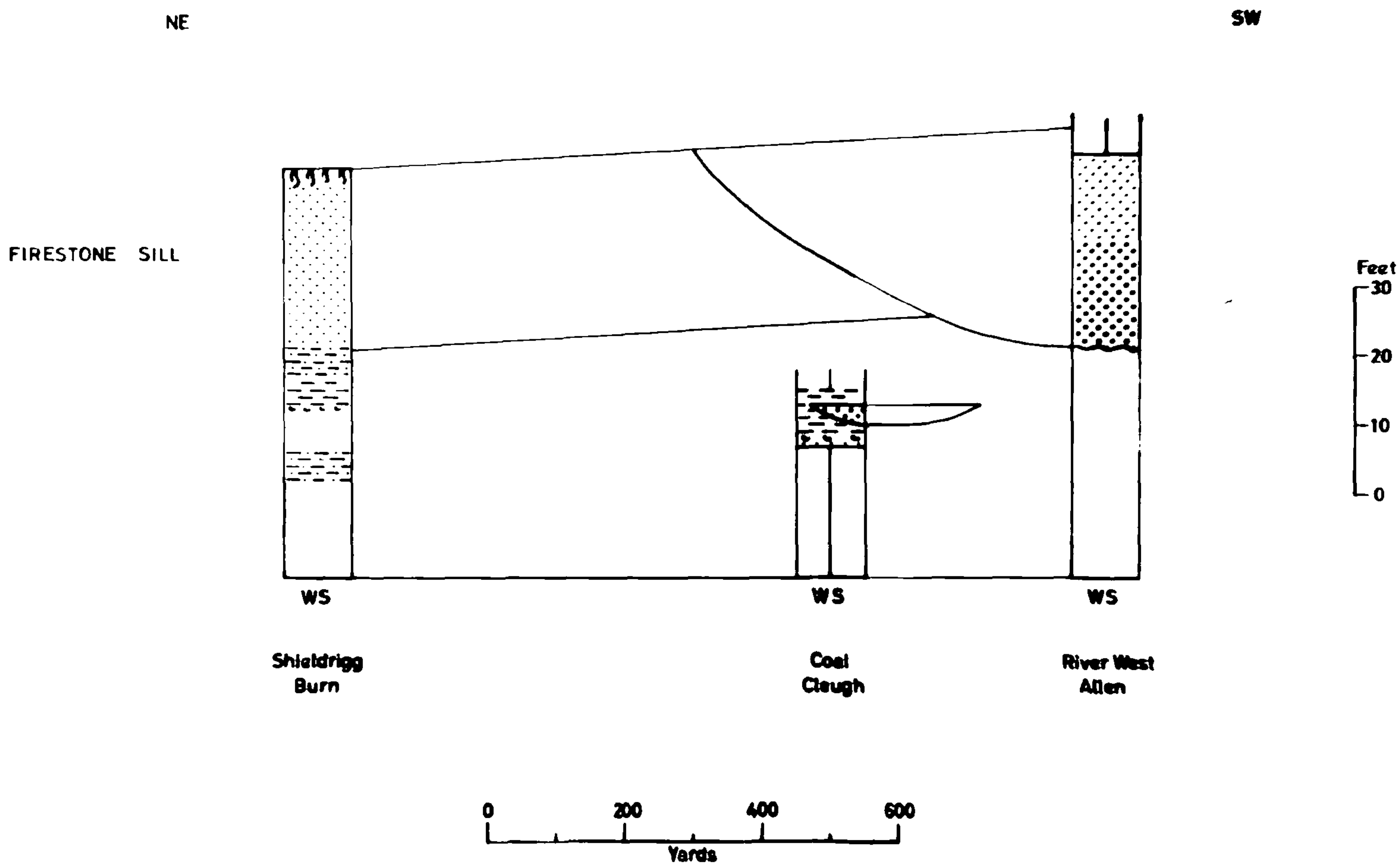
In the Killhope-Swinhope district the Firestone is represented by a medium grained micaceous sandstone with ripple lamination. Inevitably, there is a good ganister forming the top 2 or 3 feet. In the River West Allen at Coalcleugh there is an interesting development of very coarse grained felspathic sandstone, which may locally become a granule conglomerate. It rests sharply on the black shale below, contains mud-flakes near the base, and is obviously erosive. It has very strong cross-stratification throughout its exposed 30 feet, but becomes slightly finer grained, although still a coarse grained sandstone, towards the top. Only three-quarters of a mile to the north-east in Whetstonemea Burn the Firestone Sill has the more typical lithology, and there can be no

PLATE 7. Lenticular, conglomeratic bed within siltstone, White Band Cyclothem, Coalcleugh.

question of a gradual passage between the two types. Clearly, the coarse development marks the position of an erosive channel in the Firestone Sill (Fig.4.5). In Coal Cleugh there is a very interesting lenticular bed, occurring 22 feet above the White Sill, which thins from 2½ feet to zero within 10 feet (Plate 7). It comprises a very coarse grained felspathic sandstone containing mud-flakes and large plant remains. although it is related lithologically to the Firestone development a few hundred yards to the west they cannot be regarded as the same sedimentation unit because of the position of the lens in the stratigraphical sequence (Fig.4.5). It is regarded as a discrete fore-runner of the main channel.

Figure 4.5

INFERRED RELATIONSHIPS BETWEEN ROCK TYPES IN THE WHITE BAND CYCLOTHEM AROUND COALCLEUGH



CHAPTER 5

CRAG LIMESTONE CYCLOTHEM

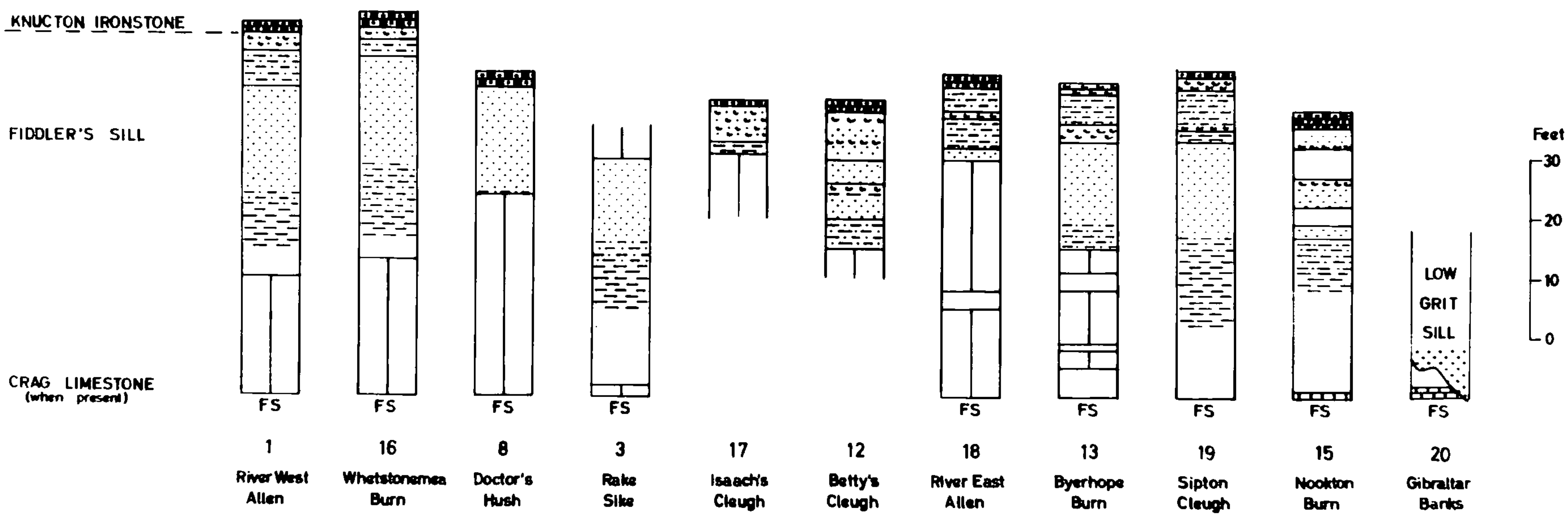
The Crag Limestone is a widely recognised horizon on the Alston Block, though it is not always developed in the area surveyed. It marks the base of the Crag Limestone Cyclothem except where the limestone is absent, when the top of the Firestone Sill is taken as the base. The sandstone at the top of the cyclothem has not previously been given a specific name in the area of study. Although of debatable validity, the name Fiddler's Sill has been applied to it (see p. 36). The topmost shell bed, termed the Knucton Ironstone, is taken as the basal member of the next cyclothem (p. 13).

The Crag Limestone Cyclothem is well-exposed throughout the area, especially in Nookton Burn, Sipton Cleugh, West Allendale, and Killhope Burn. The thinnest section through the cyclothem was 35 feet measured at Isaach's Cleugh, Killhope, and the thickest was 70 feet at Whetstonemea Burn, West Allendale, although 50 to 60 feet is more typical (Fig.5.1). If the thin sandstone above the Firestone seen in Rotherhope and Hagg's Mines (V.S. Sheet 66) is correctly interpreted as the Fiddler's Sill, then thicknesses here average 30 feet. The 116 feet measured to the Fiddler's Sill in Dowgang Shaft must be viewed with suspicion.

Crag Limestone. The Crag Lime is a term first applied by Carruthers (1938, p.238) to a "dark, shelly sandstone" occurring

Figure 5.1

MEASURED SECTIONS IN THE CRAG LIMESTONE CYCLOTHEM



above the Firestone Sill at Coalcleugh. It has subsequently been used to denote a prominent limestone found at this horizon in many parts of the Alston Block, and believed to correlate with the Crow Limestone farther south. Although Coalcleugh is the type locality for the Crag Limestone, as it is now called, it is not really suitable, because it is not exposed at outcrop, and is, in any case, not a true limestone. A better type-locality in the research area would be Nookton Burn, the only district, in fact, where the "Crag Lime" occurs as a limestone. Here it is a dark grey, argillaceous and arenaceous, crinoidal limestone, with a very variable fossil content. Locally, it may be almost barren of fossils (as at Coal Crag), but there are also occasional shell beds where brachiopods, especially, are abundant. In Nookton Burn the basal 6 inches are highly arenaceous, and usually decalcified, containing the casts of many fossils. The maximum thickness seen is 2 feet, but it may be as little as one foot. The following fossils have been found:-

Aulophyllum sp.
Chaetetes sp.

Fenestella sp.

Composita ambigua (J. Sowerby)
Eomarginifera longispina (J. Sowerby)
Phricodothyris sp.

In addition to the macrofossils the Crag Limestone contains a considerable microfauna, and it is surprising that Green (1954) records that microfossils are absent in this limestone in Devil's Water, only a few miles to the north.

Over the remainder of the research area the Crag Limestone is not present as a limestone; this question has already been discussed on page 28. In Rookhope Burn, the New Lintzgarth Quarry in the Firestone ganister, reveals that above the Crag Coal there is a 6 inch bed of medium grained sandstone with brachiopods, followed by one foot of dark grey, silty clay, which, presumably, is the local representative of the Crag Limestone. Exposure is poor at this horizon in Weardale, but the Crag Limestone can be shown to be undeveloped in a number of instances. It may be present on Carr Brow Moor where 10 inches of ochreous sandy clay (known locally as "famp") occur. There is no evidence of the Crag Limestone at outcrop in East Allendale, and only one record of it in mine workings, i.e. in Studdon Dene Shaft on the Blackett Level (Dunham, 1948, p.34). Its occurrence at Barneycraig Mine in West Allendale and its passage into ironstone (op. cit., p.34) testifies to its variability and impersistence. It is interesting to note that an 18 inch argillaceous limestone was recorded by Dunham and Johnson (1962, p.247) in Swinhope Boring Number 3 above the sandstone which is here regarded as the Firestone Sill. This would seem to be the Crag Limestone, and the fact that it is not present in the other three boreholes emphasises its impersistent nature. Previous authors in other areas also report the Crow Limestone to be variable in lithology and thickness, (Reading, 1957, p.40; Rowell and Scanlon, 1957, p.13), a character which is certainly shared by the Crag Limestone in the present area.

Fine Clastics. The fine clastics which immediately follow the Crag Limestone, (or the Firestone Sill where the limestone is absent), follow the same pattern throughout the area. The initial black shales contain siderite nodules, some pyrite, and a sporadic fauna of crinoid columnals, lamellibranchs, gasteropods, and rare corals. Then follows a gradual upward passage into grey, micaceous siltstone, and eventually into fine grained sandstone. The latter forms the base of the Fiddler's Sill.

Fiddler's Sill. There is some doubt as to whether the Fiddler's Sill of this survey is the same as that described by Trotter and Hollingworth in the Brampton area. Wallace (1861) originally used the term for a sandstone between the Firestone Sill and the Low Slate Sill on Alston Moor. The author's usage of the expression complies with this definition, but Dunham (1948, p.34) believes that the Fiddler's Sill of Brampton may, in fact, be the equivalent of part of the Firestone Sill. The Fiddler's Sill in the research area is generally 15 to 20 feet thick, and has 5 to 10 feet of fossiliferous sandstones and siltstones above, which comprise the Knucton Shell Beds.

In all areas, the Fiddler's Sill has a transitional passage into the siltstone and shales below it. Some of the best exposures occur at Coalcleugh, Swinhope, and Killhope, where it is a fine grained, micaceous sandstone with occasional argillaceous partings. There is a tendency, however, for the Fiddler's Sill to become medium grained towards the top. The fine sandstone frequently has ripple, as well as regular, lamination, and contains sporadic vertical worm burrows. The medium grained sandstone usually contains brachiopods including Schellwienella rotundata, Camarotoechia pleurodon, and Eomarginifera lobata, a facies which is common as thin beds in the overlying Knucton Shell Beds. The Knucton Shell Beds were first noted by Carruthers (1938, p. 238) at Coalcleugh, but not described in detail. The type locality was subsequently chosen by Dunham as Coal Crag in Nookton Burn (Whittard and Scott Simpson, 1960, p.200), where they are well seen. In the western region, around Killhope Law, the Knucton Shell Beds comprise a series of burrowed, medium grained sandstones, dark grey siltstones, and black shales (Fig.5.1). The finer clastics may contain lamellibranchs, but the burrowed sandstones are characterised by the presence of thin shell beds, usually less than one foot in thickness, containing abundant brachiopods. The Knucton Ironstone, which forms the topmost of the shell beds, is described in detail in Chapter 14.

In Nookton Burn the Fiddler's Sill has a typical lithology, although with a greater proportion than elsewhere of the massive, medium grained sandstone with scattered fossils. Above the Fiddler's Sill there are generally 10 to 12 feet of black, somewhat micaceous shale, containing siderite nodules. The lowermost few feet of this shale may have a mollusc, horny brachiopod fauna. A 6 foot medium grained sandstone then occurs, upon which rests the Knucton Ironstone.

PLATE 8. Troughs in Knuct-
on Shell Bed series,
Grindstone Cleugh.

PLATE 9. "Caudagalli"
in sandstone, Knuct-
on Ironstone Cyclo-
them, Coal Cleugh.

This sandstone, in Grindstone Cleugh, and possibly in Beldon Burn, contains small erosive channels and lenticular beds (Plate 8). The possible significance of these is discussed elsewhere (see p. 199). At Coal Crag the sandstone below the Knucton Ironstone is not present, possibly indicating that some erosion has taken place at the base of the Knucton Ironstone (p. 41).

CHAPTER 6

KNUCTON IRONSTONE CYCLOTHEM

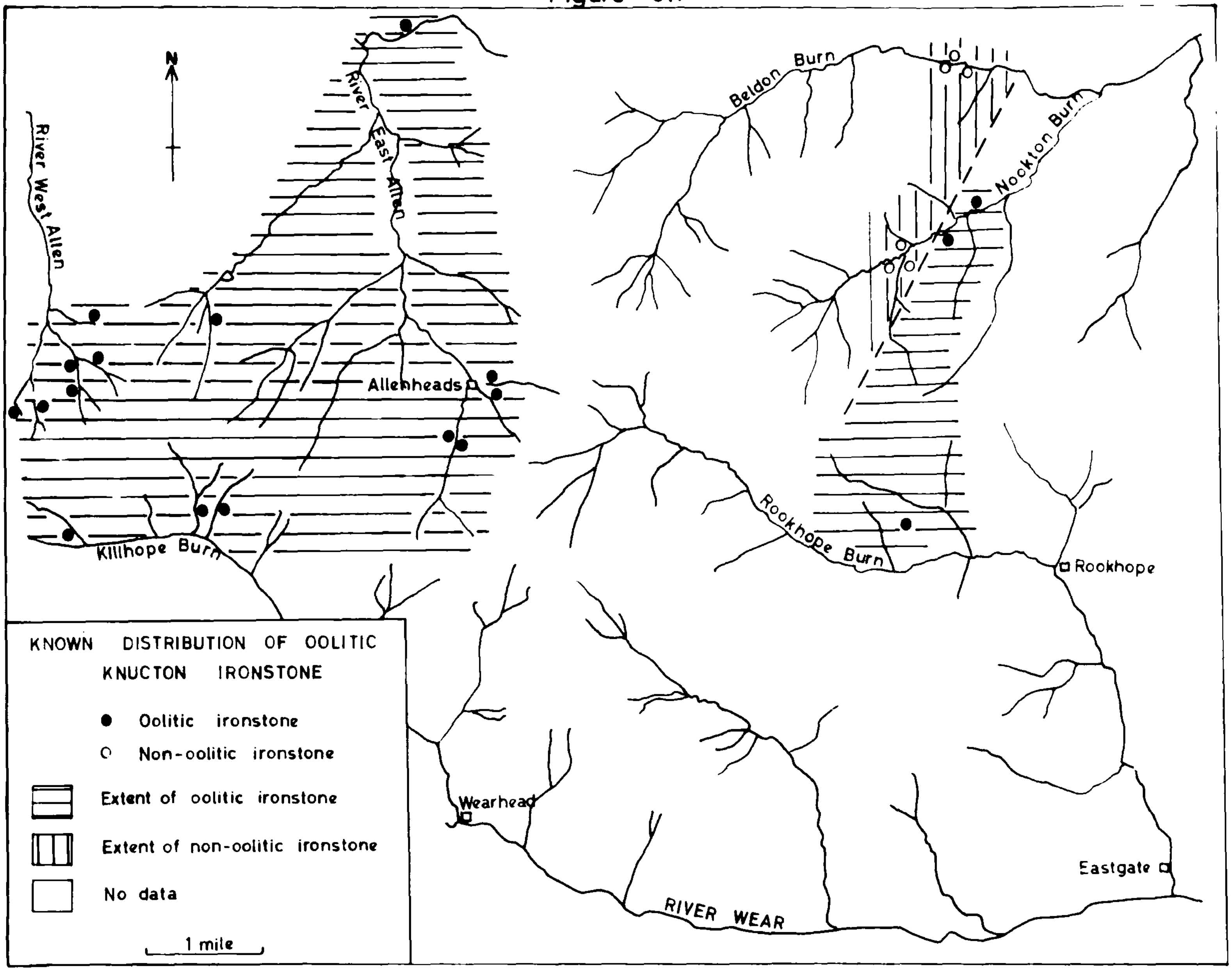
The base of this cyclothem is well defined by the Knucton Ironstone, but attempts to define the top are thwarted in this region by the complex series of lenticular sandstones, shales, and shell beds occurring above the Low Slate Sill. The Knucton Ironstone Cyclothem is perhaps unusual in that, over almost the whole area, the coarsening upward sequence, which is associated with the Yoredale type of cyclothem, is abruptly terminated by the erosive base of the Low Slate Sill. Local erosion is, of course, common in other cyclothems, but none has so far been so widespread. Whilst, it is admitted, the Low Slate Sill probably belongs to the Knucton Ironstone cycle of sedimentation, the break at the base of this member is considered to be of sufficient importance to warrant the establishment of a new stratigraphical unit, the Slate Sills Formation. This decision immediately makes the expression "Knucton Ironstone Cyclothem" a misnomer, because, by definition (p. 10), it can never be complete in this area. However, for the sake of conformity, the term is retained, for it is not impossible that outside the area surveyed the full sequence is present.

Knucton Ironstone. The Knucton Ironstone Cyclothem is quite well exposed over the whole area, despite the fact that it is almost wholly composed of fine clastics. The thickness remains remarkably constant, between 25 and 35 feet (Fig.7.1).

The Knucton Ironstone is an arenaceous chamosite oolite with a siderite cement which occurs as the topmost of the Knucton Shell Beds. The term is coined by the author in view of its distinctive lithology and widespread development in the research area. In his Coalcleugh section Carruthers (1938, Pl.13, p.252), denoted part of his Knucton Shell Beds as "ironstone", but no description was included. The Knucton Ironstone is well developed at Coal Crag (Nookton Burn), the type locality of the Knucton Shell Beds; this is also taken as the type locality of the Knucton Ironstone. The geographical limits of the Knucton Ironstone are not known in detail, but they may well lie outside the present study area (Fig.6.1). Jones (1956, p.85) only recorded calcareous sandstones in the position of the Knucton Shell Beds around Middleton-in-Teesdale, and Reading (1957, p.40) reports that they are effectively absent in the Cotherstone district.

The petrography of the ironstone is described in full in Chapter 14. It is important to appreciate that the Knucton Ironstone is laterally very variable in composition. In its best development, as at Coal Crag, around Allenheads, and parts of West Allendale, it is 2 to 3 feet thick, and almost the whole thickness contains chamosite ooliths. The relative proportion of the three main constituents, ooliths, quartz, and siderite, may vary over wide limits. When the Knucton Ironstone is traced westwards up Nookton Burn it passes within one mile into a non-oolitic sideritic ironstone. Similarly, when seen in Sipton Cleugh, three miles

Figure 6.1


N
River West Allen
River East Allen
Allenheads
Killhope Burn
Beldon Burn
Nookton Burn
Rookhope Burn
Rookhope
Wearhead
RIVER WEAR
Eastgate
KNOWN DISTRIBUTION OF OOLITIC KNUCTON IRONSTONE
Oolitic ironstone
Non-oolitic ironstone
Extent of oolitic ironstone
Extent of non-oolitic ironstone
No data
1 mile

north of Allenheads, the Knucton Ironstone contains a very small percentage of ooliths. In Washpool Cleugh in West Allendale, ooliths are restricted to the top three inches, whereas, half a mile to the north on Carrshield Moor the whole 2½ feet contain abundant ooliths. The fact that the lowermost foot may contain very coarse sand, which can rest on black shale, suggests that local erosion occurs at this level (see p. 38). This is in accord with the study of the Northampton Sands Ironstone by Taylor (1949, p.8), who also records that local erosion is common in association with ironstones of this type. The following is a list of fossils found in the Knucton Ironstone:-

Fenestella sp.
Stick bryozoa

Camarotoechia pleurodon (Phillips)
Chonetes sp.
Composita ambigua (J. Sowerby)
Crurithyris sp.
Eomarginifera lobata (J. Sowerby)
Phricodothyris sp.
Productus concinnus J. Sowerby
Schellwienella rotundata Thomas
Spirifer bisulcatus J. de C. Sowerby group
S. trigonalis (Martin) group

Lamellibranchs

Gasteropods

Weberides mucronatus (M'Coy)

Fish teeth

Fine Clastics. Above the Knucton Ironstone the fine clastics conform to the general pattern of Upper Limestone Group sedimentation. Beginning as black shales with ironstone nodules, they eventually pass through micaceous shale into dark grey siltstone. One or two local variations are, however, worth noting. In three widely separated localities, Nookton Burn, Coal Cleugh and Sipton Cleugh, a thick sideritic ironstone, 1 to 2 feet thick, occurs some 7 feet above the Knucton Ironstone. It is often highly weathered, but does not appear to contain ooliths. The fine clastics are not entirely devoid of fossils, and the following collection was made in a series of thèn, fine grained, ripple laminated sandstones in Sipton Cleugh:-

Bryozoa *indet.*

Buxtonia scrabricula (Martin)
Camarotoechia pleurodon (Phillips)
Eomarginifera lobata (J. Sowerby)
Phricodothyris sp.
Schellwienella crenistria (Phillips)

Lamellibranchs

Bellerophontids

The sandstones often have a cement composed of either calcite or siderite. The intervening beds are also fossiliferous in

Grindstone Cleugh (Nookton), Rookhope Burn, Sipton Cleugh, and Far Sike (East Allendale). Within the siltstones Chonetes hardrensis is the most prolific fossil, suggesting that it may be restricted to this facies. At the latter locality, however, the following are also recorded:-

Athyrid indet.
Cancrinella sp.
Eomarginifera longispina (J. Sowerby)
Phricodothyris sp.
Productus sp.
Spirifer cf. bisulcatus J. de C. Sowerby

In Beldon Burn and West Allendale there occurs a dark grey, medium to fine grained sandstone 10 feet above the Knucton Ironstone. It is much reworked by burrowing organisms, including "caudagalli" (Plate 9). Although it is not justifiable to correlate these two widely separated and thin beds, it is interesting to note that the same general environment occurs in different parts of the area at approximately the same time.

In three localities, in Whetstonemea Burn (West Allendale), Eastend Burn (East Allendale), and Silly Sike (Beldon), there is a transition into medium to fine grained sandstone, occurring below the Low Slate Sill proper. It is presumed that the Low Slate Sill did not erode so deeply at these localities, so that part of the coarse clastics at the top of the Knucton Ironstone Cyclothem were preserved.

CHAPTER 7

SLATE SILLS FORMATION

The cyclothemic concept of sedimentation in the Upper Limestone Group becomes difficult to apply at the horizon of the Low Slate Sill (p. 39). The beds between the base of the Low Slate Sill and the base of the Lower Felltop Limestone are complicated by considerable lateral variation and do not readily conform to a cyclothemic classification; these beds are thus grouped together under the term "Slate Sills Formation". The Lower Felltop Limestone is chosen as the top of the Formation because it is a readily identifiable and reliable marker horizon, despite the fact that it is locally removed by subsequent erosion (p. 61). The Rookhope Shell Beds and Ironstones which occur within the Formation are too impersistent and variable to be used as stratigraphical markers. For ease of description the Formation will be subdivided into the following members:-

e) Upper Rookhope Shell Beds
d) High Slate Sill
c) Lower Rookhope Shell Beds
b) Low Grit Sill
a) Low Slate Sill

The Low Slate Sill is probably the only member which can be correlated with certainty over the area. Correlation of the other members may, on occasions, prove to be incorrect, because they are based only on general considerations.

a) Low Slate Sill. The thick basal sandstone member of the Slate Sills Formation, here called the Low Slate Sill, has been referred to by a variety of names in the past. The use herein of the terms Great Sill (Dunham, 1948, p.39) and Rogerley Transgression Beds (op. cit. p.39) is not advantageous, but the expression Low Grit Sill will be retained for the coarse channel facies occurring at Hunstanworth. The Low Slate Sill was originally defined by Forster (1809), who recorded it as 21 feet thick. In the research area the minimum full thickness measured is 30 feet, and values up to 55 feet are not uncommon (Fig.7.1). The channel at Hunstanworth contains up to 140 feet of coarse clastic sediments (i.e. the Low Grit Sill).

The base of the Low Slate Sill, wherever exposed, is always erosive. The lowermost beds, perhaps only one or two feet, are almost invariably very coarse or coarse grained felspathic sandstones. They rest abruptly on black shale, which, occasionally, is slightly silty and may contain plant remains. Shale-fragments, presumably derived from the shale below, may be abundant in the basal sandstone, as well as large fossil tree fragments.

A generalised lithological sequence within the Low Slate Sill can be recognised over the whole area (Fig.7.1). It begins with the erosive base and a coarse to very coarse grained sandstone. There follows a consistent reduction of grain size upwards, attendant with marked changes in bedding structure. Above the basal coarse beds there occurs a much

Figure 7.1

MEASURED SECTIONS IN THE KNUCTON IRONSTONE CYCLOTHEM AND THE SLATE SILLS FORMATION

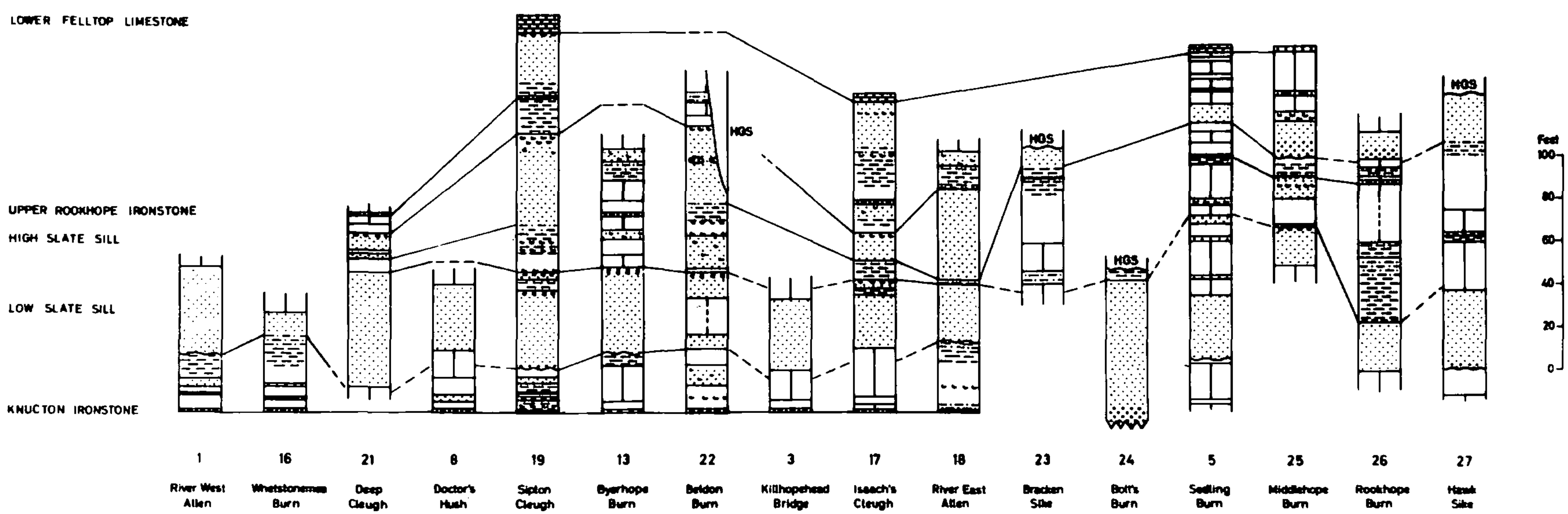


PLATE 10. Small sandstone-filled channel overlain by thick coal, Slate Sills Formation, Nookton Burn.

PLATE 11. Base of Rogerley Channel at horizon of Fiddler's Sill, containing boulders of Knucton Ironstone, Nookton Burn.

thicker development of medium grained sandstone with planar and festoon cross-stratification. This series may also contain thin intercalations of both coarse and fine grained sandstone. Gradually, the medium grained sandstone gives way to a medium to fine grained sandstone which has small scale trough cross-lamination. This and other sedimentary features of the Low Slate Sill are discussed in greater detail in another section (see p. 226).

The top of the Low Slate Sill may or may not be marked by a ganister. In Beldon Burn the ganister is 2 feet thick, and another 2 feet of black, plant-rich shale separates it from a 2 inch coal seam. Eighteen inches of coal occur in this position at Nooktonhead, and the sandstone below the carbonaceous shale has a markedly lenticular form and contains large Stigmaria (Plate 10). Evidently, a small, very local channel existed at this point. The top of the Low Slate Sill in Sipton Cleugh has an intercalation of black, sandy shale, 5 feet thick, with occasional ironstone nodules; this is followed by 4 feet of medium to fine grained sandstone containing rootlets in situ on the top (Fig.7.1). Elsewhere, and particularly in Rookhope Burn, the topmost beds of the Low Slate Sill are represented by a series of carbon-rich sandstones, much reworked by burrowing organisms, and thin beds of silty shale. A similar sequence is seen in Isaach's Cleugh (Killhope) and Deep Cleugh (Swinhope).

b) Low Grit Sill. The Low Grit Sill, occupying the Rogerley Channel at Hunstanworth, has most of the features of the Low Slate Sill, but on a much more impressive scale.

Figure 7.2

SCHEMATIC VERTICAL SECTION THROUGH THE SLATE SILLS FORMATION IN BELDON BURN ILLUSTRATING RELATIONSHIPS TO ENCLOSING STRATA

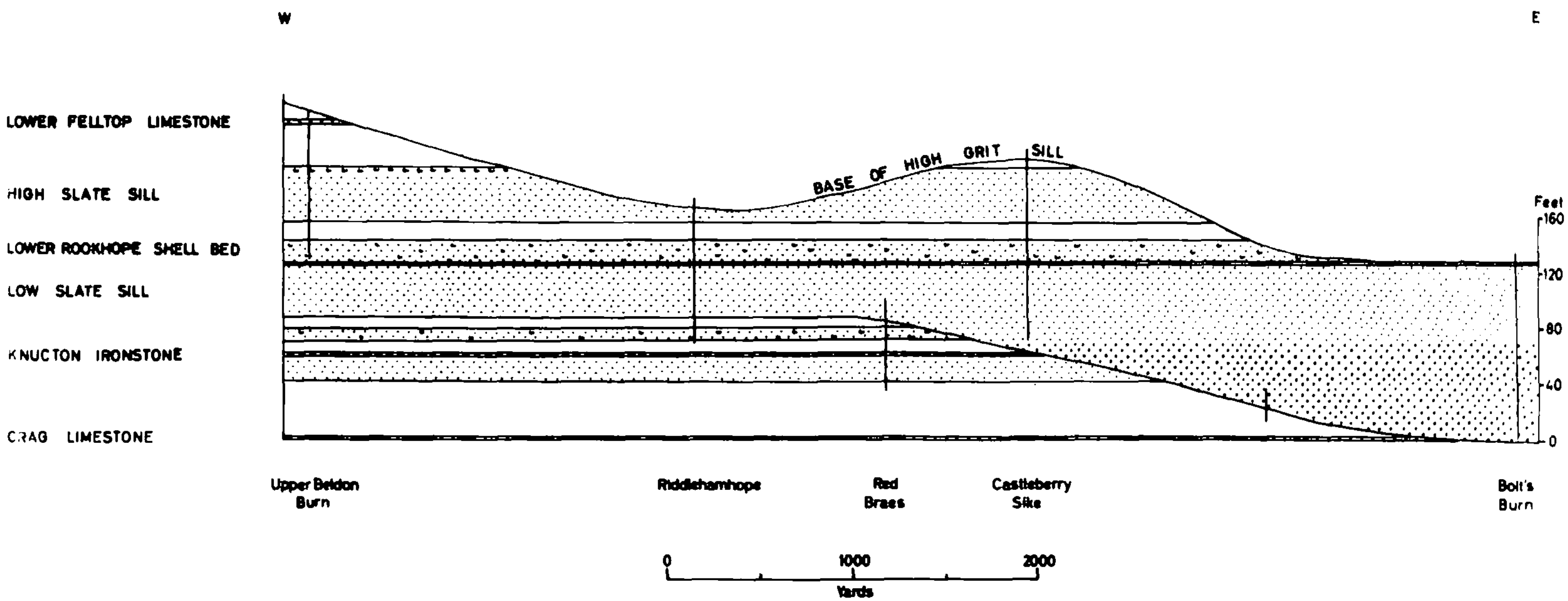


PLATE 12. Large boulders of Knucton Ironstone in Rogerley Channel, Nookton Burn.

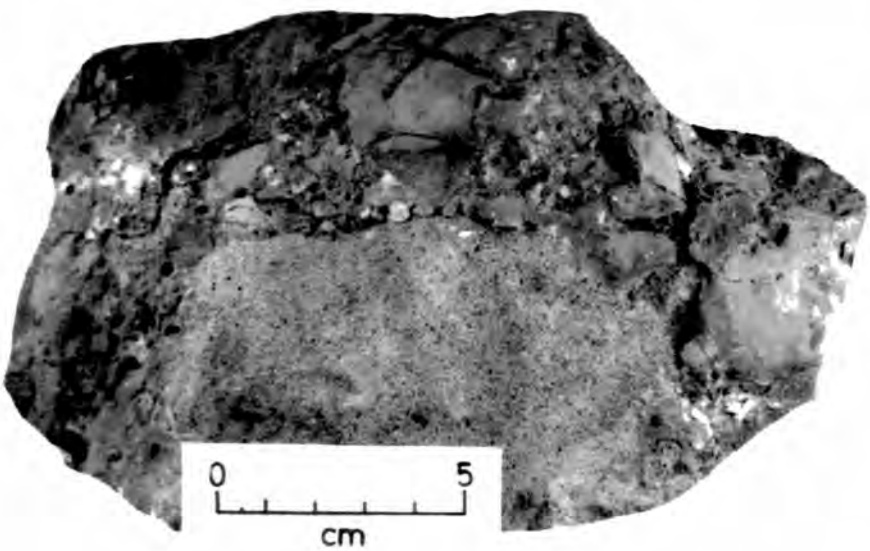


PLATE 13. Boulder bed in Rogerley Channel, showing boulder of Knucton Ironstone and irregular matrix with pebbles of siderite.

Dunham (1948, p.37) describes how the erosive base of the Low Grit Sill cuts right down to the Crag Limestone in Nookton Burn (Fig.7.5). It is interesting to observe the irregular base of the channel, especially where, a short distance downstream from Coal Crag (Nookton), there is a small wash-out containing large boulders of the Knucton Ironstone (Plate 11). This washout, which, most probably, is a part of the Low Grit Sill complex, has cut down at least 30 feet through the Knucton Ironstone and most of the underlying Fiddler's Sill. The large size of the ironstone boulders, up to 2 feet, (Plate 12) suggests their origin as the result of undercutting by the river. Similar boulder beds have been described by Black (1928) from washouts in the Lower Estuarine Series of Yorkshire. The matrix of the boulder bed contains a variable array of pebbles, of which fine grained sandstone and siderite nodules are the most abundant (Plate 13).

In the lower reaches of Nookton Burn and the River Derwent the behaviour of the base of the Rogerley Channel can be studied. It is very irregular in Nookton Burn, sometimes resting directly on the Crag Limestone or perhaps separated from it by a few feet of black shale (Fig.7.3). On the south bank of the River Derwent the Low Grit Sill has cut out the Crag Limestone and rests on the Firestone ganister, eventually even, removing the whole of this bed. The basal beds of the Low Grit Sill reach their maximum grain size at the point of maximum erosion. In the River Derwent, and to a less extent, around Gibraltar Banks, the Low Grit Sill is very coarse,

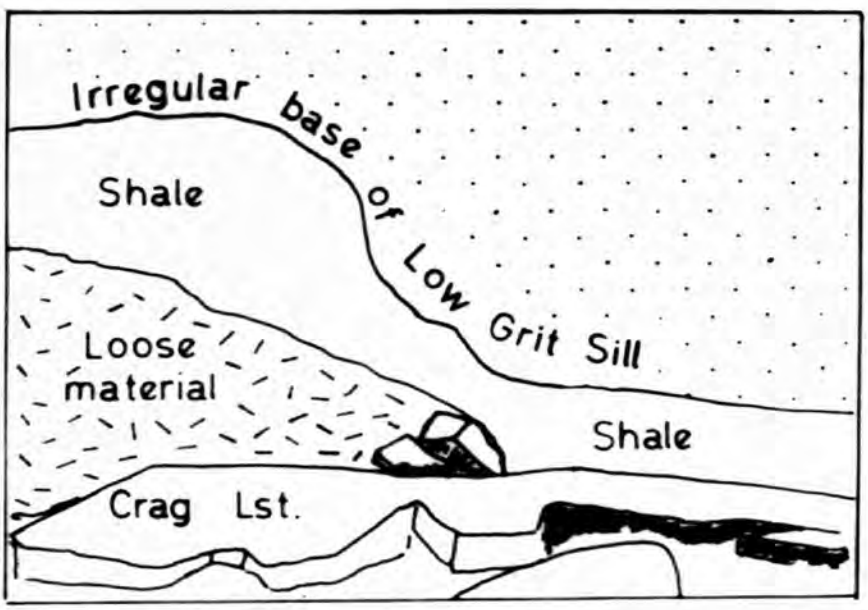


Figure 7.3

Irregular base of Rogerley Channel at horizon of Crag Limestone, Nookton Burn.

pebbly subarkose (p. 120), which often reaches the grade of granule conglomerate. Several of the quartzite pebbles reach 5 cm. in long diameter, and shale-fragments are common. When traced westwards up Nookton and Beldon Burns the general grain size diminishes, as does the size and frequency of the pebbles. However, even at Castleberry Crags in Beldon Burn, the Low Grit Sill is a medium to coarse grained sandstone, with a great many coarse grained sandstone horizons. Cross-stratification in these basal coarse beds is predominantly of the very large scale trough type; but this topic is discussed in detail in Chapter 15. In common with the Low Slate Sill the deposits of the Low Grit Sill become finer upwards. This particular feature is well seen in Bolt's Burn (Derwent), where virtually the whole thickness is exposed. The topmost beds are composed of medium, and occasionally fine, grained sandstone, although intercalations of coarse grained sandstone are still quite common. Two examples of large scale trough cross-stratification occur in medium grained sandstone in Bolt's Burn, and, in the finer beds, small scale trough cross-stratification is present. It is interesting to note that at Grindstone Cleugh (Nookton) the whole series is diminished in grain size, and the sequence runs from medium grained cross-stratified sandstone at the base to dark grey silty shale at the top. The actual top of the Low Grit Sill is rarely exposed, but in Castleberry Sike a 2 foot coal occurs. The Geological Survey records of the Derwent Mine sections (V.S. Sheet 63) suggest that this coal is not always present.

In Nookton Burn, near Wagtail Farm, an anomalous

PLATE 14. Calcareous concretion in Lower Rookhope Shell Beds, Riddlehamhope, Beldon Burn.

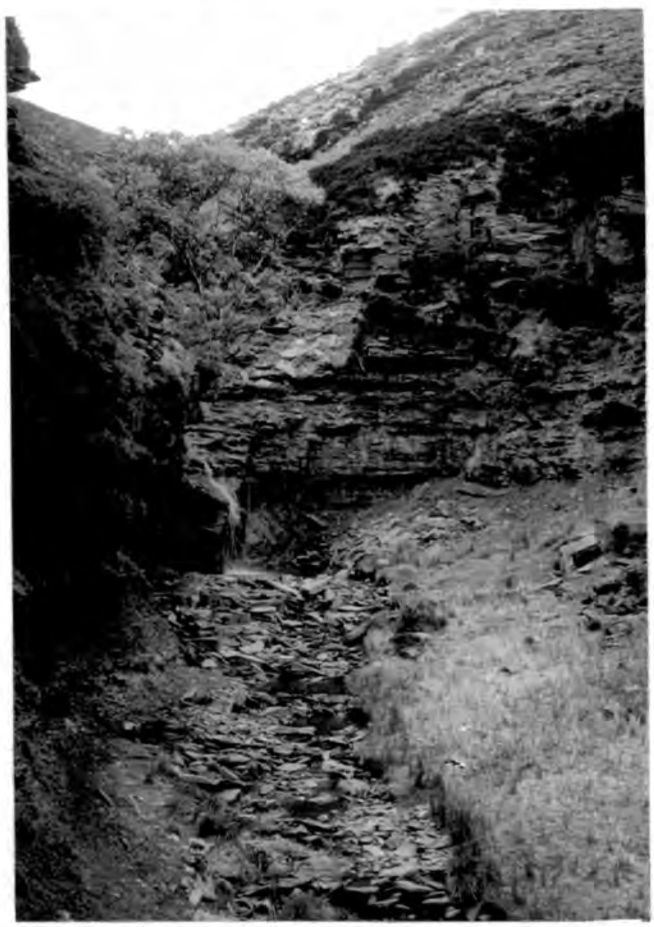


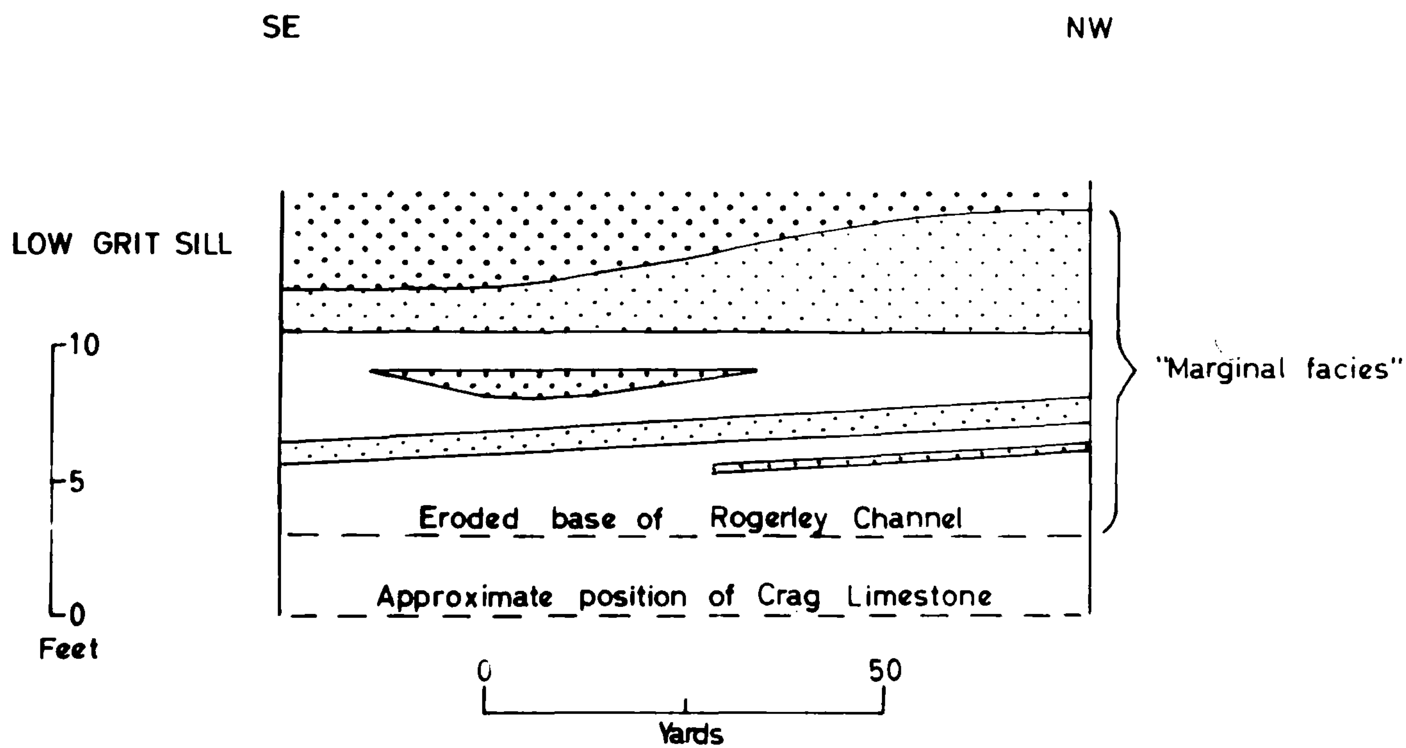
PLATE 15. High Slate Sill, Sipton Cleugh, showing transitional base.

section of dark grey siltstones and fine grained sandstones occur only a few feet above the extrapolated position of the Crag Limestone (Fig.7.4). A nearby exposure of the same section has a lenticular bed of very coarse sandstone, and the whole has a rather abrupt contact with the Low Grit Sill above. Clearly, it cannot be part of the Crag Limestone Cyclothem, because a perfectly normal section occurs only a short distance upstream. It is thus regarded as a marginal facies of the Rogerley Channel. A similar facies is developed at the margin of a channel in the Coalcleugh Transgression Beds (Fig8.2).

c) Lower Rookhope Shell Beds. Rookhope Shell Beds is a term originated by Carruthers (1938) for thin, fossiliferous sandstones occurring above his Grit Sills in Rookhope Burn. Indiscriminate use has been made of this expression for horizons above both the Low and High Slate Sills; it is thus necessary to designate these separate series Lower and Upper Rookhope Shell Beds respectively. Carruthers (ibid.) used the term "Rookhope Main Shell Bed" for the one above the High Slate Sill at Coalcleugh (present author's interpretation), but the expression Upper Rookhope Shell Bed is preferred. In Sipton Cleugh the basal Lower Rookhope Shell Bed is very poorly developed, but in Beldon Burn a massive, medium grained sandstone with a scattered brachiopod fauna and large calcareous concretions (Plate 14), rests directly on the coal at the top of the Low Slate Sill (Fig.7.2). It is worthy of

Figure 7.4

SCHEMATIC VERTICAL SECTION THROUGH THE "MARGINAL FACIES" OF THE ROGERLEY CHANNEL IN NOOKTON BURN

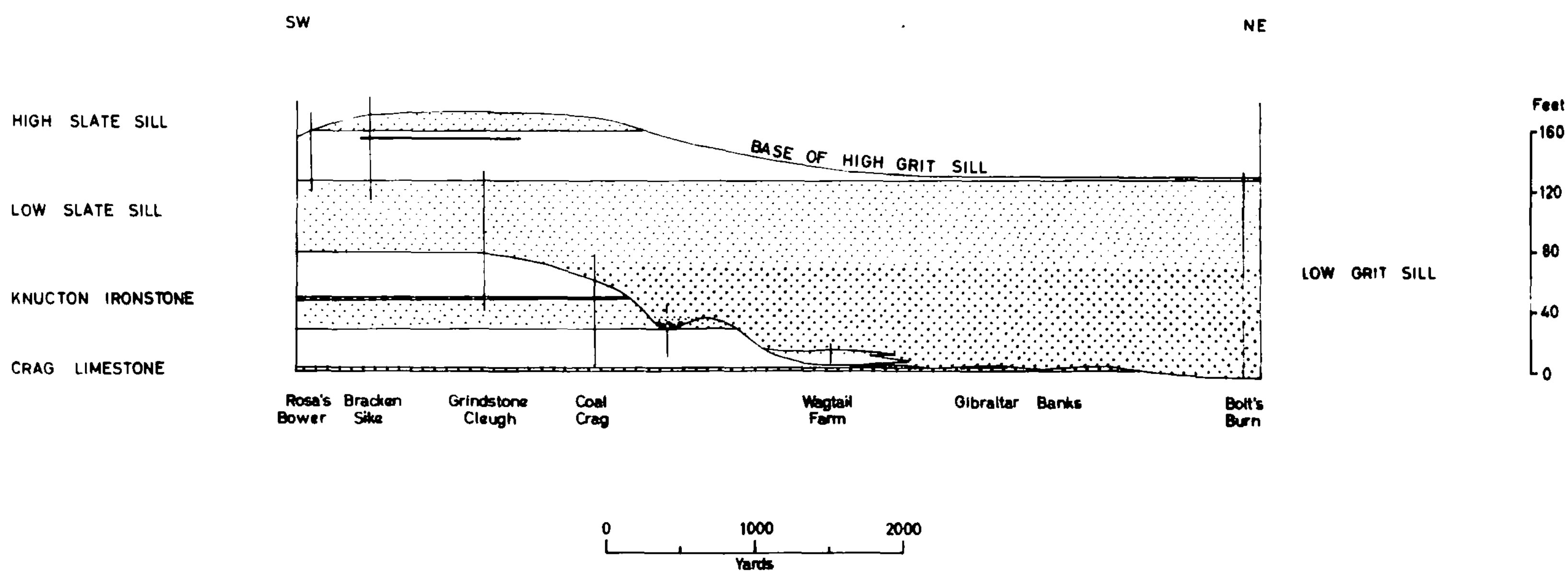


note that the Geological Survey refer to this sandstone as the Corbridge Limestone (One-inch Hexham Sheet 19,1956). In both Sipton Cleugh and Beldon Burn there follows a varied series of silty shales with thin ripple laminated sandstones and shell beds, with both calcareous and sideritic cements. In Beldon Burn, a few feet above the basal, fossiliferous sandstone, there is a one foot limestone, almost wholly composed of crinoid columnals and broken shell fragments. It also contains rounded chert nodules up to 2.5 cm. across. This is one of the rare occurrences of chert in the Upper Limestone Group of the research area, although several authors have recorded siliceous "lime plate" at a number of horizons (Carruthers, 1938; Dunham, 1948; Johnson and Dunham, 1963). There is a general increase in grain size as the base of the High Slate Sill is approached, so that the contact is quite transitional, (Plate 15). In relatively few other districts is this unit completely exposed. Even where exposure is good there is often only a superficial resemblance between measured sections.

The section observed at Nooktonhead is particularly difficult to correlate, because none of the Lower Rookhope Shell Beds appears to be present (Fig.7.5). Instead, there is a series of 40 feet of shales, sandy siltstones, and thin, ripple-laminated, fine grained sandstones, which often contain abundant plant remains. The sandstones also contain U-shaped burrows. A very similar sequence is observed in Hawk Sike (Rookhope), and in adjacent Stogel Cleugh the silty shale

Figure 7.5

SCHEMATIC VERTICAL SECTION THROUGH THE ROGERLEY CHANNEL IN NOOKTON BURN



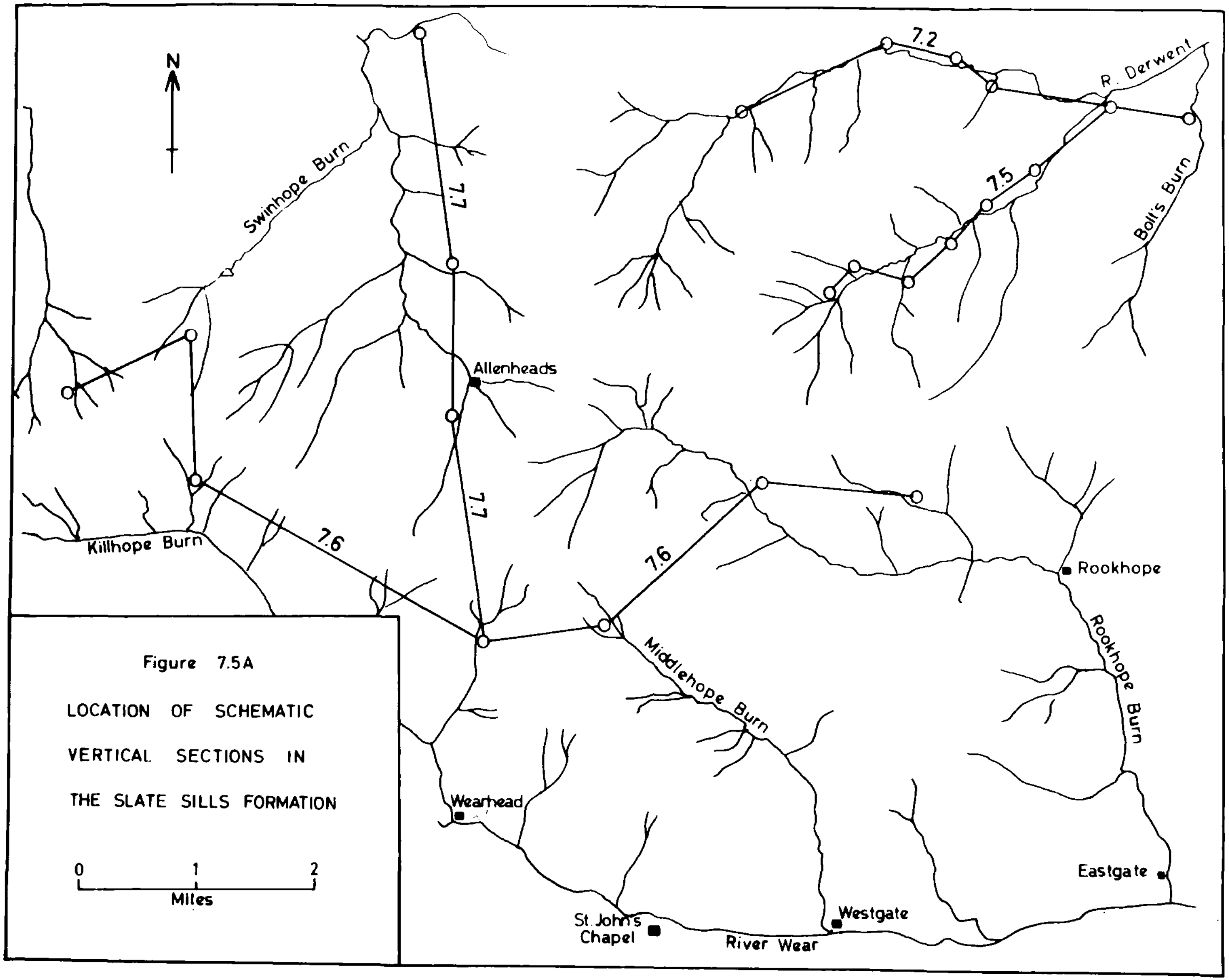


Figure 7.5A

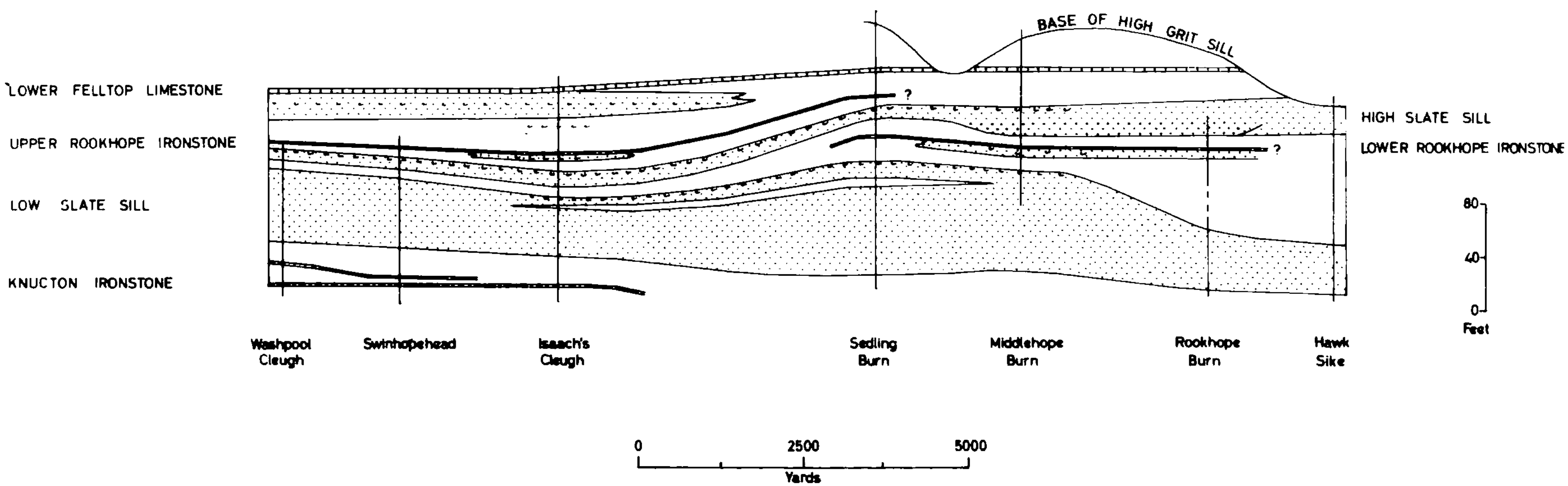
LOCATION OF SCHEMATIC VERTICAL SECTIONS IN THE SLATE SILLS FORMATION contains Lingula mytilloides and abundant plant material. The general impression obtained is that this suite of rocks is less marine than its equivalents in other districts, but this is only proposed as a tentative hypothesis. In Nookton Burn this thickness of beds is reduced to 2 or 3 feet of shale around Smithy Cleugh and Little Nookton Burn, where the transgressive base of the High Grit Sill cuts down almost as far as the Low Grit Sill (Fig.7.5). No fossils were found in this attenuated sequence.

At Coalcleugh, Carruthers (1938, Pl.13 p.252) recognised an ironstone above his "Rookhope Main Shell Bed", which he named the Rookhope Ironstone. This particular horizon is here called the Upper Rookhope Ironstone (Fig.7.1). In the type locality of the Rookhope Shell Beds in Rookhope Burn another ironstone occurs some 20 feet above the Low Slate Sill, which, in view of its position, must be designated the Lower Rookhope Ironstone (Fig.7.6). Carruthers (ibid. Pl.13), showed a 4 inch ironstone at a lower horizon, and, although he did not describe its lithology, it clearly does not represent the Lower Rookhope Ironstone.

The Lower Rookhope Ironstone is restricted to parts of East Allendale, Rookhope, Sedling, and Middlehope Burns (Figs.7.6,7.7,7.8). The best exposure of this ironstone occurs in Byerhope Burn (East Allendale), where, although only 9 inches thick, chamosite ooliths may comprise 30 to 40 per cent of the whole rock. A similarly high proportion of oolitic material occurs in Rookhope Burn, where it is best

Figure 7.6

SCHEMATIC VERTICAL SECTION THROUGH THE SLATE SILLS FORMATION



seen by the roadside near Grove Rake Quarry. This appears to be the area of maximum development of chamosite ooliths in the Lower Rookhope Ironstone. To the north it is not present as a chamosite oolite, although it may pass into sideritic ironstone. Southwards from Rookhope the Lower Rookhope Ironstone is found in Middlehope Burn and also in Sedling Burn. The exact equivalent in Middlehope Burn is not certain, because there are two horizons which contain chamosite ooliths. The lower one rests directly on the Low Slate Sill, and is a medium grained, burrowed sandstone 2 feet thick, with an upwards increasing amount of siderite and ooliths. The upper oolitic bed occurs 25 feet above and has a lower oolith content. Carruthers (1938, p.239) mistakenly regarded these as the Knucton Shell Beds. In Sedling Burn the Lower Rookhope Ironstone occurs 15 feet above the Low Slate Sill, and is noteworthy in that, although it appears to have abundant chamosite in the matrix, none of it occurs in oolitic form. All occurrences of the ironstone contain fossils which include the following:-

Crinoid columnals

Athyris sp.
Buxtonia scrabricula (Martin)
Chonetes hardrensis (Phillips) Group
Composita ambigua (J. Sowerby)
Crurithyris sp.
Eomarginifera longispina (J. Sowerby)
Phricodothyris sp.

Productus concinnus J. Sowerby

Schellwienella rotundata I.Thomas

Spirifer sp.

Pectinacea

Bellerophontids

Neither of the Rookhope Ironstones has so far been found south of Weardale (Reading, 1957; Jones, 1956, p.56). The Rookhope Shell Beds near Middleton-in-Teesdale appear to be commonly represented by chert and siliceous limestone with glauconite.

d) High Slate Sill. The coarse clastic rocks occurring above the Lower Rookhope Ironstone are among the most variable in the area. The thickest development of the High Slate Sill, apart from an unusually thick succession near Allenheads, is seen in the north in Sipton Cleugh and Beldon Burn (Fig.7.1). It is 35 feet thick in Sipton Cleugh, where the lowermost 16 feet comprise fine grained sandstone with alternating burrowed horizons and small scale cross-stratified horizons. The next 10 feet are medium grained sandstone with large scale cross-stratification, and this rests quite sharply on the fine grained sandstone below. In the topmost 9 feet the sandstone has perfectly regular bedding, occurring in beds 6 to 9 inches thick. There is a transition, begun by the incoming of animal burrows, into the Upper Rookhope Shell Bed. Only in Sipton Cleugh is this tripartite division of the High Slate Sill discernible (Plate 15). In Beldon Burn, where it is 30 feet thick, it is a medium to fine grained, well-laminated sandstone throughout.

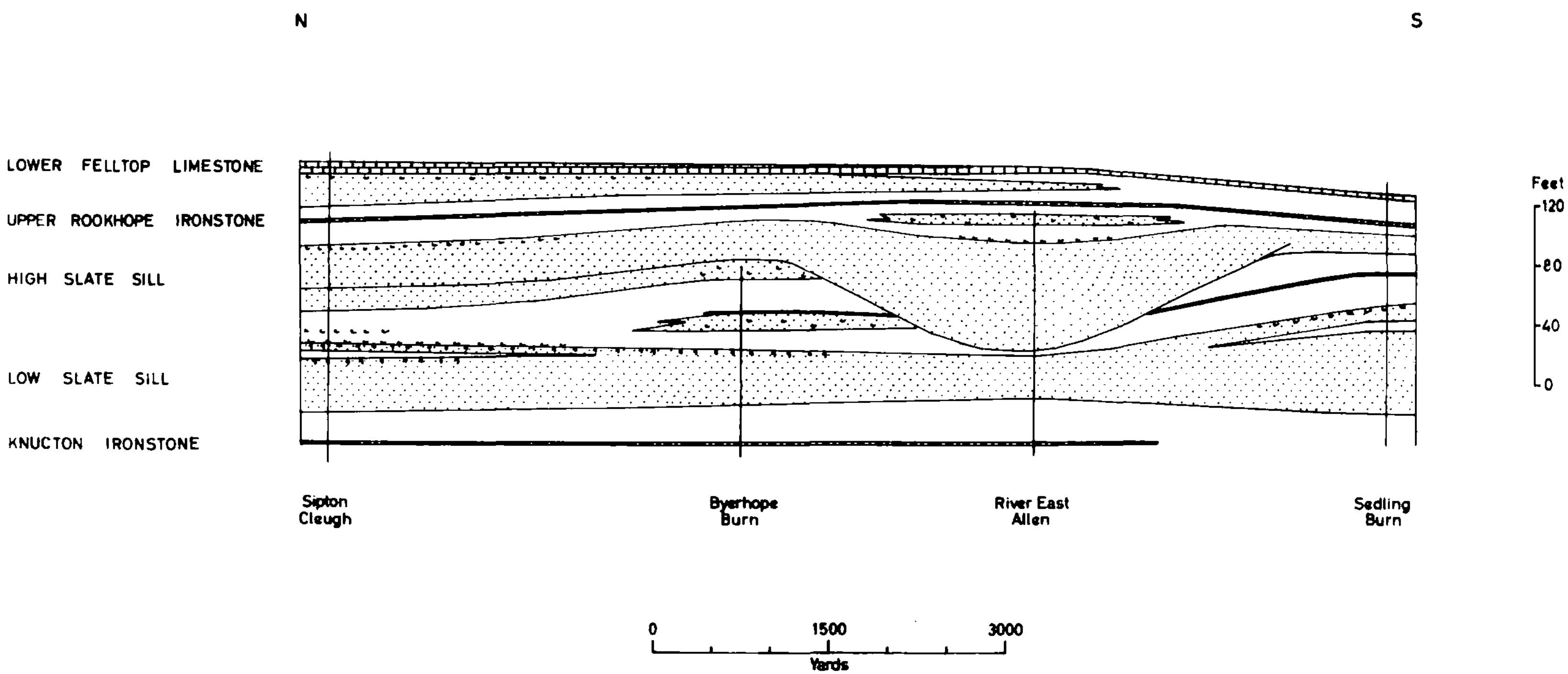
It contains large calcareous concretions, and also has very good examples of trough cross-stratification (Plate 7o).

Towards the south-west from Sipton Cleugh there is a dramatic decrease in the thickness of the High Slate Sill, and also of the shales below. In Deep Cleugh (Swinhope) the High Slate Sill is represented by a medium to fine grained sandstone 8 feet thick, and this impoverishment is continued into Upper Weardale. In Isaach's Cleugh (Killhope) there are 12 feet of medium to fine grained sandstone with cross-stratification in shallow sets, and, in Sedling Burn, this horizon appears to be represented by only 7 feet of fine grained sandstone.

The High Slate Sill is difficult to trace in East Allendale on account of the thick drift cover. In Eastend Burn, it is impossible to differentiate it from the Low Slate Sill, although exposure is far from continuous. Despite the fact that nearby Collier Shaft (V.S. Sheet 62) shows three sandstones in the position of the Low and High Slate Sills, there is a strong suggestion in Eastend Burn that this whole interval is largely composed of sandstone. This is confirmed by the section seen in the River East Allen, south of Allenheads, where only 2 feet of siltstone separate the High Slate Sill from the Low Slate Sill (Fig.7.7). The High Slate Sill is here a medium grained sandstone, 45 feet thick, which has well-developed planar cross-stratification. It becomes slightly finer grained towards the top and it is markedly erosive. It completely removes the Lower Rookhope Shell Beds and Ironstone, and appears to represent a local

Figure 7.7

SCHEMATIC VERTICAL SECTION THROUGH THE SLATE SILLS FORMATION



channel facies of the High Slate Sill. The combination of the Low and High Slate Sills in this area gives rise to the term Great Sill (Dunham, 1948, p.39).

In part of Rookhope Burn and in Middlehope Burn the High Slate Sill contains a basal development of coarse, felspathic sandstone (Fig.7.6). It rests sharply on shales and contains large fragments of fossil trees. The coarse sandstone passes up into medium grained sandstone, and the whole is not more than 17 feet thick. In some localities a thin ganister is developed on top of the High Slate Sill, followed by impure coal. The High Slate Sill here has a definitely fluvial aspect, and it is probably related in some way to the channel facies seen near Allenheads.

The coarse facies of the High Slate Sill in Rookhope Burn occurs in the vicinity of Grove Rake. When followed eastwards into Hawk Sike it is seen to be entirely composed of medium grained sandstone with trough cross-lamination and animal burrows; it rests quite sharply on sandy shale. The top of the High Slate Sill is not seen here, because the very coarse sandstone of the High Grit Sill (or Coalcleugh Transgression Beds) has cut right down to this level. However, in Stogel Cleugh, farther to the east, erosion is not so great, and a 2 inch ganister at the top of the High Slate Sill is present. A similar sequence is seen in Beldon and Nookton Burns. Here again the High Slate Sill is gradually cut out by the High Grit Sill, which reaches its maximum erosive condition near Hunstanworth (Fig.7.2)

In a number of sections at Nooktonhead, in Beldon Burn, near Riddlehamhope, and in Castleberry Sike, the normal medium grained development of the High Slate Sill can be seen.

e) Upper Rookhope Shell Beds. This member, in effect, comprises the strata from the top of the High Slate Sill to the base of the Lower Felltop Limestone. It thus includes beds which are not entirely fossiliferous, and not really shell beds (Fig.7.1). The sequence is very poorly known in the present area, but there is an excellent section in Sipton Cleugh, and good exposures in some of the streams draining Killhope Law. Little information can be gleaned from the poor exposures in East Allendale, Weardale, and Rookhope Burn. An important factor governing the exposures of this member is the disappearance of the sandstone just below the Lower Felltop Limestone to the south and east of the region. Furthermore, this whole unit is removed by the strongly erosive High Grit Sill (or Coalcleugh Transgression Beds) in lower Beldon, Nookton, and lower Rookhope Burns. The total thickness of the unit varies considerably: it reaches 60 feet in Isaach's Cleugh and 47 feet in Sipton Cleugh, but in Weardale and possibly also in Rookhope Burn it is of the order of 25 to 30 feet.

Above the High Slate Sill in Sipton Cleugh there are 25 feet of fine clastics, and 40 feet in Isaach's Cleugh; these are the only two completely exposed sections in the area. Much of this unit is composed of dark grey siltstone with subordinate sandstones. The basal member of the Upper

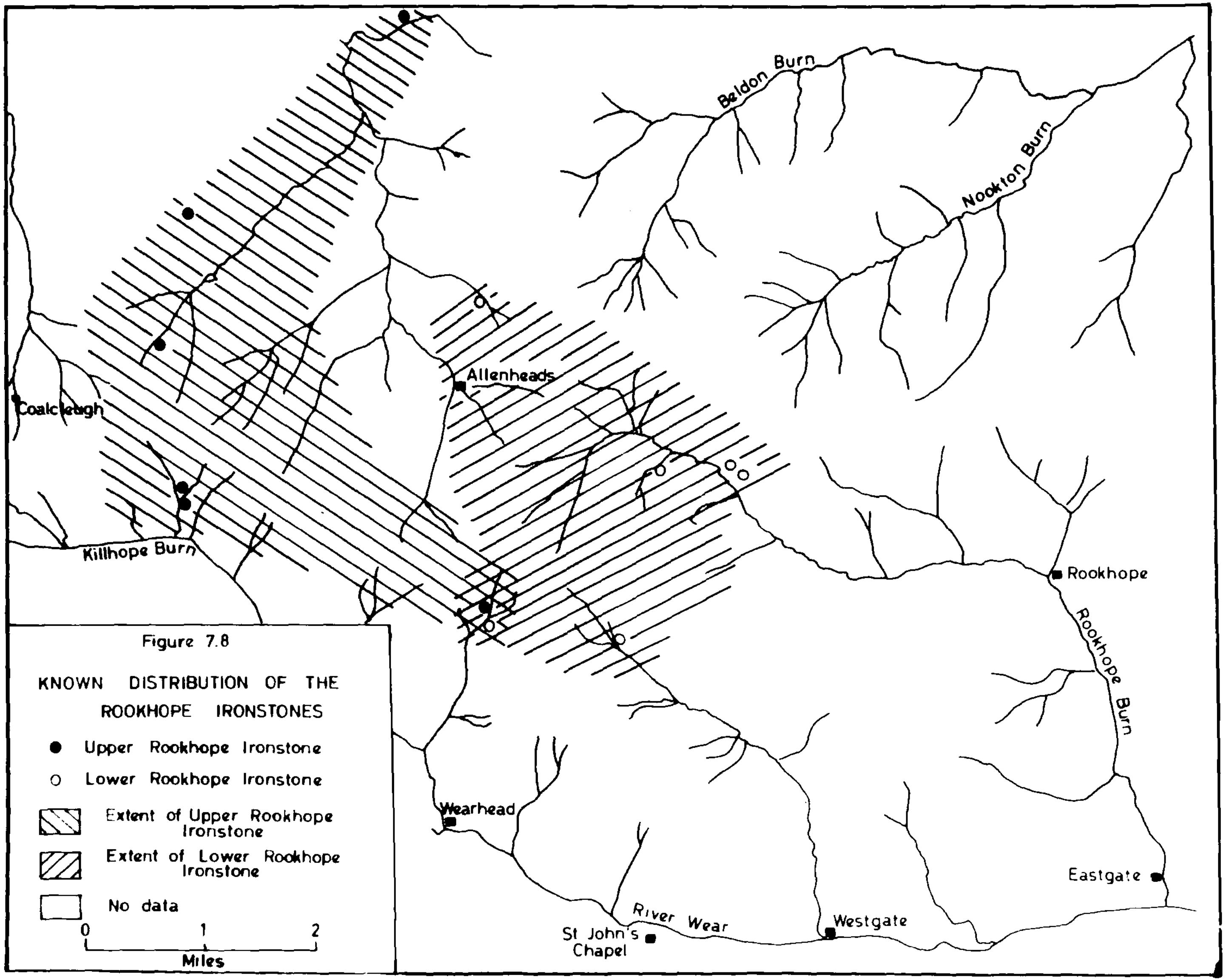


Figure 7.8

KNOWN DISTRIBUTION OF THE ROOKHOPE IRONSTONES

Rookhope Shell Beds is a medium grained, fossiliferous sandstone which is calcareous in part. The following fossils have been observed in this shell bed:-

Fenestella sp.

Athyris sp.
Derbyia sp.
Schellwienella rotundata I. Thomas
Spirifer sp.

Gasteropods

Ostracods

In the River East Allen, there are 10 feet of shale separating the High Slate Sill from the Upper Rookhope Shell Bed (Fig.7.1). The shale contains a similar fauna to the shell bed, but includes Orbiculoidea nitida. The horizon correlated as the Upper Rookhope Ironstone in Sipton Cleugh (Fig.7.7), occurs 15 feet above the basal shell bed, and is, essentially, a medium to fine grained, fossiliferous sandstone, only 5 inches thick. Locally it has a siderite cement and contains some chamosite ooliths. The following fossils have been collected from this band:-

Buxtonia scrabricula (Martin)
Composita ambigua (J. Sowerby)
Eomarginifera longispina (J. Sowerby)
Schellwienella rotundata I. Thomas

The identification of this horizon as the Upper Rookhope

Ironstone is open to some doubt in view of the fact that the lowermost of the Upper Rookhope Shell Beds also contains sporadic chamosite ooliths in some places. However, the ironstone at the upper horizon is better developed and more persistent. Exactly the same sequence is seen in several tributaries of Swinhope Burn, where the Upper Rookhope Ironstone occurs as a thin sideritic band (9 inches thick) containing abundant chamosite ooliths; the siderite matrix is often limonitised. The best exposure in Killhope Burn, at Isaach's Cleugh, shows the Upper Rookhope Ironstone, with the same lithology, occurring 15 feet above the High Slate Sill. It is unusual here in that it contains occasional Clisiophyllid corals and Spiriferellina sp.

The sandstone which occurs below the Lower Felltop Limestone is only present in East Allendale and around Killhope Law. It is believed to die out south of Allenheads and possibly even to the east (Fig.7.6,7.7). In Sipton Cleugh it is represented by 22 feet of fine grained sandstone, which has small scale festoon cross-stratification (Plate 16). The top 3 feet are of medium grained sandstone, and contain Schellwienella rotundata and crinoids. The sandstone is difficult to trace in East Allendale, but it can be picked up again near Allenheads, where it is separated from the Lower Felltop Limestone by a few feet of shale. Even farther south, however, in Allenheads Park, it appears to die out completely, and is not present at all in either Sedling or Middlehope Burns (Fig.7.1). In Coal Cleugh, Swinhope, and Killhope Burns the sandstone is still present, and maintains a remarkably constant lithology. Where seen, it is of the order of 20 feet thick, and is a medium to fine grained cross-stratified sandstone, which is characterised by the presence of occasional thin shell beds containing abundant Schellwienella rotundata. The highest beds also contain abundant crinoid fragments, as in Sipton Cleugh.

At Rookhopehead, exposure at this horizon is very poor, and no evidence of a thick sandstone below the Lower Felltop Limestone has been found. In Grove Rake Quarry, however, at least 3 feet of fine grained sandstone occur below this limestone, though it has not been observed in other localities. Carruthers (1938, Pl.13, p.252) likewise records 3 feet of sandstone below the Lower Felltop at Rookhopehead. The only other exposure in the area is in upper Beldon Burn, but here the evidence is somewhat confusing. In the main valley near Heatheryburn, a good section is exposed from the top of the High Slate Sill to the top of the Coalcleugh Transgression Beds. The Upper Rookhope Shell Bed rests quite normally on the High Slate Sill, with, 10 feet above this, a thin bed of very fine grained, fissile sandstone. However, the rest of the section is composed of shale and siltstone, and neither the Lower Felltop Limestone nor the sandstone below it is exposed. It is possible that the 5 feet of very fine grained sandstone is the only representative of the much thicker sandstone seen in Sipton Cleugh, but the absence of the Lower Felltop is puzzling. It seems difficult to escape the conclusion that it is removed by the erosive Coalcleugh Transgression Beds, which is partly represented by fine clastics. This question is discussed in more detail later (p. 68).

CHAPTER 8

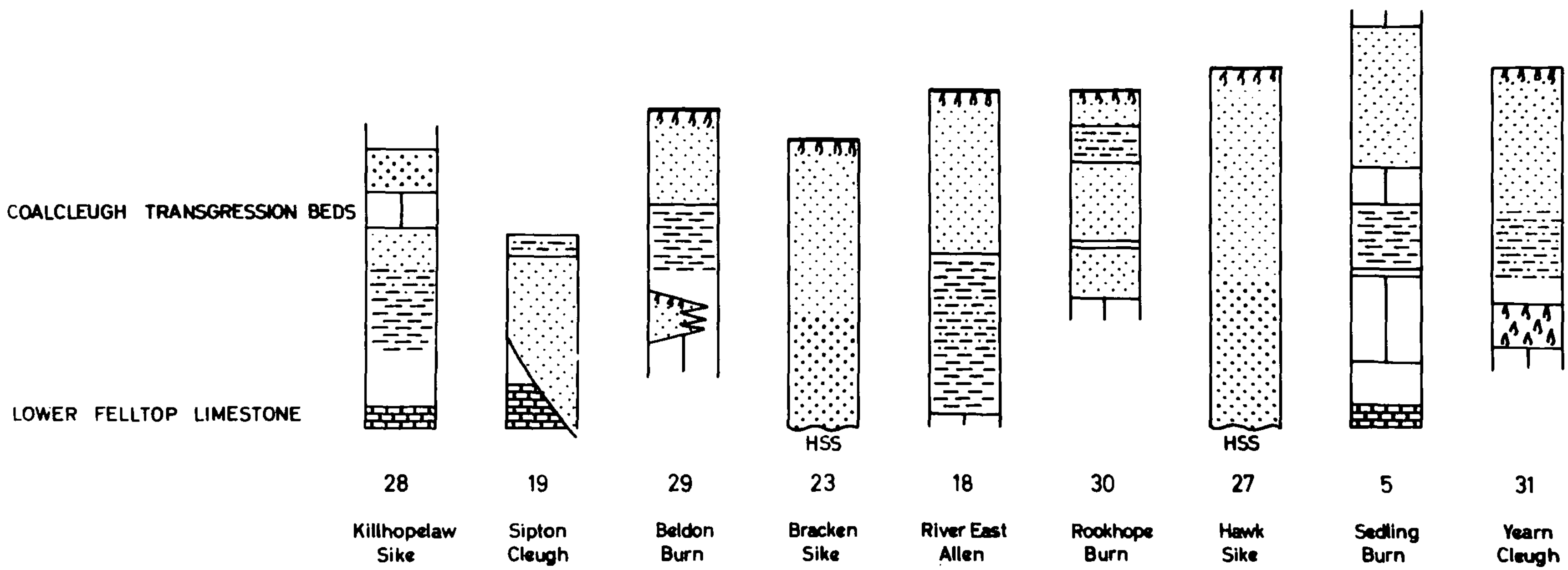
LOWER FELLTOP LIMESTONE CYCLOTHEM

The theoretical limits of this cyclothem are the Lower Felltop Limestone at the base, and the Coalcleugh Coal at the top (Fig.8.1). In many instances, to be described presently, the Lower Felltop Limestone is removed by the erosive Coalcleugh Transgression Beds, so recognition of this variable unit is based to some extent on interpretation. Exposures are moderately good throughout the area, though commonly restricted to the coarse development. In fact, in the vicinity of Hunstanworth, the High Grit Sill (equivalent to the Coalcleugh Transgression Beds) is the only representative of the cyclothem, here acquiring thicknesses ranging from 62 to 108 feet according to the Geological Survey (V.S. Sheet 63). Generally, however, thicknesses ranging from 30 to 60 feet are more common.

Lower Felltop Limestone. There is some confusion in the literature concerning the use of the term Lower Felltop Limestone. The name was first used by Burns in 1873 (G.S. Six-inch Sheet, Northumberland, 111), where he defined it as the second limestone below the Millstone Grit of Westgarth Forster (1809). The term "Lower Felltop Limestone" was used in this context by Carruthers (1938) for Alston Moor, but in an earlier publication (1925) on the Tyne area, he referred to a limestone above the Thornborough as the Lower Felltop Limestone. Although agreement is far from universal, recent work

Figure 8.1

MEASURED SECTIONS IN THE LOWER FELLTOP LIMESTONE CYCLOTHEM



on the problems of correlation within the Upper Limestone Group, suggests that the Lower Felltop on the Alston Block is, in fact, equivalent to the Thornborough Limestone in the Northumberland Trough (Whittaker, 1963). This correlation was apparently accepted by Carruthers and Robertson as early as 1956 (G.S Hexham Sheet 19). The use of the term Lower Felltop for a limestone above the Thornborough seems undesirable on these grounds. In this thesis, therefore, the name Lower Felltop Limestone is used in the sense originated by Burns, and continued by Carruthers (1938), Dunham (1948), and other workers on the Alston Block.

The Lower Felltop Limestone is believed to be present over much of the area surveyed. It is definitely absent in the north-east and east, around Hunstanworth and Rookhope, where it has been removed by the erosive High Grit Sill. Dunham (1948, p.222) reports that the Lower Felltop Limestone is locally absent in the Burtree Pasture lead workings, but it is present at outcrop in nearby Sedling and Middlehope Burns. Another factor severely limiting the value of the Lower Felltop Limestone in this study, is that it has undergone widespread mineralisation to the east of the Burtreeford Disturbance. In Sedling, Middlehope, and Rookhope Burns the limestone has been converted into ankerite and siderite, and may contain spherulitic sphalerite (Dunham, 1948, p. 219). It has been widely quarried in Middlehope Burn and at Rookhopehead for ironstone. The original texture of the limestone has been destroyed, and the carbonate has crystallised in more or less perfect rhombs. The full thick-

PLATE 16. Trough cross-stratification in the sandstone below Lower Felltop Limestone, Sipton Cleugh.

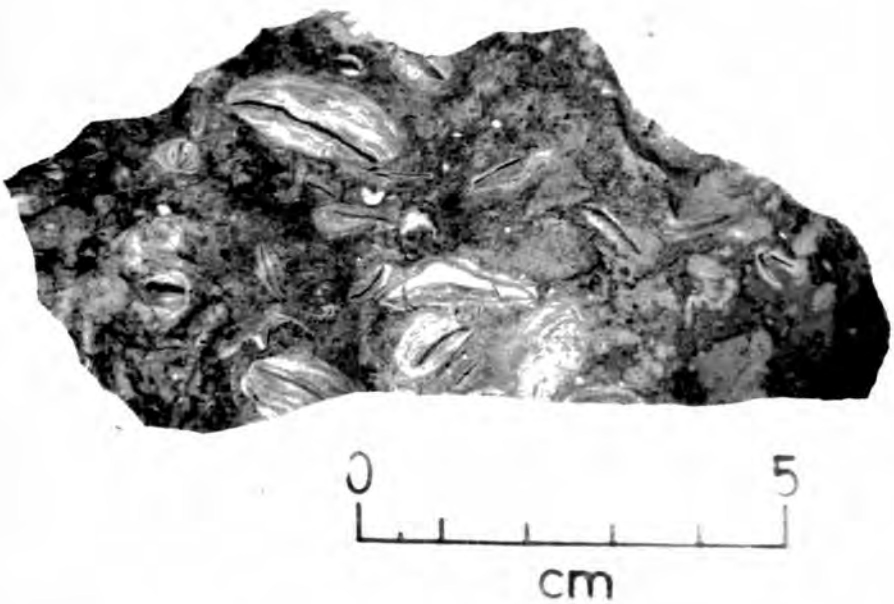


PLATE 17. Osagia nodules in the Lower Felltop Limestone, Sipton Cleugh.

ness is never greater than the average of 4½ feet quoted by Dunham (1948, p.246). The Lower Felltop Limestone is finely crinoidal and dark grey in the south of the region but light grey in the north. The limestone contains the algal form genus Osagia (Girvanella, auctt.) encrusting shell fragments (Plate 17), which has been found to be typical of the Lower Felltop Limestone in the research area. It has also been recorded outside the area on Middle Fell, west of Nenthead (Dunham, 1948, p.40), but not to the south around Middleton (Jones, 1956) or Cotherstone (Reading, 1957).

Sporadic outcrops in the streams draining Killhope Law serve to illustrate that the Lower Felltop Limestone is present over much of this district. True outcrop is encountered only in Varty's Sike, but loose blocks of dark grey algal limestone are found in Betty's Cleugh and Coal Cleugh, and rotted limestone occurs in Killhopelaw Sike. The locality at Killhopelaw Sike shows that the Lower Felltop here has a sandy base containing much shell debris, including productids and lamellibranchs. Dunham and Johnston (1962, p.249) record the full thickness of the limestone as 4 feet in this district.

The Lower Felltop Limestone in Sipton Cleugh and upper Beldon Burn has a different lithology, in that it is remarkably pure and light grey in colour. It has wavy bedding (Plate 18) and contains few macrofossils. A number of small Chaetetes colonies were seen in both localities and Osagia is present. In Sipton Cleugh the maximum thickness observed is 7½ feet, although it is completely cut out by the Coalcleugh

PLATE 18. Wavy bedding in the Lower Felltop Limestone, Sipton Cleugh.

PLATE 19. Lower Felltop Limestone, Beldon Burn.

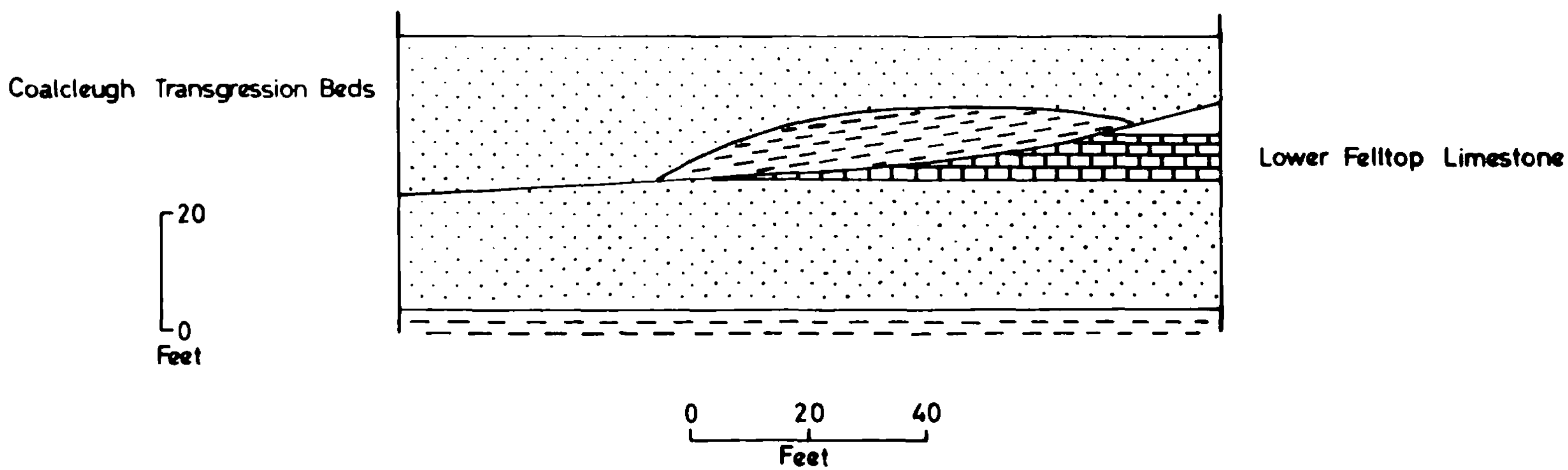
Transgression Beds within about 50 yards along the valley side (Fig. 8.2). In Beldon Burn (Plate 19), the Lower Felltop Limestone is seen for a thickness of only 3 feet, but it is recognisable by its lithology and the presence of Osagia nodules. The Geological Survey have incorrectly mapped this exposure as the Upper Felltop Limestone (G.S. Hexham Sheet 19).

Fine Clastics. The fine clastic rocks above the Lower Felltop Limestone are rarely seen in the study area. In the occasional outcrops, as in Sedling Burn, the general sequence of shale, passing into interbedded siltstone and sandstone still holds good. There are certain outcrops, as in Beldon Burn, where the fine grained rocks below the Coalcleugh Transgression Beds do not appear to belong to the usual coarsening upward cycle, but rather to the channel deposits of the Coalcleugh Transgression Beds. This is discussed in greater detail later (p. 68).

Coalcleugh Transgression Beds. Carruthers (1938) used the term "Transgression Beds" in describing this member from the type locality at Coalcleugh. Dunham (1948, p. 40), made the expression more precise when he specified it as the "Coalcleugh Transgression Beds", to avoid confusion with his "Rogerley Transgression Beds". Carruthers (ibid., p. 237) remarked that the Coalcleugh Transgression Beds are "extraordinarily variable in their details, but always present", a description with which the writer would accord. At the type locality it is, in fact, not well seen, but good exposures occur throughout much of the area. The writer agrees with Dunham (1948, p. 40) that the

Figure 8.2

SCHEMATIC SECTION SHOWING "MARGINAL FACIES" IN THE COALCLEUGH TRANSGRESSION BEDS, SIPTON CLEUGH



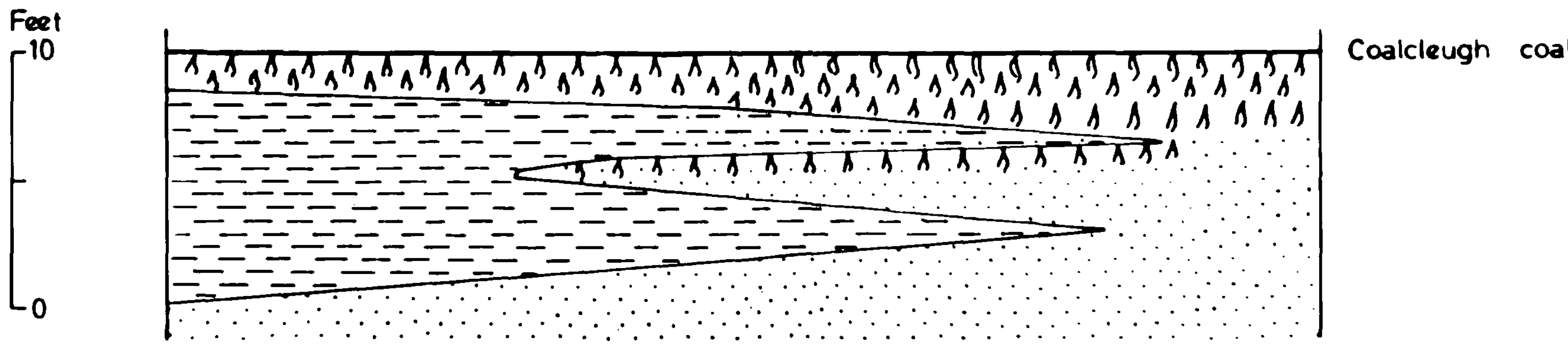
Coalcleugh Transgression Beds are equivalent to the High Grit Sill of the eastern part of the area around Hunstanworth and Rookhope (Fig. 8.4). Use of the latter term will be continued in this thesis, as it usefully describes the coarse clastic development of the Coalcleugh Transgression Beds in that vicinity. The thickness of the coarse clastic sediments of this cyclothem varies from 15 feet (upper Beldon Burn) to 108 feet (Routh's Shaft, Derwent Mines). Most commonly, however, it averages 25 to 50 feet thick (Fig. 8.1).

It is interesting to note that, in a study of the rocks in the Cotherstone Syncline, Reading (1957, p. 43) recorded two facies of the Coalcleugh Transgression Beds. His "mixed facies", or Coalcleugh Transgression Beds *sensu stricto*, were shown to be the lateral equivalents of the "grit facies", or Transgression Beds Grit (*ibid*., p. 44). It will be shown later that exactly the same situation occurs in the present area. The Coalcleugh Transgression Beds are of "mixed facies" as defined by Reading, and the High Grit Sill is the sedimentological equivalent of his Transgression Beds Grit.

Typical exposures of the Coalcleugh Transgression Beds can be seen in Rookhope Burn west of Grove Rake Quarry, in Middlehope Burn, and in East Allendale south of Allenheads. Commonly in this area, as at Rookhopehead and Yearn Cleugh (Middlehope), there are two arenaceous horizons, separated by a few feet of plant rich silty shales. The basal sandstone is at least 13 feet thick, and contains *Stigmaria* in parts. In Grove Rake Quarry, the lower, massive sandstone contains

Figure 8.3

SKETCH SECTION SHOWING INTERDIGITATING RELATIONSHIPS OF ROCK TYPES IN COALCLEUGH TRANSGRESSION BEDS, FRAZER'S QUARRY



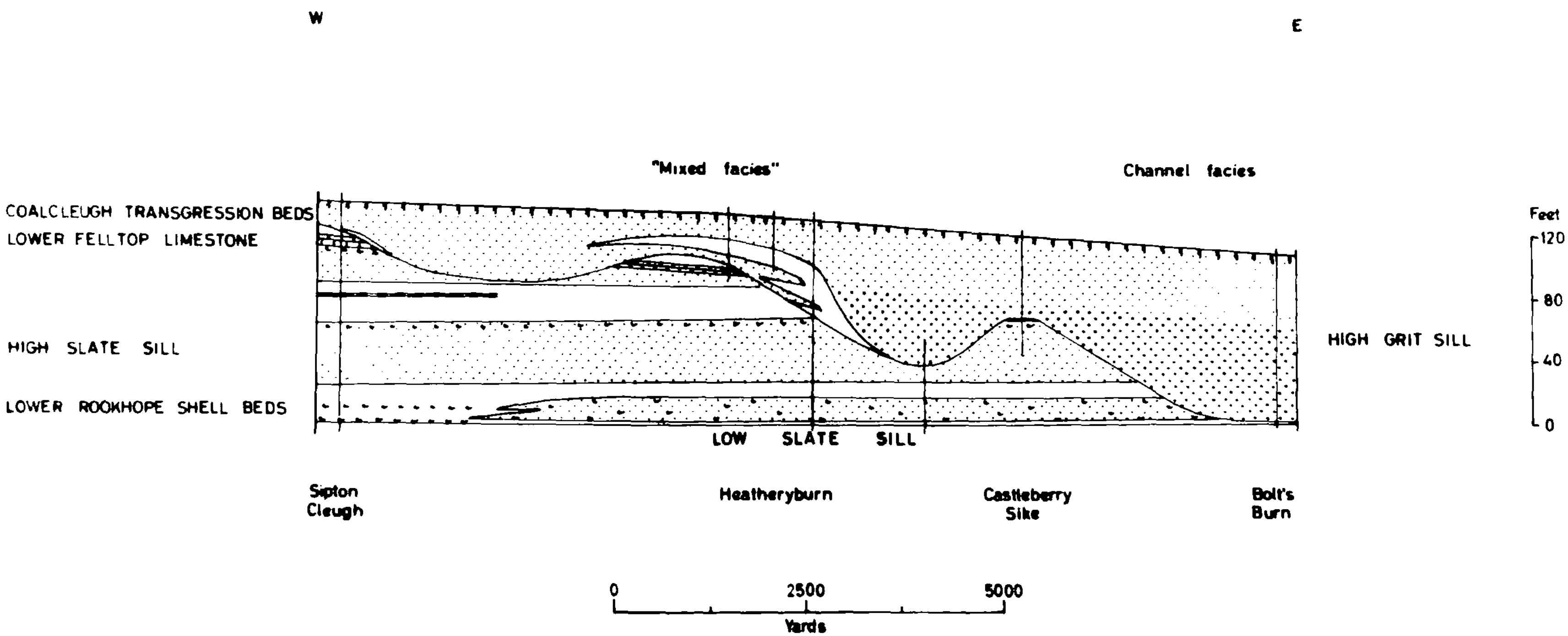
abundant U-shaped worm burrows. The upper sandstone is medium to fine grained, often highly carbonaceous and usually with some ripple lamination. A thin ganister, 1 to 2 feet thick invariably follows. This ganister is, in fact, the most commonly exposed part of the Coalcleugh Transgression Beds in the vicinity of Killhope Law, largely because of the extensive opencast workings for the Coalcleugh Coal. The seatearth is represented by a medium to fine grained sandstone with small sphaerosiderite concretions.

The channel-fill nature of the Coalcleugh Transgression Beds in the Sedling-Middlehope district suggested by Dunham (1948, p. 222), may be indicated by the slight change in facies which the beds undergo in Sedling Burn, where they are represented by 20 feet of medium to coarse grained sandstone with large scale cross-stratification. A similar lithology, but with included shale-fragments, occurs at Middlehopehead. In Frazer's Quarry, Rookhopehead, 22 feet of medium to coarse grained sandstone are exposed, and the upper part is seen to interdigitate with a series of plant-rich siltstones and sandstones of more typical "mixed facies" (Fig. 8.3). A similar interdigitation, but on a larger scale, is believed to take place between the Coalcleugh Transgression Beds and the High Grit Sill of the eastern part of the area. This transition can be deduced from the sequence seen in Beldon Burn (Fig. 8.4).

The best exposures of the <u>High Grit Sill</u> are found in Hawk Sike (Rookhope), the many tributaries of Nookton Burn,

Figure 8.4

SCHEMATIC VERTICAL SECTION THROUGH THE COALCLEUGH TRANSGRESSION BEDS



and the lower reaches of Beldon Burn. The High Grit Sill belongs to a highly erosive channel facies, whose base occurs at varying horizons. Invariably, the Lower Felltop Limestone and the Upper Rookhope Shell Beds are removed in this eastern district, so that the High Grit Sill rests on the High Slate Sill (Fig. 8.4). At Rosa's Bower, Nookton Burn, even this is removed, although at Stogel Cleugh (Rookhope) the base occurs about 2 feet above the High Slate Sill. Carruthers (1938, p. 239) misinterpreted the Hawk Sike section (Fig. 8.1) where he incorrectly believed that his "High Grit Sill" was the equivalent of the High Slate Sill. He considered that his "High and Low Grit Sills" joined to form his "Grit Sill" (= the Low Slate Sill of this thesis) at Coalcleugh (ibid., Fig.1, p.248).

Description of the lithology of the rocks comprising the High Grit Sill is rendered simple by the fact that there is a remarkable uniformity within much of the channel. There is always a sharp lithological break to mark the base of the High Grit Sill, and the first deposits are of coarse to very coarse subarkoses with large scale cross-stratification. Quartzite pebbles up to 1 cm., shale fragments, and large fragments of fossil trees may occur in these basal deposits. The average grain size of the formation diminishes upwards, becoming a medium grained sandstone with less well pronounced cross-stratification, and, eventually, a medium to fine grained sandstone with small scale trough cross-stratification. The latter sandstone may contain calcareous concretions, and may pass up into an even finer development, with silty shale

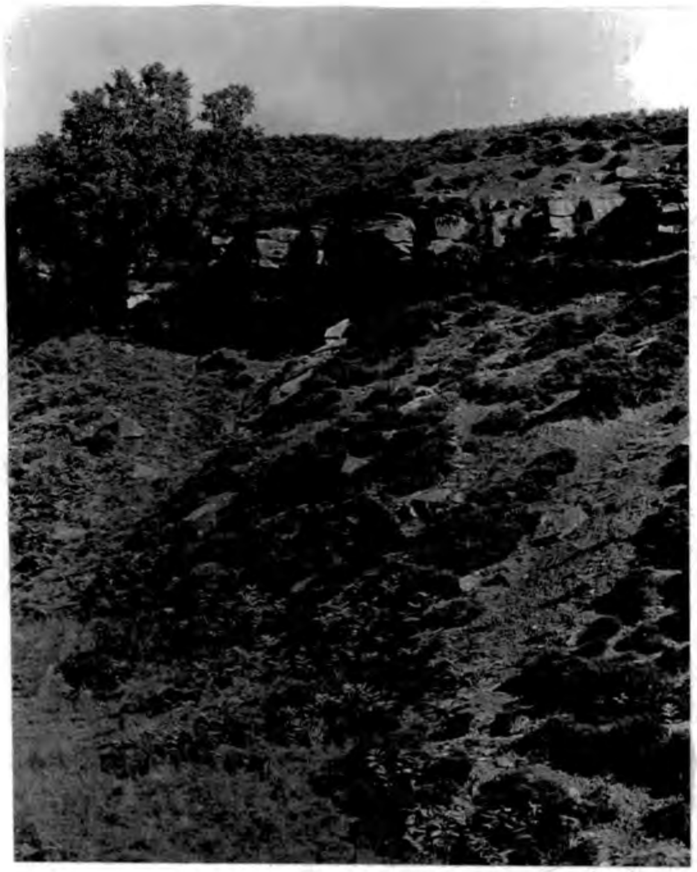


PLATE 20. Coalcleugh Transgression
Beds, Beldon Burn.

resting below the Coalcleugh Coal. Commonly, but by no means invariably, there is a ganister with Stigmaria about 2 feet thick on top of the High Grit Sill.

In Beldon Burn, the fining upwards sequence of the High Grit Sill holds good for sections east of Nocham Burn. In this burn, and in all exposures to the west, the coarse sandstone facies of the High Grit Sill is no longer in evidence. Instead, there are a series of sandstones and siltstones more typical of the Coalcleugh Transgression Beds. At first, the Coalcleugh Transgression Beds are represented by a single sandstone, only 15 feet thick. This has a well-developed ganister on top, and consists largely of medium to fine grained sandstone, frequently with ripple lamination. Many bedding planes are coated with comminuted carbonaceous material. The sandstone has a rather rapid transition into the siltstone below. This sequence is seen in Beldon Burn at the mouth of Heathery Burn, where 28 feet of shale can be seen below the Coalcleugh Transgression Beds (Plate 20). The absence of the Lower Felltop Limestone in this section (p. 59) must indicate that the fine clastics here belong to the erosive channel facies of the Coalcleugh Transgression Beds (Fig. 8.4). Another alternative is that the Lower Felltop Limestone was not deposited in this district, but its presence only three-quarters of a mile away to the west, with exactly the same lithology as seen at Sipton Cleugh, strongly suggests that it would not die out so quickly. As if to emphasise the complex variations within the Coalcleugh Transgression Beds, another medium to fine grained sandstone appears, just upstream of Heathery Burn, only 11 feet below the topmost sandstone. This is at least 8 feet thick, and has an impure coal 12 inches thick, on top. The sandstone dies out completely only 200 yards to the east (Fig. 8.4). This twofold arenaceous development of the Coalcleugh Transgression Beds is comparable with that seen at Rookhopehead and Yearn Cleugh, and is maintained in every outcrop to the west of this locality. As already noted, the erosive base of the Coalcleugh Transgression Beds rises sufficiently to reveal the Lower Felltop Limestone near Green Cleugh (Fig. 8.4).

The Coalcleugh Transgression Beds in Sipton Cleugh are of interest, not only because they can be observed to remove completely the full thickness of the Lower Felltop Limestone, but also because there is a further development of fine grained clastics within the channel facies. Here the base of the Coalcleugh Transgression Beds is locally marked by an impure coal, which reaches 9 inches in thickness, although sandy detritus contributes greatly to this. A lenticular series of black sandy siltstones with thin, medium grained sandstone ribs has a restricted development above the coal (Fig. 8.2), and this gradually passes up into the medium grained sandstone which comprises most of the Coalcleugh Transgression Beds. The sandstone at this locality has a unique trough bedded structure which is described elsewhere (p. 234). Generally, however, bedding appears to be fairly regular and the sandstone passes up into a sandy siltstone, and, eventually, a yellow-weathering clay.

The Coalcleugh Coal is apparently 16 to 22 inches thick in the vicinity of Coalcleugh, where it has been extensively worked. Over most of the area, however, it is only represented by an impure coal varying from 1 to 6 inches thick. Only in two sections, Smithy Cleugh (Nookton) and Hawk Sike (Rookhope), does it reach 16 inches. The Coalcleugh Coal does not appear to have been worked outside the Coalcleugh district.

CHAPTER 9

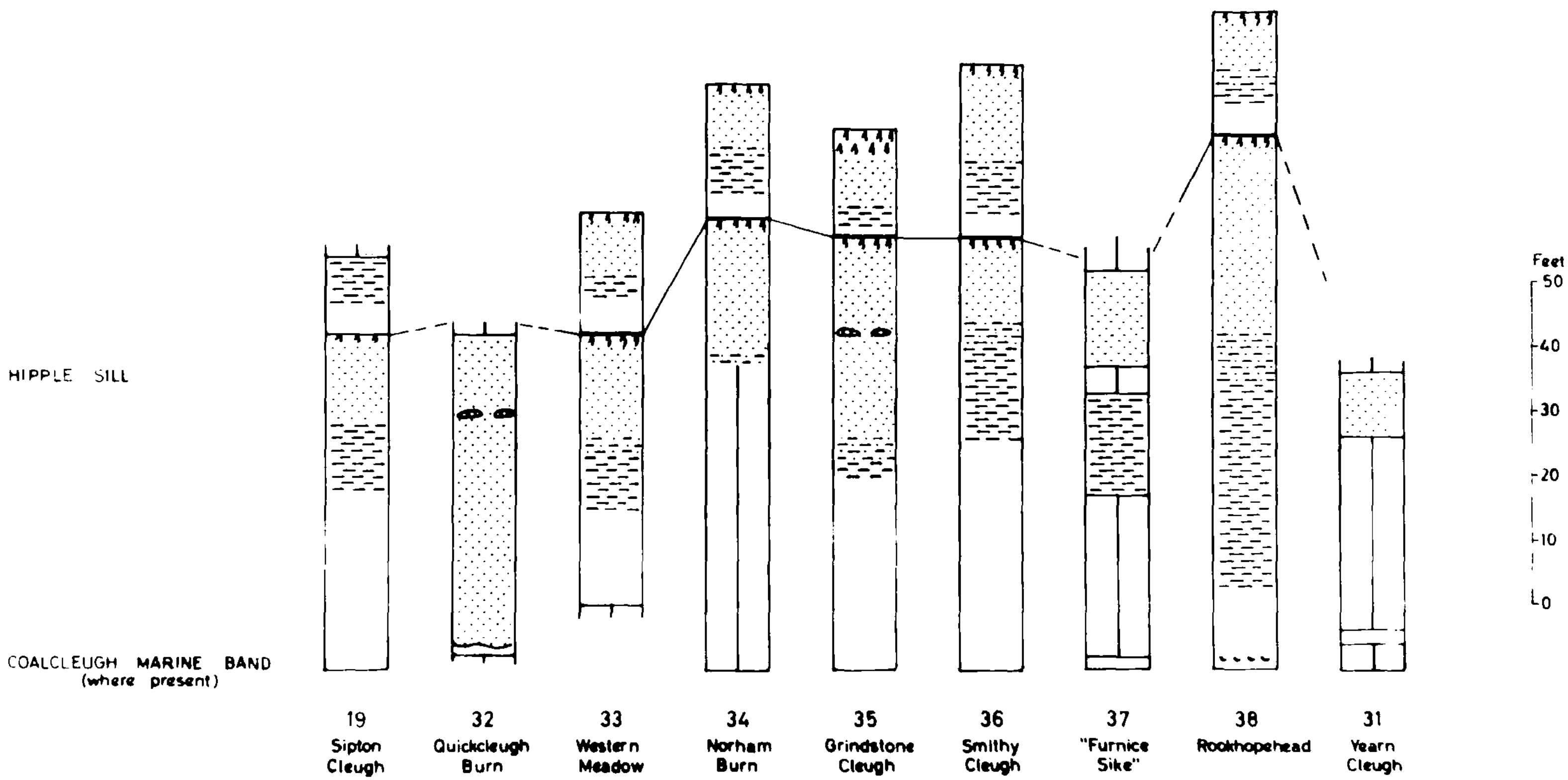
COALCLEUGH BAND CYCLOTHEM

The Coalcleugh Marine Band, which forms the base of this cyclothem, is not always developed, but the cyclothem can be recognised over most of the study area; the top is taken as the base of the Upper Felltop Limestone. It must be emphasised, however, that the uppermost 20 feet or so of this cyclothem, i.e. those beds between the Hipple Sill and the base of the Upper Felltop Limestone, could be regarded as a separate cyclothem (Fig. 9.1). They exhibit all the features of an Upper Limestone Group cycle, except that no marine band is present. However, in view of their small thickness, their simple nature, and their poor exposure, they are included as a "minor" cyclothem in this section, but described separately. Exposures of the Coalcleugh Band Cyclothem are generally poor in Weardale, where it crops out at a high level, and tends to be masked by peat. Excellent exposures occur at Rookhope-head, in Nookton and Beldon Burns, in Sipton Cleugh, and, to a less extent, at Coalcleugh. On the whole, the unit up to the top of the Hipple Sill is quite thick, averaging 80 to 90 feet in Rookhope and Nookton Burns, although a value of only 50 feet was recorded in Routh's Shaft by the Geological Survey (V.S. Sheet 63).

<u>Coalcleugh Marine Band</u>. The type locality of the Coalcleugh Marine Band is Coalcleugh (Carruthers, 1938), where it was discovered in the opencast workings in the Coalcleugh

Figure 9.1

MEASURED SECTIONS IN THE COALCLEUGH MARINE BAND CYCLOTHEM



Coal. The disused workings are rapidly becoming overgrown, and, although the Marine Band can still be seen in places, better exposures are afforded by the abandoned ironstone quarries in Rookhope Burn. The first 6 to 18 inches of shale above the Coalcleugh Coal are generally not fossiliferous. They do, however, contain worm burrows and, rarely, chitinous brachiopods such as Lingula mytilloides. The Marine Band proper occurs above this burrowed shale, and simply comprises black shale with large siderite nodules and a scattered brachiopod and molluscan fauna. The brachiopods generally die out after not more than 2½ feet. The following fauna has been collected:-

Composita ambigua (J. Sowerby)
Dictyoclostus sp.
Krotovia sp.
Orbiculoidea sp.
Productus aff. concinnus J. Sowerby

Lamellibranchs

Conularia quadrisulcata Sowerby
Euphemites urei (Fleming)

Gnathodotidae

Fish scales

The impersistent nature of the Coalcleugh Marine Band is well known (Carruthers, 1938, p. 238; Reading, 1957, p. 46), and, although exposure is not always good at this horizon, it appears to be absent in Nookton Burn and Sipton Cleugh. Reading (*ibid*., p. 46) has suggested that differential compaction of the underlying sediments was the cause of its localised distribution.

Generally, about 15 feet above the base of the cyclothem a coarser detrital fraction appears and initiates the gradual upward passage through silts and silty sandstones to the Hipple Sill. The lower siltstones at least may still contain thin-shelled lamellibranchs, as well as plants such as cf. *Lepidostrobus*. A local channel facies is, however, developed in the Hipple Sill in Quickcleugh and here the contact is abrupt and presumably erosional.

Hipple Sill. The term Hipple Sill originated in the Derwent mining district, where it came to be used for a prominent sandstone lying between the High Grit Sill and the Upper Felltop Limestone. According to Dunham (1948, p. 41) the Hipple Sill is the equivalent of the Low Grindstone Sill on Killhope Law. Its thickness ranges from 15 to 30 feet as a rule, but a thickened succession of 50 feet is recorded at Quickcleugh in the position of the postulated channel. Values up to 40 feet have also been recorded in several shaft sections in the Derwent Mines (V.S. Sheet 63).

The Hipple Sill retains essentially the same lithological characteristics over a wide area to the east of the Burtreeford Disturbance, apart from a broad belt extending south-east from Sipton Cleugh to Rookhope (Fig. 9.2). The more typical development will be described first. The base

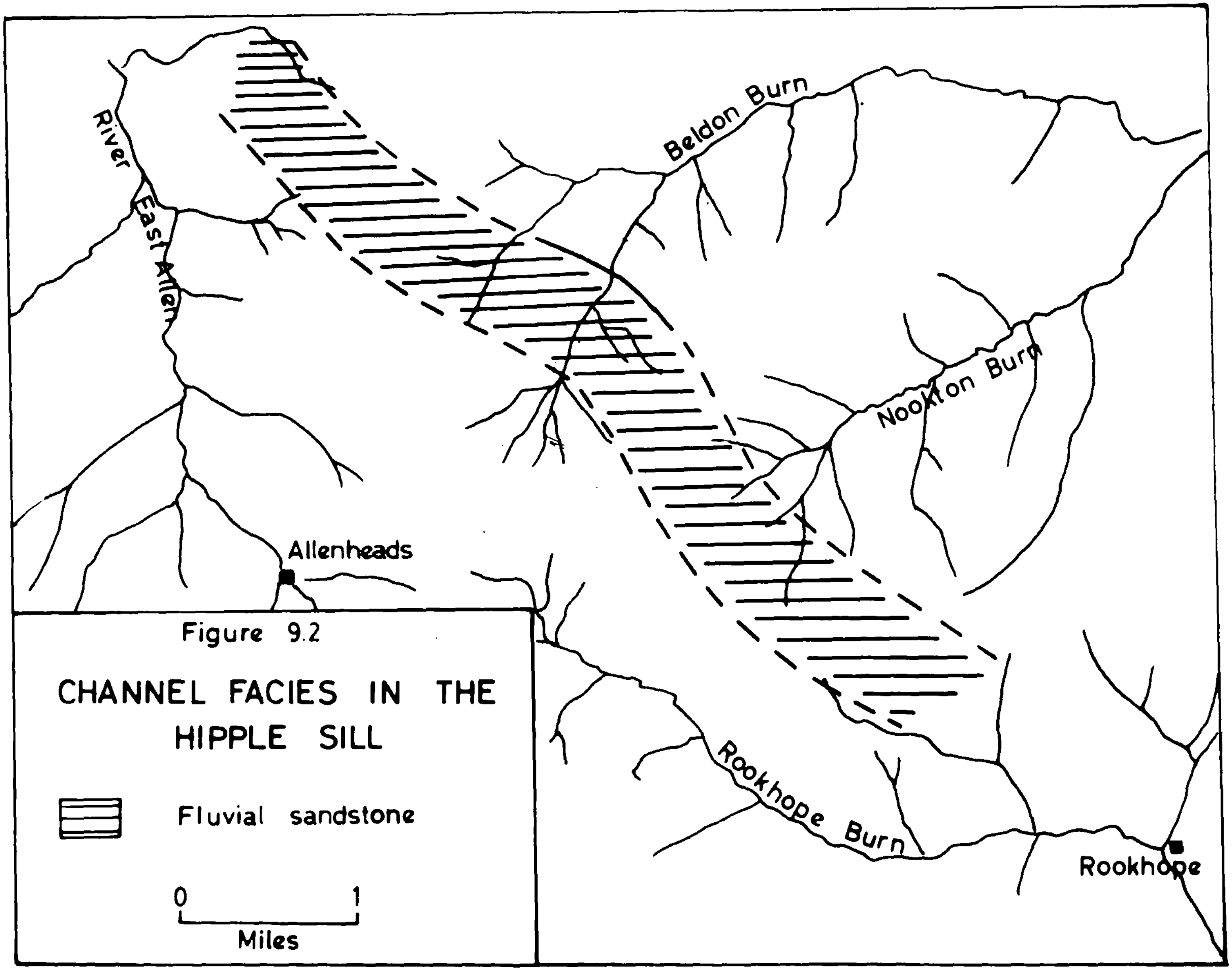


Figure 9.2

CHANNEL FACIES IN THE HIPPLE SILL

of the Hipple Sill is transitional to the siltstones below, and the siltstone intercalations in the lower part often contain abundant tubes and trails on the bedding surfaces. The sandstone itself is medium to fine grained, with a finely banded appearance due to the variable amount of detrital carbonaceous material. Ripple-lamination is usually well developed, but this alternates with perfectly regular, uniform lamination, often with parting lineation. Large worm burrows, which may be U-shaped, are quite common. In two widely spaced localities, one in Beldon Burn and the other in Grove Rake Quarry (Rookhope), small scale penecontemporaneous slumping has taken place (Plate 21). Development of large calcareous nodules is a very common feature of the Hipple Sill, although these have not been seen in Rookhope Burn. The nodules reach 2 feet in thickness and always follow the bedding. The top of the Hipple Sill is invariably a seatearth, with a vitrainous coal above it. In Nookton Burn there is usually a 6 inch ganister followed by 2 to 3 feet of silty fireclay below a coal which is 4 to 7 inches thick. In Beldon Burn and Rookhope Burn, where the seatearth is entirely arenaceous, containing large _Stigmaria_, the coal is much thinner (only 1 to 2 inches) and less pure.

The channel facies of the Hipple Sill is well seen in Sipton Cleugh, where the medium to fine grained, cross-stratified sandstone rests with an apparently erosive base on black shale. The sandstone also contains shale-fragments, presumably derived from the shale below. Towards the top of

PLATE 21. Small scale convolutions in Hipple Sill, Grove Rake Opencast, Rookhope Burn.

PLATE 22. Large scale symmetrical ripple in Hipple Sill, Sipton Cleugh.

the Hipple Sill the sandstone becomes trough cross-stratified, and large scale symmetrical ripples occur (Plate 22). No discrete ganister can be seen on top, although localised zones with rootlets in situ can be distinguished. A very similar sequence is seen in Quickcleugh and Black Burns, where 50 feet of continuously exposed sandstone can be observed; the same facies is also well exposed at Nooktonhead. In Quickcleugh Burn, the base of the Hipple Sill is very variable in height. In Western Meadows Sike, it has the "normal facies" described earlier, but, only 400 yards to the south-west, the Hipple Sill has changed to the channel facies, which has an erosive base at a much lower level. As before, the lowermost beds are composed of medium grained sandstone with large scale cross-stratification, and contain shale-fragments and plant remains. The sandstone becomes slightly finer grained above, and begins to develop small scale, trough cross-lamination. The usual, thin calcareous horizon is still developed. Within the upper parts local erosion has taken place on a small scale, presumably representing contemporaneous channels. Frequently, sandy shale intercalations appear at the top of the sill, with the usual fireclay and coal forming the topmost beds. This channel facies can be followed through a series of poorer exposures in Rookhope Burn, where the Hipple Sill may locally be a coarse grained sandstone (Fig. 9.2).

It is interesting to note that Reading (1957, p. 45) records that the sandstone below the Upper Felltop

Limestone in the Cotherstone district contains a "grit" development in one locality, and that he infers a correlation with the "third grit" of the Transgression Beds Grits. If this is the equivalent of the Hipple Sill, it would appear that channeling is a not uncommon feature of this horizon. A coarse, cross-stratified development has also been recorded by Green (1954) in Devil's Water to the north of the present area.

Little, unfortunately, can be seen of the Hipple Sill in the district to the west of the Burtreeford Disturbance. Exposures in the western tributaries of the River East Allen indicate that it is still a medium grained sandstone with occasional plant fragments and worm burrows. Farther west, however, in the opencast workings at Coalcleugh, and in "Killhopehead Bridge Sike", it is highly likely that another channel occurs. Here the sandstone is medium grained, tending to coarse, and is well cross-stratified; it contains large shale fragments and tree-fragments. The base of the Hipple Sill is not seen in this region, but it is suspected that it is one of erosion. The top of the sandstone, also, is never seen.

"Minor Cyclothem" above the Hipple Sill. This very thin unit is only recognisable in Rookhope, Nookton and Beldon Burns. It cannot be ascertained whether it occurs in other areas, largely on account of poor exposure. Previous authors have not recorded the rhythmic nature of the deposits (Fig. 9.1), although Dunham (1948, p. 41) briefly describes them. None of the members has been given a name. The average thickness of the unit ranges from 20 to 25 feet, but values as low as 10 feet, (Shildon Shaft), and as high as 37 feet (Little Nookton Burn) have been recorded.

The black shale which immediately overlies the coal on top of the Hipple Sill has never been observed to contain marine fossils; it may, however, contain plant remains. The shale is very thin, usually between 1½ and 2½ feet thick, and passes up into dark grey, micaceous siltstones. About half of the unit is composed of coarse clastics, and there is always a perfect transition from the siltstones to the sandstones. However, in Taylor's and Shildon Shafts (V.S. Sheets 63, 62), the sandstone is apparently missing altogether. Where seen, most of the sandstone is fine grained and highly laminated, occasionally with good symmetrical ripples. The top 2 to 3 feet are in face composed of medium grained sandstone which has rootlets _in situ_. There appears to be no coal above this ganister, and the Upper Felltop Limestone rests directly on it.

CHAPTER 10

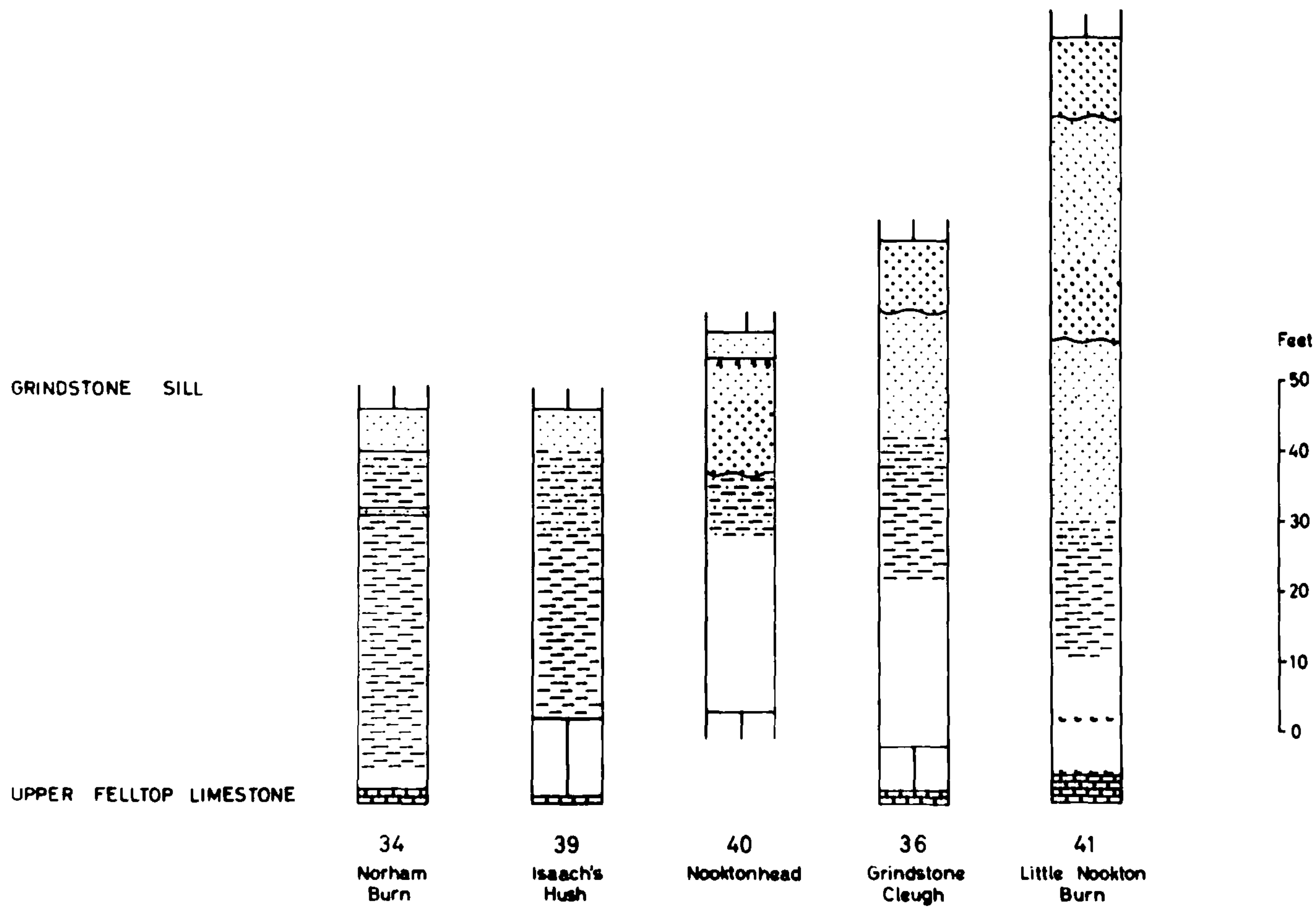
UPPER FELLTOP LIMESTONE CYCLOTHEM

The marine horizon marking the base of this cyclothem is the Upper Felltop Limestone. The top of the cyclothem is equally well-defined in theory, being the top of the widespread Grindstone Sill. In practice, however, it is not frequently seen, occurring as it does, on the flat peat-covered tops of the fells. The best exposures of the cyclothem occur in Rookhope, Nookton, and Beldon Burns (Fig. 10.1). In the Derwent Shafts (V.S. Sheet 63), the recorded thickness is 85 feet, of which 55 feet are composed of fine clastics. At outcrop, values of 40 to 55 feet for the latter are common, although a figure as low as 30 feet has been recorded from Bracken Sike in Nookton Burn.

Upper Felltop Limestone. As with the Lower Felltop Limestone, a certain nomenclature problem exists with the Upper Felltop Limestone. The name was coined by Burns in 1873 (Six-inch Sheet, Northumberland, 111) for the highest limestone beneath the "Millstone Grit". It is presumed to be equivalent to the "Felltop Limestone" of Forster (1821, p. 97). Subsequently, the term has been used by Carruthers (1925) for a limestone in the Tyne Valley, which appears to be at a different horizon. The expression "Upper Felltop Limestone" is, therefore, used here in its original context, following Dunham (1948) and other recent workers. In the study area the full thickness of the Upper Felltop Limestone is rarely, if ever, seen. The maximum thickness seen is 3

Figure 10.1

MEASURED SECTIONS IN THE UPPER FELLTOP LIMESTONE CYCLOTHEM



feet in Heathery Burn (Beldon), but values ranging from 5 to 8 feet appear to be more typical of the Derwent Shafts (V.S. Sheets 62,63). The Upper Felltop Limestone retains a constant lithology throughout the area. It is a dark grey, often highly crinoidal limestone, which is sometimes seen to have a sand-rich base greatly disturbed by burrowing organisms. "Caudagalli" markings may proliferate, giving the rock a platy aspect, but usually it is more massive. It is characteristically rusty weathering and, when highly weathered, may be represented only by a decalcified, ochreous clay known locally as "famp". When fresh the limestone contains clots of iron sulphide, which probably accounts in large measure for the ferruginous weathering. The Upper Felltop Limestone contains a diversified fauna, the most constant member being Fenestella sp., which occurs abundantly in every sample studied in thin-section. The following list has been compiled from all localities:-

Zaphrentids indet.

"caudagalli"

Fenestella sp.
Stick bryozoa

Athyris sp.
Camarotoechia pleurodon (Phillips)
cf. Derbyia sp.
Dictyoclostus sp.
Eomarginifera longispina (J. Sowerby)
Lingula sp.

Phricodothyris sp.

Productus productus (Martin)

Pustula sp.

Spirifer bisulcatus J. de C. Sowerby group

Nuculids

Gasteropods

Weberides mucronatus (M'Coy)

Ostracods

Fine Clastics. The fine clastic rocks above the Upper Felltop Limestone follow essentially the same pattern observed in all other cyclothems in the Upper Limestone Group. The black shale at the base gives way to dark grey, micaceous siltstones, and these, by the intercalation of fine sandstones, eventually pass into the Grindstone Sill. It is interesting that the Geological Survey record 14 feet of "cockle beds" 28 feet above the Upper Felltop Limestone in Jeffrey's Shaft (V.S. Sheet 63). According to Dunham (1948, p. 42) these thin to 2 feet in Taylor's Shaft, less than a half-mile away. Despite relatively good exposures, this horizon is scarcely identified at outcrop. In Smithy Cleugh (Nookton) there is a thin shell bed containing *Spirifer sp.* only 10 feet above the limestone, which may or may not be the "cockle bed" of the Geological Survey. There is another example of a thin shell bed occurring at a relatively high position in the shales below the Grindstone Sill in Silly Sike (Beldon). On the other hand, there is some evidence for a marine horizon within the Grindstone itself, which is discussed later (p. 84). In any case, Dunham's evidence indicates that it is subject to rapid changes in character.

Grindstone Sill. The Grindstone Sill is a member which has been known on the Alston Block since Westgarth Forster first introduced the term in 1809. The type area is the Allendale-Weardale Watershed, where it is exposed in a series of shallow quarries. Unfortunately the full thickness is not often seen, but generally it would appear to be at least 30 feet, and occasionally up to 55 feet thick. Considerations as to its thickness are complicated by the lack of information concerning the beds above the Grindstone Sill. There is a strong possibility that the merging with a sandstone normally above the Grindstone, perhaps due to the erosive nature of the former, may give the impression of increased thickness. In fact, over much of the area, an appreciable sandstone member has been separated from the main Grindstone Sill outcrop. This interpretation is based on the presence of a distinct topographical feature. Although the intervening beds are nowhere seen, this is taken to indicate a fine grained (perhaps shaly) intercalation. This rather speculative upper sandstone is medium grained with small scale trough cross-stratification. It must still be regarded as part of the Grindstone Sill, because it maps into the top part of this member at Ferney Gill (Bolt's Burn). The ganister and coaly beds on top can be traced for a short distance to the west of Ferney Gill, and confirm this correlation. Perhaps some support for this interpretation is afforded by Dunham (1948, Fig. 25, p. 269), who records an apparent split in the Grindstone Sill along the section of Jeffries Vein.

The Grindstone Sill has a very variable lithology, which is further complicated by the development of an erosive facies. This feature is well seen in Nookton and Beldon Burns. It is likely that it is represented by the "coarse grit lenses" in the Grindstone Sill near Middleton-in-Teesdale (Jones, 1956, p. 99). As a rule, however, the base of the Grindstone is transitional to the siltstone below. Both the thin, fine grained sandstone intercalations in the siltstone, and the lower, fine grained part of the Sill itself, have well developed ripple lamination. This eventually passes up into the medium grained flaggy sandstone which is characteristic of much of the Grindstone Sill. Shale fragments may be abundant on some bedding planes, and U-shaped burrows occur sporadically within the sandstone at some localities. No generalisations can be made concerning the stratification, because both planar and festoon cross-stratification, as well as regular stratification, occur. The erosive facies occurs at various levels in the medium grained sandstone just described, but never cuts down very far into the siltstones below. The base of this facies is very irregular, and shows most of the features previously described for the channel facies of the Low and High Grit Sills. The lowermost beds are usually coarse to very coarse felspathic sandstones with large scale cross-stratification.

They may contain quartzite pebbles up to 2 cm., or derived siderite nodules up to 6½ cm. Large shale fragments and fossil plants are usually much in evidence. This coarse facies is usually less than about 12 feet thick, and it passes up into medium grained sandstone, which eventually develops small scale trough cross-stratification. Commonly the uppermost exposure of the Grindstone is of a poor ganister, which may or may not represent the actual top. In Little Nookton Burn, the top of the Grindstone appears to be marked by a white, leached clay, upon which rests a second development of coarse felspathic sandstone (Fig. 10.1). This is presumed to represent a second erosive phase, which, for want of detailed evidence, must be regarded as belonging to the Grindstone Sill episode.

An interesting sequence occurs in Ferney Gill (Bolt's Burn), where the Grindstone Sill is a uniform, medium to coarse sandstone throughout, with the usual large shale fragments and plant remains. Six feet below the top of the Grindstone a great deal of disseminated carbonaceous material and actual plants appear, which, after 3½ feet, develop into thin lenses of coal, 2 inches thick at maximum. The remainder of the bed is a good ganister, followed by a 3 foot vitrainous coal plus 3½ feet of vitrainous shale. Whether this thick coal is developed above the Grindstone Sill at other places within the area cannot be ascertained by surface mapping.

In East Allendale, there is a strong possibility that a marine horizon is developed within the Grindstone Sill itself. In two localities, near Green Quarry in the north, and at Byerhopehead Quarry farther south, loose fragments of crinoidal sandstone with Schellwienella sp. and athyrids, have been found. It is debatable whether this represents a widespread marine horizon, and, if it does, whether it is equivalent to the "cockle beds" below the Grindstone Sill in Jeffrey's Shaft, or to the Fossil Sandstone of the Cotherstone area (Reading, 1957, p. 47).

The rather poor outcrops of the Grindstone Sill in Weardale and around Killhope Law contribute little to the preceding description. Large scale contemporaneous slumping occurs within the sandstone on Sedling Fell (Plate 80). Carruthers records the complete removal of the Grindstone Sill by the Basement Grit to the west of Corbitmea Dam in Rookhope Burn. No evidence can be obtained to substantiate this statement, however, and the Grindstone Sill is apparently still well developed in this district. The writer also fails to agree with the mapping of the Geological Survey (One-inch Sheet 102 N.E., 1883) on the fell east of Killhope Law. They indicate here that the topmost sandstone is the Grindstone Sill, whereas, purely from thickness considerations and general mapping, it is clear that it must be the Hipple Sill. Another disagreement with the Geological Survey mapping concerns the coarse sandstone seen at Saxtonlaw Old Quarry. The Geological Survey record this as the First Grit, but the author's mapping has shown that it is more likely to be the coarse facies of the

Grindstone Sill.

Although there is no substantiating evidence in the present area it is possible that the Botany Grit of the Cotherstone region is equivalent to the coarse upper leaf of the Grindstone Sill, and not, as suggested by Reading (1957, p. 48) the "First Grit" (p. 89). Certainly the field relations are very similar in the two districts. Reading's correlation is supported by Jones (1956, p. 341), but it is now known that the "First Grit" is of R zone age (Summ. Prog., 1962), whereas the Botany Grit is unquestionably E zone.

C H A P T E R 11

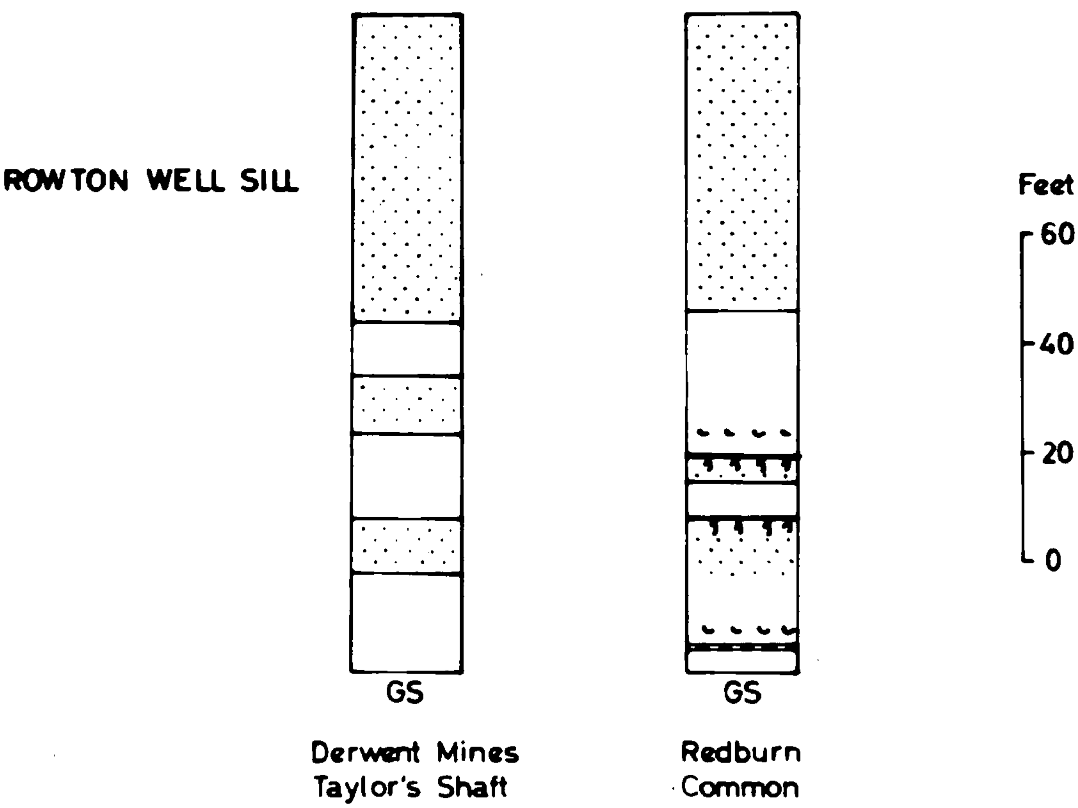
ROWTON WELL FORMATION

This formation includes those beds between the top of the Grindstone Sill and the top of the Rowton Well Sill (or "First Grit"). Exposures above the Rowton Well Sill are, in fact, very poor, so a brief description of these beds will be included at the end of this section. The best exposures are, again, in the north-east of the area, in the tributaries of the River Derwent, and, to a less extent, in Rookhope Burn. Knowledge of the thicknesses of the various members of the Rowton Well Formation is sparse. In Taylor's Shaft (V.S. Sheet 63), 64 feet of sandstones and shales were recorded below the Rowton Well Sill, which is 57 feet thick. In Routh's Shaft, however, 86 feet of fine clastics occur below the Rowton Well Sill (Fig. 11.1).

Fine Clastics. Above the Grindstone Sill in Nookton Burn there is a series of black shales, which contains thin sandstones with a siderite cement. One sandstone, however, has a chloritic matrix, giving it a strong green colour in hand specimen. It is interesting to note that Jones (1956, p. 99) records an identical sandstone in the same position only a few miles to the south in Teesdale. The shales in this sequence contain abundant Lingula mytilloides, and the sandstones contain a good fauna of brachiopods and molluscs.

Figure 11.1

DIAGRAMMATIC SECTION THROUGH THE ROWTON WELL FORMATION



This includes:-

Composita ambigua (J. Sowerby)

Productus concinnus J. Sowerby

Pustula sp.

Edmondiid

Nuculid

Planospiral gasteropods

Pleurotomariids

Above this series there is a white siltstone having a ganister on top, 2 feet thick, which is believed to be equivalent to a similar horizon seen in Rookhope Burn just north of Grove Rake Quarry, and in Hawk Sike. Here there is a white, fine grained sandstone containing rootlets *in situ*. It has a thin, coaly shale above, which contains some vitrainous material. It is noteworthy for the overlying 7 feet of black shale which contains abundant small sphaerosiderite concretions averaging 0.2 mm. in diameter; above this are 4 feet of fireclay and 6 inches of impure coal. This coal horizon is also seen in Ferney Gill (Derwent), where it overlies a thin, medium grained sandstone with ripple lamination. Following the impure coal are varying thicknesses of black shale with siderite nodules. In Rookhope, 15 feet are seen, and contain a shell bed from which the following have been collected:-

Crinoid columnals

Camarotoechia pleurodon (Phillips)

Productus concinnus J. Sowerby

Schellwienella sp.

Pectiniform lamellibranchs

If the correlation of the Botany Grit with the upper part of the Grindstone Sill is accepted, then this shell bed is in the approximate position of the Botany Limestone in the Cotherstone district (Reading, 1947, Fig. 2., p. 31). Whether or not they are in fact equivalent is a highly speculative point in view of their different lithologies. The Geological Survey (J. H. Hull, personal communication), believe that the correlative of the Botany Limestone occurs at a lower horizon on the Alston Block. In fact, it is correlated with the Grindstone Limestone which occurs directly on top of the Grindstone Sill in the Barnard Castle district. It is possible, therefore, that the Botany horizon is represented in the present area by the ferruginous sandstones occurring a few feet above the Grindstone Sill (Fig. 11.1). Previous views on the apparent absence of the Botany Limestone on the Alston Block were that it was either not deposited or present only in an attenuated form (Reading, 1957, p. 50). If either of these shell beds is the representative of the Botany Limestone on the Alston Block, then it would also equate with the Harlow Hill Limestone in the Tyne Valley, according to the correlation proposed by Green (1954).

There appears to be a passage upwards, as in Nookton

Burn, to the medium grained sandstone forming the lower part of the Rowton Well Sill in Rookhope Burn. In Ferney Gill, however, there are only 6½ feet of black shale with large siderite nodules above the thin coal, before a rather coarse development of the Rowton Well Sill comes in, apparently with an erosive base.

<u>Rowton Well Sill</u>. The term Rowton Well Sill was coined by the Derwentdale miners for a thick sandstone above the Grindstone Sill (Vert. Section, Sheet 63). The expression is synonymous with the "First Grit" of the Geological Survey (Dunham, 1948, p. 47), with the "Basement Grit" of Carruthers (1938, p. 237), and with the "Millstone Grit" of Forster (1821, p. 96). None of these terms is considered suitable for the present survey. The expression "Millstone Grit" has outlived its usefulness in Carboniferous stratigraphy, and the term "First Grit" could easily be confused with other horizons in the Namurian (Whittard and Scott Simpson, 1960, p. 126). The term Rowton Well Sill can, therefore be used without ambiguity until such times as the stratigraphy of these upper beds is better established.

In Nookton and Rookhope Burns the Rowton Well Sill appears to be represented both by a "normal" and an erosive facies. The "normal" facies is a medium grained sandstone with cross-stratification, which has a transitional passage into the siltstones below. The erosive facies rests sharply on this, and comprises the usual, very coarse felspathic sandstone, with large fossil tree fragments and quartzite pebbles up to 1 cm. Good exposures of this occur in Boltslaw Quarries, where it is seen to have good planar cross-stratification (Plate 68). The coarse sandstone eventually passes up into medium grained sandstone, and there is a suggestion of ganister on top. In Ferney Gill, the erosive facies has cut through the basal medium grained sandstone, and rests directly on black shale. It contains siderite nodules and shale fragments derived from the bed below, as well as large fragments of Lepidodendron. There are actually only 2 feet of coarse, conglomeratic sandstone, and the bulk of the sill is medium grained sandstone, which eventually becomes trough cross-stratified on a small scale. Jones (1956, p. 248) reports that his "First Grit" may rest on the Grindstone Sill. This has never been observed in the present area, and it is possible that Jones may have misinterpreted one of the "grit lenses" he records in the Grindstone Sill.

Strata above the Rowton Well Sill. On Redburn Common, the watershed between Nookton and Rookhope Burns, poor outcrops reveal a black shale above the Rowton Well Sill, which appears to pass up into a medium grained sandstone. Whether or not this represents the so-called "Second Grit" is debatable. On Bolt's Law, there are thought to be two sandstones, mapped largely on topographical features, between the Rowton Well Sill and a granule conglomerate which is exposed on top of the hill. Similarly, on Killhope Law in the west, there is at least one sandstone, and possibly two, below the very coarse sandstone which forms the summit. In view of the complications which can arise in a sedimentary sequence of this type, it is impossible to speculate further on these poor exposures.

CHAPTER 12

CORRELATION

The Namurian rocks in the research area are subject to considerable variations in lithology and thickness. For a suite of strata such as this, the best system of correlation would be based on palaeontological evidence; in particular, on fossils which are not restricted as to environment, and which have a wide geographical range. The most important fossils of known zonal value in the Namurian are goniatites, but, unfortunately, none has been found by the writer in the present area. At best, it is only possible to suggest correlations based on general considerations of lithology, comparative thicknesses, and sedimentary cycles. For short range work this often proves adequate; the zonal position of the rocks is of secondary importance. When correlations are attempted over a larger area, however, the age of the rocks in terms of goniatite zones becomes paramount in importance. Without knowledge of this no correlation can be regarded as sacred.

I Correlation within the area surveyed

Traditionally, in the Middle Limestone Group, the limestones are most used for correlation purposes, and although they are in themselves subject to some variation this principle has generally proved satisfactory. In the Upper Limestone Group, limestones are less numerous and thinner, but, nevertheless, are equally important for short and medium range correlations. The Little Limestone forms the base of the succession studied by the writer. It is easily recognised by its proximity to the prominent Great Limestone, but, in addition, it is often characterised by problematical sedimentary structures (see p. 275), which render it readily identifiable. The Crag Limestone is of little value *per se* in the area, because its distribution is restricted (p. 35). The Lower Felltop Limestone is easily identified, where it is not metasomatised, by the presence of *Osagia* nodules. It is a useful marker horizon, except in the east, where it has been removed by the erosive High Grit Sill. The Upper Felltop is more useful, however, because it is present over the whole area. It is easily recognised too, by its ferruginous, yellow-brown weathering, and, in thin-section, its abundance of *Fenestella* fragments.

A special feature of the Upper Limestone Group is the presence of "shell beds", which generally occur in the position of the limestone in the Middle Limestone Group cyclothem. There is a strong tendency, however, for these shell beds to be very variable in character, and they are known to die out altogether. Both the fauna and the lithology may change markedly over short distances, so they must be used with caution as marker horizons. Many of them contain a distinctive ironstone horizon, at least locally, which is of great value for short range correlation.

The Knucton Ironstone is particularly important in this respect. Of the two Rookhope Ironstones the upper one is the more persistent and, therefore, the more valuable. The Coalcleugh Marine Band, although probably an important stratigraphical horizon, appears to have a restricted development, but is, in any case, not often well-exposed because of its lithology.

Trotter and Hollingworth (1932, p. 71) believed that many of the sandstone horizons in the Upper Limestone Group were sufficiently constant "to be correlated with some confidence" between the Alston and Brampton districts. The present writer would agree that many sandstones possess distinctive lithological features which enable them to be recognised in widespread localities. They undoubtedly provide a sound basis for short-range correlation, but, probably more than any other facies, they are subject to extremely rapid changes in character. For medium-range correlations, therefore, sandstones should only be used with additional criteria. In the research area a number of sandstones were found to have a constant lithology. In particular, the Pattinson, Fiddler's, and Hipple Sills are quite distinctive.

The thin coals which occur within the Upper Limestone Group often have a widespread development. Poor exposures, however, limit their usefulness in the present area, with the possible exception of the Coalcleugh Coal. Individual coals are of little value by themselves, but, taken with the rest of the succession, they can be usefully employed as marker horizons.

In conclusion, it may be stated that, by employing as many criteria as possible, such as lithology, thickness, and fauna, a rational stratigraphy may be resolved. It is manifestly impossible to regard any one criterion as being superlative in importance, because of the variation of the members comprising the Group. When this variation becomes extreme, as it does in the Slate Sills Formation, then the validity of any correlation becomes uncertain.

II Correlation outside the area surveyed

Most workers on the Namurian strata of Northern England in recent years have been concerned with the problems of correlation. These problems are aggravated by the paucity of zonal fossils, particularly goniatites, in the Upper Limestone Group. Bisat's goniatite zones, establishes in 1924 in the Bowland Trough, have been applied with some success to Namurian strata on the south of the Askrigg Block (Wilson and Thompson, 1959), but farther north the goniatite horizons die out or change character (op. cit., pp. 47, 52). On the Alston Block, the few records of identifiable goniatites are mainly due to Johnson, who also notes that fragmentary goniatites are relatively common in the succession (Johnson et al., 1962; Johnson and Dunham, 1963). No zonal fossils have yet been found above the Firestone Sill on the Alston Block (Johnson and

Dunham, 1963, p. 18), but the Geological Survey have made a number of important finds in the Cotherstone Syncline. Above the Firestone Sill correlations are largely based on general factors derived from detailed mapping. In fact, those criteria which are successfully employed in short range correlations are extended to cover medium range correlations; in being so applied they become less accurate and inevitably subjective. The present writer's correlations differ in detail from those of Reading (1957). A summary of the major contributions to the problem of correlation within the Upper Limestone Group is given in Table 1,(p. 97).

A Pendleian Stage (E_1)

The base of the Pendleian Stage is generally taken as the base of the Great Limestone (Johnson et al., 1962), but it has been found impossible so far to define the top on the Alston Block because of the lack of goniatite evidence. In the research area Hodge and Johnson discovered Cravenoceras aff. malhamense, indicative of the E_1 stage, in the shales above the Little Limestone (Johnson et al., 1962, p. 355). The record of Tylonautilus nodiferus (Armstrong) early mut. (Johnson and Dunham, 1963, p. 52), from the Little Limestone on the Moor House Reserve supports the E_1 age for this part of the succession. The latter fossil has also been found in the Faraday House Marine Band on the Askrigg Block (Rowell and Scanlon, 1958,

TABLE I

To illustrate several recently proposed correlations in the Upper Limestone Group of northern England, especially those relating to the E2/E1 boundary.

Alston Block Terminology	Smith 1912	Trotter & Hollingworth 1932	Hudson 1933	Carruthers 1938	Hudson 1941	Robertson & Hickling 1948	Trotter 1951	Green 1954	Jones 1956
Rowton Well Sill									Botany Grit
"Botany Limestone"			Shunner Fell Thornborough Harlow Hill	Lower Felltop				'Grindstone Limestone'	
Grindstone Sill									
Upper Felltop Limestone		Upper Oakwood	(Hearne Beck is base of E_2, 1939)	Candleseave Limestone		Harlow Hill	(Lad Gill = Colsterdale Limestone)	Hearne Beck Thornborough	Upper Oakwood
Coalcleugh M.B.				Lad Gill					
Lower Felltop Lst.		Lower Oakwood			Mirkfell Ist.	Thornborough	Mirkfell Is. and M. Oakwood	Corbridge	(Base of E_2 below CTB) ? M. Oakwood ?
Rookhope Shell Beds									
Knucton Shell Beds				Mirkfell Ist.	Stonesdales				
Crag Limestone	Lower Oakwood Coal = Crag Coal			Little				Lower Oakwood	

(—— E_2/E_1 boundary)

Alston Block Terminology	Reading 1957	Rowell & Scanlon 1957b	Dunham & Johnson 1963	Whittaker 1963 N. Yorkshire	Whittaker 1963 Northumberland	Geological Survey 1964 (unpublished)	Pattinson 1964 Alston Block	Pattinson 1964 Cotherstone
Rowton Well Sill					Nafferton Gt.			
"Botany Limestone"	Shunner Fell			Botany = Upper Felltop	Peterel S.B. = Styford Shs.			
Grindstone Sill								
Upper Felltop Lst.	Hearne Beck	Hearne Beck = Lad Gill = Candleseave	?M. Oakwood?		Harlow Hill			
Coalcleugh M.B.		(CTB = Kettle-pot Ganister)	Base of E_2?					
Lower Felltop Limestone	Up. Stonesdale Lst.	Upper Stonesdale			Thornborough	Mirkfell Ist.	Up. Rookhope Ists.	?Mirkfell Ists.
Rookhope Shell Beds	Lr. Stonesdale Lst.			Mirkfell Ists.	?Corbridge	Up. Stonesdale		Up. Stonesdale
Knucton Shell Beds	(dies out to south)			Stonesdale	Upper Oakwood (M. Oakwood)	Lr. Stonesdale		
Crag Limestone	Crow			Crow	Lr. Oakwood	Crow		

p. 3). The present writer would correlate this with the White Marine Band of the area surveyed (p. 26). At a slightly higher horizon, in the shales just below the Firestone Sill, a specimen of Cravenoceras sp. has been found on the Moor House Reserve (Johnson and Dunham, 1963, p. 54), but indicates nothing more definite than a Eumorphoceras age. Hey (1956, p. 289), suggested that the Crow Series near Richmond, Yorkshire, is of upper E_1 age: although there is no direct evidence for an E_1 age it is strongly suggested by the fact that the Crow Limestone on the Askrigg Block is cut out by the intra-E_1 unconformity at the base of the Grassington Grit (Rowell and Scanlon, 1958, p. 86; Wilson, 1960, p. 302). In this connection, it is also significant that the Stonesdale Limestones are similarly cut out by this unconformity, thereby implying that they are wholly E_1 in age. Agreement has not yet been reached as to which horizon on the Alston Block is the equivalent of the Stonesdale Limestones. Clearly, it would be useful to resolve this problem, as it would provide more information about the extent of the E_1 stage on the Alston Block.

The most recently published correlation of the Stonesdale Limestones, with their possible equivalents on the Alston Block, is that due to Reading (1957). He equates the Lower Stonesdale Limestone with the Rookhope Shell Beds (op. cit., p. 40), and the Upper Stonesdale Limestone with the Lower Felltop Limestone (op. cit., p. 42). Reading himself considered the possibility that the

Stonesdale Limestones were equivalent to the two Rookhope Shell Beds, but concluded that the above correlation was more likely. Jones, in an unpublished thesis (1956, p. 340) is not convinced that the Upper Stonesdale is equivalent to the Lower Felltop Limestone, and seems to favour correlation with the Upper Rookhope Shell Bed. Both Reading and Jones, therefore, correlate part of the Stonesdale Limestones with the Rookhope Shell Beds at least. An entirely different view was put forward by Hudson in 1941. He (op. cit., p. 265) based his correlations on comparative thicknesses and rhythmic sequence, and equated the Stonesdale Limestones with the Knucton Shell Beds, and the Mirk Fell Ironstones with the Rookhope Shell Beds and possibly the Lower Felltop Limestone (Table 1). Green (1954) supported this general idea but did not go into details. However, he correlates the Mirk Fell and Stonesdale horizons with the thin limestones and shell beds between the Lower Felltop and Crag Limestones, i.e. the Knucton and Rookhope Shell Beds. Thus, there are conflicting opinions concerning the equivalents of the Stonesdale Limestones and the Mirk Fell Ironstone on the Alston Block. In view of the fact that the Stonesdale Limestones are apparently of E_1 age (p. 97), and the Mirk Fell Ironstone is generally taken as the base of E_2 (Hudson, 1941), it is very important to find their equivalent horizons on the Alston Block.

B The E_2/E_1 boundary

The position of the E_2/E_1 boundary on the Alston Block can only be ascertained at the moment by reference to the Cotherstone Syncline and the Northumberland Trough where the zonal position of the strata is better known. During a recent resurvey of the Cotherstone Syncline (Brough-under-Stainmore, Sheet 31; Barnard Castle, Sheet 32) the Geological Survey Officers have somewhat revised Reading's correlations with the Alston Block; their conclusions relating to the Stonesdale Limestones and the Mirk Fell Ironstones are summarised in Table 2.

TABLE 2

Cotherstone Syncline	Alston Block
Mirk Fell Ironstones	Lower Felltop Limestone
Upper Stonesdale Limestones	Rookhope Shell Beds (in part only)
Lower Stonesdale Limestones	Knucton Shell Beds
Crow Limestone	Crag Limestone

On the basis of general cyclothemic sequence and assuming that no cyclothem thins to zero, this correlation is feasible. The Lower Stonesdale Limestone is the next fully marine member on top of the Crag Cyclothem, and thus would seem to correlate with the Knucton Shell Beds and Ironstone; the Lower Stonesdale may occur only 8 feet above the Crag Limestone on the Askrigg Block (Rowell and Scanlon, 1957, p. 15). Furthermore, the Lower Stonesdale Limestone has an increasing amount of sand to the north-east in that area (op. cit., p. 17), so a transition into the arenaceous Knucton Shell Beds seems possible. The Rookhope Shell Beds in the vicinity of Middleton-in-Teesdale comprise a series of cherts with glauconite, siliceous limestones and mud-stones (Jones, 1956, p. 90), and could represent a transition stage between the limestones of the Cotherstone district and the ironstones and shell beds in the area surveyed by the writer.

Hudson (1941), in his original description of the Mirk Fell Ironstones correlated these beds with the Rookhope Shell Beds and possibly the Lower Felltop Limestone (ibid., p. 266). Trotter (1951, p. 96) correlated the Lower Felltop Limestone of Alston with the Mirk Fell "Limestone", and subsequent authors have noted that the Mirk Fell Series is impersistent (Reading, 1957, p. 43; Rowell and Scanlon, 1957, p. 19). Reading (ibid., Fig. 2, p. 31) preferred not to correlate the Mirk Fell Series with any specific horizon on the Alston Block, but later authors have used his correlation to place the E_2/E_1 boundary in the vicinity of the Coalcleugh Transgression Beds (Johnson and Dunham, 1963, p. 20). The Coalcleugh Transgression Beds are wholly E_2 in age, because they locally remove the Mirk Fell Ironstones (Reading, 1957, p. 43), so the E_2/E_1 boundary must occur below the Coalcleugh Transgression Beds. No zonally diagnostic fossils have been found in the Lower Felltop Limestone in the research area, but proposed correlations with rocks in the Northumberland Trough strongly suggest that the Lower Felltop Limestone is also E_2 in age (p. 102).

TABLE 3

Recently proposed equivalents of the Lower Felltop Limestone in the Northumberland Trough.

Lower Felltop equivalent	Author
Thornborough Limestone	1) Robertson & Hickling, 1948
	2) Geological Survey, Hexham Sheet 19, 1956
	3) Whittaker, 1963
Corbridge Limestone*	1) Green, 1954
Middle Oakwood Limestone	1) Trotter, 1951
	2) ?Jones, 1956
Lower Oakwood Limestone	1) Trotter and Hollingworth, 1932

*Whittaker (1963, p. 259) subsequently showed that Green misidentified the Lower Felltop Limestone on the northern Alston Block; Green's Upper Felltop is actually the Lower Felltop Limestone, and this he correlates with the Thornborough.

DURHAM UNIVERSITY SCIENCE 12 JUN 1964 LIBR

The most recent works directly concerned with the problem of correlation are due to Green (1954), the Geological Survey (Hexham Sheet 19, 1956), and Whittaker (1963). The general tendency nowadays is to equate the Lower Felltop Limestone of the Alston Block with the Thornborough Limestone of the Trough (Table 3). The presence of *Osagia* nodules in both the Lower Felltop (p. 63) and the Thornborough Limestones (Green, 1954) appear to argue in favour of this correlation. The writer, therefore, follows the recent work of Whittaker in taking the Thornborough Limestone to be the equivalent of the Lower Felltop.

This correlation is very important because, according to Trotter and Hollingworth (1927) *Anthracoceras* sp. of the *A. discoides* Bisat group has been found in the Thornborough Limestone. This fossil indicates an E_2 age, which must also apply to the Lower Felltop Limestone. This conclusion immediately makes the correlation of this limestone with the Upper Stonesdale Limestone of the type area impossible; the Lower Felltop Limestone is of E_2 age, and the Upper Stonesdale is unquestionably E_1 (p. 97). On the other hand, the correlation of the Lower Felltop Limestone with at least part of the Mirk Fell Ironstones is feasible because they are both Arnsbergian in age. Furthermore, *Tylonautilus nodiferus* s.s., an E_2 fossil, has been recorded from the Corbridge Limestone (Green, 1954), a limestone below the Thornborough. This implies that the base of E_2 lies some way below the Thornborough, and suggests that the Lower Felltop Limestone may not be the basal member of E_2 on the Alston Block. If this can ever be shown to be the case then the E_2/E_1 boundary may occur at approximately the horizon of the Upper Rookhope Ironstone. Proof of this would make Hudson's original correlation (1941) of the Mirk Fell and Rookhope Ironstones correct.

C. Arnsbergian Stage (E_2)

With the evidence available the lowest probable E_2 horizon on the Alston Block is the Lower Felltop Limestone, but it cannot be stated with confidence that this is also the base of the Arnsbergian Stage (p. 103). The Lower Felltop Limestone is commonly removed by the erosive Coalcleugh Transgression Beds in the research area; this disconformity is believed to correlate with that below the Kettlepot Ganister on the Askrigg Block (Reading, 1957, Fig. 2, p. 31). The Kettlepot Ganister contains a number of erosive channels (Rowell and Scanlon, 1957b, p. 88), and is also known as the Upper Howgate Edge Grit (Rowell and Scanlon, 1957a, p. 20). It appears to belong to the same sedimentological regime as the Coalcleugh Transgression Beds, so the correlation seems reasonable. Reading (1957, p. 46) records Tylonautilus nodiferus from the Coalcleugh Marine Band in the Cotherstone Syncline, indicating a definite Arnsbergian age for this member. Reading's correlation of the Upper Felltop Limestone with the Hearne Beck or Lad Gill Limestone on the Askrigg Block is also generally accepted. Wilson (1960, Fig. 6, p. 442) regards this horizon as being quite low in the Arnsbergian Stage, although Trotter (1951, p. 103) correlates the Lad Gill Limestone with the Colsterdale Limestone on lithological grounds (Table 1). Rowell and Scanlon (1957a, p. 28) prefer to equate the Colsterdale Limestone with the Shunner Fell Marine Beds in the north of the Askrigg Block. Wilson and Thompson (1959) have described an E_2 fauna from the Colsterdale Limestone, which is characterised by Cravenoceratoides nitidus (Phillips). They agree (ibid., p. 63) with Rowell and Scanlon on the correlation with the Shunner Fell Marine Band and with Reading (1957, Fig. 2, p. 31) on the correlation with the Botany Limestone. In support of the latter correlation the Geological Survey recently found Cravenoceras sp., indicating Eumorphoceras age, in shales below the Botany Limestone in the Cotherstone district (Summ. Prog., 1960, p. 41). A limestone is known to occur above the Grindstone Sill in the Woodland Borehole (D.A.C. Mills, in "The Geology of the High Kays Lea Borehole, Woodland, Co. Durham, Bull. Geol. Surv. Gt. Britain - in preparation); on the Barnard Castle Sheet a limestone in the same position is believed to be the equivalent of the Botany Limestone (J.H. Hull, in "The

Geology of the Country around Barnard Castle, Memoir of the Geological Survey of Great Britain - in preparation). This horizon may be represented by the ferruginous, fossiliferous sandstones occurring above the Grindstone Sill in the present area (p. 86). Evidence has recently been obtained by the Geological Survey (Summ. Prog., 1962) that the "First Grit" is of R_1 age (ibid., p. 45). This discovery invalidates Reading's correlation of the "First Grit" with the Botany Grit, which is provably pre-R_{1a} (p. 85), and probably E_2 (Wilson and Thompson, 1959, p. 63).

Much of the evidence relating to the top of the E_2 stage comes from Geological Survey boreholes. Of uncertain value is the record from the borehole at Tranwell on the Morpeth Sheet (One-inch Series, Sheet 14) (Summ. Prog., 1960, p. 41), in which fossils indicating a Eumorphoceras age were found just below the "Basement Grit" of the "Durham Millstone Grit". It is not certain whether this bed has any direct equivalent on the Alston Block. The top of the Arnsbergian Stage on the Alston Block cannot be accurately defined at present. It can be stated with certainty, however, that it lies somewhere between the Botany Limestone or its equivalents, and the "First Grit". Green (1954) regards the Styford Shales of the Northumberland Trough as representing the top of E_2, and Whittaker (1963, p. 297) considers that their equivalents on the Alston Block are those shell beds between the Grindstone and Rowton Well Sills. If the lowermost of these in the present area correlates with the Botany Limestone (p. 88), then only the upper shell beds (Fig. 11.1) could be referred to this horizon.

D. Sabdenian (H) and Kinderscoutian (R_1) Stages

The apparent absence of Sabdenian fossils in the north of England is very striking: the discovery by Burgess of Homoceras henkei Schmidt in the Brough-under-Stainmore area (Summ. Prog., 1962, p. 45), is very important in this respect. This fossil belongs to the R_{1a} zone and more or less indicates the H/R boundary: the exact horizon is 280 feet above the presumed equivalent of the Botany Limestone, and 400 feet below the presumed equivalent of the Gastrioceras subcrenatum Marine Band (Owens and Burgess, in press). The discovery of Reticuloceras stubblefieldi Bisat and Hudson, a few feet below the "First Grit" on the Barnard Castle Sheet (Hull, Summ. Prog., 1962, p. 45) indicates an R_{1b} age for this member. A further discovery of Reticuloceras sp. was made in the nearby Woodland Borehole (Mills, ibid., p. 46), but, more interesting still, only 100 feet below this horizon were found abundant Posidonia corrugata Etheridge jun., which indicate Eumorphoceras age. Thus, in at least one locality there are only 100 feet of strata to contain the Homoceras Stage, and possibly quite a thickness of the E_2 and the R_1 Stages too. Sabdenian deposits are likely to be thin in northern England, because in the Lancaster Fells they are less than 100 feet thick (Moseley, 1954, p. 436). Trotter

(1951, Fig. 2, p. 101), goes so far as to suggest that the whole of England north of Kendal was "land" in both H and R_1 times. However, absence of strata, or, rather, absence of diagnostic fossils, does not indicate terrestrial conditions, so this interpretation cannot be accepted with the evidence available. The possibility that there might be an unconformity between the Kinderscoutian and the Arnsbergian, or even within the Sabdenian, must be borne in mind.

Only very recently have Kinderscoutian strata been proved to exist on the Alston Block (Summ. Prog., 1962). It is still too early to attempt a close definition of this Stage in terms of Alston Block nomenclature. The Geological Survey have not yet published the details of their discoveries, and it is only possible to quote the "First Grit" as being of Kinderscoutian age.

P A R T   I I

S E D I M E N T O L O G Y

CHAPTER 13

PETROGRAPHY OF UPPER LIMESTONE GROUP SANDSTONES

I Classification of sandstones from a paralic environment

Sandstone classification is a problem which confronts most geologists sooner or later, but, although a unique classification would be of universal benefit, none has yet been proposed which has universal acceptance. The human factor plus the polygenetic nature of the material comprising sedimentary rocks is responsible for this situation. An all-embracing classification, satisfying all opinions, would be so generalised as to be virtually useless, perhaps even contradictory. Many authors, therefore, have established classifications based on criteria which they think are important to illustrate particular features of certain sandstones. In fact, since 1948, at least fourteen important sandstone classifications have been proposed (McBride, 1963). One factor which immediately divides would-be classifiers is the object of their proposed classification. The number of authors who believe that the genesis of a sandstone should be an important factor in classification (such as Pettijohn, 1957) is greater than those who believe that mineralogy and provenance should be placed first in importance (Folk, 1954). Differences of opinion on this point have led to varying degrees of emphasis being placed on the physical properties of sandstones in the many classifications. A comprehensive review of this subject is given by McBride (1963).

A much discussed question is the position of greywacke in the classification schemes. Most authors include greywacke, usually based on amount of clay matrix, in their general sandstone classification, but a minority regard it as a special rock type occurring in a separate suite (Gilbert, 1954; Packham, 1954; Crook, 1960; McBride, 1963). Harbord, in an unpublished thesis (1962), proposed three distinct sandstone suites based on the tectonic condition of the depositional area. These were:-

1) Non-tectonic, or orthoquartzite series;
2) Late tectonic, or arkose series;
3) Early tectonic, or greywacke series.

He established a quaternary composition diagram for each suite with end-members quartz, felspar, rock fragments, and clay matrix. The mineralogical differences between the suites exist only in the nature of the rock fragments, which were either sedimentary, granitic, or metamorphic respectively. The present writer believes, however, that whereas some form of distinction between sedimentary domains is a useful concept in sandstone classification, it is not practicable to subdivide the depositional environments too closely. In particular, the difference between the orthoquartzite and arkose suites is often minimal as far as sandstone types are concerned: similar, if not identical rock types must occur in both domains.

Figure 13.1

TEXTURAL GROUPS IN SEDIMENTARY ROCKS (FOLK, 1954)

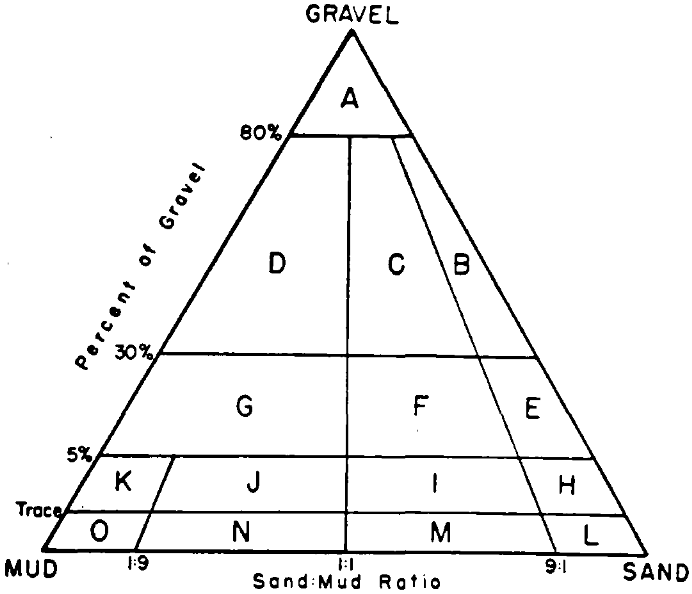


TABLE 1*

TERMS APPLIED TO MIXTURES OF GRAVEL, SAND, AND MUD DELIMITED IN FIGURE 1

Major Textural Class	Examples of Usage
A. *Gravel*	Cobble gravel
Conglomerate	Granule conglomerate
B. Sandy *gravel*	Sandy pebble gravel
Sandy *conglomerate*	Sandy boulder conglomerate
C. *Muddy* sandy *gravel*	Muddy sandy granule gravel
Muddy sandy *conglomerate*	Clayey sandy pebble conglomerate
D. *Muddy gravel*	Silty boulder gravel
Muddy conglomerate	Muddy pebble conglomerate
E. *Gravelly sand*	Pebbly coarse sand
Conglomeratic sandstone	Granular very fine sandstone
F. *Gravelly muddy sand*	Pebbly silty fine sand
Conglomeratic muddy sandstone	Bouldery muddy coarse sandstone
G. *Gravelly mud*	Cobbly clay
Conglomeratic mudstone	Pebbly siltstone
H. Slightly *gravelly sand*	Slightly granular medium sand
Slightly *conglomeratic sandstone*	Slightly pebbly coarse sandstone
I. Slightly *gravelly muddy sand*	Slightly pebbly muddy medium sand
Slightly *conglomeratic muddy sandstone*	Slightly cobbly silty fine sandstone
J. Slightly *gravelly sandy mud*	Slightly granular fine sandy mud
Slightly *conglomeratic sandy mudstone*	Slightly pebbly coarse sandy claystone
K. Slightly *gravelly mud*	Slightly pebbly clay
Slightly *conglomeratic mudstone*	Slightly cobbly mudstone
L. *Sand* (specify sorting)	Well-sorted fine sand
Sandstone (specify sorting)	Poorly sorted medium sandstone
M. †*Muddy sand*	Well-sorted silty very fine sand
Muddy sandstone	Muddy coarse sandstone
N. †*Sandy mud*	Fine sandy clay
Sandy mudstone (specify structure)	Coarse sandy siltstone (if fissile, coarse sandy silt-shale)
O. †*Mud*	Silt
Mudstone (specify structure)	Mudstone (if fissile, mud-shale)

* Both unconsolidated and consolidated equivalents are shown in this table. It is suggested that the italicized terms be further specified as to their grain size, as shown in the examples.

† Textural classes M, N, and O are expanded, as shown in fig. 1*b*. For classes N and O see also table 2.

The present writer believes that the prime purpose of a sandstone classification is to provide an objective description of the mineralogy of sandstones. Inherent in its fundamental types, which should have simple names, should be the relative proportions of all significant minerals. There should be additional information about the grain size of the rock and any important constituents occurring in lower abundance. The name should epitomise the physical properties of the sandstone so that the environment of its deposition may be inferred, but not stated or implied as an accepted corollary. In this way, all subjective criteria concerned in classification are abolished; the sandstone names, which are in fact short-hand descriptions, are objectively derived, but lend themselves readily to subjective interpretation. The only classification proposed to date which embodies these properties is that due to Folk (1954), which was subsequently expanded (Folk, 1961), and modified by McBride (1963). The three basic requirements for this classification are as follows (after Folk, 1954):-

1) The Wentworth Scale for particle sizes (1922);
2) Classification of textural groups based on relative proportion of gravel, sand, and mud (Folk, 1954) (Fig. 13.1);
3) Mineralogical classification of sandstones based on relative proportion of major framework minerals (McBride, 1963) (Fig.13.2).

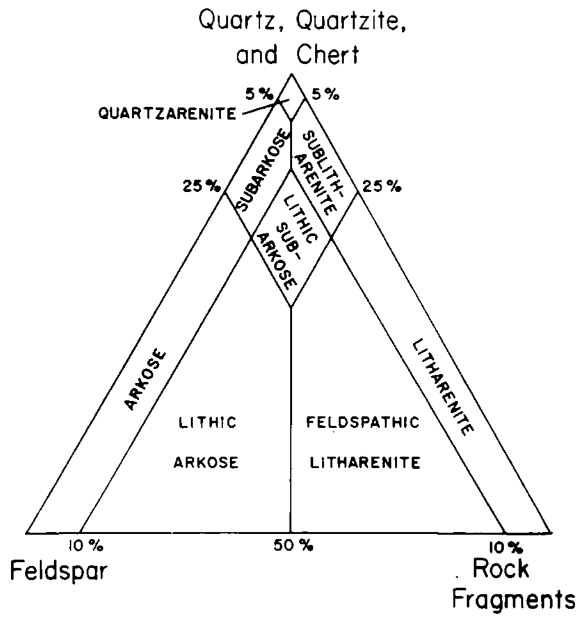


FIG. 1.—Proposed classification of common sandstones.

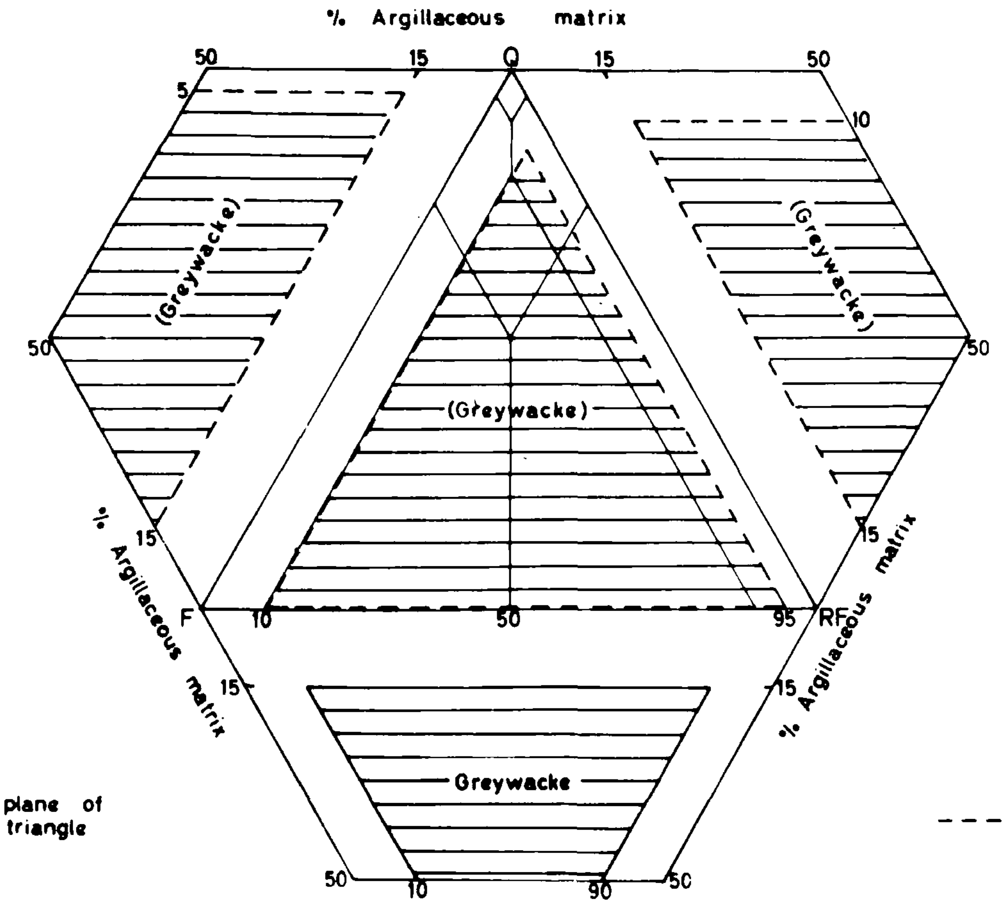
Figure 13.2

(above) McBride's classification of sandstones

(opp.) A representation of the greywacke suite according to McBride (1963).

Figure 13.2

REPRESENTATION OF THE GREYWACKE SUITE ACCORDING TO McBRIDE, 1963



—— Boundary in plane of composition triangle

- - - Boundary not in plane of composition triangle

In 1961 Folk added the properties of cement and "miscellaneous transported constituents" to his descriptive scheme. McBride's sandstone classification, which is accepted in this thesis, differs from Folk's principally in its removal of the terms "greywacke" and "subgreywacke". McBride considers that greywacke is a special rock type essentially with matrix content over 15%, rock fragments over 10%, and felspar over 5% (1962, p. 614; 1963, p. 668). McBride's sandstone classification and a representation of his greywacke field are illustrated in Figure 13.2. Clearly, however, an objective description of a greywacke is in most cases covered by an expression such as "muddy felspathic litharenite" or "muddy lithic arkose", depending on the proportion of the framework constituents. The prefix "muddy", however, could indicate a mud content as low as 10%, and, therefore, not a greywacke in this classification. The name "greywacke" would presumably be applied to this rock by most workers if it occurred in a turbidite environment, thus introducing the genetic factor into the classification. Because of its geosynclinal connotation the present writer would hesitate to use the term "greywacke" for a "muddy felspathic litharenite" in a paralic environment. The purely descriptive term is less likely to lead to confusion and misinterpretation. McBride's classification is believed to be sufficiently comprehensive to include all the sandstone types encountered in a paralic environment such as is represented by the Upper Limestone Group of the area studied. Whether it can be equally applied to geosynclinal sediments is beyond the scope of this thesis.

II Petrography

A Introduction

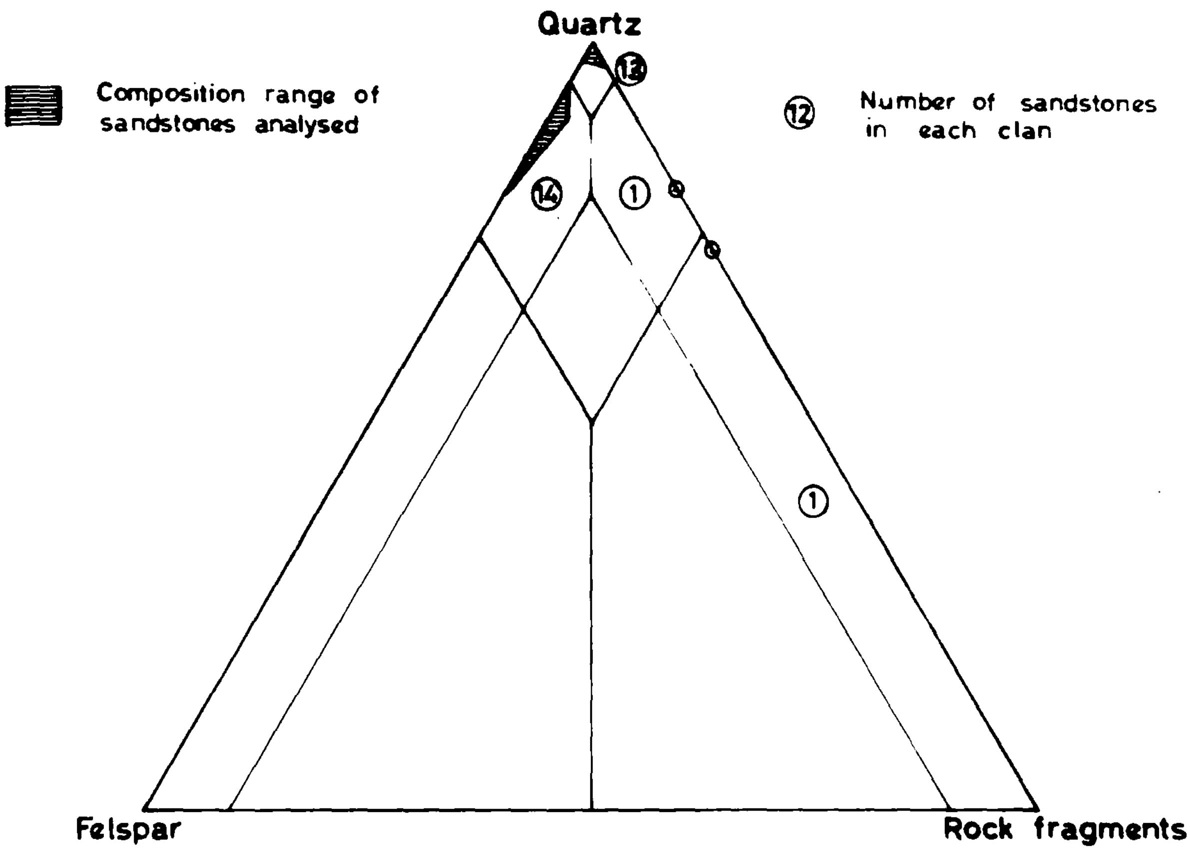
According to Pettijohn (1957), a classification of sandstones is of little value unless it has some reflection on the genesis of the rock. The classification adopted in this thesis does indicate to a certain extent the provenance of the sediment and, to a lesser extent, gives an indication of its environment of deposition. Modal analyses of twenty-nine sandstones from the Upper Limestone Group show that the commonest types are subarkoses and quartzarenites. There is no direct correlation between rock type and inferred mode of deposition, and some marine sandstones may have a similar gross lithology to a fluvial sandstone. There are differences, however, in that fluvial sandstones are frequently coarser and less well-sorted than marine sandstones. The argillaceous facies, viz. muddy quartzarenites, are especially abundant in seatearths and shell beds, and presumably were deposited in relatively slack-water conditions. Sublitharenite and litharenite occur but infrequently, and may be regarded as unusual rock types in the Upper Limestone Group.

B Method

The practical application of McBride's classification to any system of strata requires only a modicum of information which can be gained easily by a study of rocks in hand specimen and thin section. Naturally most of the useful information comes from a study of the thin sections. In the present work the median grain size was found by

Figure 13.3

COMPOSITION OF NAMURIAN SANDSTONES IN THE AREA STUDIED



averaging a small number of measurements made with an eye-piece micrometer on a thin section of the sample. The Wentworth Scale is used for descriptive purposes, and the results were found in all cases to be the same as those obtained from the hand specimen as studied under a binocular microscope. A visual estimate of the degree of sorting can also be made in this way. The percentages of granule or pebble size material can be estimated with sufficient accuracy to place a sample in either the "slightly conglomeratic" or "conglomeratic" class (Fig. 13.1). Fine grained argillaceous material, if present, was measured by using a point-count mechanical stage, and a similar grain size classification was made. All of the major minerals present in the sandstones were analysed using the point-counter. For medium and fine grained sandstones 400 to 500 points were analysed in each thin section, using 0.05 mm. spacing and traversing at 2 mm. intervals. In the coarser sandstones 800 to 1,000 points were analysed. For the purposes of the classification used the mineral percent thus obtained were recalculated in terms of the three end-members, quartz, felspar, and rock fragments, and plotted on a triangular composition diagram (Fig. 13.3). The results of these analyses are summarised in Tables 4 and 5.

C Quartzarenite

Seven of the twenty-nine sandstone analyses can be classified as quartzarenites; that is, of the framework constituents over 95% is quartz, and less than 10% of the total rock analysis is composed of argillaceous matrix.

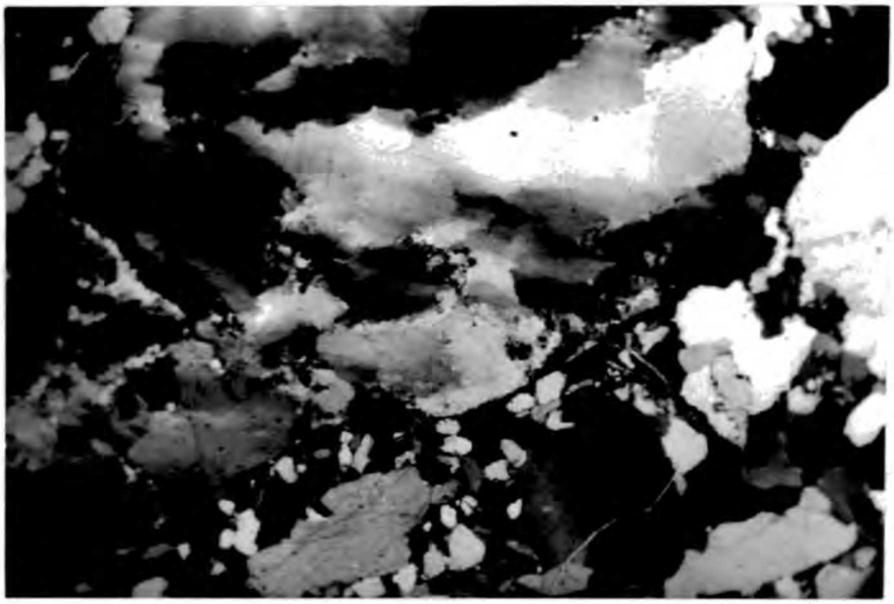


PLATE 23. Large fragment of polycrystalline quartz in subarkose; note poor sorting. Grindstone Sill. (x 30)

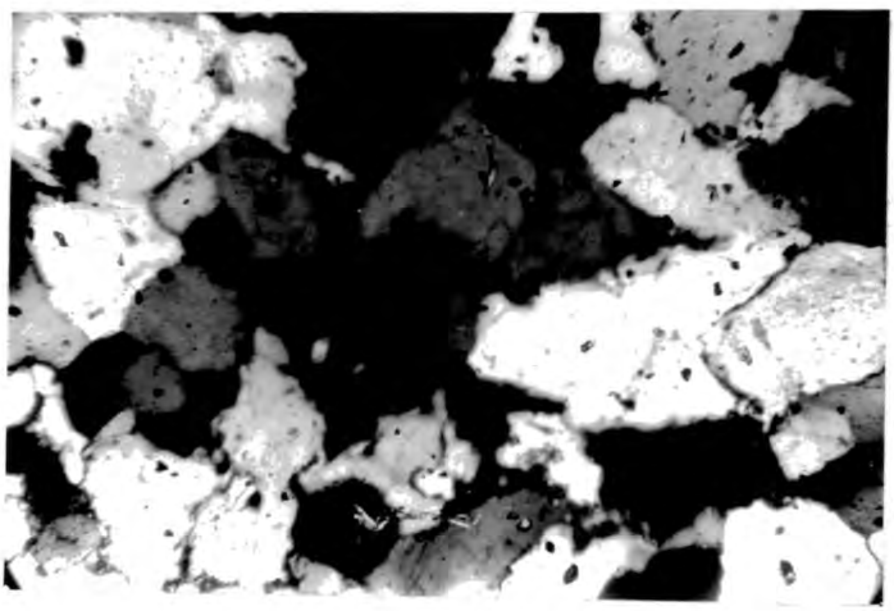


PLATE 24. Sutured quartz grains in ganister, Firestone Sill. (x 120)

TABLE 4

DATA FOR CLASSIFYING SANDSTONES

Sample No.	Degree of Sorting	Median size grade	Percentages			Percentages			Cement	
			Pebbles	Sand	Mud	Quartz	Felspar	Rock Frag.		
7	Poor	Coarse	0	100	0	92	8	0	Silica	Rare plagioclase
16	Moderate	Coarse	0	100	0	94	6	0	Chalcedony	Muscovite rare, plag. co
20	Good	Very fine	0	100	0	86	c.14	1	Calcite	Muscovite abundant
47	Bimodal	Fine	0	83	17	97	0	3	Qz welding	Mica 3%
51	Poor	Med. w. cgl. layer	10	90	0	80	20	0	Silica	Some mica
57	Poor	Coarse	8	92	0	81	0	19	Siderite	Little mica
70	Good	Medium to fine	0	100	0	90	10	0	Silica	Mica sparse
93	Fairly poor	Very coarse	0	100	0	88	12	0	Silica	
94	Poor	Coarse	0	100	0	81	19	0	Silica	
96	Moderate	Very fine	0	100	0	73	0	27	Silica	Siderite pellets. Mica
123	Fair	Medium	0	100	0	98	2	0	Carbonate	
133	Bimodal	Fine	0	72	28	100	0	0	Sil., mud	Pyrite bearing
135	Poor	Fine	0	71	29	100	0	0	Sil., mud	Some muscovite
139	Poor	Medium	0	76	23	100	0	0	Sil., mud	
142	Bimodal	Medium	0	90	10	100	0	0	Silica	Mica v. rare
145	Moderate	Medium	0	100	0	87	13	0	Silica	Mica rare
173	Poor	Coarse	3	97	0	80	20	0	Silica	Mica rare
192	Moderate	Medium	0	100	0	89	11	0	Silica	
286	Moderate	Very fine	0	100	0	100	0	0	Sil. + Cc	Calcite 30%, mica 2½%
305	Poor	Coarse	3	97	0	90	8	2	Silica	Mica rare
310	Very poor	Granule/medium	45	55	0	92	7	1	Silica	Mica rare
317	Moderate	Fine	0	100	0	100	0	0	Carbonate	
321	Poor	Medium	0	100	0	99	1	0	Silica	Mica rare
326	Moderate	Fine	0	100	0	100	0	0	Silica	
327	Moderate	Medium to fine	0	100	0	87	13	0	Silica	
330	Fair	Fine	0	109	0	85	15	0	Silica	Mica rare
369	Bimodal	Granule/medium	40	60	0	88	12	0	Silica	Mica rare
374	Bimodal	Fine	0	75	25	100	0	0	Sil., mud	
375	Bimodal	Fine	0	65	35	100	0	0	Mud	

TABLE 5

MODAL ANALYSES OF NAMURIAN SANDSTONES

Sample No.	Quartz	Silica cement	Felspar	Rock frags.	White mica	Calcite	Argill. matrix	Siderite	Access.
7	92.3		7.5						0.2
16	65.1	30.8	4.1						
20	49.7		8.2		3.3	38.8			
47	78.1			2.6	3.1		16.2		
51	79.3		19.6						0.1
57	64.8			15.6				19.0	0.6
70	89.0		10.5		0.5				
93	81.9	6.8	11.3						
94	80.5		18.1						1.4
96	66.1				7.3			24.2	2.4
123	52.7							46.4	0.9
133	72.1						27.9		
135	69.1				2.0		27.9		1.0
139	76.5						23.2		0.3
142	90.1						9.9		
145	86.5		13.2		0.3				
173	79.3		20.0		0.7				
192	88.9		11.1						
286	66.5				2.5	29.7			1.3
305	91.8	8.1							0.1
310	92.7	6.8							0.5
317	51.8				2.3	44.0			1.9
321	81.7		0.6			17.2			0.5
326	96.1		3.7						0.2
327	86.5		12.5		1.0				
330	81.8		18.2						
369	88.1		11.5		0.3				0.1
374	73.4		25.9		0.5				0.2
375	63.0						33.7		3.3

According to the adopted classification quartzarenites are not necessarily quartz-rich, and, in fact, carbonates could account for up to 50% of the total composition.

Framework constituents. Many authors, including Krynine (1940, 1946) and Folk (1961), have attempted to classify quartz into several types on the basis of its extinction properties; these types were then related to a particular source rock. Recently, Blatt and Christie (1963) demonstrated that the problem of quartz genesis has been oversimplified by previous authors, and that no one type of quartz comes from a unique type of rock. They show (*ibid.*, p. 565) that only three types of quartz can be distinguished:-

1) non-undulatory; that with straight extinction,
2) undulatory; that exhibiting strain features,
3) polycrystalline; that composed of more than one crystal with variable orientation.

All three types can be observed in the quartzarenites from the Upper Limestone Group, but the polycrystalline variety (Plate 23) is by far the least abundant. The very fine quartzarenites, in fact, have a negligible amount of polycrystalline quartz. This is in agreement with the findings of other authors that texturally mature sandstones, such as quartzarenites, are more likely to have low percentages of undulatory and polycrystalline quartz than immature sandstones. This phenomenon is the result of the lower stability of strained and compound grains (*ibid.* p. 571) which renders them liable to fracture during prolonged transport and reworking.

None of the quartzarenites has a median grain size greater than the medium size grade of the Wentworth Scale. Sorting is usually moderately good; only one very fine quartzarenite could be classed as well-sorted. Inman (1949) has pointed out that sediments approximating to the fine grade are usually better sorted than those which are coarser or finer. No statistical proof of this observation has been obtained from the quartzarenite suite, but it is observable that the coarse subarkoses are generally poorly-sorted (Table 4). The roundness of the quartz grains in the quartzarenites varies widely from well-rounded to angular. In many cases the angularity is due to corrosion by the carbonate cement, but there are certain grains in which this angularity appears to be a primary feature.

Alkali felspar is never present in an unaltered state in any of the quartzarenites; it is invariably made over, either wholly or in part, to hydromuscovite, and never accounts for more than 2% of the rock.

Cement. Silica, calcium carbonate, and iron carbonate (probably siderite in most cases) comprise the common cements of the quartzarenite suite. A small amount of argillaceous matrix locally occurs as a bonding agent; its principal effect appears to be to prevent the formation of other cements. Most quartz grains are mutually in contact and both pressure welding and suturing are common phenomena, usually in association with quartz overgrowths.

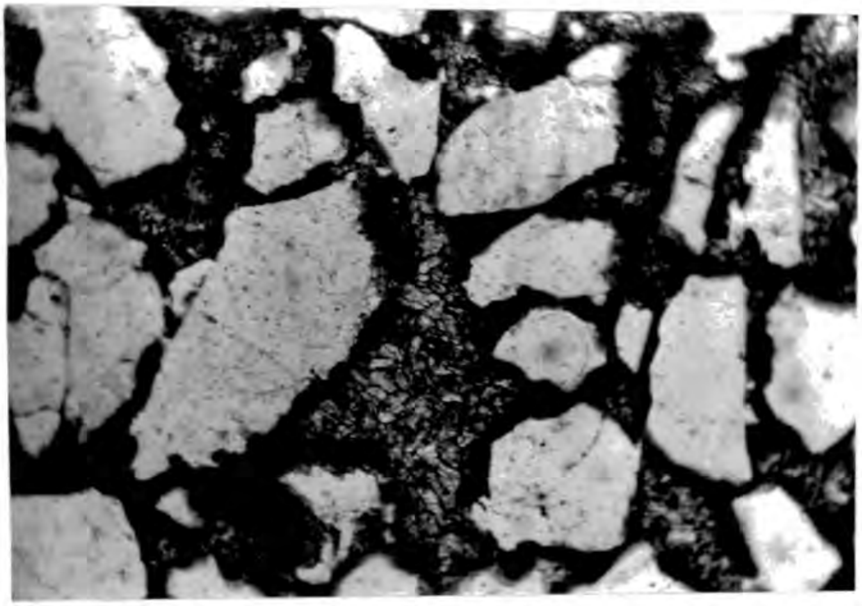


PLATE 25. Carbonate cement in poorly sorted quartz-arenite, Low Slate Sill (x 120)

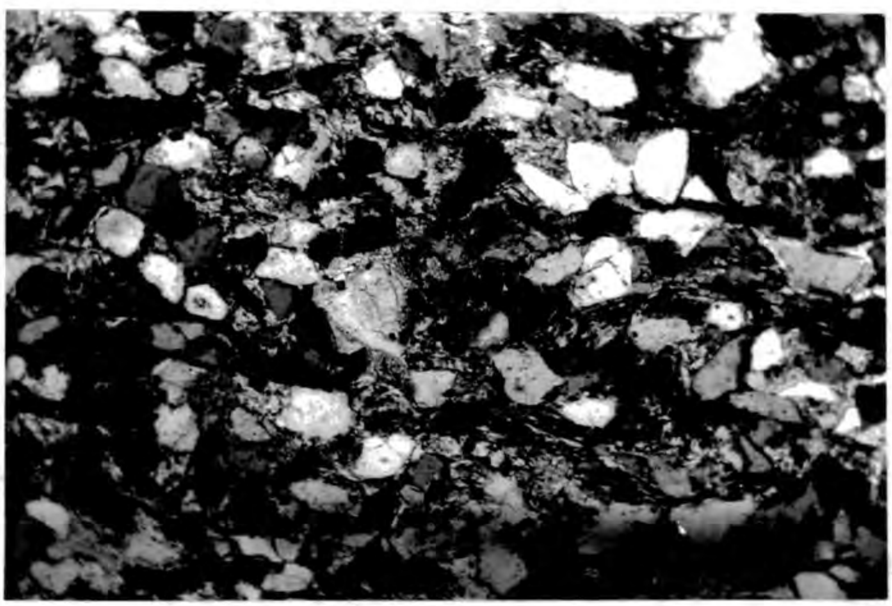


PLATE 26. Calcite-cemented subarkose, showing the calcite poikilitic to detrital quartz, Firestone Sill. (x 120)

The ultimate in this type of cementation is represented by the Firestone ganister (No. 326), which appears in thin section as a multi-crystalline mosaic of interlocking quartz crystals (Plate 24). The vast majority of quartz-arenites studied, however, have both silica and carbonate cements.

Calcite and siderite can be distinguished in thin section by the fact that calcite is always clear and occurs as large crystals, whereas siderite has ferruginous pigmentation and only occurs as small crystals, of the order of 0.02 mm. Frequently, the siderite occurs only as a thin veneer coating the detrital quartz grains, while calcite occupies the larger pore spaces (Plate 25). Some of the siderite occurs preferentially along some bedding laminations and is believed to be of detrital origin. On the other hand, small crystals of siderite also occur authigenically within calcitic crinoid columnals. Much of the calcite may also be a primary detrital mineral; it is difficult to escape this conclusion when calcite accounts for 44% of the total rock (No. 317). A mechanism involving an increase in the percentage of calcite by extensive corrosion of the detrital quartz grains could be postulated, but the absence of skeletal and badly corroded grains argues strongly against this. Even though the calcite is largely detrital it has also undergone authigenic enlargement; large crystals of calcite commonly enclose several grains of detrital quartz (Plate 26). Rarely, secondary calcite can be seen intruding the basal partings of white mica, which may itself be authigenic. Small rhombs of calcite can, in fact, be observed within the mica in the process of formation. Small spherules of microcrystalline quartz may occasionally be observed in thin sections of carbonate cemented quartzarenites, but it forms a very small percentage of the total cement.

Accessory constituents. White mica is the most abundant of the accessory minerals, sometimes amounting to 2½% of the whole rock analysis. Fragments of coal and other carbonaceous detritus are commonly present in small amounts. Zircon is the commonest of the heavy minerals, occurring in most of the thin sections examined. In one sample of the Low Slate Sill (No. 123), tourmaline and sphene were also recorded.

D Muddy quartzarenite

Six examples of this rock type have been described from the Namurian strata in the research area. Muddy quartzarenites are not common in the sequence and invariably occur as thin beds. Two of the samples are seatearths (Nos. 135, 374), two are burrowed shell beds (133, 139), one belongs to the marginal facies of the Rogerley Channel (No. 47), and another (No. 375) is a burrowed sandstone of doubtful affinity but possibly belonging to the same facies as the shell beds. Muddy quartzarenites have between 10 and 50% of argillaceous matrix according to the classification used in this thesis. In practice, values between 20 and 30% are more typical of those muddy quartzarenites occurring in the area.

Framework constituents. Quartz is the only framework constituent which occurs in the muddy quartzarenites studied. All three mineralogical types (p. 114) occur, but, as with pure quartzarenites, the frequency of polycrystalline quartz is very low. In poorly sorted varieties there is a definite tendency for the polycrystalline quartz to occur as larger grains. Only in one sample, from the Rookhope Shell Beds (No. 133), is there an observable preponderance of non-undulose quartz, but no systematic analyses have been made. Despite the relatively high matrix content, contacts between quartz grains are common and the effects of pressure solution are in evidence; this often takes the form of sutured contacts. Straight contacts between quartz grains are usually produced by the conjunction of adjacent authigenic overgrowths.

The presence of argillaceous material in considerable amounts indicates that the grain size distribution is bimodal. Within the sand-sized fraction degree of sorting varies quite widely between poor and good. Of those quartz grains in which the original outline may be discerned it can be seen that well-rounded grains are extremely rare, and that the vast majority are sub-rounded to angular.

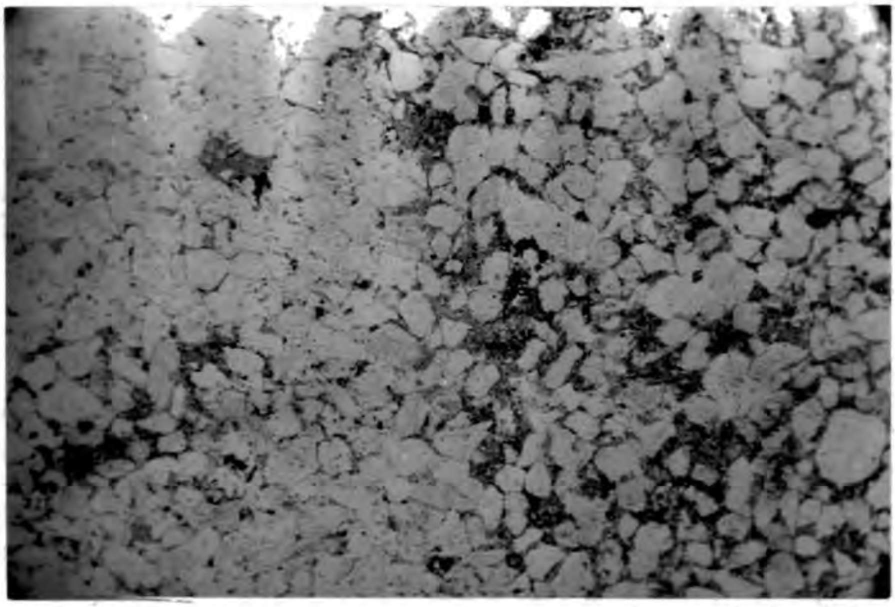


PLATE 27. Patchy argillaceous matrix in muddy quartzarenite, part of Lower Rookhope Shell Beds. (x 30)

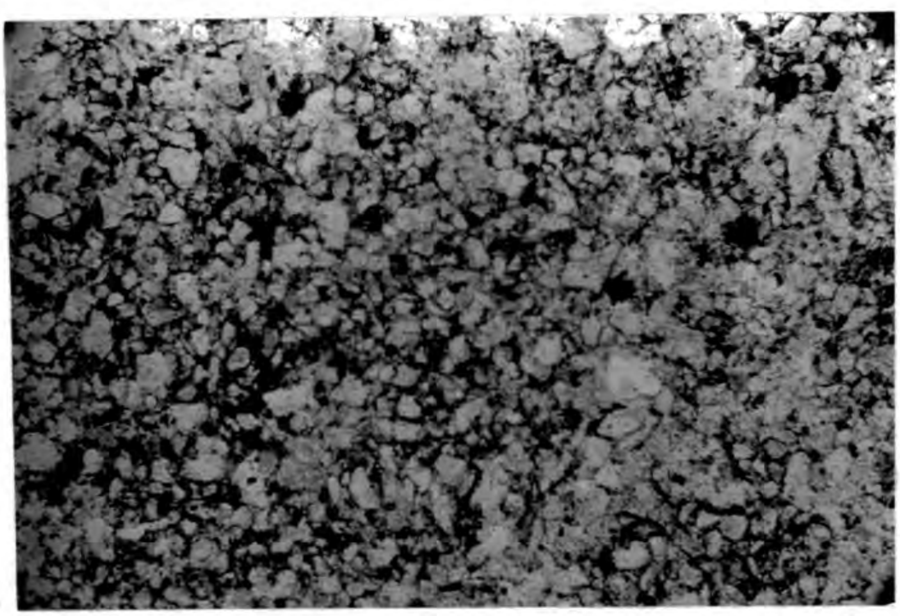


PLATE 28. Evenly distributed argillaceous matrix in muddy quartzarenite, Coalcleugh Transgression Beds. (x 30)

Cement and matrix. In all examples of muddy quartzarenites studied there is a combination of silica cement and, inevitably, the fine grained detrital matrix. The clay mineral may occur as irregular clots and patches associated with clearer areas of relatively pure quartz (Plate 27), or more uniformly distributed throughout the rock (Plate 28). The mineralogy of the clay matrix has not been investigated, but from the limited petrographical data available it appears commonly to be hydromuscovite or chlorite. The chlorite matrix (No. 275) is often partly limonitised, and relatively large crystals of authigenic chlorite may develop locally. In the Lower Rookhope Shell Beds (No. 139) a single oolith occurs, apparently composed of the same mineral, which also contains a large authigenic crystal of chlorite. By comparison with the more detailed petrographic work on the Knucton Ironstone (Chapter 14) it is possible that this mineral is in fact a 14Å chamosite. Crystals of pyrite occur within the clay matrix of one sample (No. 133).

Accessory constituents. Carbonaceous material and coal fragments may be abundant among the minor constituents of the muddy quartzarenite suite. Coal fragments, in fact, account for 2½% of the whole rock in the marginal facies of the Rogerley Channel (No. 47). Detrital siderite and white mica occur rarely, and, of the heavy minerals, zircon is the only one recorded.

E Subarkose

Fourteen specimens of subarkose have been investigated from the Namurian strata of the research area. Statistical sampling methods were not used in the field, but, in spite of the probable bias in collecting, it is clear that subarkose is an important rock type in the Upper Limestone Group. It may, in fact, be possible to subdivide this group further on the basis of grain size and sorting characteristics, but the results of the present investigation are not sufficiently objective for this to be accomplished satisfactorily. However, it will become apparent that those subarkoses which are considered to be fluvial in origin are generally moderately to very poorly sorted; subarkoses with a marine origin are medium to fine grained with good to moderate sorting.

Framework constituents. Quartz accounts for 80 to 95% of the major detrital constituents in the subarkoses investigated; the balance is made up in all cases by felspar. Undulose and non-undulose as well as polycrystalline quartz occur in varying proportions. Most of the granule and pebble sized fragments of the subarkose suite (the "quartzite pebbles" of field terminology), are composed of polycrystalline quartz (Plate 23), and only rarely is a non-undulose quartz granule observed. Some of the polycrystalline fragments resemble the "megaquartz" of Chanda (1963), which occurs as a diagenetic cement in sandstones.

The sand sized grains contain markedly less polycrystalline quartz, and it is apparent that the abundance of this type of quartz is related to grain size. The breakdown of the large composite fragments produces small grains of either undulose or non-undulose quartz. The lower frequency of polycrystalline quartz in the finer grained subarkoses does not, therefore, necessarily indicate a different provenance, but it could indicate a greater amount of reworking. The relative abundance of undulose and non-undulose quartz grains does not appear to be constant in the subarkoses studied, although details are not available. Most of the samples have a preponderance of undulose quartz, and only rarely does non-undulose quartz attain significant amounts. Minute liquid inclusions, sometimes containing gas bubbles, occur in some quartz grains; they commonly occur as linear "trains" and may be so numerous as to give the whole grain a clouded appearance.

Degree of sorting in the subarkose suite covers a wide range from very poor to good; this may be a reflection in some degree of the equally wide range of median grain sizes (Inman, 1949). Many of the conglomeratic subarkoses approach a bimodal size distribution with discrete size ranges for the pebble and sand fractions; sorting of the sand sized grains is usually poor. In all cases most of the quartz grains are mutually in contact so solution phenomena, such as sutured contacts, are common. The original shape of the grains is usually masked by authigenic overgrowths, but in some samples dusty coatings on the detrital grains show that many are well-rounded. The observed range of roundness for the sand sized grains is from well-rounded to subangular. The quartz grains in the Firestone Sill subarkose (No. 20) are predominantly angular; a feature which is probably at least partly due to the corrosive effect of the calcite cement. The polycrystalline quartz pebbles are usually well-rounded (Plate 23).

Despite the sometimes considerable amounts of the felspar component in the subarkose suite little is known of its mineralogy. Alkali felspar is the commonest variety but it is usually altered to hydromuscovite; the process of alteration begins preferentially along cleavage planes. Some of the fresher examples show a well-developed perthitic texture, and one felspar crystal exhibits Carlsbad twins. Plagioclase felspar usually occurs only as an accessory constituent, but in one specimen from the Low Grit Sill (No. 16) it forms about half of the total felspar content. The plagioclase crystals show a combination of albite and pericline twins and are clearly zoned; one crystal at least, is approximately andesine in composition.

Cement. In the absence of a fine grained detrital matrix the pore spaces of the subarkose suite of rocks are in all cases filled with chemical cement. Most commonly

PLATE 29. Microcrystalline silica cement in sub-
arkose, Low Grit Sill. (x 30)

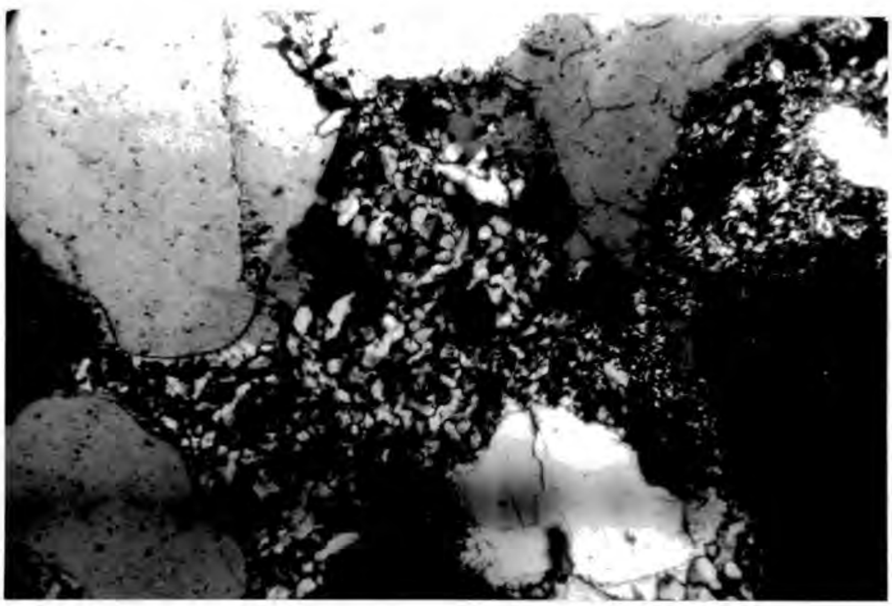


PLATE 30. Microcrystalline silica cement in sub-
arkose, Low Grit Sill. (x 120)

the cement is silica, but one sample of the Firestone Sill (No. 20) has a calcite cement. The most abundant type of silica cement occurs in the form of authigenic overgrowths on original detrital grains. The material for this process is believed to have come from pressure solution of contiguous grains as a result of burial (Siever, 1962). In medium grained sandstones this is generally sufficient to close the pores, but coarser sandstones tend to have larger pore spaces and this seems to be the prerequisite for another type of silica cement, known as microcrystalline quartz (Chanda, 1963). Excellent examples of this have been observed in the poorly sorted, coarse subarkoses of the Low Grit Sill (Plates 29, 30). It may be very abundant, and in one sample (No. 16) microcrystalline quartz accounts for 31% of the total rock analysis. Chanda (ibid.,) considered that this kind of silica cement is a replacement of original calcite, but in the rocks investigated by the writer no evidence of this mechanism can be observed. A little megaquartz (ibid., p. 730) has also been seen in these rocks.

The calcite cement in the Firestone Sill (No. 20) represents 39% of the total rock analysis, and it is likely that at least some of it is detrital in origin. Its original form is unknown because it has now recrystallised to large crystals which poikilitically enclose several detrital grains. A minor, poor cement is patchily provided by the hydromuscovite derived from the alteration of the

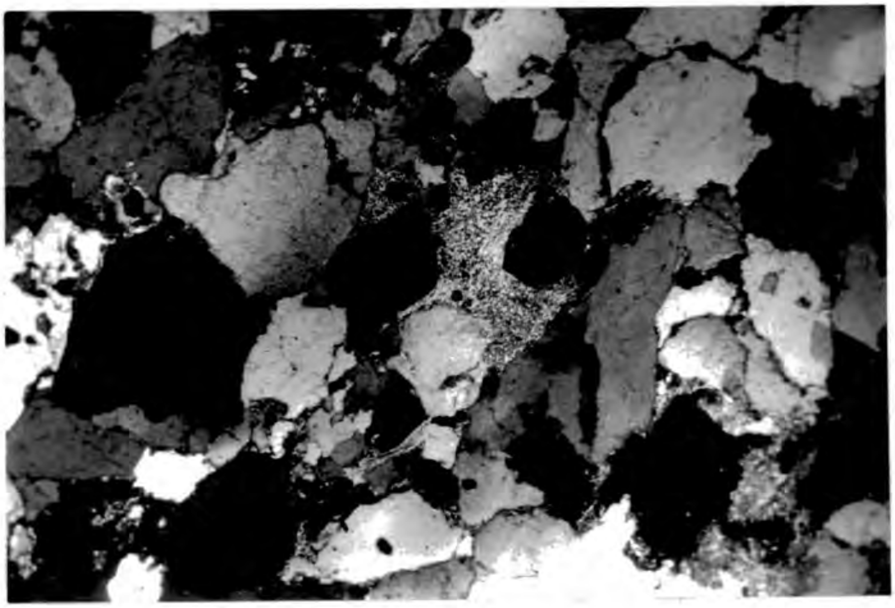


PLATE 31. Hydromuscovite invading pore spaces in subarkose, High Slate Sill (x 30)

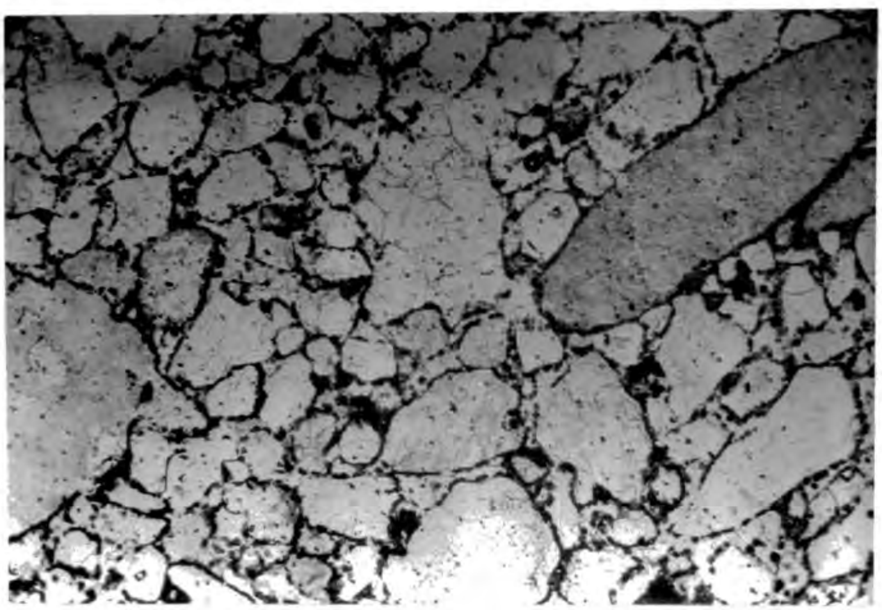


PLATE 32. Sublitharenite, showing rounded clay pellets, "Marginal facies", Low Grit Sill. (x 30)

alkali felspars. This frequently is able to invade adjacent pore spaces during diagenesis, which suggests that this process must occur at an early stage before the development of a silica cement (Plate 31).

Accessory constituents. The most common accessory minerals of detrital origin are, in order of abundance, white mica, zircon, plagioclase, tourmaline, and sphene. Mica is particularly rare in the coarse subarkoses, presumably because the high energy regime which that rock represents (p. 226) is not conducive to the settling of mica flakes. Rounded coal fragments are not particularly common, but do occur. Authigenic, flaky clay minerals can be observed in some specimens, and may be termed hydromuscovite for want of a detailed X-ray investigation; they grow from the aggregate of hydromuscovite crystals produced by the alteration of alkali felspars.

F Sublitharenite

Only one of the twenty-nine sandstone specimens studied falls into the category of sublitharenite. Its unusual composition may stem from its uncommon sedimentological position as part of the channel margin facies of the Low Grit Sill (Fig. 7.4).

Framework constituents. Quartz comprises 81% of the framework constituents of this sublitharenite, the remainder being made up entirely of rock fragments. The median size of the quartz grains is coarse and the sandstone is poorly sorted. Most of the quartz grains have undulose extinction, but polycrystalline quartz is also quite common; the percentage of non-undulose quartz is relatively small. The presence of an apparently original veneer of detrital siderite (Plate 32) enables the roundness to be assessed as varying from subrounded to subangular. The detrital coating on the quartz grains is not sufficiently thick to prevent the development of silica overgrowths in optical continuity, which are quite common. Sutured contacts as a result of pressure solution also occur, and some corrosion as a result of siderite replacement has taken place.

The rock fragments contained in this rock are all of one type and appear to have been derived penecontemporaneously from previously deposited sediments (Plate 33). They are entirely composed of clay mineral which from its low birefringence and other optical properties, and its pale green colour in hand specimen, may be regarded as chlorite, perhaps even a 14Å chamosite of the type described from the Knucton Ironstone (Chapter 14).

Cement. Detrital siderite acounts for 19% of the total rock composition but it does not form the dominant cementing material; it occurs as silt sized grains, mostly incompletely coating detrital quartz. Authigenic silica, occurring as overgrowths on the quartz grains, is a more important cement.

Accessory constituents. Accessory minerals are of little importance in this sublitharenite, forming as they do, only ½% of the total rock. White mica is the most abundant of these, and tourmaline, occurring within a detrital quartz grain, is the only heavy mineral present. Limonite occurs in the weathered zone as an alteration product of siderite.

G Litharenite

Litharenite is another uncommon rock type within the Upper Limestone Group, and only sandstone (No.96) so far described can be assigned to it. The specimen comes from the top of the Fiddler's Sill in Nookton Burn but it is unlikely that this term should be applied to the unit as a whole, it refers particularly to a banded unit within the sill. Another sample, from the base of the White Sill, has been recorded as belonging to this mineralogical suite, but it has been discounted on the grounds of grain size; it is only a sandy siltstone.

Framework constituents. The quartz grains in this very fine grained litharenite comprise 73% of the major detrital components (Table 4). Polycrystalline quartz grains are not apparent, and by far the most abundant are the non-undulose and undulose varieties. A certain amount of pressure solution has taken place but many of the grains fall within the rounded to subangular range; sorting is

PLATE 33. Sublitharenite, "Marginal facies", Low Grit Sill, Nookton Burn.

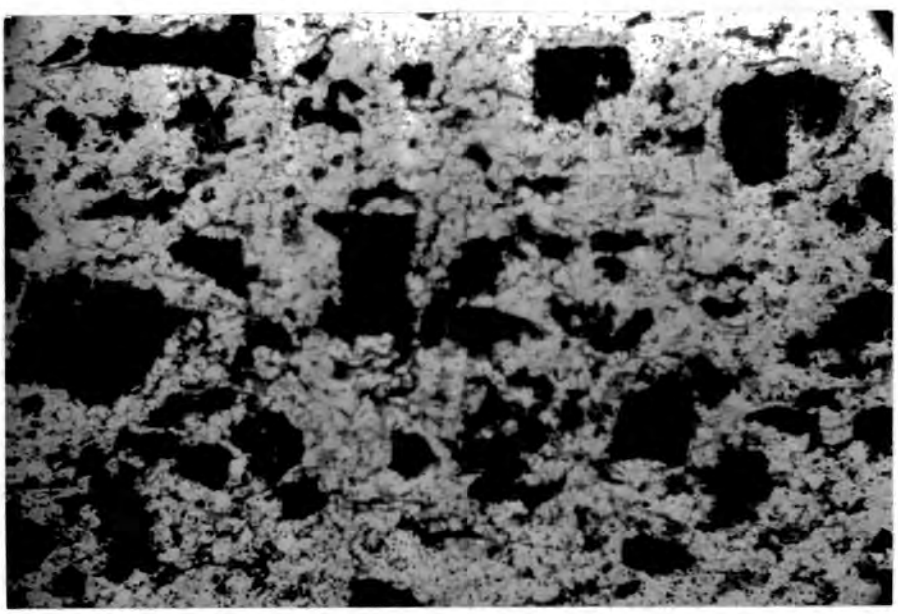


PLATE 34. Litharenite, showing angular siderite fragments. (x 30)

moderately good.

The most abundant type of rock fragment in the sandstone is sideritic ironstone; rounded coal fragments also occur but are of minor importance. The siderite occurs as pure segregations of silt sized crystals which vary from about 0.02 to 0.08 mm. in long diameter. Occasionally the ironstone fragments are elongate in the plane of the primary lamination and occur in prominent bands about 5 mm. wide separated by siderite-free bands of similar width. The modal analysis (Table 5) is an average for the whole rock; individual bands will be appropriately biased towards either the quartz or siderite component. The margins of the rock fragments are not always smooth and water-rounded (Plate 34), but they are clearly detrital, and it is assumed that some siderite penetrated the pore spaces after deposition.

Cement. Siderite has, in fact, invaded the pore spaces sufficiently for it to be regarded as a partial cementing agent, but in the non-sideritic bands silica is the common cement. As usual, this takes the form of authigenic overgrowths on quartz grains.

Accessory constituents. White mica occurs quite abundantly in this sandstone and makes up 7% of the total rock analysis; it is usually segregated along particular bedding planes. An authigenic clay mineral also occurs, which is pleochroic in shades of brown. Without an X-ray study this mineral cannot be identified, but it may be some variety of chlorite. One or two small crystals of plagioclase felspar, with the approximate composition of oligoclase, occur. Zircon is the only heavy mineral observed.

CHAPTER 14

THE KNUCTON IRONSTONE

I Introduction

The Carboniferous rocks of the British Isles are known to contain abundant syngenetic sedimentary iron deposits. These generally occur in the form of siderite, most commonly as clay ironstone concretions in shales. They also occur as sphaerosiderite concretions in underclays (Deans, 1934), and as matrix in locally persistent beds of sideritic sandstones and limestones (Hudson, 1941). A mineral commonly associated with siderite in many sedimentary iron formations of Mesozoic age is the iron alumino-silicate chamosite ($3FeO.\ Al_2O_3.\ 2SiO_2.\ aq.$). Recorded occurrences of this mineral in the Carboniferous of this country are very few, however, and only one chamosite bearing horizon has previously been recorded in the Upper Limestone Group (Reading, 1957). In the research area the writer has discovered three horizons, the Knucton Ironstone, and the Lower and the Upper Rookhope Ironstones (p. 51), at which chamosite ooliths may occur abundantly, as well as several other impersistent oolitic bands.

Chamosite was first recorded from British Carboniferous deposits by Deans in 1934, who described it from nodules in the underclays below the Halifax Hard Bed and the Cottingley Crow Coal of Lower Coal Measure age (lenisulcata zone). The chamosite forms the matrix to sphaerosiderite concretions, amounting to 70% in some nodules, and is apparently the diagenetic alteration product of felspathic and ferromagnesian material (ibid., p. 57). In 1936 Deans described a less common type of spherulitic ironstone which he found at three horizons in the Millstone Grit and Coal Measures near Leeds and Bradford. The iron-stones each occur immediately above coal seams and characteristically contain oolitic clay minerals and siderite. The Robin Hood Oolite (modiolaris zone) is the only horizon at which the "isotropic clay" occurs in oolitic form. Petrographically "there is nothing to suggest that the isotropic clay is not primary" (ibid., p. 174). A subsequent X-ray study by Brindley and Robinson (1950, p. 87) showed that the "isotropic clay" gave only a kaolinite pattern and they concluded that this mineral probably existed in a finely divided form in the ooliths. In view of the apparent ease with which chamosite is converted to kaolinite (plus goethite), (Hallimond, 1925; Taylor, 1949, p. 37), it is conceivable that the concentrically layered ooliths were originally chamosite, although there is no direct evidence to support this conjecture (Deans, 1961, personal communication).

An interesting occurence of chamosite has been recorded by Williamson (1946) from the Etruria Marls (Upper Coal Measures) of North Staffordshire. The chamosite is associated with "rhombohedral carbonate" in the matrix of grits which are intercalated in the formation. The chamosite also occurs in ooliths where it may alternate with zones of clear carbonate or darker isotropic material.

Chamosite has been recorded in the Ayrshire Bauxitic Clay of "Millstone Grit" age, where it is thought to have formed in pools and lakes from material derived from the contemporaneous decomposition of the underlying lavas. Brindley (1951) confirmed the original diagnosis of Eyles and others (1949) by an X-ray study of the chamosite.

Strong (in Edwards, 1951, p. 18 and in Falcon and Kent, 1960, pp. 50-54) recorded light to dark green "grains" of chamosite at several horizons in the Coal Measures (Ammanian) and Upper Namurian as seen in borings in the East Midlands.

In the literature to date there is only one reference to chamosite in the Lower Namurian rocks of Britain. This was made by Reading (1957, p. 46) who discovered chamosite ooliths in the Coalcleugh Marine Bed in Baldersdale, North Yorkshire. The ooliths occur in a lenticular, fossiliferous, sandy mudstone which also contain glauconite.

A series of small diameter bores in the Upper

Limestone Group west of Allenheads (Northumberland) showed that "thin, red-brown, limy, ferruginous oolite bands" containing fossils occur at four horizons between the Little and Lower Felltop Limestones (Dunham and Johnson, 1962). The writer has recently had the opportunity to study these borehole specimens. They are largely composed of siderite, but the scattered ooliths are believed to be chamositic. Sideritic chamosite oolites of this type have also been examined from the Geological Survey borehole at Woodland, near Middleton in Teesdale, indicating that chamositic ironstones are more widespread in the Upper Limestone Group than has previously been supposed.

II Petrography

Ironstones in the Upper Limestone Group of the study area include a number of types which apparently form a series of variable composition with the three end members, sand, ooliths, and siderite. The gross lithology of the recorded ironstone horizons is by no means constant. They show considerable lateral variation, perhaps passing within relatively short distances, from a sandy sideritic chamosite oolite to a sideritic sandstone or a sandstone with scattered ooliths. Major differences in depositional environment are brought out by the marked concentration of oolitic deposits at three horizons, the Knucton Ironstone, and the Lower and Upper Rookhope Ironstones. Extreme variation in lithology is a character which the Namurian ironstones share with those in other formations, such as the Northampton Sands Ironstone (Taylor, 1951, p. 79), the Dogger Ironstones (Rastall and Hemingway, 1939 et seq.), and the Banbury Ironstone (Whitehead et al., 1952, p. 164). Both the petrography and mineralogy of the Knucton Ironstone, the best developed chamositic horizon, have been studied in detail.

A. Hand Specimen petrography

The Knucton Ironstone in its oolitic development is a sandy, sideritic, chamosite oolite using the nomenclature of the Geological Survey as devised by Taylor

(1949, p. 5). Siderite is invariably the most abundant mineral in the best developed oolites, and quartz commonly takes a subordinate position, although still present in considerable amounts. The quartz grains are usually of medium grain size, but the lowermost few inches of the ironstone may contain very coarse sand up to 1.5 mm. in diameter. When this very coarse sandy type contains ooliths they too are larger than usual, averaging 0.5 mm, suggesting that the same depositional factors affected oolith and quartz grain alike (p. 219). It is impossible to speak of a "typical Knucton Ironstone" in view of its extreme variation, but the modal analyses given in Table 6 provide a general impression of the lithology of the oolites.

TABLE 6

Modal analyses in percent of the Knucton Ironstone and the Lower Rookhope Ironstone

Sample number	73	251	290	328	196	365
Siderite	48.0	37.2	36.1	52.0*	24.7	23.0
Chamosite ooliths	34.2	23.8	29.8	25.5	32.5	15.5
Quartz	15.0	37.4	27.9	20.5	24.7	45.5
Others	2.8	1.6	6.2	2.0	2.8	16.0
	Knucton Ironstone				Lr. Rookhope Ironstone	

* Heavily limonitised

The ooliths are generally very pale green in hand specimen, although some may be slightly darker and appear grey. In fact near Coal Crag in Noökton Burn approximately 45% of the ooliths in the sample collected are dark grey to black in colour. These are the result of opalisation of chamosite ooliths and are similar to the "black ooliths" of the Dogger (Middle Jurassic) described by Rastall and Hemingway (1939). This question is discussed more fully on page 150. The size of the chamosite ooliths in the Knucton Ironstone of Nookton Burn ranges from 0.1 to 0.5 mm., measured along the longest diameter, and the mode of the distribution lies at 0.35 mm. Ellipsoidal or disc-like ooliths are by far the most common, but more or less spherical ones also occur. The disc-like ones achieved their shape as a result of post-depositional compaction. This is shown by the frequent cases of ooliths with deep indentations, which can be seen, in thin section, to have been caused by the pressure of contigous quartz grains (Plate 39). The ellipsoid shape, however, may be a primary feature. It is quite common to find ellipsoidal calcareous ooliths in areas of recent carbonate sedimentation, such as the Bahama Banks, where the final shape is often related to that of the core.

The siderite in the oolites occurs dominantly in the matrix, and gives the rock its dark grey colour. Distribution of siderite in the rock as seen in hand specimen is rarely uniform, and typical oolite has a blotchy or

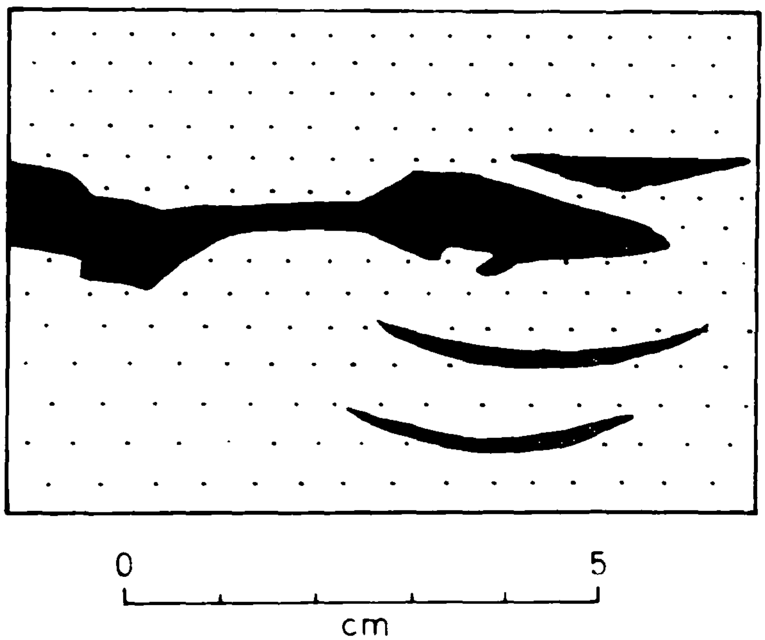


Figure 14.1

Pure siderite segregations of believed primary origin in sandstone, Knucton Ironstone.

mottled appearance. This in part is due to the fact that the concentration of the ooliths is patchy, but also partly due to the presence of worm burrows, in which siderite is the only constituent. The burrows may have a well-developed tube-like form or they may be more irregular. There is a marked contrast and a sharp margin between the host rock, where quartz grains and ooliths abound, and the burrows, where both these components are absent. One particular kind of burrow seems almost to be diagnostic of the Knucton Ironstone and has been found widely over the study area. It is characterised by having a quasi-concentric arrangement of the materials composing the burrow and often by an open passage running along its length, which rarely may be filled by coarsely crystalline calcite. Usually the bulk of the material in the burrow is siderite, but chamosite ooliths may occur within it, occasionally disposed in concentric bands. The quasi-concentric arrangement is believed to be related to the grazing habits of the creature in the sediment. A similar type of burrow, but occurring in groups, is represented by Phycodes Richter.

In Sipton Cleugh, the non-oolitic lower part of the Knucton Ironstone contains saucer-like bodies of siderite about 4 cm. in diameter and ranging in thickness from 1 mm. to 1.5 cm. (Fig. 14.1). The saucers or lenses lie in the bedding plane, are composed entirely of siderite, and have sharp contacts with the surrounding sandstone. Semi-continuous sideritic bands with varying thickness also occur. These segregations cannot be attributed to worm action, and they cannot have formed by secondary processes of accretion after deposition because they would otherwise contain as much quartz as the rest of the rock. There seems, therefore, to be a good case for postulating a primary origin for these siderite bodies. Dunham (1960, p. 259) has suggested that chemical precipitation of siderite, probably initially in the form of a gel, may be possible under sufficiently anaerobic conditions. It is possible, therefore, that the siderite lenses just described represent such a gel which was sufficiently competent to resist the inclusion of sedimentary quartz grains. Rastall and Hemingway (1940, p. 270) have also proposed a primary origin for siderite occurring as a matrix to a sandstone in the Dogger of Yorkshire.

It is interesting to note that the Knucton Ironstone has virtually the same petrographic features as the Ajalon facies of the Dogger Ironstones (Rastall and Hemingway, 1941, p. 362; 1943, p. 227). The Ajalon facies may vary from an "ill-graded sideritic sandstone with a few ooliths at the base through an oolite with sand grains to a black oolite" (1943, p. 228).

Of the remaining rock forming constituents in the Knucton Ironstone the fossils are perhaps the most important. Brachiopods are by far the most abundant group, but molluscs, bryozoa, trilobites and crinoids also occur.

They occur scattered throughout the whole thickness of the rock, but also segregated in thin bands.

Collophane, although present, is rarely abundant, and its presence cannot usually be detected in hand specimen. Greenish mud-pellets, ranging in size from a few millimetres to three centimetres, are common at some localities. It is suggested that these represent an original chamosite mud which has been reworked.

B. Effect of Weathering

A factor which has undoubtedly contributed to the chamosite oolites in the Upper Limestone Group being overlooked has been the failure to recognise them when weathered. All the rocks which have been studied were obtained from outcrop and consequently are weathered to a greater or lesser degree. It would appear that siderite is the most easily affected by oxidation. It quickly takes on a brownish tint due to partial limonitisation. This process is rapidly brought to completion upon prolonged exposure, and commonly the ironstone may appear as a medium grained sandstone, having a limonite cement, but still with abundant green ooliths. A similar rock has been described by Taylor from the Northampton Sands Ironstone (1949, p. 38), and from the Banbury Ironstone by Whitehead (1952, p. 165). Weathering of the ooliths themselves does not produce an immediate breakdown into hydrous ferric oxides because of the development within many ooliths of a large crystal of authigenic 14A° chamosite. The chamosite is believed to have formed at more or less normal temperatures (p. 149), and as such is relatively stable under ordinary weathering conditions. A common rock type found at outcrop is a sandstone with a limonite cement and abundant large flakes of the pale green 14A° chamosite. Whitehead also found in the Banbury Ironstone (1952, p. 162) that "the 'oxidation' of the chamosite crystals always lags behind that of the ooliths..". Although not actually recorded as such it is conceivable that his "chamosite crystals" are in fact of authigenic origin. Small crystals of limonite-stained siderite do occur within the chamosite, so the final product of weathering of all the iron minerals will be essentially limonite, probably in association with non-ferriferous clay materials. In the Northampton Sands Ironstone Taylor (1949, p. 37) found that the alteration products comprise "a finely divided mixture in varying proportions of kaolinite with geothite or possibly with some silicate of ferric iron". They may either retain the oolitic structure or occur as an aggregate of unorientated fibres. Kaolinite has not been detected in any of the ooliths of the Knucton Ironstone. In any case this would be very difficult to diagnose by X-ray analysis because of its association with chlorite (p.164).

C. Thin section petrography

Concentric rims of the ooliths. The chamosite forming the concentric layers in the ooliths is generally pale brown to more or less colourless in plane polarised light, and it is not noticeably pleochroic. This shows considerable differences from most of the chamosite occurring in the Jurassic Ironstones of Great Britain, which is green of various shades and markedly pleochroic (Taylor, 1949, p. 17; Dunham 1952, p. 17). However, ooliths of pale brown chamosite do occur in fresh rock of the Ajalon facies of the Dogger Ironstones at Rosedale Abbey Bank (Rastall and Hemingway 1949, p. 277). Pulfrey, in studying the Ordovician chloritic chamosite oolites of North Wales (1933), found that he could recognise several chlorites on the basis of their optical properties, and he tentatively suggested a correlation with chemical composition (ibid., p. 419). One of his "types" is a greyish chlorite developing yellow or brown tints on slight weathering, which is non- or feebly pleochroic. This appears to be optically very similar to the Knucton chamosite. Pulfrey's chemical analyses showed that this type was "mainly chamosite". This statement could probably be elaborated by a more up-to-date investigation of the Welsh chamosites, but, for the moment, it can be regarded as a tentative confirmation of the present writer's diagnosis.

The mean refractive index of the chamosite from the Knucton Ironstone has been measured in one sample as being 1.637. Although a single reading is not very significant it compares favourably with those determined by previous workers in other formations. Dunham found that in the

Liassic Ironstones (1952, p.19) the mean index ranges from 1.605 to 1.660, and Taylor's measurements on the Northampton Sands chamosite (1949, p. 18) range from 1.62 to 1.66. Taylor also found that the lower index chamosites were paler in colour, and he concluded that both the depth in colour and the variation in optical properties were partly due to the amount of clay associated with the chamosite.

The birefringence can be estimated from the interference colour and is found to be commonly around 0.003 (dark grey), and never greater than 0.009 (white to very pale yellow). The birefringence in the Liassic Ironstones may be as high as 0.015 (first order orange) (Dunham, 1952, p.19). The chamosite in the concentric rims has the slow ray orientated parallel with the basal cleavage, indicating a positive sign of elongation. According to Albee (1962, p. 863) the sign of elongation in chlorites is always opposite to the optic sign. It can be shown by X-ray analysis that the Knucton chamosite is a true chlorite (p. 168); thus, although a direct measurement cannot be made, the chamosite must be optically negative. For the chlorites that Albee studied, he found that optically negative ones had β refractive indices ranging from 1.63 to 1.68, and that those without anomalous interference colours were iron-rich varieties. These also have the highest refractive indices. This observation confirms Taylor's contention that the least contaminated chamosites (and therefore the most iron-rich) have a high refractive index near 1.66. The chamosites of the Knucton Ironstone conform to the optical properties of Albee's iron-rich chlorites except in so far as the refractive index seems too low for one with normal interference colours. This argument, of course, hinges on the assumption that the Knucton chamosites are strictly comparable with the chlorites studied by Albee, which did, in fact, include samples from sedimentary iron formations.

Evidence from several authors (Pulfrey, 1933; Taylor, 1949) suggests that pale-coloured chamositic ooliths are not pure monomineralic substances. Albee's work demonstrates that iron-rich chlorites should have a high refractive index (near 1.68), and any anomalies require an explanation. Taylor's evidence (largely based on chemical analyses) supports a contamination hypothesis to explain this, and it is necessary to investigate independent lines of evidence with regard to the mineralogical make-up of the Knucton oolites.

It is difficult to ascertain from thin-section studies whether more than one clay mineral occurs in the ooliths; the minute size of the crystals is the limiting factor. Generally, however, in the concentric rims, chamosite and/or other clay minerals have two manifestations. In the first place they may occur as extremely minute, almost submicroscopic, crystals which have a concentric arrangement, but one which is only vaguely defined (Plate 36).

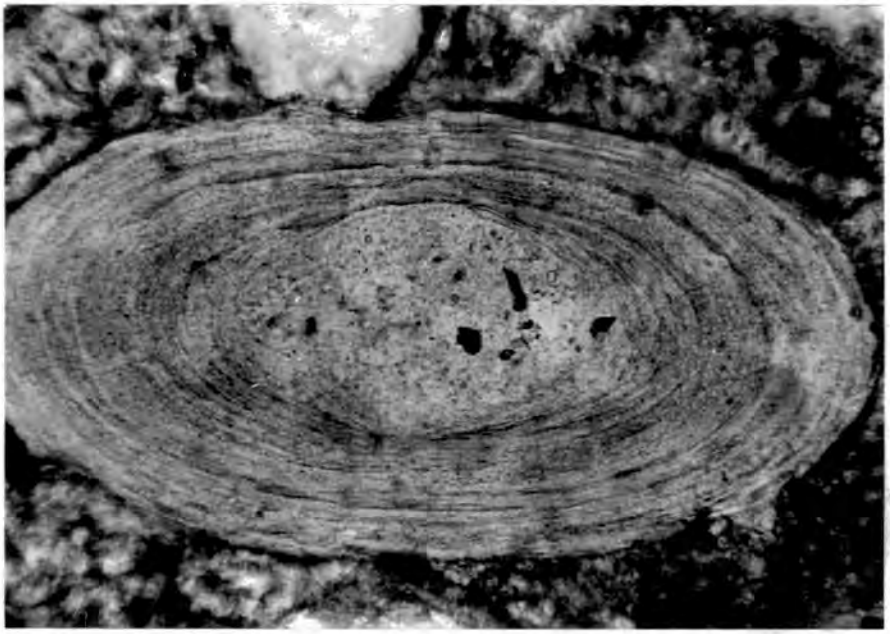


PLATE 35. Chamosite oolith, showing structureless core and coarse crystallisation of rims. (x 400)

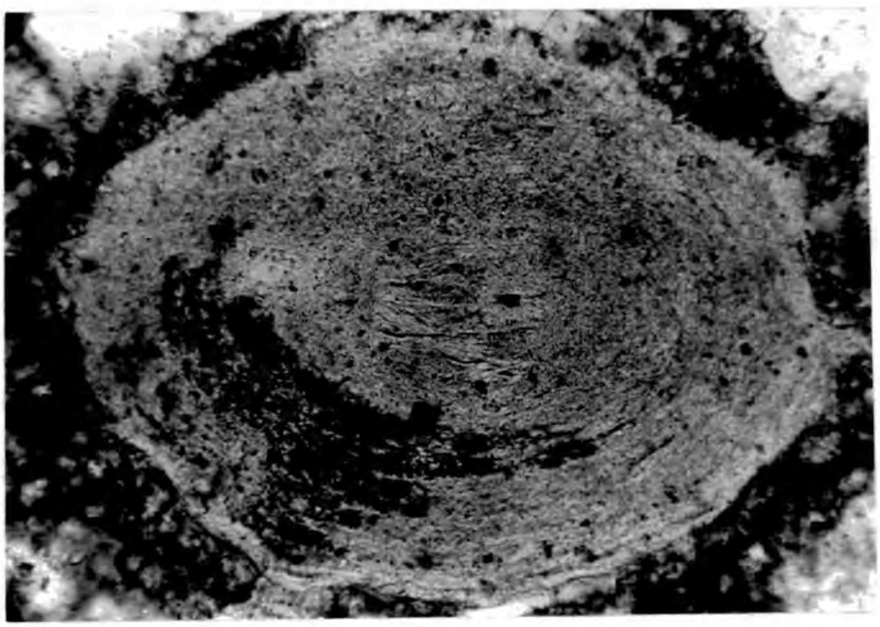


PLATE 36. Chamosite oolith, showing development of authigenic chamosite in core, fine crystallisation of rims, and partial opalisation. Note parallelism of long axis of oolith and authigenic chamosite. (x 400)

In the second, the crystals occur as much coarser concentric layers which may almost completely encircle the oolith (Plate 35). These seem to be large single crystals of chamosite, quite distinct from the layers of collophane discussed later (p. 155). Commonly both types of crystal occur in the same oolith, and it is conceivable that the difference in form reflects an intrinsic difference in composition or structure. This question is further discussed in relation to the interpretation of X-ray diffraction data on page 164. Equally tenuous evidence for a heterogeneous constitution is afforded by the slight differences in refractive index and birefringence which can be detected throughout the concentric rims of some ooliths. None of this evidence, of course, can be said to prove that the ooliths are composed of anything other than chamosite, but it serves to illustrate that the physical properties of the concentric rims are by no means uniform.

Reference has already been made to the concentric layers of collophane which occur commonly within the ooliths. The collophane is pale yellow or yellow brown in plane polarised light and is isotropic. X-ray analysis of the Knucton ooliths leaves the identification as collophane in no doubt (p. 161). The collophane layers completely encircle the oolith and, as they may be quite numerous they serve to enhance the concentric nature of the chamosite. The most likely explanation of the collophane bands is that they represent contemporaneous phosphatisation on the sea floor. The presence of associated phosphate pebbles in the ironstone (p. 156) gives added weight to this hypothesis.

Cores of the ooliths. In the Knucton Ironstone the cores of the ooliths are commonly composed of unorientated flakes of chamosite. This diagnosis is supported by the general optical properties as far as these can be ascertained, but it is perhaps unlikely that the core material is 100% chamosite. The chamosite in the cores of some ooliths may be virtually colourless even though that in the concentric shell is pale brown. This suggests a two-fold origin, and lends support to the conjecture that the structureless core represents a previously deposited chamosite mud which has been reworked by the encroachment of a more vigorous environment. Ooliths with this type of core are abundant in all known chamosite oolite deposits, and in many cases, such as the Northampton Sands Ironstone, they are the most common (Taylor 1951, p. 80).

The proportion of ooliths with cores of material other than chamosite mud is relatively small, but grains of quartz, collophane and calcite have been observed to form original nuclei. The general absence of quartz as nucleus to the ooliths is a strong point in favour of their origin in an area where clastic sedimentation was absent. The ironstone is always very quartz-rich, and there are many grains of a size suitable for the formation of ooliths which do not have even the finest coating of chamosite. This indicates that the ironstone is a product of sediment mixing which necessarily involved the removal of the ooliths from their place of origin. Other authors (Cayeux, 1922;

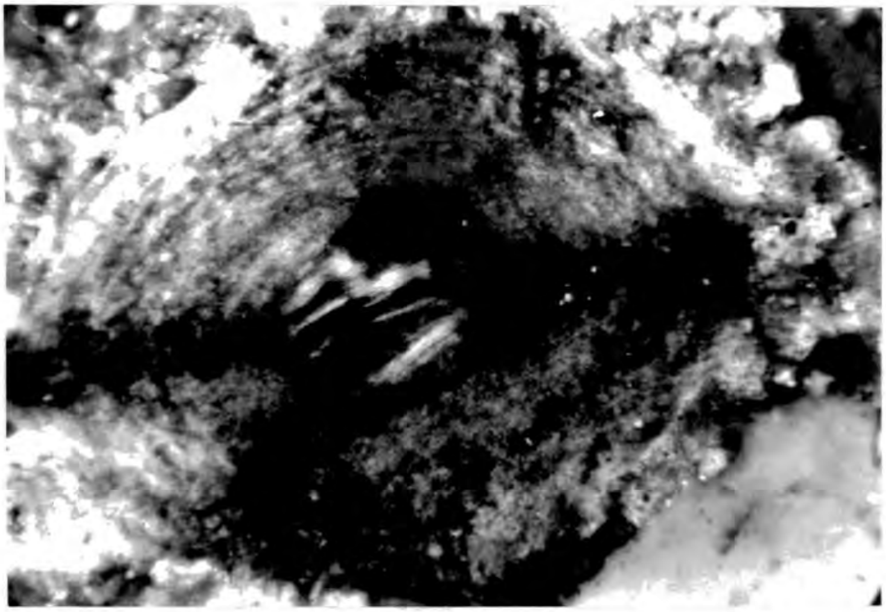


PLATE 37. As for Plate 36, but with crossed nicols.
(x 400)

PLATE 38. Crystal of authigenic chamosite just occupying the core of the oolith.
(x 400)

Hallimond, 1925, p. 9; Taylor, 1949, pp. 7, 78), have also noted that oolitic ironstone deposits are often redeposited.

Authigenic chamosite. Several authors (Taylor, 1949, p. 17; Dunham, 1952, p. 27), have observed ooliths from sedimentary ironstones which apparently have nuclei of large, well-developed crystals of chamosite. The usual interpretation placed upon this observation is that the crystals represent an original core around which the rest of the oolith accumulated. Evidence from the Knucton Ironstone, however, suggests that such large flakes are secondary in origin, and have grown authigenically from a structureless core. Examples are common in which the large book-like crystals of 14Å chamosite occupy the core of the oolith more or less exactly (Plate 38), but even more common are those in which the chamosite cuts across the concentric chamosite laminae (Plates 40, 41). The replacive nature of these crystals can be in little doubt, but it has yet to be established that the non-transgressive chamosite just occupying the core is not a primary nucleus. This is more difficult, and there is no irrefutable proof that this is so. Even though the modus operandi is not understood, a plausible mechanism for the formation of authigenic chamosite has been deduced by a study of thin sections from the Knucton Ironstone.

Development of authigenic chamosite has taken place in every sample of the Knucton Ironstone investigated. In any specimen there is always a mixture of unaffected

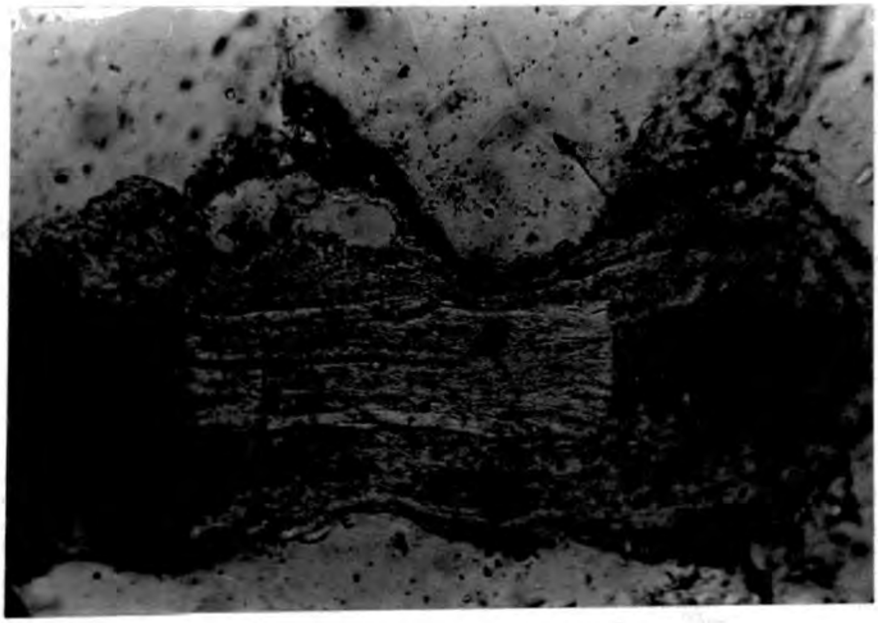


PLATE 39. Large crystal of authigenic chamosite in elongate oolith with impinging quartz grain. (x 400)

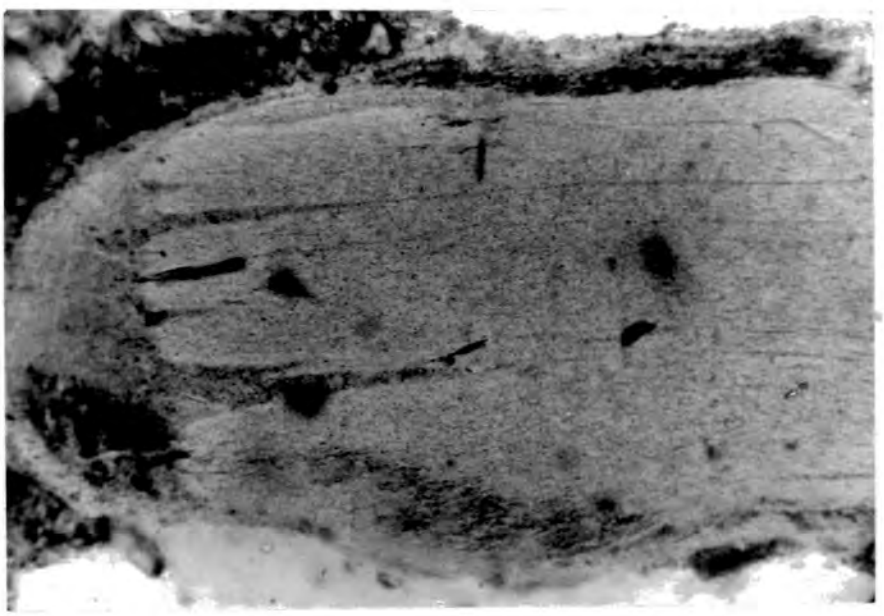


PLATE 40. Authigenic chamosite almost completely occupying oolith. (x 400)

ooliths retaining their original structureless core and those in which authigenic chamosite has become dominant. Extreme cases occur where the chamosite has completely taken over the oolith, leaving no evidence of its former oolitic structure. It can be demonstrated (Plates 35 to 41) that there is every gradation between the two types mentioned. The authigenic chamosite appears first in the formerly structureless core as a series of small, wispy flakes of high birefringent material having a preferred orientation parallel to the long axis of the oolith (Plates 36, 37). These flakes are so filamentous and fragile that it is highly unlikely that they could have existed as such in an aqueous environment, and an authigenic origin seems most probable. It is believed that these small orientated chamosite crystals grew at the expense of the original chamosite mud nucleus, eventually becoming a single crystal completely occupying the core of the oolith. This is the stage which has most commonly been observed by other workers, and which has been taken to represent an original nucleus. Some ooliths contain large flakes of chamosite which are orientated with their basal cleavage at right angles to the length of the oolith (Plates 42 to 44). This is an impossibly unstable system in an oolith-forming environment, in view of the ease of disaggregation along the basal partings. In one crystal of authigenic chamosite there are traces of smaller, randomly orientated crystals, which do

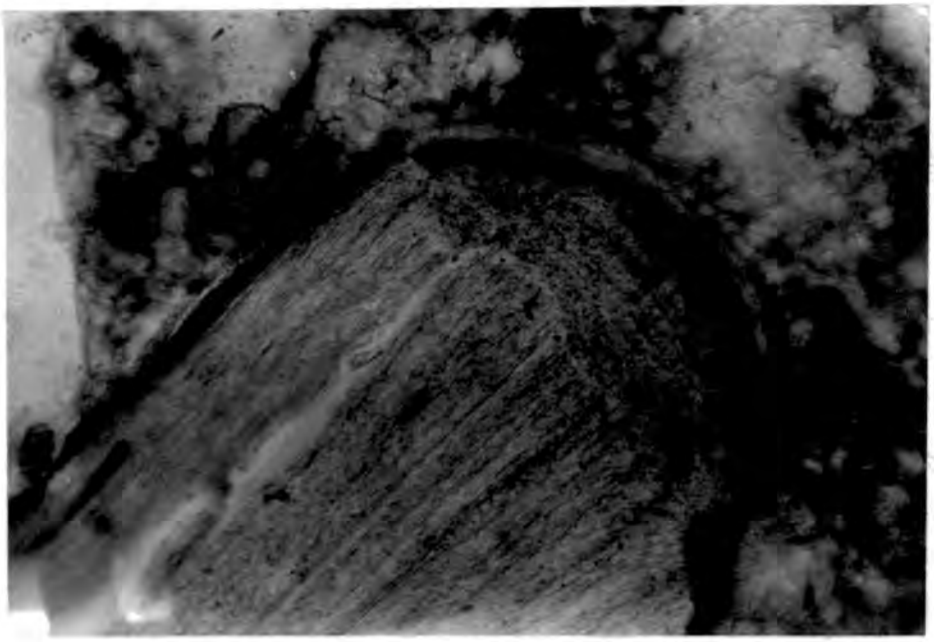


PLATE 41. Authigenic chamosite almost completely replacing original oolith. (x 400)

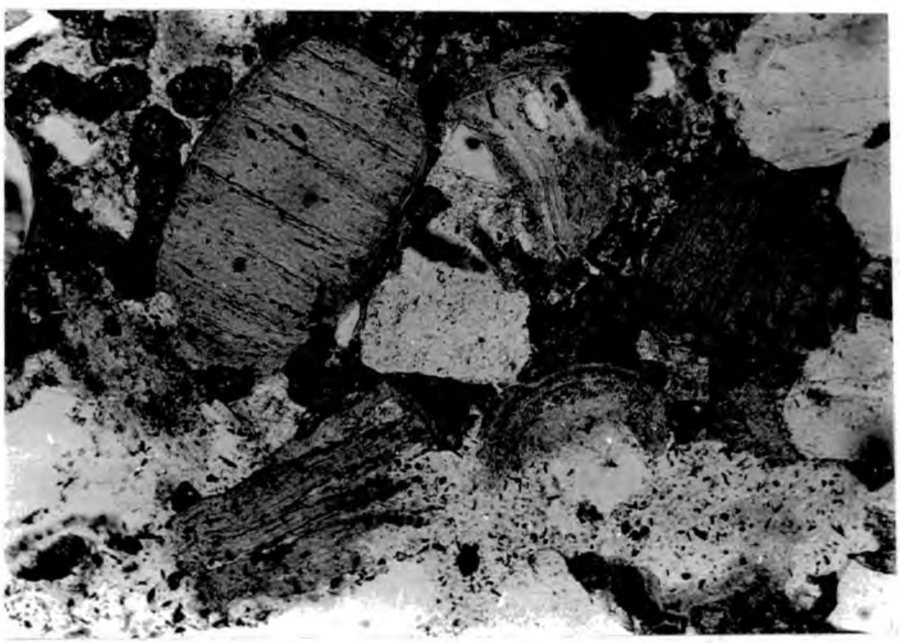


PLATE 42. Quartz, siderite, and ooliths showing both orientations of authigenic chamosite. (x 120)

not extinguish at the same time as the rest of the crystal, but which are definitely part of it. This is regarded as evidence in support of the suggestion that the crystal recrystallised from a disorientated mass. The next stage is simply the enlargement of the chamosite crystal until it eventually obliterates the original oolith (Plates 41, 44). The various stages in this process are usually quite well preserved.

The marked preferred orientation of the authigenic chamosite within the ooliths is one of the most puzzling features of the transformation. By far the most common orientation has the strong basal cleavage exactly parallel with the long axis of the oolith, but there are other examples where the chamosite is orientated exactly at right angles to this. There are never any intermediate orientations. Clearly, therefore, this phenomenon is not fortuitous, but its explanation is open to much speculation. Petrographic evidence indicates that parallelism with the long axis of the oolith is a feature which is inherent in the authigenic development of the chamosite in the first place, because even the early formed crystals show it. It might be suggested that any authigenic mineral which might form within an oolith would tend to use the pre-existing minerals as a nucleus, especially if they had the same or similar structure. Flattened ooliths already have a strong preferred orientation of the original chamosite, so, if this process were operative, it would seem natural to expect the authigenic mineral to have the same orientation. However this does not seem a likely mechanism, because it does not explain those chamosites with cleavage at right angles to the axis of the ooliths. Furthermore, some of the early crystals grow in the core in contact with, but at right angles to, chamosite in the concentric rims. Clearly, there can be no question of "seeded growth" in this case.

If the larger scale textural relations within the ironstone are examined it can be seen that authigenic chamosite in adjacent ooliths often has the same orientation, thus imparting a pseudo-bedded appearance to the rock. This effect is purely local, and nearby ooliths may have chamosite developing at right angles. Nevertheless, this "regional orientation" is believed to be a significant feature, and it argues in favour of the suggestion that the chamosite developed in response to the same factor which produced flattening in the ooliths. This factor is, of course, compaction. It is also significant that very few ooliths which are circular in cross-section (and, therefore, presumably, little affected by compaction) have developed authigenic chamosite (Plate 45). Thus, it would appear that a certain amount of pressure is required before conditions are favourable for the formation of the chamosite. Many of the chamosite crystals which have grown with their cleavage at right angles to the length of the oolith have also developed

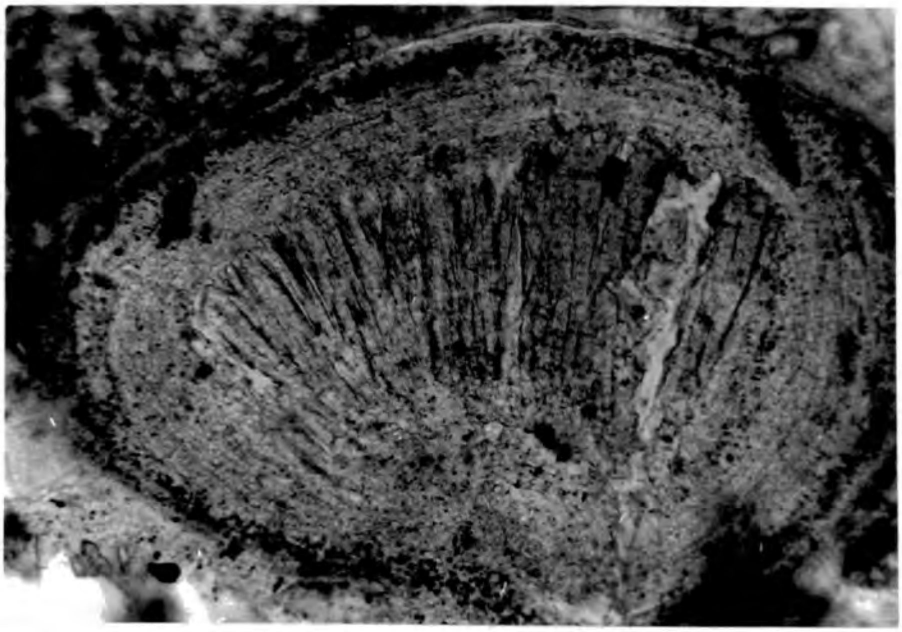


PLATE 43. Authigenic chamosite forming with basal cleavage at right angles to long axis of oolith. Note "accordian-structure". (x 400)

PLATE 44. "Accordian-structure" in authigenic chamosite. (x 400)

an "accordian-like" structure (Plates 43, 44), which is possibly the result of local variations in the direction of the stress field. The diagenetic process involved in the growth of the chamosite seems, therefore, to be very much akin to metamorphism. The chamosite developed in response to slight, more or less unidirectional pressure in an environment which must have been aqueous and at a relatively low temperature. Work on recent sediments in the Gulf of Mexico (Murray and Harrison, 1956, p. 367) and on Tertiary sediments from the Gulf Coast (Burst, 1959; Powers, 1959, p. 318) has shown that chlorite does indeed become better crystalline with increasing depth of burial; such transformations are primarily a function of time, pressure, and temperature (Yoder and Eugster, 1955).

The formation of authigenic chamosite at the expense of primary oolitic chamosite has not been described from any British oolitic ironstone formation, although Pulfrey (1933, p. 408) does record a high birefringent chlorite developing in the matrix of the North Wales oolites; this is believed to be the result of metamorphism. Similarly, in the Ajalon facies of the Dogger Ironstone, Rastall and Hemingway (1941, p. 362) record "flakes of chloritic chamosite . . . with the usual properties and a slightly higher birefringence", which may well refer to an authigenic chamosite of the type described from the Knucton Ironstone. A careful restudy of oolitic ironstones from several formations should bring to light further evidence which should confirm or disprove the hypothesis outlined above.

Optically, the authigenic chamosite is generally similar to the "oolitic chamosite", but, because of its better crystallinity, its physical properties can be more readily obtained. The two types are believed to be essentially the same mineral (p. 163). It is usually strongly pleochroic on the scheme X-neutral, Y, Z- brown: the slow ray is orientated parallel to the basal cleavage, although it may be displaced by up to 3°. The authigenic chamosite is biaxially negative, with a 2V less than 10°. The birefringence is invariably higher than that of the concentric chamosite in the same oolith, being, on average, around 0.009 (low first order yellow). The optical properties of the authigenic chamosite conform with that of Albee's iron rich variety of chlorite.

<u>Opalisation</u>. Chamosite ooliths in the Knucton Ironstone have been observed to undergo partial opalisation (Plate 36). This diagenetic process occurs most commonly in Nookton Burn where it can be shown to be a post-depositional feature, at least in part. This phenomenon has been observed to be particularly common in the vicinity of the open worm burrows described elsewhere (p. 136). These clearly aid the migration of silicifying solutions, but are not absolutely essential for the process. The opal is dark brown, virtually opaque, in transmitted light, but dead white in reflected light. Opalisation may locally be

almost complete, affecting both matrix and ooliths. Occasional ooliths show arrested stages in the process of opalisation and seem to indicate the limit of opalising fluids making their way through the rock from a particular centre. Only rarely are ooliths completely made over to structureless opal, and in most cases the concentric arrangement of the ooliths is still preserved. It can be seen that the opal occurs in intimate association with a clay mineral of low birefringence which X-ray analysis shows to be chamosite (p. 165).

Opalisation of the ooliths may also occur, however, without apparent external influences. In these cases the process is never complete and the opaline silica occurs only in small patches or thin concentric bands. The concentric bands show the same optical features as other opalised areas, but can be seen to be composed of minute, almost submicroscopic grains of an unidentifiable mineral. The largest of these are not in themselves opaque, but the smaller ones are apparently so. These are presumably equivalent to the "semi-opaque bands" described by Hallimond in ooliths from the Cleveland Ironstone (1925, p. 45). It seems difficult to escape the conclusion that these represent contemporaneous opalisation of the ooliths prior to cementation. Examples are known in which the core of the oolith has been preferentially opalised. This is usually irregular and never wholly confined to the core, so contemporaneous opalisation of the nucleus must remain a more conjectural process.

The process of opalisation observed in the Knucton Ironstone has also been reported as an important and widespread feature in the Cleveland Ironstone of Yorkshire (Dunham, 1952, p. 24). Dick (1856, p. 95) first discovered that "silica in a soluble state" with a concentric arrangement occurs within the ooliths. This feature was also noticed by Stead (1910) and recorded as "siliceous envelopes". Hallimond later concluded (1925, p. 45) that his "semi-opaque bands" were due to slight alteration, with the formation of finely divided silica or clay. Dunham (ibid., p. 25) inferred that opalisation may be the result of oxidation when he stated that "there is no microscopical evidence of the presence of opal in the unoxidised Frodingham or Marlstone ironstones". He emphasized this further by writing (ibid., p. 26), "in oxidised ores it is probable that the limonite is accompanied by opaline silica, derived from the breakdown of chamosite". Evidence from the Knucton Ironstone in no way contradicts this suggestion, as all the samples studied are partially oxidised. The most intense post-depositional opalisation occurs around obvious holes in the rock (p. 150), through which oxidising groundwater could pass.

A very useful study of opalised ooliths in the Dogger of north east Yorkshire was made by Rastall and

Hemingway in 1939. They found that after heating their "black ooliths" they were observed to be made of "zones of a finely lamellar pale yellow mineral, powdery in parts, alternating with lenses and zones of colourless cryptocrystalline and of opaline silica. Frequently the nuclei of the ooliths are similarly preserved in opaline silica"(ibid., p. 231). Clearly, the opalised ooliths of the Knucton Ironstone are petrographically identical with those described from the Dogger. Rastall and Hemingway concluded from their chemical analyses and petrological studies that the original mineral in the ooliths was chamosite which suffered penecontemporaneous leaching, with the development of a pale yellow chlorite and kaolinite. This process was believed to be accompanied by silicification, with most of the silica being derived from an outside source (ibid., p. 232).

The concentric bands of opal in ooliths from the Knucton Ironstone confirm that silicification can be a contemporaneous process (p. 151). Whether it is accompanied by the formation of other minerals is a question which cannot be resolved by a purely petrographical investigation, but an X-ray study of "black ooliths" from the Knucton Ironstone revealed only opal and chamosite (p. 165). Evidence from the opalisation produced in the Knucton Ironstone after cementation and from Dunham's work on the Liassic Ironstones strongly suggests that the process is encouraged by oxidising conditions. It is possible, therefore, that the bands of opal in the ooliths may represent temporary periods of oxidation in their area of formation.

Siderite. Siderite occurs ubiquitously as a matrix mineral in the Knucton Ironstone. It never achieves a coarse state of crystallization and is common as crystals less than 0.05 mm. Siderite can usually be distinguished from calcite in thin-section by its brown colour which is due to the development of limonite. Siderite forms the bulk of the matrix in those areas with abundant ooliths. An increase in quantity of quartz, however, results in the siderite occurring rather more sporadically, usually tending to rim chamosite ooliths and quartz grains.

The question of whether the siderite in the matrix is a primary or secondary mineral has been discussed earlier (p. 136), and it is regrettable that thin-section studies contribute little to this problem. No evidence has been forthcoming to confirm Taylor's suggestion (1949, p. 81) that "much of the siderite . . . results from the carbonation of chamosite", but in the Knucton Ironstone it can be seen that at least some of it has a replacive origin. Complete replacement of chamosite ooliths by siderite as in the Cleveland Ironstone (Dunham, 1952, p. 27) is never achieved, but siderite does invade the outer shells of the ooliths, locally destroying its concentric arrangement;

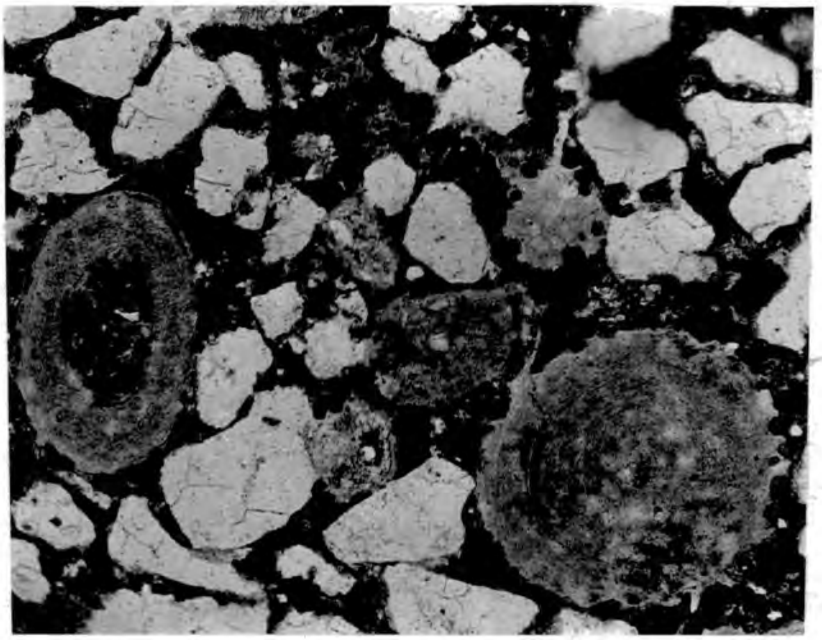


PLATE 44A. Chamosite ooliths marginally invaded by siderite. (x 400) it never penetrates the ooliths deeply, (Plate 44A). The siderite also cuts across authigenic chamosite suggesting that some sideritisation post-dates the formation of the latter. Quartz grains are commonly attacked by siderite (see p. 155), and rather larger crystals than usual tend to develop on the margins of shell fragments, where siderite has grown at the expense of calcite. Sphaerosiderite, with radially disposed crystals may develop within the shells.

Quartz. Quartz is always an abundant constituent of the Ironstone although variable in amount (Table 6, p.134). Most of the grains are of medium size (0.25 to 0.5 mm.), but they are poorly-sorted and range from 0.1 (very fine) to 1.5 mm. (very coarse). On the whole the quartz grains are not much bigger than the associated ooliths. Abrupt increases in the grain size occur at particular horizons and presumably represent changes in the depositional regime. Roundness of the quartz grains varies from angular to sub-rounded, but many grains show signs of corrosion by siderite, so this factor is of little significance. Most of the sharply angular grains can in fact be attributed to resorption. The quartz may be deeply penetrated by siderite and heavily criss-crossed with siderite filled cracks. Undulose and non-undulose quartz are the most abundant types, but polycrystalline quartz also occurs.

Collophane. Apart from the collophane occurring within the ooliths (p. 143) a number of phosphatic pebbles are invariably present in the ironstone. In transmitted light the collophane is brown and isotropic except for very small crystals of apatite, which have crystallized out of the reputedly amorphous phosphate. Usually, however, the collophane occurs as featureless pebbles, or, perhaps, incorporating a number of small quartz grains. The origin of these phosphate pebbles remains obscure. They may represent primary precipitates on the sea floor, or a process of replacement of pre-existing rocks. For the most part, however, they occur as discrete, rounded pebbles, and are probably derived from elsewhere. One example has been observed in which the boundary of the collophane follows so intimately the margins of adjacent grains, even enclosing ooliths, that it must be concluded that some of the phosphate accumulated in place.

Calcite. The bulk of the calcite occurring in the ironstone is organic in origin. Crinoid columnals, brachiopods, lamellibranchs, and gasteropods all contribute to the make-up of the rock. Frequently, sparry calcite has crystallized inside the shell cavities. Calcite may also contribute to the matrix as a coarse crystalline mosaic, often partially enclosing quartz grains; it has probably undergone recrystallization in this case.

Minor constituents. The accessory minerals associated with the Knucton Ironstone are plagioclase (of andesine composition), muscovite, sphene, zircon and tourmaline.

III Mineralogy

A Introduction

Petrographic study of the Knucton Ironstone indicates that the ooliths are composed of chamosite, and X-ray analysis has confirmed this diagnosis. In all cases a strong 14Å reflection was present on the powder photographs, demonstrating that most, if not all, of the chamosite has a chlorite type of structure. The mineralogical affinity of chamosite has been a controversial topic for many years, but most authors agree that two types exist, one with a 7Å repeat pattern along the c-axis and the other with a 14Å repeat. Orcel and others (1949) suggested the name "berthierine" for 7Å chamosite, but, although it is generally agreed that a nomenclature problem exists, this term has not been universally accepted.

Present day workers cannot agree on the basis of the classification of chamosite. The relative importance of the following factors have to be resolved before progress can be made:-

(a) Significance of type locality material. This takes preference in zoological nomenclature, but no similarly stringent rule exists in mineralogy. The chamosite from Chamoson, Switzerland, has a 14Å structure.

(b) Chemical composition. Minerals with the same composition may be manifested either as 7Å or 14Å structures. A mineral with trioctahedral 14Å structure is classified as a chlorite. The same composition with a trioctahedral 7Å structure would be classified as an "aluminian serpentine" by Brindley (1961, p. 278) but as a chlorite (septechlorite) by Nelson and Roy (1958).

(c) Crystallographic structure. Brindley is strongly in favour of classifying "chamosites" on the basis of their structure (1961, p. 278). In particular he objects to the use of the term septechlorite, (which includes chamosite), for trioctahedral 7Å structures. He considers that, in this case, chemical composition is of less importance. On this point he is in partial agreement with Mackenzie (1959, p. 62), who, however, accepts that 7Å chamosite is a septechlorite, although separating it from the true 14Å chlorites.

(d) Common usage. The term chamosite has been widely used in Britain to refer to the 7Å mineral occurring in the Jurassic ironstones. On account of this, plus the fact that the 7Å chamosite is allegedly more abundant than the 14Å variety, Brindley considers that the name "chamosite" should be retained for the 7Å type.

(e) Genetic relationship. Nelson and Roy (1958) have demonstrated that their 7Å septechlorite can be converted to 14Å normal chlorites at suitable temperatures and pressures. Largely on these grounds they advocate retaining the 7Å trioctahedral minerals among the chlorites. They propose the term "septechamosite" for 7Å chamosite.

In two recent classification schemes (Mackenzie, 1959; Frank-Kamenetsky, 1960), the term berthierine has been used to refer to 7Å chamosite, but no specific mention was made of 14Å chamosite. On the other hand, Lazarenko's classification (1959) includes chamosite as the "commonest chlorite". Clearly, although several attempts have been made to clarify the situation concerning chamosite, no solution has yet been reached. As Hey (1954, p. 279) has pointed out, different names should be found for the two structural types of chamosite, but, at the moment, the same name must apply to both.

B Method

X-ray diffraction data for the chamosite of the Knucton Ironstone have been obtained using a 114.6 mm. powder camera on a Philips Norelco machine. Filtered CoKα radiation was used throughout. In extracting the ooliths the rock was gently crushed and sieved between 60 and 120 mesh; fresh ooliths could then be picked from this material with relative ease. It was found that singly mounted ooliths gave results as good as those obtained by using powdered material, so this method was adopted. It has the advantage that the presence of large flakes of authigenic chamosite would be detected by its preferred orientation spots on the powder photograph.

C Identification of chamosite

In the early days of X-ray diffraction studies chamosite was regarded as a chlorite type of mineral with a somewhat anomalous structure and a distinctive powder pattern (Bannister, 1939). More recently a considerable amount of detailed work has been done on the British Jurassic ironstones, particularly by Brindley and Youell, who concluded that they contained only 7Å chamosite. Brindley (1951) showed that variations in the powder data of 7Å chamosite could be resolved in terms of the relative concentration of two structural components, viz., an orthohexagonal (or orthogonal) and a monoclinic stacking of the layers. On the other hand, 14Å chamosites (Englehardt, 1942; Shirozu, 1958), appear only to have an orthohexagonal lattice: monoclinic varieties have not been described.

The strength if the 14Å line is sufficient to indicate that chloritic material is an abundant constituent of the Knucton ooliths. Several authors have assumed that a weak 14Å reflection is due to impurity, but the 001 reflection of iron rich chlorites is usually weak in any case, so this criterion is largely subjective. The behaviour of the 00ℓ reflections on heating leaves no doubt that the chamosite has a 14Å structure (p. 162). Comparison of powder data from the Knucton 14Å chamosite with monoclinic chlorites shows that they are incompatible, even with those relatively rich in iron (Table 7). The first five orders of 00*l* compare favourably, but the details of the other reflections are considerably different. The Knucton chamosite does, however, bear a marked similarity to the orthohexagonal chlorites (Table 7) of Engelhardt (1942) and Shirozu (1958): Brindley considers that both these chlorites are examples of 14Å chamosite (1961, p. 266).

The many reflections due to collophane (apatite) tend to mask or alter those due to chamosite. Nevertheless, all the major reflections of Shirozu's data occur in the Knucton chamosite with a high degree of accuracy, both as to position and intensity. Bearing in mind the effect that small differences in composition have on powder data, it must be concluded that the Knucton Ironstone material is a 14Å orthohexagonal chamosite. The absence of reflections 2.83Å (005), 2.40Å (025), 2.02Å (007), 1.412Å (0,0,10), and 1.180 Å (0,0,12) is believed to be due to the fact that the oolitic chamosite is too finely crystalline for them to be recorded as definite lines; they are all present in the powder data from the better crystalline authigenic chamosite (p. 167). The relatively strong reflection around 2.67Å is probably associated with either the

TABLE 8

COMPARATIVE X-RAY DIFFRACTION DATA FOR CHAMOSITE

1		2		3		4		5	
Å	I/I_1	Å	I/I_1	Å	I/I_1	Å	I/I_1	Å	I/I_1
		14.0	90	14.2	60	14.3	70		
7.05	100	7.1	90	7.07	100	7.07	100		
4.67	20	4.62	60	4.69	60	4.66	70		
4.58	20								
4.28	5	4.27	60						
3.90	10								
3.52	100	3.54	70	3.53	80	3.54	80		
				3.45	50	3.46	20	3.44	20
				3.20	20	3.19	10		
				3.09	20	3.08	10	3.07	30
2.80	?	2.79	70	2.80	100	2.80	70	2.81	100
2.68	40	2.67	40	2.71	60	2.71	60	2.71	60
				2.64	50	2.64	30	2.63	30
2.52	90	2.52	100	2.52	80	2.51	90	2.53	5
2.40	40								
2.34	5					2.30	5	2.30	5
2.27	5	2.27	40	2.26	30	2.25	20	2.26	20
2.14	60	2.12	70	2.14	30	2.14	70	2.14	10
								2.06	10
2.01	10							2.00	5
		1.968	20	1.969	20				
				1.943	30	1.940	40	1.94	40
1.894	10			1.887	20	1.887	20	1.89	10
				1.841	40	1.841	40	1.84	60
				1.807	20	1.802	20	1.80	30
1.769	40	1.769	60	1.777	20	1.771	50	1.77	30
				1.751	20	1.753	10	1.75	30
				1.725	20	1.725	10	1.72	30
1.665	5								
				1.639	10			1.64	10
				1.602	10			1.61	5
1.555	70	1.550	90	1.555	40	1.553	70	1.54	5
1.521	30	1,516	60	1.519	10	1.518	50	1.52	5
1.473	10	1.477	60	1.474	20	1.475	40	1.47	20
				1.451	10	1.450	10	1.46	10
1.425	10	1.421	40	1.425	10	1.424	20	1.43	10
1.407	5								
1.361	5								
1.347	5								
1.326	5	1.320	50			1.320	20		
		1.294	50			1.299	10		
				1.280	10	1. 279	10		
		1.254	20	1.259	10	1.257	10		
		1.232	20	1.235	10	1.233	10		
				1.215	10	1.215	5		
		1.169	40			1.164	5		
		1.159	10						
				1.112	10	1.115	5		
				1.098	10	1.099	5		
		1.073	50			1.072	5		
		1.047	60			1.046	10		
		1.040	20						
		1.020	20						
		1.008	60			1.005	10		
		0.980	60	0.971	5	0.976	10		
		0.937	60	0.937	5	0.938	5		
		0.918	40						

1. Ayrshire Bauxitic Clay. (Brindley, G.W., 1951)
2. Cleveland Ironstone, Longacres (Bannister, in Whitehead _et al._, 19
3. Knucton Shell Bed, Nookton Burn (3275)
4. Knucton Shell Bed, East Allendale (3277)
5. Fluorapatite (McConnel, 1937, p. 981)

TABLE 7

COMPARATIVE X-RAY DATA FROM CHLORITES AND CHAMOSITES FROM THE KNUCTON IRONSTONE

1		2		3		4		5		6		7	
Å	I/I	Å	I/I	Å	I/I	Å	I/I	Å	I/I	Å	I/I	Å	I/I
14.2	80	14.2	70	14.3	70	14.2	50	14.1	50	14.2	30	14.0	30
7.12	100	7.10	100	7.07	100	7.07	100	7.05	100	7.1	100	6.93	100
4.75	80	4.72	70	4.66	70	4.70	80	4.69	50	4.68	20	4.64	50
						4.48	40						
						4.2	30						
3.56	100	3.54	100	3.54	80	3.53	100	3.52	90	3.55	80	3.50	90
2.85	40	2.83	40	2.80 c	70	2.82	70	2.83	40	2.85	5	2.784	30
				2.71 c	60	2.67	50	2.67	10	2.68	30	2.694	10
2.58	30	2.60	40			2.57	70						
2.55	50	2.56	40	2.51 c	90	2.50	80						
2.44	40	2.45	40										
2.38	20	2.39	20					2.40	5	2.43	3		
2.27	30	2.27	30	2.25 c	20	2.24	10						
				2.14 c	70	2.14	60	2.14	40	2.15	20	2.138	30
		2.07	5										
2.04	20	3.02	10			2.02	30	2.02	20	2.03	3		
2.01	40	2.00	50										
1.891	20	1.888	20	1.887c	20								
1.833	20	1.830	10										
				1.771c	50	1.761	60	1.776	40	1.77	10	1.770	20
1.732	10												
1.672	10	1.668	10										
1.577	20	1.570	40										
1.541	60	1.549	50	1.553	70	1.548	70	1.559	50	1.557	50	1.559	50
1.507	20	1.513	20	1.518	50	1.513	30	1.523	30	1.521	30	1.527	20
						1.497	30						
				1.475	40	1.475	10	1.479	40	1.480	5	1.476	10
1.429	10	1.415	20	1.424c	20	1.416	50	1.424	10	1.422	10	1.428	10
1.403	40	1.395	40					1.402	30				
				1.337c	5	1.335	5	1.347	5	1.343	5		
1.323	20	1.327	10	1.320c	20	1.317	30	1.326	10	1.323	10		
1.294	30	1.299	5	1.299c	10	1.293	30	1.300	10	1.302	5		
				1.257c	10	1.248	5	1.253	10	1.263	3		
1.228	10	1.222	5	1.233c	10								
		1.196	3										
1.192	10	1.180	10			1.177	5	1.179	20	1.183	5		
						1.161	5						
				1.072	5	1.063	5						
				1.046	10	1.042	10						
				0.976c	10	0.977	5						
				0.938c	5	0.937	5						

1, 2, : Monoclinic chlorites (see Brown, 1961, p. 288)
3, : Oolitic chamosite, Knucton Ironstone (3277)
4, : Authigenic chamosite, Knucton Ironstone (3897)
5, 6, 7 : Orthohexagonal chlorites (see Brown, 1961, p. 291)

c - partly due to collophane

2.64 or the 2.71Å reflection due to collophane.

Brindley and Youell agree that all British Jurassic chamosites have a 7Å structure, but it is interesting to note that Bannister (1952, p. 22) recorded a strong 14Å reflection for chamosite ooliths from the Cleveland Ironstone; his identification of the chamosite was supported by chemical evidence. The X-ray diffraction pattern of the Cleveland chamosite corresponds closely with that obtained from the Knucton Ironstone, and they appear to be the same mineral (Table 8). However, Youell (1962, personal communication), believes that Bannister's work may be unrepresentative of the Cleveland Ironstone. His observations suggest that where 14Å material occurs it is either an impurity or an alteration product. The present writer believes that 14Å chamosite may indeed be of diagenetic origin, but it is not the product of a random process (pp. 145-150).

D <u>Thermal behaviour</u>

Chlorites are generally recognised by the presence of an 001 reflection between 14.0 and 14.3Å, and iron rich chlorites are characterised by relatively weak 001, 003 and 005 reflections. The chamosite from the Knucton Ironstone conforms to all these requirements, but as a further check, two samples have been subjected

TABLE 9

COMPARISON OF X-RAY DIFFRACTION DATA FOR HEATED AND UNHEATED SAMPLES OF CHAMOSITE

1		2		3		4		5		6	
Å	I/I_1	Å	I/I_1	Å	I/I_1	Å	I/I_1	Å	I/I_1	Å	I/I_1
14.3	70	14.2	100	14.2	60	13.7	90				
		8.02	10			8.19	20				
7.09	100	6.96	40	7.07	100			7.12	100	7.06	100
4.67	50	4.50	60	4.69	60	4.48	10	4.68	50	4.54	60
								4.30	20		
		4.09	5			4.10	10				
		3.87	5			3.90	10	3.93	30		
3.54	80			3.53	80			3.55	100	3.53	100
3.45	60	3.46	80	3.45	50	3.46	80				
3.36	10	3.37	30								
3.20	20	3.18	40	3.20	20	3.18	40				
3.08	20	3.08	40	3.09	20	3.07	50	3.07	20		
2.80	80	2.80	90	2.80	100	2.81	100				
						2.78	30				
2.71	60	2.71	80	2.71	60	2.71	90	2.71	50	2.63	70
2.64	20	2.63	50	2.64	50	2.64	60				
2.57	10	2.59	10								
2.51	60	2.53	70	2.52	80	2.53	20	2.53	100	2.46	80
		2.30	10			2.29	10				
2.27	30	2.26	40	2.26	30	2.25	60				
2.24	30	2.22	5								
2.141	50	2.143	5	2.141	30	2.142	10	2.15	70	2.11	60
1.965	10	2.004	10	1.969	20						
1.940	40	1.943	50	1.943	30	1.941	70				
1.887	30	1.889	40	1.887	20	1.886	50				
1.841	40	1.846	60	1.841	40	1.842	70				
1.800	30	1.802	40	1.807	20	1.800	50				
1.775	30	1.774	50	1.777	20	1.772	50	1.779	60	1.752	50
1.750	30	1.752	40	1.751	20	1.751	50				
1.727	30	1.726	40	1.725	20	1.725	50				
		1.646	5	1.639	10	1.642	10				
		1.608	5	1.602	10						
1.550	70			1.555	40			1.563	70	1.517	70
1.517	40	1.497	50	1.519	10	1.500	10	1.526	50	1.486	40
1.473	20	1.477	20	1.474	20	1.470	20	1.481	60	1.465	40
1.452	10	1.454	20	1.451	10	1.450	20				
1.425	20	1.432	10	1.425	10	1.428	20	1.433	40	1.398	40
		1.280	5	1.280	10	1.278	10				
		1.258	5	1.259	10	1.258	10				
		1.235	5	1.235	10	1.234	20				
		1.216	5	1.215	10	1.216	20				
				1.112	10	1.113	10				
				1.098	10	1.098	10				
				0.971	5						
				0.937	5						

1 : Chamosite from the Knucton Ironstone, unheated (3125)
2 : Chamosite from the Knucton Ironstone, heated at 500°C for two hours (3131)
3 : Chamosite from the Knucton Ironstone, unheated (3275)
4 : Chamosite from the Knucton Ironstone, heated at 600°C for three hours (3279)
5 : Chamosite from Corby, Northants., unheated (Brindley and Youell, 1953)
6 : Chamosite from Corby, Northants., heated at 400°C (Brindley and Youell, 1953)

to heat treatment. Heating a chlorite in air to around 500° C has the effect of partially dehydrating the brucite layer, which results in an appreciable reduction in the c-parameter of the unit cell. This effect is enhanced by the oxidation of Fe" to Fe''', which involves a reduction in ionic radius from 0.83 to 0.67Å.

Sample 3125 was prepared by powdering a number of hand picked ooliths. The X-ray powder photograph showed a normal pattern with a strong 001 reflection at 14.3Å. The material was then heated at 500°C for two hours and X-rayed again (Table 9). Very little change occurs in the 001 spacing, but the 14Å line becomes considerably enhanced. The diminished intensity or disappearance of the 7Å and 3.5Å reflections follow the pattern expected of sedimentary chlorites (Warshaw *et al.*, 1960, p. 119). There is also an apparent small increase in the intensity of the 003 reflection (4.67Å) associated with a shift in value to 4.50Å. The chlorite studied by Warshaw and her co-workers (*ibid.*) developed only one basal reflection at 13.8Å after heating to 500°C. This difference in behaviour may be attributable to small differences in composition. Nelson and Roy (1954, p. 340) pointed out, however, that length of heating period, particle size, and degree of crystallinity are all factors which affect thermal behaviour.

A single oolith was chosen for the second sample (3275). A powder photograph was prepared before and after heating for three hours at 600°C (Table 9). In this case the 001 reflection diminished from 14.2 to 13.7Å, but with increased intensity, and both the 7 and the 3.5Å reflections disappeared completely. These observations parallel those made by Warshaw and others (ibid., p. 119), except that in the Knucton sample the 003 reflection is still present as a very faint line.

Brindley and Youell (1953) found that heating a 7Å chamosite from the Northampton Sands Ironstone produced a ferric chamosite at 400°C with different unit cell dimensions. Further heating to the 450-500°C range resulted in the material becoming amorphous. The behaviour of the 7 and 4.68Å reflections appear to be similar to that of the Knucton specimens (Table 9), but the remainder do not generally follow the same pattern.

The thermal treatment of the Knucton ooliths has not been sufficiently critical to discern whether a 7Å mineral, either septechlorite or kaolinite, is present. Mixtures of these minerals are very difficult to detect because of the superposition of most of the strong lines. Careful heat and acid treatment can sometimes be used to distinguish the two components if present (Brindley et al., 1951; Vivaldi and Gallego, 1961). Brindley (1962, p. 262) suggested that the presence of a strong reflection at

2.383Å may be a good indicator of kaolinite. This could represent the 003 reflection of that mineral, as the coincident 006 reflection of chlorite is usually very weak. The absence of this reflection in the Knucton data may indicate that no kaolinite is present in the ooliths. The position with 7Å chamosites is more difficult. Comparison of the Knucton X-ray data with those calculated for 7Å chamosite (Brindley, 1951), at least shows that none of the reflections characteristic of monoclinic chamosite is present. It is still conceivable, however, that small amounts of 7Å orthohexagonal chamosite are associated with the 14Å chamosite.

The numerous reflections due to collophane are, of course, unaffected by the heat treatment. However, it is interesting to note that on heating two extra lines appear at 8.19 and 4.10Å. These reflections are also due to apatite, but they only occur in good powder patterns (Brown, 1962, p. 482). It seems, therefore, that heating has aided the crystallisation of the collophane, perhaps inducing the small crystals of apatite already present to enlarge.

E Black ooliths

An X-ray analysis of the opalised "black ooliths" was undertaken to obtain more information concerning their constituents. The resultant X-ray photograph of a single oolith showed only very faint lines even after prolonged exposure. There must, therefore, be less crystalline material than in green ooliths of the same size. The powder pattern indicates that both collophane and chamosite are present. All the chamosite reflections are weak, and the 14Å reflection is apparently absent. However, a faint 14Å line developed after heating at 600°C for two hours. This observation is more likely to represent the usual enhancement of the 001 reflection in a chlorite than the transformation of a septechlorite structure to a normal chlorite: it cannot truly be used as evidence of a 7Å mineral in the black ooliths.

Petrographic evidence indicates that opal accounts for a large proportion of the black ooliths. X-ray identification of opal depends on the presence of a diffuse band around 3.9Å (Bannister, 1952, p. 20), and in the Knucton specimen a broad band occurs between 3.7 and 4.7Å, which may be taken as tentative identification of opal. The evidence so far indicates that opalisation took place at the expense of the chamosite.

F Authigenic chamosite

The process whereby authigenic chamosite grows at the expense of oolitic chamosite has been described on page 145. Flakes of authigenic chamosite were removed from the ooliths, and, after gently crushing, X-ray photographs were prepared. The photographs show marked preferred orientation effects due to the relatively large size of the chamosite crystals, and, consequently, the estimated intensities of the low angle reflections may not always be significant. However, the correlation of the Knucton data with the orthohexagonal chlorites (=chamosite) of Shirozu and Engelhardt (Table 7) is very good. The comparison is much closer than that of the oolitic chamosite, because the absence of collophane and the better crystallinity enables more reflections to be resolved. There are slight differences in the values of some reflections between the oolitic and authigenic chamosite. This may be entirely due to modification by superimposed collophane lines, or partly to slight differences in composition. The proportion of Fe''', for example, may have increased during the authigenic process.

The presence of impurities, even in the authigenic chamosite, is indicated by a 10.9Å reflection due to a mica clay mineral, possibly illite. The reflection at 4.48Å may also be partly, or even wholly, due to illite. It is too low to represent the 020 reflection of chlorite, which should lie between 4.6 and 4.7Å. The high order of crystallinity of the chamosite is illustrated by the presence of the 007 (2.02Å), the 0,0,10 (1.416Å), and the 0,0,12 (1.77Å) reflections. The line at 2.57Å was not recorded by either Engelhardt or Shirozu, but it may represent the 202 reflection. The 240 reflection at 1.76Å has a lower value than that recorded by Shirozu; it occurs as a broad line in the Knucton specimens, as do two out of three of the Japanese samples. The possible significance of this, if any, is not known. The reflection at 1.416Å is also rather broad and may in fact represent a combination of 064 (around 1.412Å) and 0,0,10 (c. 1.414Å).

IV Discussion

Both the oolitic chamosite and the authigenic chamosite from the Knucton Ironstone are orthohexagonal chlorite minerals. Although the present experiments have not been sufficiently sensitive to reveal the definite presence or absence of 7Å chamosite in the ooliths the occurrence of this in other formations is of considerable importance.

Previous authors have placed no special importance on the geological age or environment of the chamosites they studied. These factors, however, are considered to be of great significance. It is demonstrable that as a general rule, Palaeozoic chamosites have a 14Å structure, whereas Mesozoic ones have a 7Å structure (Table 10): there is, however, insufficient evidence to be dogmatic.

TABLE 10

Distribution of chamosite types in the stratigraphical column

System	Locality	Chamosite type	Author
Quaternary, Tertiary, Cretaceous.	None known		
Jurassic	Cleveland, Banbury, Northampton	(14Å) 7Å	Bannister, 1952 Youell, 1955
Permo-Triassic	None known		
Carboniferous	Northern Pennines	14Å	This thesis
	Ayrshire	7Å	Brindley, 1951
Devonian	Pennsylvania	14Å (at least in part)	Sheppard and Hunter, 1960
Silurian	Schmiedefeld	14Å	von Engelhardt, 1942
Ordovician	Wabana	14Å	Hayes, 1915
	Llandegai	14Å	Pulfrey, 1933
Cambrian	None known		

The crystallography of the Devonian chamosite from Pennsylvania (Sheppard and Hunter, 1960) was not specified, but

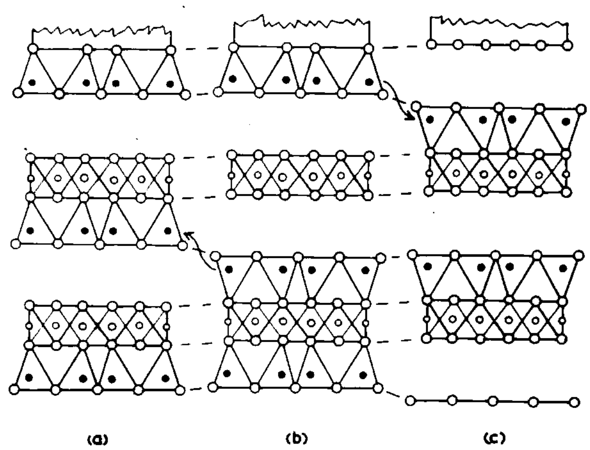


FIGURE 1. — Relation of chlorite structure (b) to kaolin-type structures (a) and (c); the arrows indicate the movements of the Si atoms required to change (b) into (a) or (c).

Figure 14.2

Mixed layer kaolin-chlorite structure (Brindley and Gillery, 1954).

some iron-rich chlorite does occur in the ooliths. Chamosite from the Ayrshire Bauxitic Clay provides the only X-ray data available from the Carboniferous of the British Isles. Its mode of formation is believed to be atypical, and Brindley (1951) showed it to have a 7Å structure. Brindley and Youell have also clearly demonstrated that British Jurassic chamosites generally have a 7Å structure, but Bannister's record of 14Å orthohexagonal chamosite should not be overlooked.

These observations need to be substantiated by more evidence from other chamosite localities, but a tentative hypothesis to explain the formation of 14Å chamosite seems justifiable. The experimental work of Nelson and Roy (1958) showed that septechlorites (such as 7Å chamosite) can be converted into "normal" chlorites by applying the right temperature and pressure conditions. Naturally occurring chlorites have been described in which this transformation is apparently only partially completed (Brindley and Gillery, 1954). The mineral has "mixed layering" and is composed of a combination of both 14Å and 7Å trioctahedral lattices (Fig. 14.2): the same phenomenon has also been described in Synthesized material (Roy and Roy, 1955, p. 173). Nelson and Roy (ibid., p. 718) suggest that septechlorites are metastable (Fig. 14.3), but point out that the transformation to 14Å chlorite is extremely sluggish and is favoured by high pressures. It follows from this statement that the metastable septechlorites are least

Figure 14.3

PHASE DIAGRAM SHOWING RELATIONSHIP BETWEEN 14 Å AND 7 Å CHLORITES (NELSON & ROY, 1958)

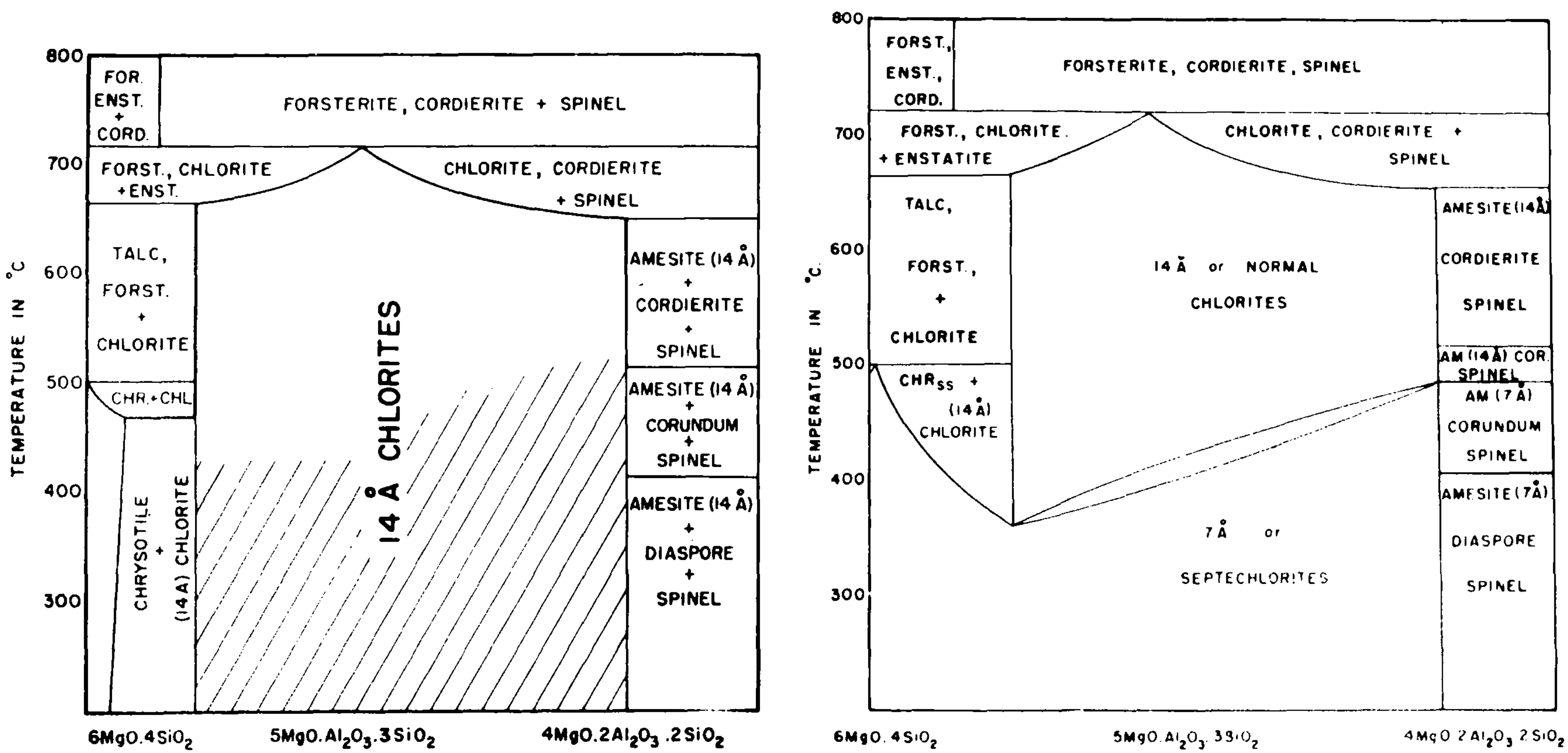


FIG. 5. *a.* Preferred version of a composition-temperature diagram drawn for a pressure of 1000 atmospheres, for the join chrysotile-amesite extended. The lower part of the diagram is a true binary join, above this, however, the equilibrium is quaternary and the diagram shows only the stable solid phases at various compositions as a function of temperature. Precision in such diagrams is poor (±15° C.) especially in the area of solid solutions which decompose to other solid solutions. The preferred version shows as a shaded area the p-t range in which (7 Å) septechlorites form and persist metastably (?) for long periods. Note also the 2-phase region chysotile+chlorite showing a discontinuity in solid solubility along the "chlorite-join."

FIG. 5. *b.* Possible alternative to Fig. 5 *a.* with septechlorites now shown as stable low temperature polymorphic forms of chlorites.

likely to persist in the most ancient deposits. This inference is, to a large extent, borne out by the distribution of the two types of chamosite in the geological record. Older deposits have commonly undergone deeper burial, perhaps even slight metamorphism, and the time factor is in favour of transformation taking place. No positive rule can be established, however, because geological environment, involving such factors as intensity of metamorphism, if any, play an important part. For instance, a Jurassic 7Å chamosite involved in the Alpine orogeny may experience the exact conditions favourable for recrystallisation to a 14Å chamosite. Excessive metamorphism, however, seems to destroy the chamosite structure and produce a different chlorite such as bavalite (Hallimond, 1939, p. 458) or thuringite (Engelhardt, 1942, p. 158). Clearly, a closer look at the geology, as well as the physics and chemistry, of chamosite would prove rewarding.

CHAPTER 15

DEPOSITIONAL ENVIRONMENT OF UPPER LIMESTONE GROUP ROCK TYPES

I The sedimentological concept of a "Yoredale-type" cyclothem

Westgarth Forster (1809) and John Phillips (1836) made important contributions to our knowledge of Carboniferous geology in Britain, but it was left to Hugh Miller (1887) to draw attention to the rhythmic nature of the Upper Limestone Series in Northumberland. A few years later, Goodchild (1890) issued the remarkably progressive statement that "during pauses in the depression of the land, deltas advanced from the north-west carrying thin sheets of sediment which spread out far and wide over the newly formed limestone. As more sinking ensued the shore line and its deltas were carried again far to the north-west and more thin wedges of limestone were formed." This hypothesis has subsequently found favour with many contemporary geologists.

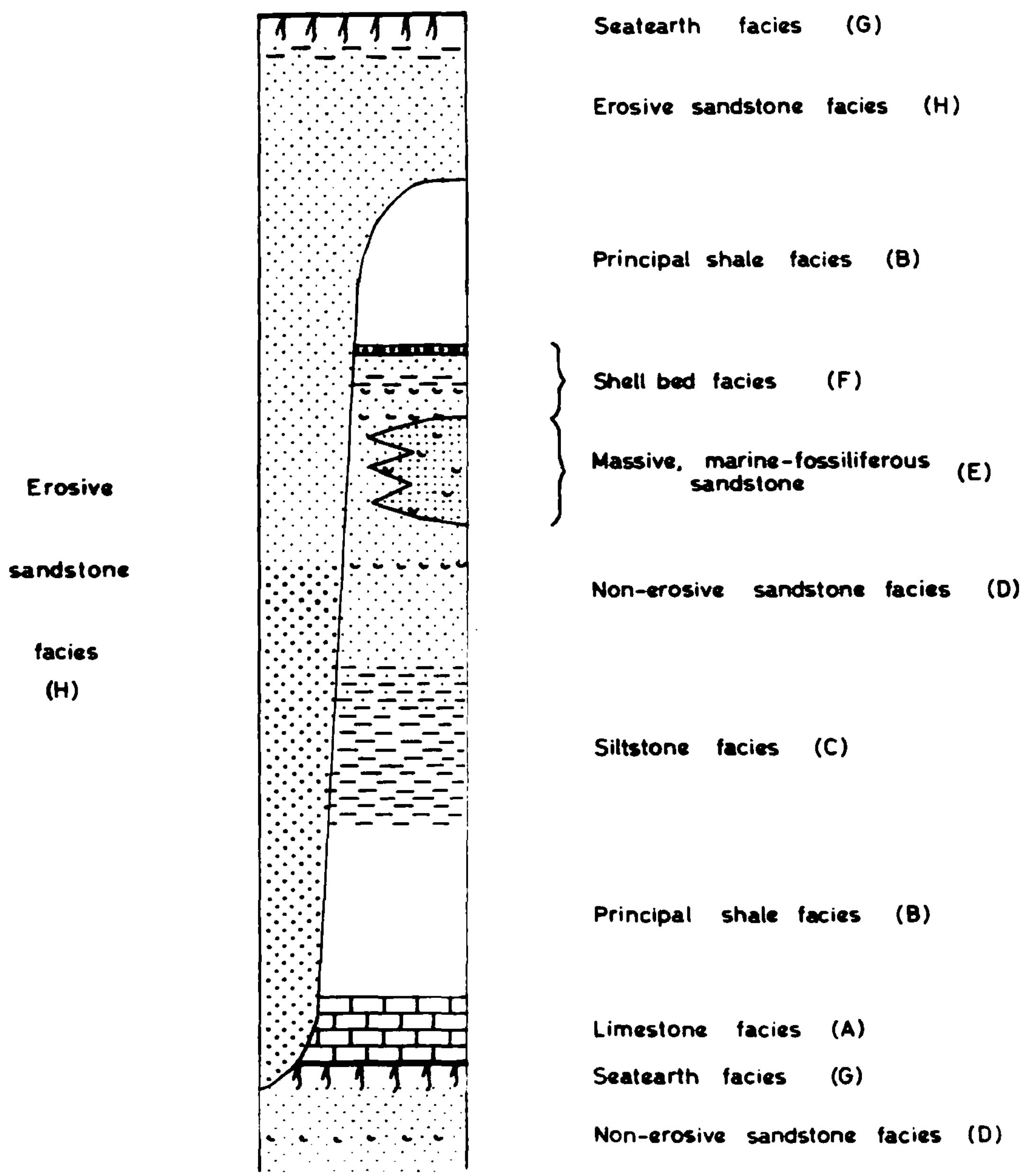
The modern approach to the question of Carboniferous cyclothems was ushered in by Hudson's (1924) detailed account of the rhythmic sequence of the Yoredale rocks in Wensleydale. The term "cyclothem" was first applied to these deposits by Dunham (1948) following the work of Wanless and Weller (1932) in the Pennsylvanian of the

United States. In recent years the whole concept of cyclothemic sedimentation has been severely criticised; both the validity of the expression and the mechanism of their repetition have been controversial issues. In this work the present writer would like only to comment on the use of the term "cyclothem" as a sedimentological concept.

Implicit in the original definition of a cyclothem by Weller (1930), is the concept of a marine sequence which becomes progressively coarser in grain size upwards and a non-marine sequence which becomes finer upwards. Duff and Walton's (1962) definition of a cyclothem as a group of rock units which tend to recur in a certain order is an oversimplification of the observable facts, at least so far as the Upper Limestone Group is concerned. The nature of the contact between the rock units was ignored by Duff and Walton. The effect of this important factor has thus been omitted from their statistical study of cyclothems making this work of limited value. In the Upper Limestone Group the present writer proposes a rigid application of the term "cyclothem" as proposed by Weller (1930). A coarsening-upward cycle is the rule rather than the exception, though at some horizons where fluvial influences are dominant, it is difficult to distinguish a cyclothemic pattern. The coarsening-upward cycle may be interrupted at any stage by the

Figure 15.1

SUMMARY OF SEDIMENTOLOGICAL FACIES IN THE UPPER LIMESTONE GROUP



introduction of a fluvial member. This may be identified by its sharp erosive contact, perhaps only picked out by an abrupt change in lithology, and a fining-upward cycle. The essential features of cyclothemic sedimentation in the Upper Limestone Group are summarised in Figure 15.1.

The pattern of sedimentation represented by the cyclothems of the Upper Limestone Group is virtually identical with that observed in recent sediments of present-day deltas (Scruton, 1960). The combination of a coarsening-upward cycle and the occurrence of shoestring erosive sandstones with a fining-upward cycle is not known from any other environment. Whether one prefers to refer to this type of deposit as a "delta" or a "low-lying coastal area of fluvio-marine sedimentation" is a matter for personal prejudice; the essential concept is the same. The expression "delta" is acceptable as a "sack term", bearing in mind the considerable range of environments which it encompasses and having no preconceived notions as to what a delta <u>should</u> be. In many instances, deposits of a so-called "deltaic sequence" may have little or no direct evidence of terrestrial influences, but in the writer's opinion the validity of the term is no less impaired. It is now proposed to discuss the various lithofacies observed in the cyclothemic deposits and to suggest in greater detail the possible environments in which they were deposited.

II , Facies A :- the limestone member.

Limestones represent a relatively small percentage of that part of the Upper Limestone Group studied by the writer. They are important from a sedimentological point of view because they indicate a definite environment and serve to delimit certain cyclothems and formations. A limestone is defined as a rock which contains over 50% of calcium carbonate (Folk, 1959, Fig. 1, p. 4). Many shell beds and calcareous concretions in sandstones qualify for the name "limestone" but these are considered under their appropriate sections; only the principal limestones forming the lowermost member of a cyclothem and occurring persistently over wide areas are considered here.

A Petrography and stratification

The Limestones in the Upper Limestone Group vary from light to dark grey in colour, but usually become limonite-stained when weathered; the iron is originally in the form of pyrite. Crinoid columnals are usually the dominant component, a feature which is readily seen in hand-specimen, and all types contain a certain amount of quartz sand: only the Crag Limestone is arenaceous throughout its whole thickness. Most commonly, sand is confined to the basal few inches, although occasionally there may be a sandy top, and very fine sand may occur sporadically throughout the whole of the limestone. The arenaceous

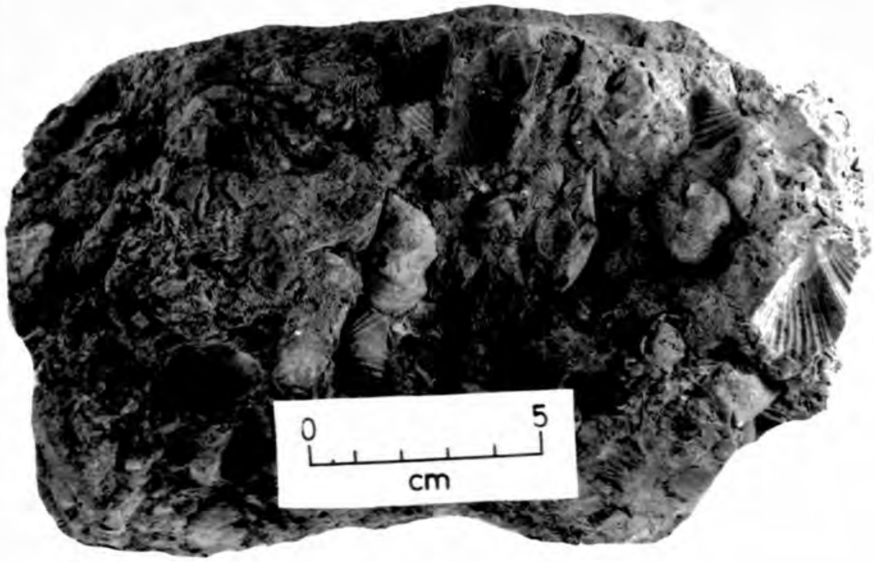


PLATE 45. Shell bed at base of Crag Limestone.
Nookton Burn.

PLATE 46. Irregular dolomitic stringers in Lower
Felltop Limestone. Beldon Burn.

base is often black in colour and highly carbonaceous, even to the extent of containing vitrainous material; it may also be markedly ferruginous.

All of the limestones studied may be referred to as biomicrites (Appendix I), according to Folk's classification (1959). A better name for some of them would be "biomicrosparite", in view of the fact that very little true micrite may be observed in them, but Folk believes that microspar is merely a recrystallisation product of micrite (ibid., p. 32). The petrography of the limestones is not always uniform throughout their thickness and the proportion of terrigenous and allochemical constituents may vary considerably. This is shown by the frequent occurrences of thin, highly fossiliferous bands within the limestone, which are analogous with the shell beds of other parts of the succession. Indeed, the sandy base of the Crag Limestone is packed with decalcified brachiopods (Plate 45), and has a strong resemblance to a true shell bed member. The Lower Felltop Limestone may locally have an almost brecciated appearance which results from the presence of irregular patches of yellow weathering carbonate which is probably dolomite (Plate 46). The problematic dolomitic structure in the Little Limestone is discussed in Appendix I; the origin of the dolomite is unknown.

Stratification is not often apparent in the thin limestones of the Upper Limestone Group; they usually weather as massive beds, but in detail, some lamination may be observed. Of the thicker limestomes, the Lower Felltop is the only one which exhibits wavy bedding (Plate 18); the Little may occasionally have irregular, but essentially plane bedding (Plate 1).

B Fossil content

The limestones are composed largely of crinoid fragments but other macrofossils are not abundant; they tend to occur on restricted horizons in the rock. Brachiopods, especially spiriferids, productids, athyrids, and Orthotetids are the commonest macrofossils, after the ubiquitous crinoid debris, but molluscs, corals, and trilobites have also been observed. Chaetetes is the only widespread compound coral ocurring within the limestones but is not abundant; zaphrentid and clisiophyllid corals are also known. "Caudagalli" burrows have been seen at several limestone localities.

No systematic work has been attempted on the microfossil content of the limestones, although this is prolific, and a study of them could be rewarding. Endothyrid and plectogyrid foraminifera are very common, and bryozoa such as Rhombopora, Fenestella, and Rhabdomesidae have been recorded.

C Lithological relationships

The base of many limestones is often transitional to the underlying beds, despite the fact that they occasionally rest directly on coal. In such cases the basal few inches of the arenaceous limestone contain considerable amounts of woody material, followed by a similar rock with shell fragments, which eventually passes into a limestone. This feature may be observed in both the Little and the Crag Limestones. At horizons without a coal, fossils may become abundant in the top of the underlying sandstone, and a passage into the limestones is effected by a reduction in the relative amount of sand detritus.

The top of the limestone member is unfortunately rarely exposed, so little is known of the relationship with the overlying facies. Some of the limestones have a sand-rich top, and in at least one case, there is a gradual passage through a thin bed of siltstone into the thick shale of Facies B above. It is also suspected, however, that some limestones have a relatively sharp contact with the overlying shale.

D Possible environment

The presence of abundant marine fossils and the absence of primary minerals indicating reducing or otherwise abnormal marine conditions demonstrates that the principal limestones were deposited in an open-sea environment. That the sea was relatively shallow is attested by the presence of a small but significant proportion of corals, some of which at least, appear to be living in situ. Elias (1937, p. 410) quotes the maximum depth for coral development as 150 feet, but Johnston (1960, p. 126) has implied a much shallower depth than this for the formation of Yoredale limestones. Certainly, the occasional shell beds suggest shallow water conditions (van Straaten, 1959; Rusnak, 1960), and the presence of calcareous algae in at least some of the limestones, indicates formation in the sea within the range of light penetration. The amount of terrigenous material in the main body of the limestones is generally small, but this does not necessarily imply deposition in an off-shore position. In fact, the observed transition with the coal swamp facies suggests that at least the base of some limestones could be formed very close in-shore, perhaps in a "tidal flat" environment, but certainly in a delta-platform position.

The persistent nature and uniform petrography of limestones such as the Little, the Lower Felltop, and the Upper Felltop suggests contemporaneous deposition over wide areas, which is compatible with the concept of the flooding of a low-lying delta plain of considerable extent. The contrast with the extremely variable shell bed facies of believed lagoonal origin (p. 213) is particularly striking, but a similar origin may be considered for the Crag Limestone in the area, which behaves in many ways like a shell bed.

The general petrography of the limestones may appear to detract from the validity of the conclusion that they were deposited in very shallow water. According to Folk (1959) biomicrites are analogous with poorly sorted muddy sandstones and, as such, are usually deposited below local wave base. There are two possibilities which might explain away this apparent anomaly. The first is that the microspar which is the usual matrix for the limestones studies, does not represent recrystallised micrite, but has some other origin: perhaps it is considerably reworked organic material (Appendix I). The second is that a series of small bars existed within the shallow sea, which were sufficient to reduce the energy level of the waves and tides, but not sufficient to enclose the area and thus convert it into a restricted lagoon; banks of crinoid debris have in fact been described from the limestone facies in the Carboniferous (Moore, 1958, p. 122). Micritic calcium carbonate could crystallise locally in this shallow water environment, but still be under the influence of marine agents bringing crinoid columnals, shells, and other organic debris. The Crag Limestone is a possible exception to this axiom in view of its observed passage into ironstone (p. 29), suggestive of a restricted environment.

III Facies B :- the principal shale member

One of the most consistant members of the Upper Limestone Group cyclothems is the thick black shale occurring above the limestone or prominent shell bed member. In this thesis, little work other than that derived by field observations has been undertaken on the fine clastic part of the cyclothem. It must be stressed, however, that not all of the fine clastics occurring within the Upper Limestone Group of the area surveyed will be included in this section. There are those thin units, often about two or three feet thick, which occur associated with shell beds or as seatearths, and which are clearly of different facies.

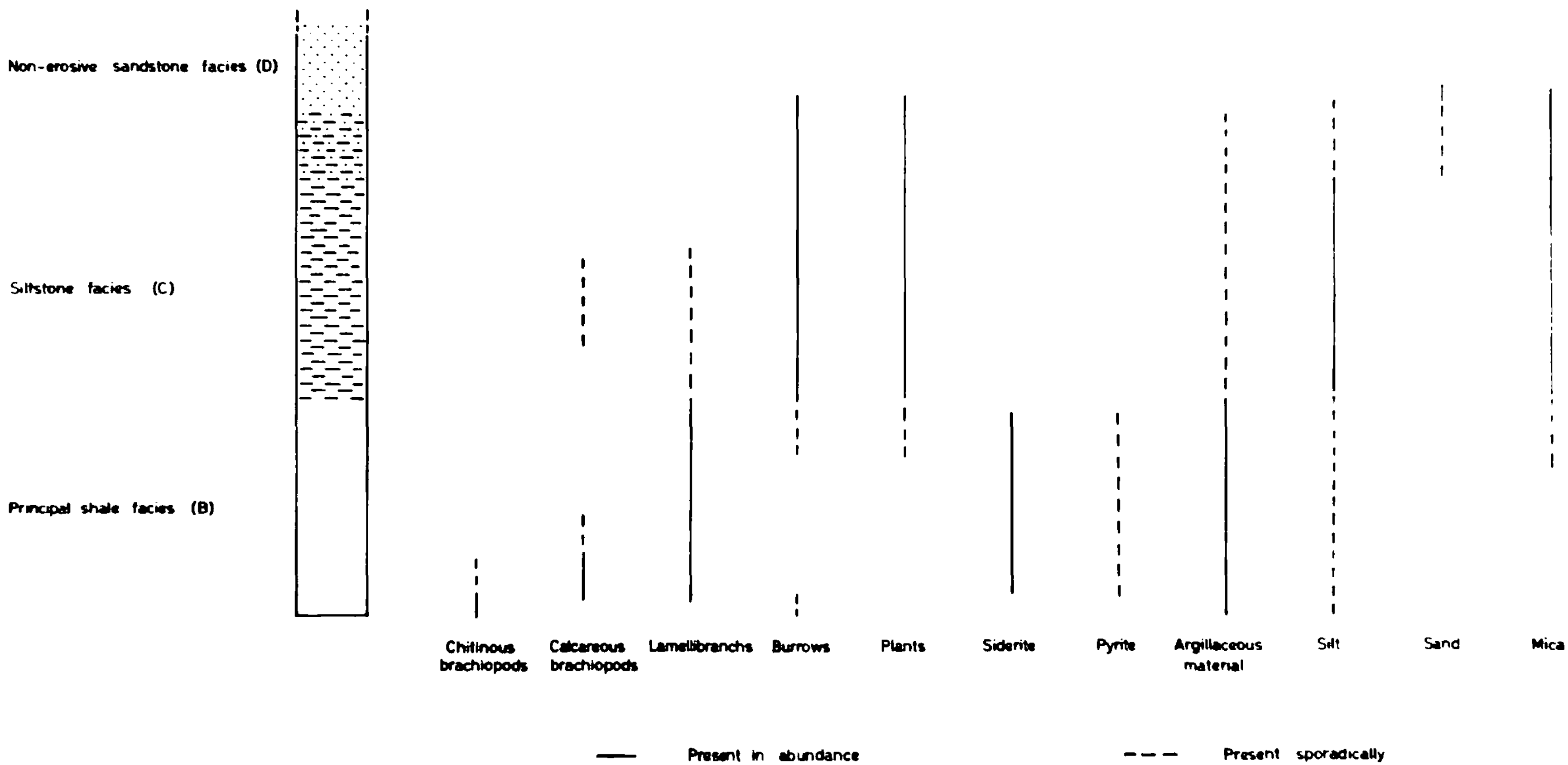
A Petrography, stratification and fossil content

Harbord (1962), in his study of Middle Limestone Group rock types, established at least six different types of shale based on their gross mineralogical properties as seen in the field; these appear to be related to different mineralogical frameworks (ibid., p. 73). In the present work no attempt has been made to subdivide the shales in a similar manner, although it is true that their petrography is by no means uniform. Harbord (ibid., p. 68) was able to show that the principal clay minerals in the shales were illite, chlorite, and mixed-layer minerals. The latter are apparently degraded illitic material (ibid., p. 70) and are typically illite-chlorites with only a small amount of chloritic material. The principal variations in the relative proportions of these minerals involve a decrease in the amount of illite upwards in the cyclothem, and an increase in the amount of mixed-layer mineral. Kaolinite has also been recorded in Carboniferous cyclothems, especially in the upper parts (Johnson and Dunham, 1963).

In the field, variations in overall petrography may be described in terms of mica content, fossil content, stratification, and type and form of carbonates, if present. A generalised, but consistent, lithological variation can be established in the fine clastics (Fig. 15.2), but details of the variation are a feature of individual cyclothems. It has become accepted as standard that in the Middle Limestone Group the shales overlying the major limestones are calcareous (Moore, 1958, p. 125; Johnson, 1959; Harbord, 1962). This axiom is not applicable to the Upper Limestone Group, where limestones are less important and the role of the calcareous shale in the cyclothemic make-up has correspondingly diminished. The generally non-calcareous nature of the shales is primarily a function of the low abundance of calcareous fossils; chemical calcite cement is never present. Where

Figure 15.2

NON-QUANTITATIVE DISTRIBUTION OF MAJOR COMPONENTS IN SHALE AND SILTSTONE MEMBERS OF AN UPPER LIMESTONE GROUP CYCLOTHEM



calcareous organisms do occur in the shale member of the cyclothem they are usually too sporadically distributed to produce a calcareous shale, and, in any case, are usually replaced by secondary non-calcareous minerals. A typical example of this is the dark grey non-calcareous shale above the Crag Limestone, which contains scattered crinoid columnals, with rare brachiopods, rugose corals and bryozoa, and relatively abundant thin-shelled lamellibranchs and ostracods. The Coalcleugh Marine Band, despite its relatively abundant brachiopod and molluscan fauna, is composed of non-calcareous shale. Siderite nodules, up to 6 inches long, are usually typical of non-stratified shales and occur within and above the brachiopod shell band. Development of septarian fractures within these nodules is a feature only of the larger examples.

The shale forming the lowermost beds of a cyclothem is predominantly non-micaceous, at least to the naked eye. It is principally mica which produces stratification in the fine clastics, so the lower shales are relatively homogeneous and tend to have a sub-conchoidal fracture. The general upward increase in mica content produces greater fissility at a higher level. Occasional horizons containing plant fragments may enhance the fissile nature of the shale, but plants do not appear in abundance until siltstone becomes the prominent rock type (Fig. 15.2). Thin lenses or bands of siltstone may in fact occur at any level within the principal shale member of the cyclothem, but generally are more common towards the junction with the overlying siltstone.

Pyrite is present in the lowermost beds especially, and may occur disseminated throughout the shale or as a replacement of fossil fragments. Its presence may often be anticipated by the development of jarosite on fracture planes within the shale. The process of pyritisation appears to have been selective in that not all specimens have been replaced. Those crinoid columnals which have been pyritised are uncrushed, but unpyritised ones are considerably fractured by compaction effects. This serves to indicate that some pyritisation took place before any appreciable load was placed on the crinoid fragments, so that the process must have been at least penecontemporaneous.

The fossil content of the fine clastic member of the Upper Limestone Group cyclothem is subject to considerable variations, which are of value in attempting a reconstruction of the environment of deposition of this series. Occasionally, the base of the shale sequence is marked by a thin, micaceous siltstone or even sandstone, not more than one foot thick, which is noteworthy for its being abundantly reworked by burrowing organisms. Above this, or even occurring as the basal bed of the series, may be a brachiopod rich shale, never more than a few feet thick, which gives rise to such members as the Coalcleugh Marine Band. Lamellibranchs, which include nuculids, edmondiids, sanguinolitids, and members of the pectinacea, occur within these shell beds, and appear to be the most wide-ranging of the faunal elements (Fig. 15.2). They occur throughout the shale, but with decreasing abundance upwards. Occasionally, towards the top of the micaceous shale sequence, anastomosing, sub-horizontal worm tubes occur, filled now with siderite. There are other examples which do not contain siderite, where the only evidence as to their presence is obtained from the reworked state of associated siderite nodules. Burrowed shale may, in fact, be a more common rock type than heretofore suspected. Plant fragments, which occur sporadically throughout the sequence, are not seen in abundance in the shale member. Other fossils such as fish-scales, ostracods, bryozoa, conodonts, chitinous brachiopods, and gasteropods, occur, but as no systematic collecting has been attempted in this study, data concerning these fossils are too unrepresentative to be discussed here.

B Possible environment

Discussion on the nature of the physical environment represented by the principal shale member of an Upper Limestone Group cyclothem can be approached in two ways. Firstly, the environment may be interpreted in terms of distance from the prevailing shoreline, as represented by the nature and relative proportions of terrigenous detritus in the deposits. Secondly, an attempt may be made to use faunal phases as direct or indirect indicators of water depth at the time of deposition. The palaeontological evidence may be open to some criticism in view of the difficulty of distinguishing between life- and death-assemblages, but it may be used in conjunction with the petrographical evidence and thus result in a more balanced conclusion. Moore (1958, p. 125) and Harbord (1962, p. 200) regard the variation in faunal content as being due to varying rates of deposition, whereas Elias (1937), in comparing fossil and recent organisms, related faunal content to depth of sea water. Both these concepts are effectively the same, although Elias' is more refined, because in deltaic deposits depth of water and rate of deposition are related phenomena (Scruton, 1960, Fig. 8, p. 93). An important element of the shale member of an Upper Limestone Group cyclothem is the brachiopod-rich shell bed. Beds below this, whether they are limestone, ironstone, or simply a burrowed shale or siltstone, are generally indicative of shallow water conditions. The rock comprising the shell bed and the sideritic shale above represents the period when terrigenous sedimentation is at a minimum. This suggests that it was deposited some distance from the source (i.e. the coast-line), and possibly therefore in relatively deep water. They thus correspond in position to the bottomset beds of the pro-delta shelf in terms of deltaic accumulation. Within the shell bed the abundant articulate brachiopods and occasional corals, bryozoa, and burrowing lamellibranchs suggest that the water was possibly between 90 and 130 feet deep (Elias, 1937, p. 410). It has been suggested (Craig, 1954, p. 107) that nuculids live at depths not greater than 180 feet, and that grégarious molluscs, perhaps such as the pectiniform lamellibranchs also recorded from this member, do not occur beyond 120 feet depth (Elias, 1937, p. 419). The presence of Fenestella, which may be adapted for very strong currents in a littoral environment (ibid., p. 418), may suggest shallower conditions, but it is likely that this fossil has been reworked and redeposited. Bottom currents sufficiently strong to winnow crinoid columnals and shell fragments into small pockets may occur (Dunham and Johnson, 1962, p. 252).

The eventual upward change from a brachiopod-lamellibranch fauna to a dominant lamellibranch fauna probably reflects an increased rate of sedimentation as suggested by Moore (1958) and Harbord (1962) and also a decrease in the depth of water as suggested by Elias (1962). Wanless (1958) notes that the Pennsylvanian lamellibranch faunas of Illinois, which are similar to those in the Upper Limestone Group, are very diverse, and most forms are apparently adjusted to special environmental situations. If the uppermost part of the shale member may be said to belong to a true molluscan facies then the depth of water may be in the region of 60 to 90 feet (Elias, 1937, p. 410). The possible shallowing of the sea due to closer proximity to the shoreline is also indicated by the upward increase in terrigenous material. In particular, silt sized mica flakes and quartz fragments become apparent, and their occasional differentiation into discrete laminae indicates that the sorting effect of currents is becoming effective. Plant fragments also become noticeably more abundant.

Little is known concerning the chemical environment of the sea at the time of Upper Limestone Group sedimentation, but the abundance of fossils suggests that the bottom waters must have been oxidising. The siderite nodules and crystals of pyrite in the shale member are probably, therefore, diagenetic, and formed perhaps some way below the sediment/ water interface (Dunham, 1961, p. 8). That reducing conditions within the shales could be produced is indicated by the presence of black organic pigment (<u>ibid</u>., p. 1) and other organic remains.

IV Facies C :- the siltstone member.

This facies is essentially a transitional member of the Upper Limestone Group cyclothem, for it passes downwards into black shale (Facies B), and upwards into fine and medium grained sandstone (Facies D). A siltstone must contain at least 50% of silt sized grains, a distinction which is often difficult to make in the field. Grain size, of course, is not the key to environment, and all siltstones are not deposited in the same facies. The following account is meant to illustrate some of the commonly occurring features of the thick siltstone member of the cyclothem and to indicate a possible environment of deposition. Other siltstones, which occur in association with other lithologies, may have different origins.

A Petrography and stratification

Mineralogically, it is evident that the most abundant component in siltstones is quartz, but they all contain varying amounts of white mica and argillaceous and carbonaceous material. This latter may take the form of black organic pigment associated with clay minerals (Dunham, 1961, p. 1), finely disseminated materials of presumed plant origin, recognisable plant fragments, and reworked vitrainous coal fragments. Many of the quartz grains are angular and thus do not contradict the hypothesis proposed by Rogers and his co-workers (1963, p. 628) that silt sized grains are produced by chipping of larger grains rather than the progressive size reduction of sand sized grains.

The admixture of clay materials and finely disseminated plant fragments is responsible in large measure for the dark or medium grey colour of the siltstone. Pure siltstone is in fact almost white, as is evidenced by the finely laminated siltstones, where white and grey laminae alternate on a very small scale. The lamination is produced by the differentiation process of currents, which separate the silt sized quartz grains from the finer or more platy detrital fraction and allow them to be deposited separately. Although many siltstones have perfectly regular lamination, others may contain small-scale asymmetrical ripples. Symmetrical, wave produced ripples have not yet been observed in a siltstone. Not all siltstones are laminated; some are relatively uniform in colour, although still with a marked fissility resulting from the abundance of mica flakes, which may reach 0.5 mm. in diameter. Siltstones do not as a rule contain concretions of any sort, but rarely, in highly argillaceous members of this group both calcareous concretions and siderite concretions, have been known to occur. Detrital siderite, occurring in discrete laminae in siltstone, has also been observed.

B <u>Fossil content</u>

Lamellibranchs are important members of the rather sparse fauna present in the siltstones series. They generally occur scattered throughout the rock and may be found in close association with plant stems and leaves, some of which are in an excellent state of preservation. In at least two cyclothems, the White Band and the Knucton Ironstone Cyclothems, thin brachiopod shell beds occur within the siltstone. The one below the Firestone Sill in the White Band Cyclothem is associated with highly fissile, micaceous and sometimes sideritic siltstone, and contains a fauna composed dominantly of productids, Spirifer, and Camarotoechia (p. 27). The shell bed occurring within the siltstone member of the Knucton Ironstone Cyclothem has Chonetes aff. hardrensis group as its most typical fossil (p. 43).

Numerous trails and annelid-like burrows may be present at some horizons in the siltstones. The sub-horizontal burrows in the more argillaceous siltstones may now be filled by diagenetic siderite. U-shaped vertical burrows, of the type also found in the sandstones of Facies D (p. 195), may occur towards the top of the siltstone member, and may indicate very shallow water and slow deposition.

C Lithological relationships

The principle of transitional passage from one rock type to another in the "Yoredale-type cyclothem" has been expounded many times and is a well-known phenomenon. It is

PLATE 47. Sandstone-siltstone intercalations in base of Hipple Sill. North Grain, Rookhope Burn.

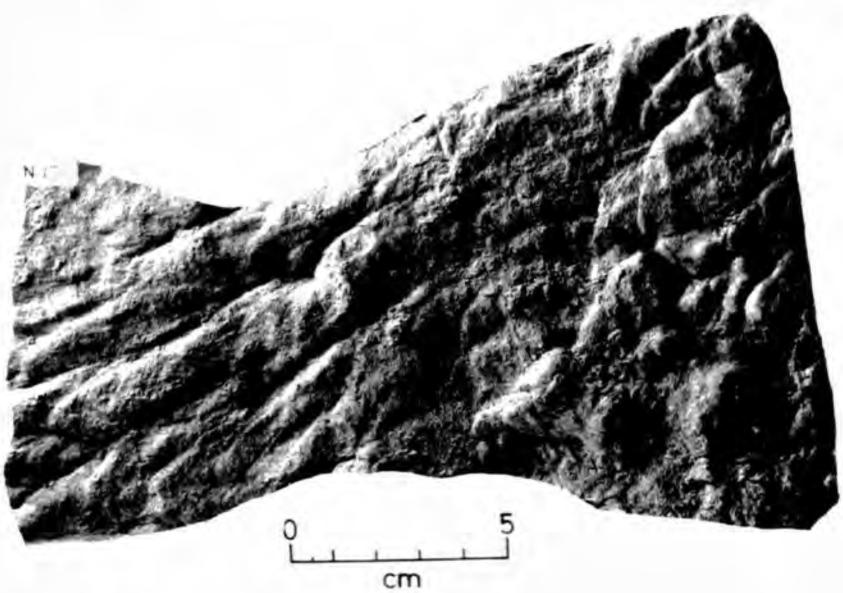


PLATE 48. Orientated load casts at base of thin sandstone below Grindstone Sill.

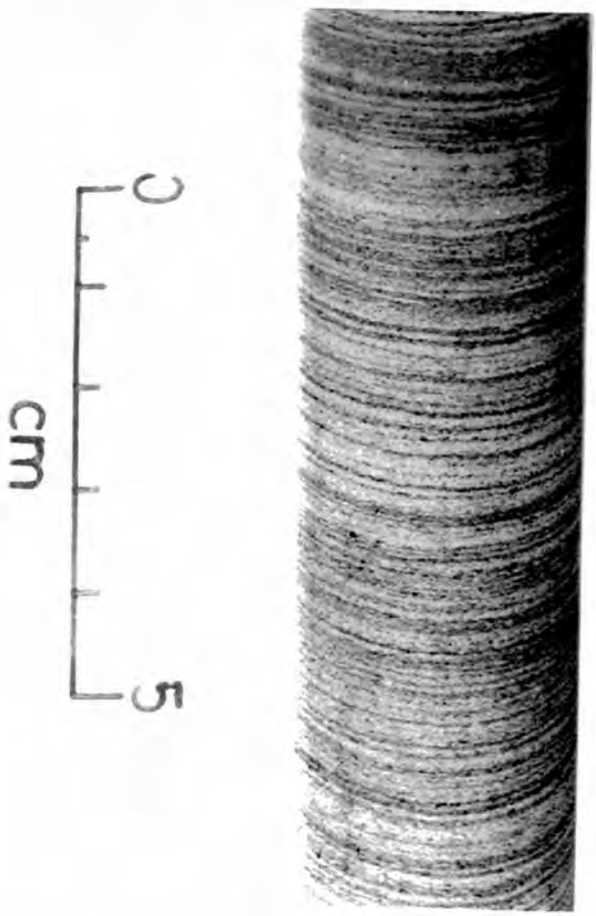
a particularly important principle for the siltstone member of the cyclothem because, by and large, both its top and bottom are gradational (Fig. 15.2). The underlying shale passes into the grey siltstone by first developing thin lenses, and then thin beds of silty material. The siltstone grades into the overlying sandstone by the incursion of fine sand as thin discrete layers, which eventually become dominant. These thin sandstones are usually well-laminated and often ripple-laminated (Plate 47), and in fact tend to be of the same type as forms the main sandstone above. The sandstone ribs may maintain a constant thickness for a distance of many yards, but others vary rapidly; one observed ripple laminated sandstone increased from one to ten inches within five feet. Orientated load casts have been observed on the base of some of these sandstones (Plate 48).

D Possible environment

Petrographical variations within the underlying shales are believed to indicate progressive shallowing of the sea and increased rates of deposition (p. 188). This situation is, not unnaturally, continued in the siltstone member. The general increase upwards in terrigenous constituents such as quartz, mica, and plant fragments is presumed to indicate a gradual approach of the shoreline. Lamination is a very common feature of the siltstones, especially in the upper part where even rippling may occur. Lamination has been recorded down to a depth of 132 feet in the Mississippi delta, and 198 feet in the Rhone and Fraser deltas (van Straaten, 1959, p. 208). Shepard (1960, p. 70) records, however, a different impression and states that some "stratification" but not lamination is present on the foreset beds of the Mississippi delta; lamination is mainly restricted to the topset beds of the delta platform. This serves to indicate at least that fine lamination is a feature of shallow water sediments.

The main siltstone member of the Upper Limestone Group cyclothem possesses the diagnostic features of a fluvio-marine environment (van Straaten, 1959, p. 207; 1960, p. 424). Marine organisms are still present, yet the effect of presumably fluvial-borne detritus is becoming more and more apparent. It appears likely, therefore, that these are deposits of a delta slope environment, and represent part of the foreset beds of a delta complex. The actual inclination of the delta slope would probably be less than 2° (van Straaten, 1960, p. 424), and the average rate of deposition would be high. The presence of occasional burrowed horizons (p. 191), does indicate that pauses in sedimentation took place and were of sufficient duration to allow colonisation by borrowing organisms. The siltstone/sandstone intercalations in the upper part of this member are presumed to represent the more proximal beds of the delta slope environment. This is borne out by the presence of ripple lamination; presumably formed in quite shallow water. The presence of brachiopod shell beds within the siltstone indicates that the fluvial element was not always the dominant depositional medium. The shell beds are not considered to be in situ and the shells could have been transported from the pro-delta platform to the shallower waters of the delta slope by on-shore marine currents and wave action. On the other hand, shell banks may have developed on the delta slope from time to time and provided the necessary organic debris for the shell beds in the sequence. Chonetes may be illustrative of this maxim, because of its inferred partiality to a silty environment (p. 191).

PLATE 49. Finely laminated, fine grained sandstone of Facies D.



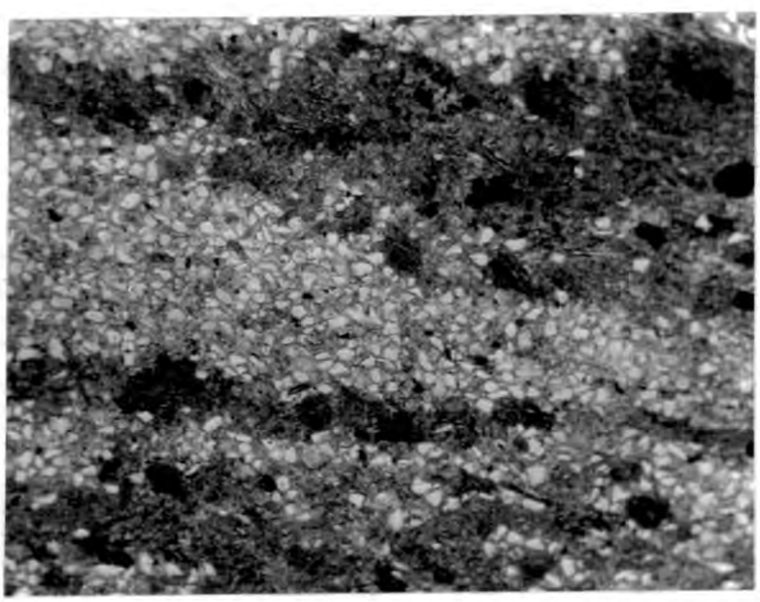


PLATE 50. Photomicrograph of calcite concretion in Hipple Sill, showing detrital nature of dusty calcite. (x 30)

V Facies D :- the non-erosive sandstone member

This sandstone member has often been referred to as the "normal" sandstone in the stratigraphical section of this thesis, because it forms the expected culmination of the coarsening upwards cycle described in Facies B and C. The sandstone is referred to as a single facies, but it may well represent more than one "environment", because the distinction between proximal foreset beds on the delta slope and topset beds on the delta platform is often marginal. Variations in physical environment parallel with the contemporaneous coastline may also be important in producing local variations within this facies.

A Petrography

The dominant rock type in this facies is a well-sorted, siliceous, micacaeous subarkose, which is typically fine grained but varies in grain size from medium to very fine. Highly carbonaceous and micaceous laminae alternate with pure quartz laminae to give the finely banded appearance typical of this facies (Plate 49). Where the plant material is not finely broken up it may be lineated as a result of current action. Calcite commonly occurs in the form of large concretions which are concordant to the stratification within the sandstone. This fact, plus the observation that calcite occurs preferentially along laminae within

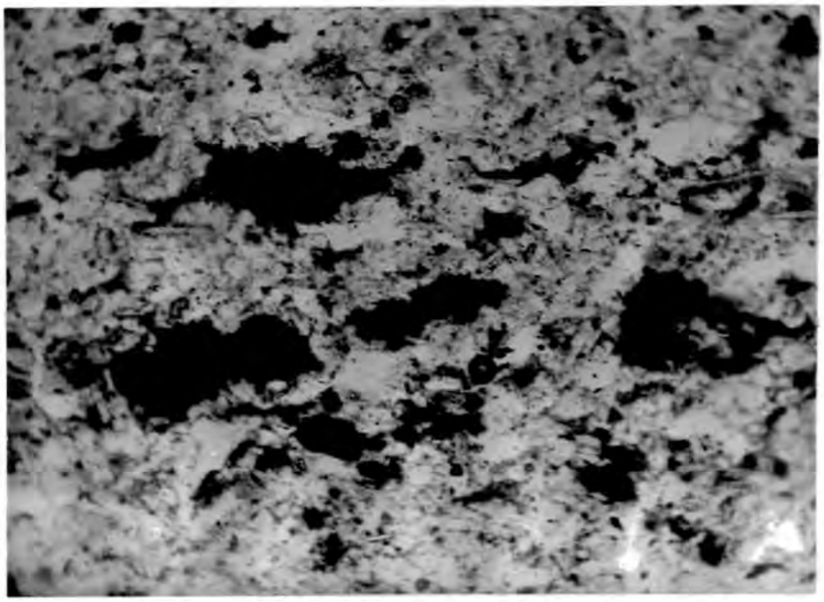


PLATE 51. Irregular flecks of argillaceous material of possible flocculated origin in sandstone. (x 120)

PLATE 52. Finely laminated, fine grained sandstone with shallow erosive troughs. Hipple Sill, North Grain, Rookhope Burn.

the rock (Plate 50), indicates that the calcite has a primary detrital origin. The calcite which ocurrs in the laminae has a clouded appearance and some crystals are rectangular; they appear to represent eroded crinoid columnals, at least in part. The present segregation into large nodules and the recrystallised nature of the calcite (p.123), argues in favour of a secondary modification of a uniform band of calcite-rich sands. The concretions, although still retaining the cross-stratification structures of the surrounding sandstone, have the composition of limestone; one modal analysis indicated 71% of calcite. The occasional thin shell beds which occur in this facies may also have an abundant calcite cement.

A sandstone with an unusual composition was collected from the base of the White Sill in Rookhope Burn. It contains 30% of argillaceous material in the form of irregular flakes much bigger than the associated white mica (Plate 51). The flakes contain a certain amount of ferruginous matter, now in the form of limonite. It is possible that they formed as a result of the flocculation process which is often described from an estuarine environment.

B Stratification

Three basic stratification types may be recognised in this sandstone facies.

PLATE 53. Uniformly laminated sandstone. Fiddler's Sill, Sipton Cleugh.

PLATE 54. Broad, shallow, trough lamination in fine grained sandstone, Firestone Sill. Nookton Burn.

These are:-

1) uniform lamination
2) small scale linguoid asymmetrical ripples
3) small scale straight symmetrical ripples.

Frequently, two of the types occur in association, but it is significant that so far, straight symmetrical ripples have not been found superimposed on sandstones with uniform lamination. It appears that the two types are mutually exclusive and suggests that they are formed in different regimes. The thickness of the regular laminae ranges from a fraction of a millimetre to one centimetre (Plates 52,53), although in the finely laminated sandstone one to two millimetres is usually the maximum (Plate 49). The laminae are perfectly parallel over considerable vertical thicknesses. Very shallow troughs up to 2 feet across occur within the uniformly laminated sandstones producing an angular discordance of only 10° or so; they disturb the orderly sequence but little (Plate 54). Many of the sandstone laminae contain parting lineation (Plate 55), indicating that bottom currents are active.

The small scale linguoid asymmetrical ripples (Allen, 1963a) of this sandstone suite are quite different from the shallow, erosive troughs just described. They are of much smaller width (Plates 56 to 58), and are believed to represent a shallower water environment. The width of the

PLATE 55. Parting lineation, Low Slate Sill. Coal Cleugh.

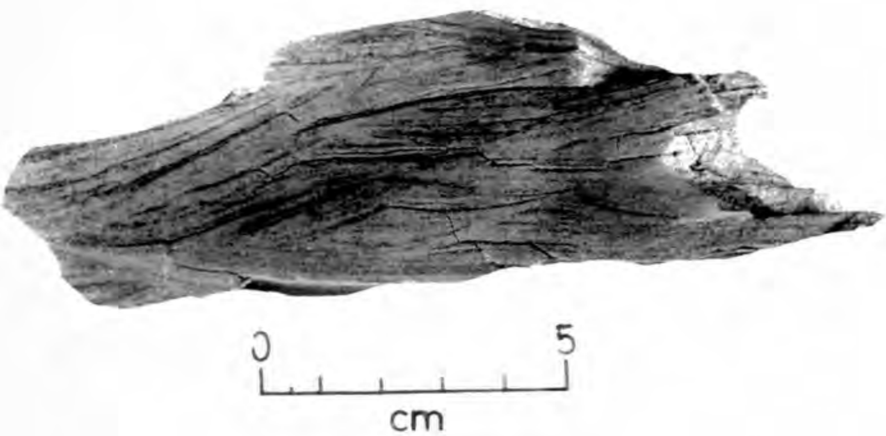
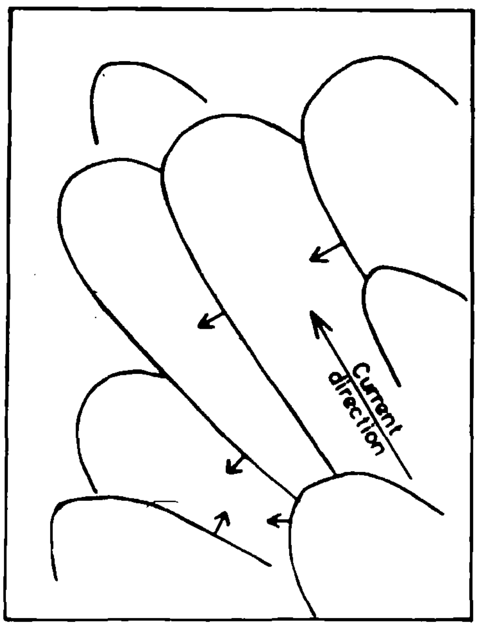


PLATE 56. Vertical cross-section of small scale trough cross-lamination, High Slate Sill, Rookhopehead.

Figure 15.3



Small arrows indicate depositing currents

Theoretical model illustrating formation of asymmetrically filled troughs.

ripples is typically 3 to 5 inches, and the thickness is 0.5 to 0.75 inch; the greatest observed length of the troughs was 12 inches. The structure is identical to that described by Hamblin (1961) which he named "micro-cross-lamination". Ideal trough cross-laminated series such as those illustrated by Allen (1963) do not always occur in reality. Both the form of the base and the form of the fill are subject to irregularities. The degree of erosion in two adjacent troughs is not always the same, and they can erode to different levels. The lamination of the contained sandstone is always concordant to the erosive base but not always parallel; in transverse section the laminae may be markedly asymmetrical. This feature is produced when troughs are filled dominantly from one side (McKee, 1954, p. 57), and is not simply the apparent asymmetry produced by observing an oblique section through the trough (Hamblin, 1961, p. 393). If a trough is to be filled with symmetrically laminated sediment then the following linguoid ripples (Allen, 1963a, Fig. 14, p. 214) will presumably have to be symmetrically placed about the trough axis. A situation could exist where effectively only one succeeding ripple was filling a trough (Fig. 15.3); the infilling sediments would then have asymmetrical laminae. Rarely, the base of the troughs may have small scour holes resembling flute casts and presumably representing locally turbulent flow.

The small scale linguoid symmetrical ripples commonly have several horizons which have been modified by small

PLATE 57. Plan view of irregular trough cross-lamination, Low Slate Sill.
Hawk Sike.

PLATE 58. Sharply defined trough cross-lamination ("rib-and-furrow"), Hipple Sill.
Smithy Cleugh.

scale straight symmetrical ripples. They are erosional features, but have a small number of continuous laminae deposited over the whole of the ripple: most examples of this type have sharp straight crests (Plate 59). The amplitude of the ripples in this sandstone facies usually varies from 0.25 to 0.75 inch, but large examples with amplitude of up to 5 inches have been observed (Plate 22). The ripple index (the ratio of wavelength to amplitude) ranges from 4.6 to 12.

Somewhat larger, solitary troughs occur in the upper part of the Fiddler's Sill in Nookton and Beldon Burns. One example is 2½ feet wide and eroded into silty shales below (Plate 8). It contains cross-stratified medium to fine grained sandstone which apparently filled the trough from the side, and which now has the amazingly steep inclination of 55°. This is not a tectonic effect and the over-steepening of an original depositional dip which could not have exceeded 28° (McKee, 1954, p. 48), must be attributed to compaction. The base of the trough presumably sank into the underlying shales, keeping the top in more or less the same position, thus producing an increased depth/width ratio. Evidence of this movement is afforded by the downturning of the shale underneath the trough and the presence of a small "diapir" of displaced "mud" alongside the trough.

C <u>Fossil content</u>

Organisms are not abundant, but of those which do occur, probably only the burrowers lived in this environment. The high rate of sedimentation and possibly the slightly lower salinity in the proximity of the river mouths, are the main factors inhibiting life. Vertical annelid burrows and sinuous tracks and trails on the bedding surfaces are the only indigenous organisms, and even these were presumably ecologically restricted to areas of locally reduced sedimentation. Brachiopods and molluscs do occur, however, as very thin shell beds within the main sandstone. They are presumed to represent a death assemblage which have been washed into their present position. Occasionally the effect of winnowing can be observed, and a shell bed perhaps comprising a single lamina, will contain only a single fossil type, such as Schellwienella or a turreted gasteropod. The brachiopods are sometimes fragmented and clearly deposited in very shallow water. Small plant fragments are frequently in close association with marine organisms, and in the sandstone below the Lower Felltop Limestone, large tree fragments have been observed only a few inches above a Schellwienella band.

D Lithological relationships

The base of this sandstone member is, by definition, transitional to the siltstone below. Numerous thin, laminated sandstones occur within the top of the siltstones, become thicker upwards, and eventually pass into the lower part of the sandstone (Plate 47). It is the top of the sandstone which shows the most variation, because it can pass into a variety of rock types, each representing a separate facies to be described presently. The upper limit of this facies may be transitional with a massive marine sandstone (p. 205), a shell bed series (p. 208), a seatearth (p. 221), or it may have a sharp contact with an erosive sandstone (p. 226).

E Possible environment

One of the most useful criteria which can be employed in an attempt to assess the depositional environment of a sandstone is the study of the contained sedimentary structures. A comparison with the results of similar studies on recent sediments is more or less essential for this. In studying the Mississippi delta region, Moore and Scruton (1957, p. 2743) have noted that there are three factors which relate minor sedimentary structures to environment of deposition. These are:-

1) sources of sediment
2) processes of primary and secondary sedimentation
3) rate of deposition.

Lamination may be produced in a sedimentary environment where the material is derived either from one source in which the amounts of the transported constituents varies, or from more than one source. The deltaic concept of Upper Limestone Group sedimentation implies that there is predominantly only one

DURHAM UNIVERSITY SCIENCE 12 JUN 1964 LIBRARY

source for the sediments, though those deposited in the sea may suffer considerable reworking before finally coming to rest. It is possible, therefore, that the lamination seen in this sandstone member could be produced by fluctuations in the volumetric discharge of the river system carrying the sediment; van Straaten (1960, p. 424) believes that this is the origin of most of the lamination in the proximal foresets of the Rhone delta. Moore and Scruton (1957) present a more sophisticated picture in their study of the Mississippi delta region, and draw attention to the complex interplay of the various factors (ibid., Fig,13, p. 2744). They note (ibid., p. 2733) that finer, though less continuous, laminae occur with increasing depth down to a maximum of 120 feet; only thick laminae, associated with cross-lamination occur in depths of the order of 6 to 8 feet. However, because of all the modifying factors, absolute depths of formation of the various structures have little value other than illustrating an approximate order of magnitude (ibid., p. 2747). Within the Upper Limestone Group the fineness of the uniform laminae and the absence of associated symmetrical ripples indicates an origin below the level of active wave scour, presumably in a depth of water greater than a few tens of feet. However, wave-induced agitation could play a part in winnowing the sediment and thus producing the laminae, so that the final effect may essentially be the result of both primary and secondary processes of sedimentation.

An example of a sediment in which an increased rate of deposition has had an effecton the type of stratification is afforded by the Firestone Sill in Nookton Burn (Plate 54). Here, the amount of argillaceous material is minimal (cf. Hipple Sill, Plate 52), and the quartz laminae correspondingly thicker. Although uniform lamination is still common, there is a greater development of erosive troughing which suggests shallower water. These features, plus the thin shell beds, indicate an environment relatively close inshore, perhaps periodically under the influence of waves.

Recent work on asymmetrical ripples by Allen (1963a,b) has shown that the structure variously known as small scale trough lamination, scour and fill (Shrock, 1948), rib and furrow (Pettijohn, 1957), and micro-cross-lamination (Hamblin, 1961) is due to the migration of trains of asymmetrical ripple marks. Conditions suitable for the formation of such ripples are turbulent water which has sinuous flow lines (Allen, 1963a, p. 200). The presence of small scale trough lamination testifies only to shallow water and strong unidirectional currents. Modern linguoid ripples are frequently observed in the intertidal zone, and it is suggested here that this is in fact the environment in which these small scale trough laminated sandstones accumulated. The frequent association with small scale straight symmetrical ripples, which are produced by wave action, also indicates very shallow water, perhaps only a few tens of feet.

In more general terms, these fine grained sandstones which contain the remains of both terrestrial and marine fossils and many features of shallow water deposition must represent the submarine topsets on the delta platform of the Upper Limestone Group delta complex. Such an environment may be subject to tidal influence, but in any case, the sandstones exhibit many of the features of a modern tidal flat (van Straaten, 1959). Regularly laminated sandstone may, however, accumulate just off the delta platform at the proximal end of the foreset beds on the delta slope (ibid., p. 208). The shallow erosive troughs which have been described from the uniformly laminated series (p. 197) may have their counterpart in similar deposits off the Rhone delta (ibid., p. 208). These occur below wave base in a region with no tidal currents, and van Straaten suggests thatthe erosive mechanism is slow turbidity currents which do not transport the sand great distances. In some examples of this facies in the Upper Limestone Group, small scale slumping has occurred (Plate 21), which could conceivably represent an incipient turbidity current.

VI Facies E :- the massive, marine-fossiliferous sandstone member

Localised developments of this facies are known at several horizons throughout the Upper Limestone Group, particularly in the upper part of the Slate Sills Formation, where it occurs as part of the Rookhope Shell Beds. The best and most widespread development, however, is the Pattinson Sill, which maintains a constant lithology over most of the area surveyed (p. 14).

A Petrography, stratification, and fossil content

The Pattinson Sill is a medium or fine grained silicic subarkose. There are invariably no major mineral constituents other than quartz and alkali felspar, the latter now mostly converted to hydromuscovite; mica and argillaceous material are very rare. Calcite occurs locally as a cement and forms large concretions. The rock invariably contains no stratification structures, possibly because of the absence of platy minerals. In one calcareous development, however, symmetrical ripples were observed, picked out by colour variations which are presumably due to varying concentrations of carbonate and quartz. Very occasionally, argillaceous material may become relatively abundant and this serves to pick out irregular bedding laminae; this type may be dark grey and mottled due to the passage of burrowing organisms.

Cylindrical or more irregular burrows may occur throughout the purer sandstone too, but they are not sufficiently abundant to destroy any stratification there may have been. The top few inches of the sandstone often contain evidence of considerable burrowing activity and probably represents a distinct pause in sedimentation. Crinoid columnals and brachiopods such as athyrids, orthotetids, and productids, tend to occur segregated in small lenses, and can occasionally be quite prolific.

B Lithological relationships

The base of this sandstone facies may be either transitional or abrupt. In the Pattinson Sill it usually has a downward passage into the uniformly laminated member of Facies D, but occasionally it is seen to rest quite abruptly on dark grey siltstone of Facies C. The Lower Rookhope Shell Bed is of this facies in Beldon Burn and this immediately overlies a thin, coal-bearing shale. The Upper Rookhope Shell Bed in Sipton Cleugh on the other hand, passes down into the fluvial sandstone of the High Slate Sill. The nature of the upper contact is also variable, but this facies is always overlain by marine shales.

C Possible environment

The general absence of mica and clay from sandstones of this facies in a suite of rocks where these two constituents are abundantly available, indicates their deposition in a high energy environment. The rare oscillation ripples and the winnowed fossil remains confirm this. Furthermore, the manner in which the base of this facies may rest on several different rock types suggests a migratory existence which is independent of the coarsening upward cycle so far described. Two sedimentary environments may be said to possess all these features, beaches and off-shore bars.

The occurrence of off-shore bars is almost a necessity for the formation of the ironstone facies of the Upper Limestone Group (p. 216), but it is a facies which is not often preserved in ancient sediments. Off-shore bars or coastal barriers are found in areas of active coastal deposition such as maintain off delta complexes. They form as a result of wave action, but their base may be in relatively deep water (van Straaten, 1959, p. 205). In the deeper parts, where wave action is not so vigorous, burrowing organisms may occur, and may explain the rare cases of reworked sandstone found in the Pattinson Sill. Some of the members of this facies may represent beach deposits, but they are very difficult to distinguish. The off-shore bar hypothesis is preferred because in contemporary examples they frequently enclose lagoons with restricted circulation and abnormal salinity (Rusnak, 1960). Such lagoons are believed to be important in the formation of the many sideritic and chamositic ironstones found in the Upper Limestone Group.

VII Facies F :- the shell bed member

Carruthers (1938) first drew attention to the preponderance of shell beds within the Upper Limestone Group, but, to date, no detailed description of this facies has appeared in the literature. They occupy a similar position to the lime stones of the Middle Limestone Group, but there are important physical and chemical differences which indicate that they were deposited in somewhat different environments. Both limestones (Johnson, 1960, p. 126) and shell beds show evidence of having been deposited in shallow water, but, whereas the limestones are indicative of open water fully marine conditions, shell beds frequently indicate a restricted environment with abnormal salinity. The following description is intended to fill a gap in our knowledge of Upper Limestone Group rock types.

A Petrography and stratification

An important feature of the shell bed facies is that it contains several rock types, which usually occur in beds only a few feet thick. The commonest of these are:-

1) ripple laminated, interbedded siltstones and sandstones
2) burrowed, medium grained sandstones with or without shells
3) ironstones.

PLATE 59. Straight, symmetrical ripples, Coal-cleugh Transgression Beds. Quickcleugh Burn.

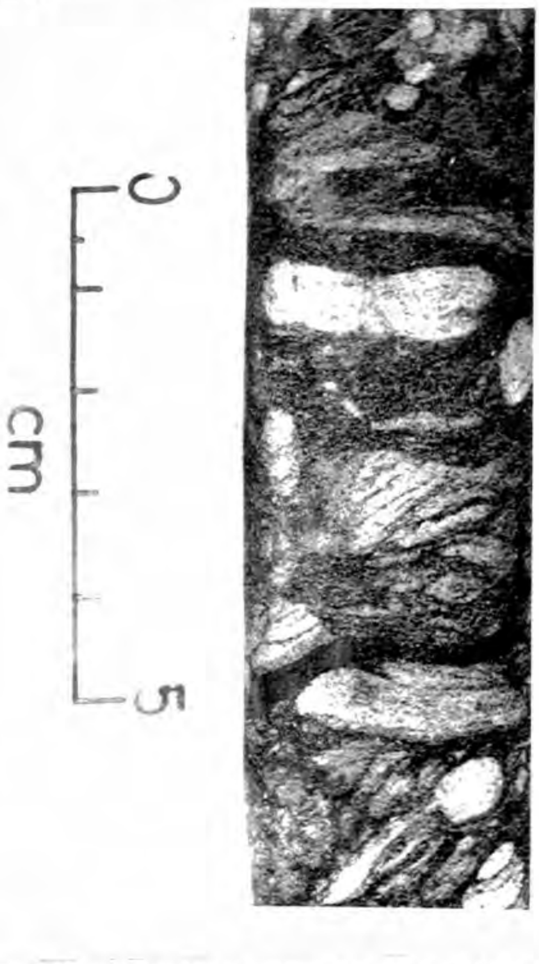


PLATE 60. Mottled sandstone of the shell bed facies.

Subordinate amounts of black, micaceous shale with occasional small lenses of black, carbonaceous sandstone also occur within this facies.

The ripple laminated siltstones and sandstones are laterally very variable. Dark grey siltstones and silty shales are the host rock types and are usually well laminated with very little disturbance by burrowing organisms. The included, light grey, fine grained micaceous sandstone may occur as thin lenses or thin beds, and is invariably ripple laminated. The sandstones may range from one to nine inches in thickness. Occasionally, thin beds of sandstone and siltstone alternate on asmall scale, each bed being less than three inches or so thick. The ripples are always of the type referred to by Allen (1963a) as small scale linguoid asymmetrical ripples (Plate 56).

The burrowed sandstones are easily recognisable in the field by their mottled appearance (Plate 60). The majority are medium grained but every grade between coarse and fine may be represented. They occur in beds which may vary from three inches to six feet, and in some localities they comprise the dominant member of the shell bed facies. The burrowed beds invariably contain carbonaceous and argillaceous material, which seems to be a prerequisite for the presence of bottom-living and -feeding organisms. Some animals have the effect of "cleaning" the sediment, leaving a burrow filled with pure sandstone, but others collect the fine material and deposit it, presumably as excrement, in their burrows. These latter are often difficult to distinguish from plant rootlets. White mica is often present, but although the bed may have been originally stratified, no stratification is now apparent.

Chemical cement in the burrowed sandstones may be absent or represented by calcite and siderite in varying proportions. Calcite is only abundant where fossils occur in considerable numbers, that is, in shell beds sensu stricto. In sparsely fossiliferous beds the sandstone and the shells themselves are decalcified. In thin-section the calcite cement is observed to occur as large, clear crystals which poikilitically enclose detrital sand grains. It is assumed, therefore, that this cement is authigenic, and perhaps derived from the associated organic calcite. Some siderite occurs as small discrete crystals scattered throughout the sandstone and may have a detrital origin. Siderite also occurs as nodules, especially in the silty shales, where it is presumed to represent secondary segregations. Plate-like or saucer-shaped bodies of siderite have also been observed in the sandstones and these are believed to be primary precipitates (p. 136).

The proportion of siderite in the rock shows a considerable increase at the top of the shell bed facies and usually forms a discrete ironstone member, This subject is considered in full in Chapter 14. Chamosite ooliths usually make their appearance at this level, but the relative proportion of ooliths and siderite is very variable. The ironstones still contain abundant shells and burrows; in fact, there is often an apparent relationship between the presence of worm tubes and siderite: this gives the ironstones a rubbly appearance (Plate 3).

B Fossil content

Within the shell beds *sensu stricto*, brachiopods comprise the most abundant fossils, but usually associated with burrows of various kinds. In many cases a certain species of brachiopod attains dominance over the others and may represent a considerable proportion of the brachiopod community. *Spirifer bisulcatus* and *Spirifer trigonalis* are the dominant brachiopods in the Knucton Ironstone in Nookton Burn, but at the same horizon on Carrshield Moor, West Allendale, *Phricodothyris* is the most abundant. It is not known whether this differentiation is due to the selective winnowing of a more heterogeneous assemblage or whether it represents the transport *en masse* of a complete fauna adapted to some particular environment. The valves of the brachiopods are often disarticulated, indicating that current action has played a decisive part in the formation of the shell beds.

The effect of many kinds of burrowers can be observed

PLATE 61. U-shaped burrow, Great Limestone. Killhope Burn.

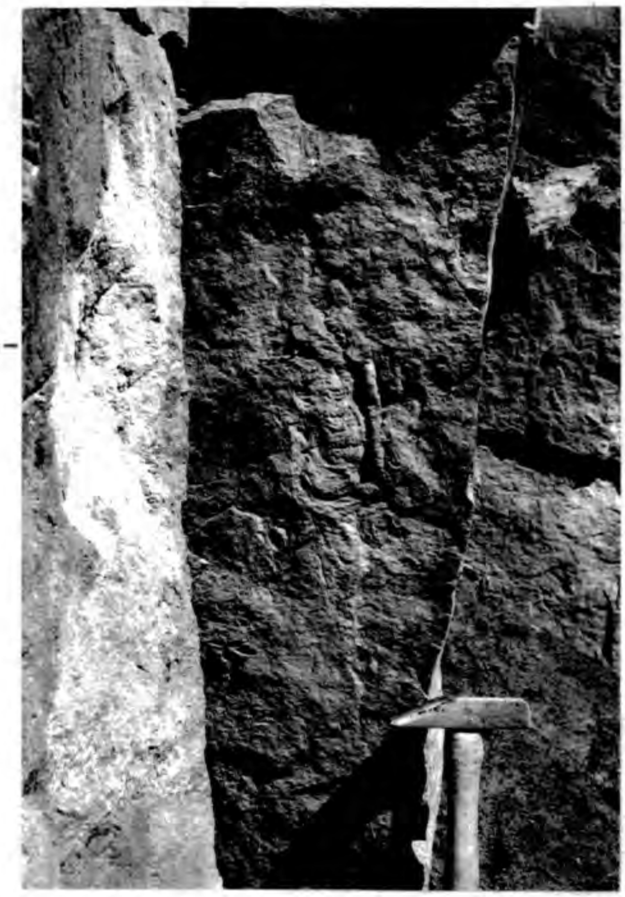


PLATE 62. Intensively burrowed sandstone, Lower Rookhope Shell Beds, Rookhope Burn.

in the shell bed facies; they may be divided into two categories, sessile and mobile. The most easily recognisable "sessile burrows" are the U-shaped ones, whose successive growth stages are marked by fine, curved lamellae. The U-shaped burrows may be several inches deep and have tubes up to three-quarters of an inch in diameter (Plate 61). Other, more simple burrows are known comprising a single vertical "tube" up to one foot long, but less than half an inch wide. Mobile burrowers usually move more or less parallel to the bedding planes. Some horizontal, possibly annelid, tubes may be one foot long and up to three-quarters of an inch in diameter (plate 62). "Caudagalli" burrows are often abundant, and generally occur to the exclusion of all other fossils (Plate 9). Occasionally, sinuous trails of possibly annelid origin occur on the bedding surfaces of some of the finer grained sandstones and siltstones. It is interesting to record that distinctive kinds of burrow may be used in short range correlation; cf. Phycodes, found in the Knucton Ironstone, has not been observed at any other horizon (p.136). The more irregular mottles in this facies may be due to other organisms such as lamellibranchs. This has been shown to be possible in recent sediments (Moore and Scruton, 1957, p. 2742) and, in fact, burrowing lamellibranchs have been observed in some of the ironstone beds of this facies; they occur embedded in the rock in their life position.

C Lithological relationships

In most cases the base of the shell bed facies is transitional to the fine grained ripple laminated sandstones of Facies D, and occasionally into a sandstone of Facies E. Both of these underlying facies contain shell beds, but the passage into the true shell bed facies is evidenced by the incoming of burrowed sandstones, the occasional development of thin beds of fine clastics, and the introduction of siderite in obvious amounts. In Rookhope Burn, the rather poorly developed Lower Rookhope Shell Beds have a gradational passage into the fluvial facies of the Low Slate Sill below. The culmination of the shell bed facies in a sideritic ironstone horizon which frequently contains chamosite ooliths is almost universal. In many cases the ironstone is immediately followed by the black shale referable to Facies B. In several cyclothems, therefore, the complete cycle is occupied by rocks which have a strong marine influence; this confirms the observations of Dunham and Johnson (1962) that a considerable amount of marine strata occurs within the Upper Limestone Group.

D Possible environment

The principal clues to the depositional environment of the shell bed facies are afforded by the presence of extensively burrowed beds and the existence of primary precipitate iron minerals. The proportion of mud-feeding, crawling and burrowing organisms varies inversely with the rate of deposition (Moore and Scruton, 1957, p. 2742). In the vicinity of the Mississippi delta the effects of burrowing organisms cannot be discerned when the rate of deposition exceeds o.15 foot per year (ibid., p. 2744). Mottled sands are known from two principal recent environments, lagoonal bays and pro-delta shelves. Of these, the lagoonal bays are more likely to exhibit shallow water features such as are seen in the Upper Limestone Group shell bed facies. Perhaps more important, they are more likely to possess an abnormal salinity and chemical environment such as might precipitate both siderite and chamosite.

Van Straaten (1959, p. 202) notes that mottled structures occur in the main part of the coastal lagoons, while Moore and Scruton (1957, p. 2735) quote the depths between two and nine feet as being the range in which the mottling of sediments occurs in some Texas lagoons. Shell beds are also very common features of coastal lagoons (van Straaten, 1959, p. 202), and in Laguna Madre may be up to one foot thick with an extensive lateral distribution (Rusnak, 1960, p. 166). The internal structures and petrography of the shell bed facies, together with its close association with a believed tidal flat environment (Facies D) are strong arguments in favour of a marine lagoonal environment for this facies.

The evidence suggested by the ironstone horizons also adds support to this general concept of a lagoonal phase in Upper Limestone Group sedimentation. A similar origin has been proposed for the Cleveland Ironstones (Rastall and Hemingway, 1940, p. 271; 1941, p. 362), and for the Northampton Sands Ironstone (Taylor, 1949, p. 79). The problem concerning the chemical environment in which siderite and chamosite may be directly precipitated is discussed in a comprehensive review by Dunham (1960). A few of the important facts concerning the formation of a chamosite oolite rock are summarised below, and discussed in terms of a lagoonal environment.

1) Normal sea-water does not carry sufficient iron to precipitate chamosite.

Lagoonal water does not have the composition of normal sea-water: one of the important features of the hydrography of coastal lagoons is the extreme range of salinity (Shepard and Moore, 1960, p. 124; Rusnak, 1960, p. 161). Salinity is variable in different parts of the lagoon and also varies at a given locality with time. This is a function of the complex interplay between sea-water on one side of the barrier beach and fresh water brought down by rivers on the other. A constant or stable situation rarely, if ever, exists for long periods.

2) In all probability, therefore, there must be rivers nearby to provide enrichment in iron.

There are two hypothesis which attempt to explain the problem of where the iron required to form sedimentary ironstones was ultimately derived. Borchert's (1960) envisaged mechanism of derivation by solution from iron-bearing sediments on the sea floor is considered unlikely to explain the often restricted development of Upper Limestone Group chamositic ironstones. The alternative hypothesis, that the iron was supplied by rivers draining a land where chemical weathering is an important agent, is therefore favoured. The known existence of a well-developed fluvial drainage pattern is a strong point in favour of this hypothesis. It is here suggested that many rivers, probably quite small, would drain directly into the coastal lagoons which are postulated as existing in Upper Limestone Group times in northern England. Furthermore, they would in all probability have passed through the coastal swamps and marshes which are believed to exist (p. 225), and the river water would therefore be very acid and able to contain relatively large amounts of iron (Dunham, 1960, p. 252).

3) Clastic sedimentation must be excluded from the region where chamosite is forming.

Chamosite ooliths in the Upper Limestone Group very rarely contain terrestrially derived or other constituents, although they may subsequently be redeposited with other components (p. 134). Thus arises the need to remove all external influences from the potential chamosite-forming environment. Either clastic sedimentation was at a minimum due to the hinterland being topographically mature, or a barrier of some kind existed which prevented the infiltration of coarse clastic sediment. The preponderance of coarse clastic sediment within the Upper Limestone Group of northern England indicates that the hinterland was not fully mature, and that coarse material was abundantly available in the area. The presence of a "clastic trap" seems more likely, and this fact again indicates a lagoonal environment. The rate of sedimentation is generally very low in coastal lagoons and, in the absence of major rivers draining directly into the lagoon coarse clastics may only be introduced by long-shore drift and the action of waves and tides. It is these very processes which form the barrier beaches and islands, and thus effectively debar clastic sediment from the enclosed lagoons. Within the lagoons the deeper water generally receives more sediment than the shallows, which may again suggest a relatively shallow water origin for chamosite.

4) Chamosite must be precipitated in shallow water where ooliths are capable of formation.

Other evidence suggesting that chamosite is formed in shallow water may be derived from the observation that it commonly occurs in oolitic form. This suggests an origin in gently agitated waters as propounded in the "classical" theory on the formation of ooliths (Beales, 1958). The alternative suggestion that chamosite ooliths grew <u>in situ</u> from a gel-like substance is not widely held; the evidence, usually based on the presence of "necked ooliths", is considered very tenous. Carbonate ooliths have been recorded (Rusnak, 1960) from Laguna Madre on the coast of Texas, indicating that oolith-formation is a practical possibility in a lagoon environment. These ooliths are restricted in distribution and occur only where the supply of terrigenous material is minimal and where wave action is prominant (ibid., p. 174): they are formed only in shallow water near the shore. A similar physical environment is proposed for the formation of chamosite ooliths.

5) In close association with the chamosite-precipitating zone there must be a siderite zone, and a zone where coquina are actively being formed.

Coastal lagoons in most cases can be subdivided into essentially separate bodies of water because of the presence of natural barriers within them (Rusnak, 1960, p. 161): each basin may have its own range of salinities and its own chemical environment. Although little is known of the actual chemical environment which must have prevailed in the lagoons of the Upper Limestone Group the analogy with contemporary lagoons strongly suggests that chamosite- and siderite-precipitating environments could exist together in different basins of the same lagoon. This could account for the rapid lateral passage from a chamositic ironstone to a sideritic ironstone, a phenomenon which is very common in the Upper

Limestone Group (p. 40).

6) Occasional strong currents must prevail to provide mixing of the various petrographical components. Hallimond (1925, p. 99) suggested that siderite and chamosite may be precipitated together by independent reactions, but the field relationships of these two components in the Upper Limestone Group suggest that this is not the case. In some sideritic ironstones, chamosite ooliths occur only in the top of the bed and in upward increasing quantities. In other cases, the size of ooliths bears a direct relationship to the size of the accompanying detrital quartz grains, suggesting transport by the same current. Furthermore, the coarsest deposits may occur above what appears to be a plane of erosion (p. 41). These observations suggest that periodic currents were operative which acted as mixing agents of deposits formed in the various environments within the lagoon. Most of the fossils now found in the ironstones probably could not have lived in the reducing conditions then prevailing. It seems necessary, therefore, to employ currents to "wash in" the brachiopods and other shells. The exact nature of these currents is uncertain, but the association with marine fossils may suggest an essentially marine rather than lagoonal origin. If this is so, then they may be induced by tidal or storm-wave influence. In the completely enclosed lagoons of the Gulf of Mexico, water circulation is largely

a function of prevailing winds (Shepard and Moore, 1960, p. 122; Rusnak, 1960, p. 161), but wind-induced currents are capable of eroding medium to fine sand particles (Rusnak, 1960, p. 164).

VIII Facies G :- the seatearth member

The term "ganister" is used in this thesis as a purely descriptive expression for an arenaceous seatearth containing plant material in situ (Plate 63): it does not refer to any particular mineralogical composition. The corresponding argillaceous member of this facies is known as a fireclay. Seatearths are usually widespread deposits, but do not occur in every cyclothem. The best examples are the Firestone ganister, the Coalcleugh ganister, and the Hipple Sill ganister/fireclay.

A Petrography

Modal analyses have been made on the Firestone ganister and the Coalcleugh ganister, both from Rookhope Burn. The Firestone ganister contains 96% of quartz and silica cement, and 4% of hydromuscovite, limonite, and carbonaceous material. This horizon has been widely quarried as a refractory product, in contrast to the economically useless Coalcleugh ganister, which is a muddy quartzarenite, containing 28% of argillaceous material in the matrix. The Firestone ganister is generally medium to fine grained and moderately well-sorted. Authigenic silica overgrowths on the quartz grains form the only cement, so that the rock is, in effect, a true

PLATE 63. Firestone ganister, showing rootlets.

PLATE 64. "Pencil ganister" above Hipple Sill, Black Sike, Rookhope Burn.

quartzite. In the Coalcleugh ganister, silica constitutes a relatively small part of the total cement, because of the high matrix content. White mica is present only as a minor constituent in the ganister.

Carbonaceous material in the ganisters is provided by the usually abundant plant rootlets and rhizomes. The plant rootlets may be long, straight and vertical, giving rise to the local term "pencil ganister" (Plate 64), or irregularly meandriform. The bark of the rhizomes is usually converted into vitrainous coal, and the softer, pithy core has disappeared to be partially or wholly filled with pure quartz sand. The partially filled rhizomes have subsequently been distorted by compaction load. As a rule, the proportion of carbonaceous material in the ganisters increases upwards, and the top few inches are commonly black in colour and much more friable.

Irregular siderite concretions may occur near the base of argillaceous ganisters like the Coalcleugh, but this feature is more common in association with fireclays. The Coalcleugh seatearth does in fact become a fireclay in the west of the research area around Killhope Law. At this horizon and a few others, small sphaerosiderite concretions, only 0.2 mm. in diameter, occur. No plant remains occur in the sideritic beds, however, but true fireclay may be present above it. The fireclay usually comprises a dark grey or black shale or silty shale, which contains abundant plant remains, most of which appear to be subhorizontal and allochthenous. The petrography of these deposits has not been studied, but Johnson and Dunham (1963, p. 74) record that kandites are the dominant clay minerals present, together with subordinate illite and mixed layer illite-chlorite.

An interesting representative of the seatearth facies, although not truly either a ganister or a fireclay, is seen above the Grindstone Sill in Bolt's Burn. The dark grey, medium grained sandstone contains strongly lenticular beds of coaly shale, one foot thick at maximum, and smaller vitrainous lenses less than two inches thick. It eventually passes up into a more typical ganister, followed by a thick development of coal.

All of the seatearths of the Upper Limestone Group in the area studied have a coal above them, but its thickness ranges from a mere smut, half an inch thick, to an economically workable coal three feet thick.

B Stratification

In the seatearth facies stratification is at best rudimentary, and, in ganisters, often restricted to the lowermost beds, where mica may be relatively abundant. Here the ganister may be described as thinly-bedded, but it quickly becomes massive and structureless above. The original bedding of the sediment, if any, tends to be removed by the passage of plant rootlets, and also, to a certain extent, by the interstratal solution of minerals other than quartz. A crude, irregular lamination may be discerned in some fireclays as a result of the disposition of the contained plants.

C Fossil content

Plant fragments are the only fossils which have been found in the Upper Limestone Group seatearths of the area surveyed. In most cases they are only represented by indeterminate rootlets, but occasional rhizomes may be recognised as Stigmaria.

D Lithological relationships

The base of the seatearth facies is usually transitional to the underlying rock. The advent of the new conditions is indicated by the entry of plant rootlets in situ and the gradual loss of bedding features with the upward increase of rootlets. Ganisters may develop both on tidal flat sandstones of Facies D and on the fluvial sandstones of Facies H; in each case the base is transitional. A seatearth may in fact comprise both a thin ganister and a fireclay, in which case the fireclay is invariably the upper member. There is a virtual transition into the overlying coal too with the gradual increase of carbonaceous material, but the contact with the ensuing shale is usually abrupt, and characterised by the incoming of marine or brackish water fossils. There are examples, however, of an apparent transition into the arenaceous base of a limestone (p. 178).

E Possible environment

The presence of terrestrial plants growing in place indicates that terrestrial conditions must have maintained during the formation of ganister. Underclays, which generally contain no rootlets preserved in situ are also believed to represent a subaerial environment. The presence of sphaerosiderite in the lower parts of some seatearths is also believed to be due to subaerial exposure. Iron dissolved in the near-surface zone of the underclay where leaching and oxidation prevail, is transported to the lower reducing zone, where it is precipitated as ferrous carbonate (Deans, 1934, p. 62). Weller (1930, p. 122) records that underclays have features which strongly suggest formation by prolonged exposure to atmospheric agents. He also states the opinion, reiterated by Johnson (1960, p. 127) that the length of time required to form an underclay may be comparable with the time required to produce the whole of the rest of the cyclothem

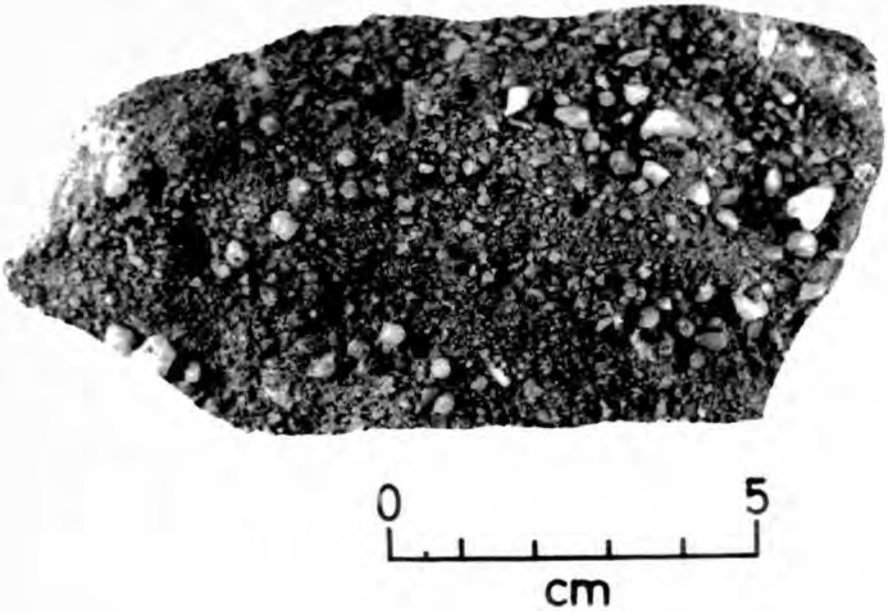


PLATE 65. Poorly sorted, conglomeratic sandstone, Low Grit Sill. Beldon Burn.

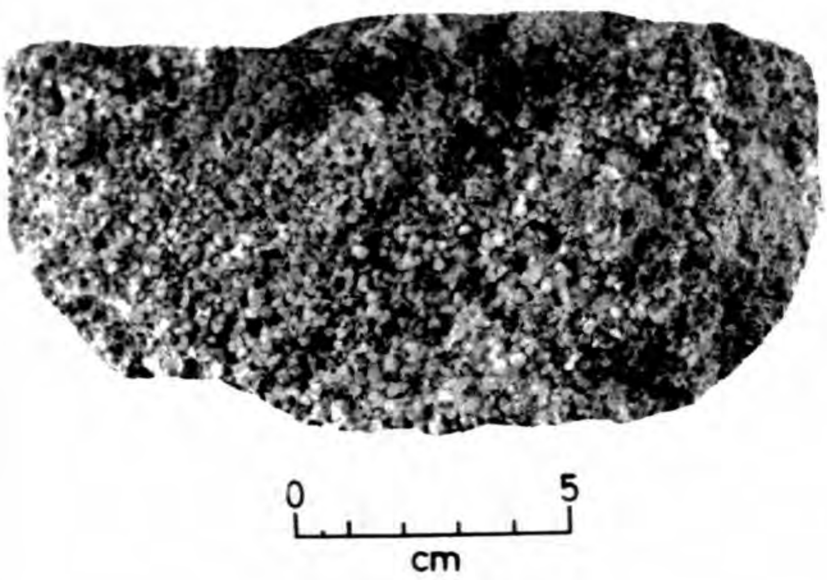


PLATE 66. Relatively well-sorted granule conglomerate, Firestone Sill, River West Allen.

IX Facies H :- the erosive sandstone member

This facies contains a multiplicity of rock types, not all of which are sandstones. The full range is from pebble conglomerates to shales, but the proportion of the end-members is so low that the whole suite may be conveniently considered in one section, especially as they are so intimately related. In the descriptions which follow, the general principle will be adopted that the rocks within this facies will be described upwards from the base of the member. Allowance must be made, however, when referring to particular examples, for the fact that local details are variable. In particular, it should be remembered that not all examples of this facies have the coarse sandstone unit present; the basal unit may be medium grained sandstone.

A Petrography

All of the coarse grained rocks occurring at the base of the erosive sandstone facies are subarkoses (p. 120). They are typically poorly or very poorly sorted (Plates 65, 66), up to very coarse in grain size and, if containing over 5% of granule or pebble sized material, may qualify for the epithet "slightly conglomeratic" (Table 4). Grain size is by no means uniform even over quite small areas of the rock. Lateral variations from coarse to very coarse sandstone may be observed, and similar variations occur as alternating laminae within a single two-inch cross-stratified bed. This feature indicates variations in the transporting potential of the responsible currents, but without necessarily a change in direction. Very poorly defined upward grading from very coarse to coarse may occasionally be observed, but this is by no means a typical feature. Grain size variations on a larger scale also occur within the basal coarse sandstones, which may contain medium to fine grained intercalations. These may be only a few inches thick and lenticular, or up to two feet thick and persistent over quite considerable distances. The cement is almost invariably silica occurring as several varieties (p. 123), but occasionally, secondary calcite may be introduced. Alkali felspar is usually more or less completely altered to hydromuscovite, but the occasional plagioclase crystals are still quite fresh. White mica is noticeably absent from the rock as a whole, but occurs on restricted horizons, often in association with argillaceous material. Rounded polycrystalline quartz pebbles may occur either scattered throughout the sandstone or as discrete pebble beds, perhaps occupying only one bedding plane, which qualify for the expression "sandy conglomerate". Some of the pebble beds do occur as thin lenticular bodies lying on an irregular erosion surface. Contrary to the observation of Robson (1956) in his study of the Fell Sandstone Series, the pebble beds do not invariably occur at the base of cross-stratified sets. Conglomeratic beds composed of material derived from within the sedimentary basin also occur. Shale fragments up to 5 cm. are the commonest of these, but occasional derived clay ironstone nodules may be found, and, very rarely, pebbles of fine grained sandstone. Thin, irregular coal seams may occur at the base of this erosive phase, and presumably represent drifted in plant material (Plate 77).

The medium grained sandstone member of this facies exhibits petrographic features very similar to the coarser phase, but appears to be more variable. It contains not only subarkoses but muddy quartzarenites as well. The principal petrographic differences, apart from the grain size, are the slightly better sorting (now moderately good), and the greater abundance of micaceous minerals. Coarse sandstone intercalations may still occur in the medium sandstone, and they may,in fact, grade laterally into one another. In the non-argillaceous sandstone silica still forms the dominant cement, although both siderite and calcite may occur locally; rare nodules of authigenic pyrite have been observed.

Many, but by no means all, examples of this facies have an upward culmination in fine clastics. These usually take the form of dark grey, silty shales, only rarely

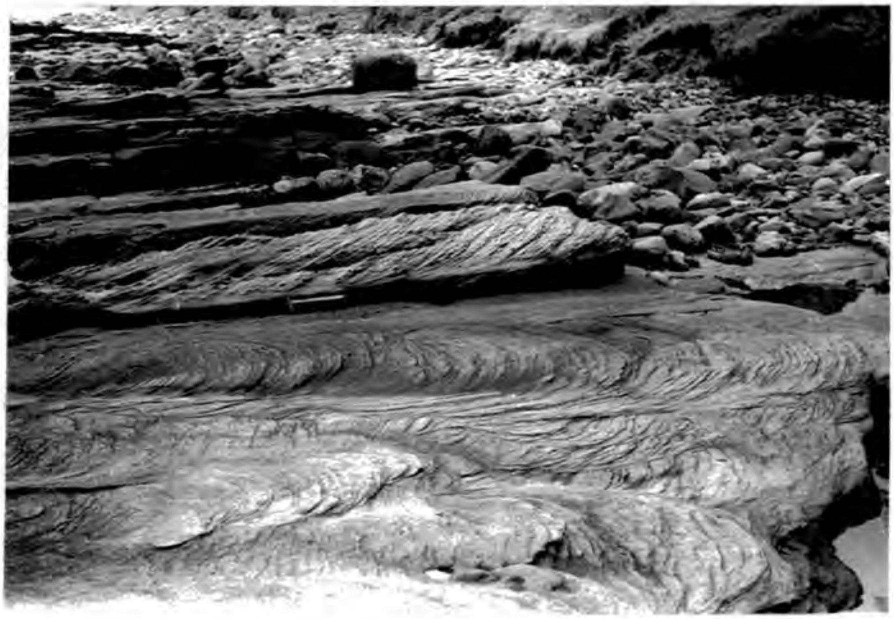


PLATE 67. Association of large scale trough cross -stratification and planar cross-stratification, Upper Limestone Group, near Howick, Northumberland.

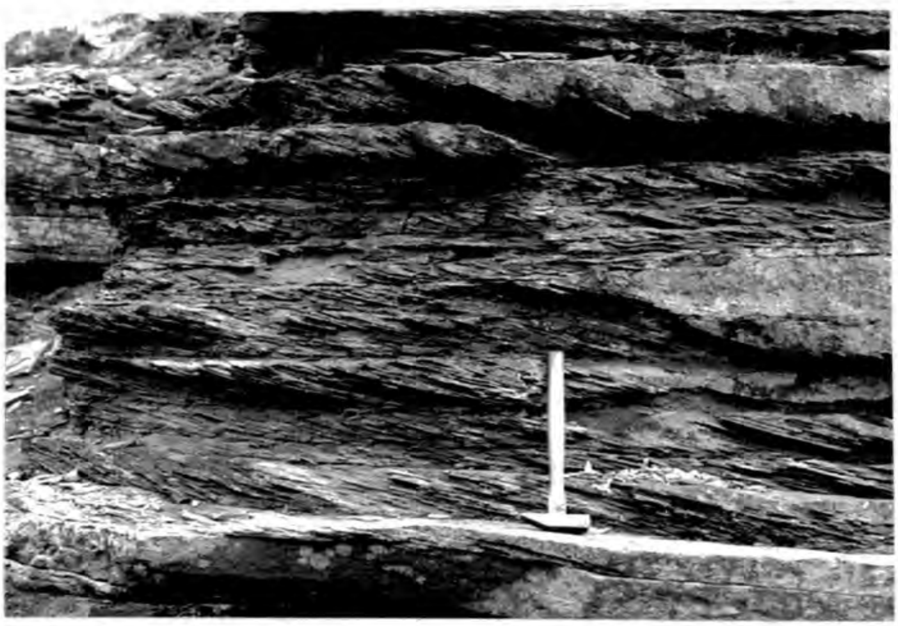


PLATE 68. Planar cross-stratification, Rowton Well Sill. Bolt's Law, Rookhope.

in beds over a few feet thick. They may occur simply as intercalations in the top of the medium grained sandstone member.

B Stratification

Well-developed cross-stratification is ubiquitous in the erosive sandstone facies, and three basic types may be recognised :-

1) planar cross-stratification
2) large scale trough cross-stratification
3) small scale trough cross-stratification.

There appears to be a certain correlation between average grain size and type of cross-stratification, which suggests that each type may be restricted to a certain flow regime. This is borne out by the work of Allen (1963 a,b) on the relationship between height of cross-stratified units and depth of water in which they were deposited. The very coarse to medium grained sandstones of this facies almost invariably have planar cross-stratification in association with large scale trough cross-stratification (Plate 67), and the fine grained sandstones predominantly have small scale trough cross-stratification.

1) Planar cross-stratification

True planar cross-stratification occurs as essentially tabular sets, varying in thickness from about three inches to three feet (Plate 68). They are quite distinct from the apparently planar cross-strata within large scale troughs, which, in small field exposures, appear to be bounded by plane surfaces (Fig. 15.6). In a detailed study of cross-stratification in the Rough Rock, Shackleton (1962, p. 114) found that the mean thickness of planar cross-stratification was 2.6 feet. The trough cross-stratified sets in the Upper Limestone Group frequently have thicknesses of this order, but there appears to be a significant difference in the planar cross-stratified sets, which frequently average only seven inches in thickness. Shackleton did not discuss the questions of polymodality or mixtures of several distinct size groups in his paper, but his histogram of set thicknesses (ibid., Fig. 2C, p. 112) reveals a distinction between the 0 to 1 foot and the 1 to 2 feet interval. Unfortunately, any subtleties of the distribution are masked by the use of too large a class interval. The distribution also has a marked positive skew, in which the greatest change of slope takes place after the 2 to 3 feet interval. The relative importance of the 1 to 3 feet interval is shown by the fact that it comprises 55% of the total number of measurements, whereas the 0 to 1 foot class contains only 6% of the total, and the over 3 feet interval, 39% of the total. Unfortunately, no systematic work has been attempted on similar measurements on Upper Limestone Group cross-strata, but a more

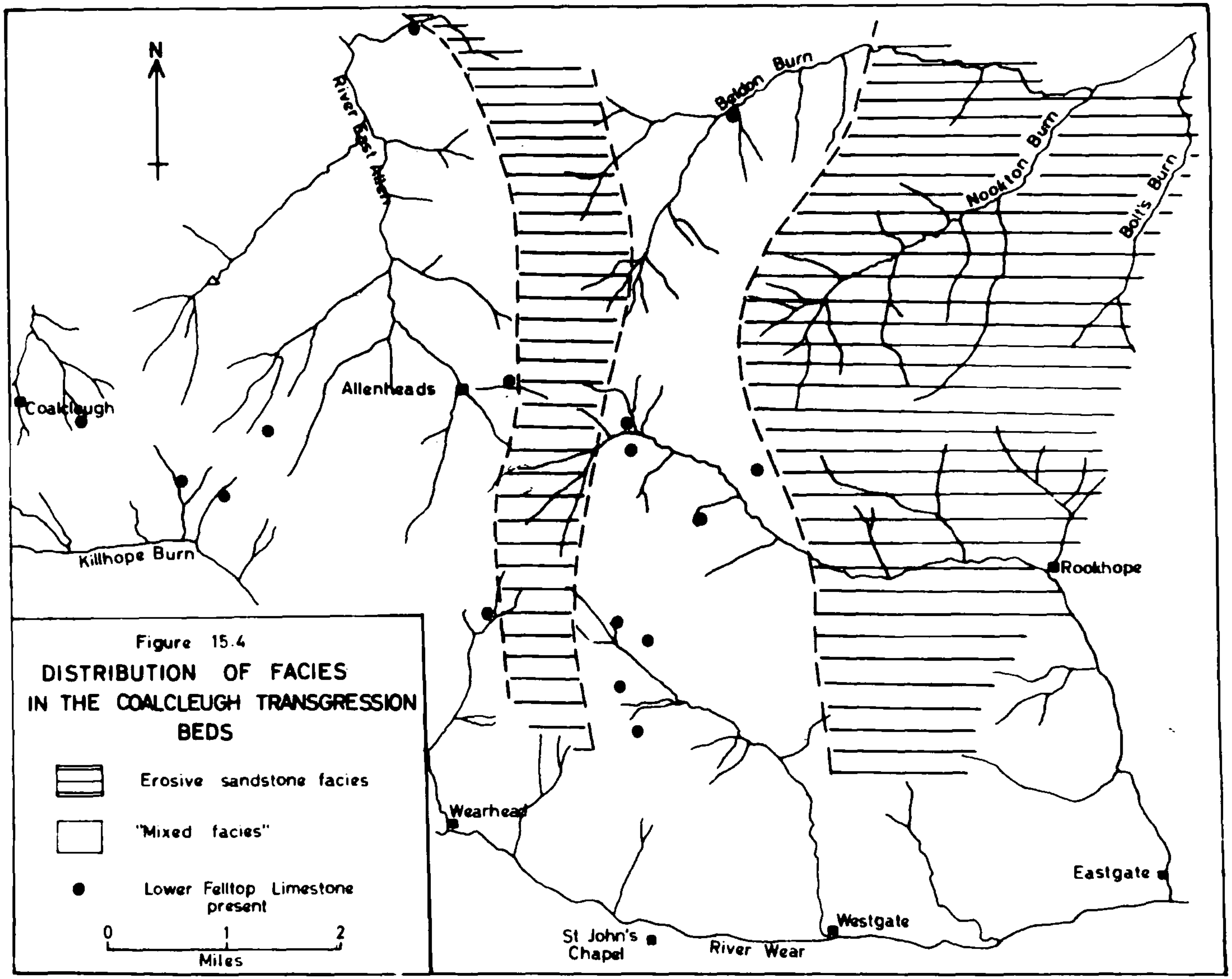


Figure 15.4
DISTRIBUTION OF FACIES IN THE COALCLEUGH TRANSGRESSION BEDS

comprehensive investigation of the thickness of planar cross-stratified sandstones may reveal that three distinct groups occur :- those with thicknesses less than one foot, those in the range 1 to 3 feet, and those over 3 feet. These groups, if they exist, may be related to differences in mode of formation. Allen (1963a, p. 213), although making a beginning on this kind of study unfortunately did not consider the skewness of the distribution curves of his bed-thickness data (ibid., Fig. 12, p. 211).

The base of the planar cross-stratified sets are always erosional, and may be either irregular or smooth. A thin pebble bed may occur at the junction between the two sets, but this is by no means universal. Some planar sets are separated by a thin bed of more or less horizontally laminated sandstone which is usually medium grained and highly micaceous. This bed is commonly two or three inches thick, and may die out within a few feet (Fig. 15.5). The planar cross-stratified sets on the other hand, are very persistent laterally, and they have been observed to extend for at least 15 yards along the strike without change; Shackleton has traced similar sets for 100 yards (ibid., p. 114). The relation of the planar cross-strata to the base of the set is commonly discordant, but there may occasionally be a tendency for the inclination of the cross-strata to decrease and become almost tangential.

Figure 15.5

PLANAR CROSS-STRATIFICATION IN THE LOW GRIT SILL

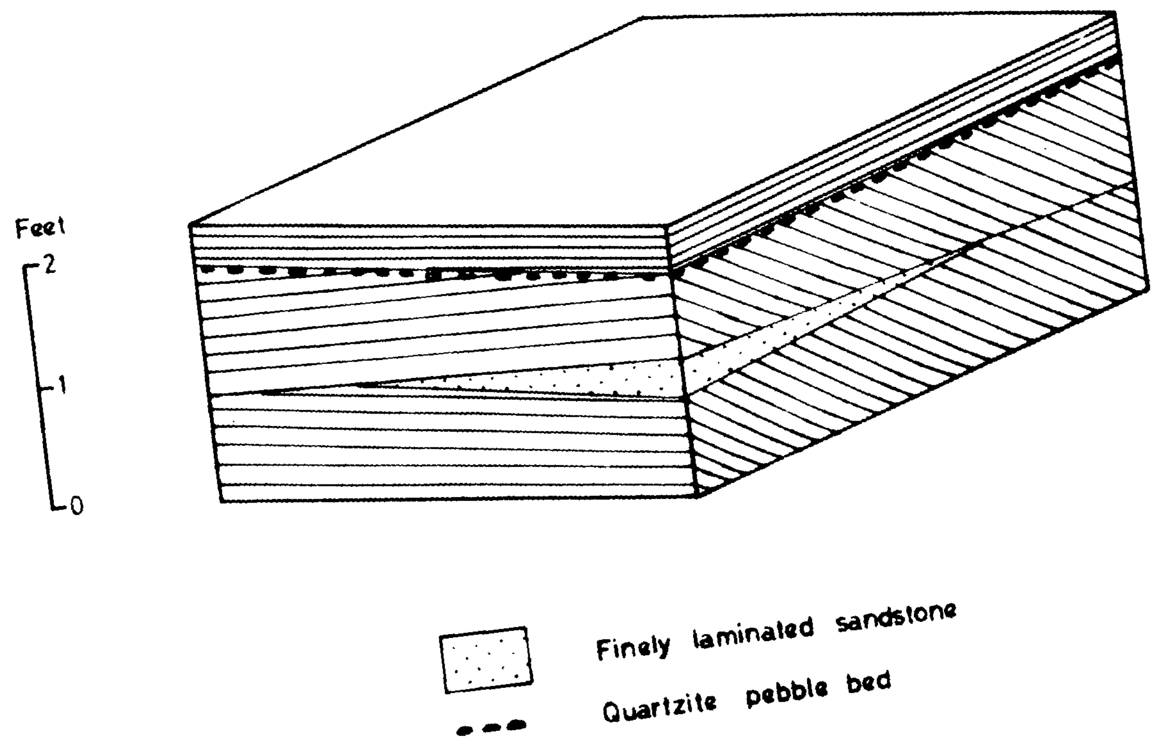


PLATE 69. Random section through large scale trough cross-stratified sandstone, Low Slate Sill. Hawk Sike.

PLATE 70. Large scale trough cross-stratification, High Slate Sill. Beldon Burn.

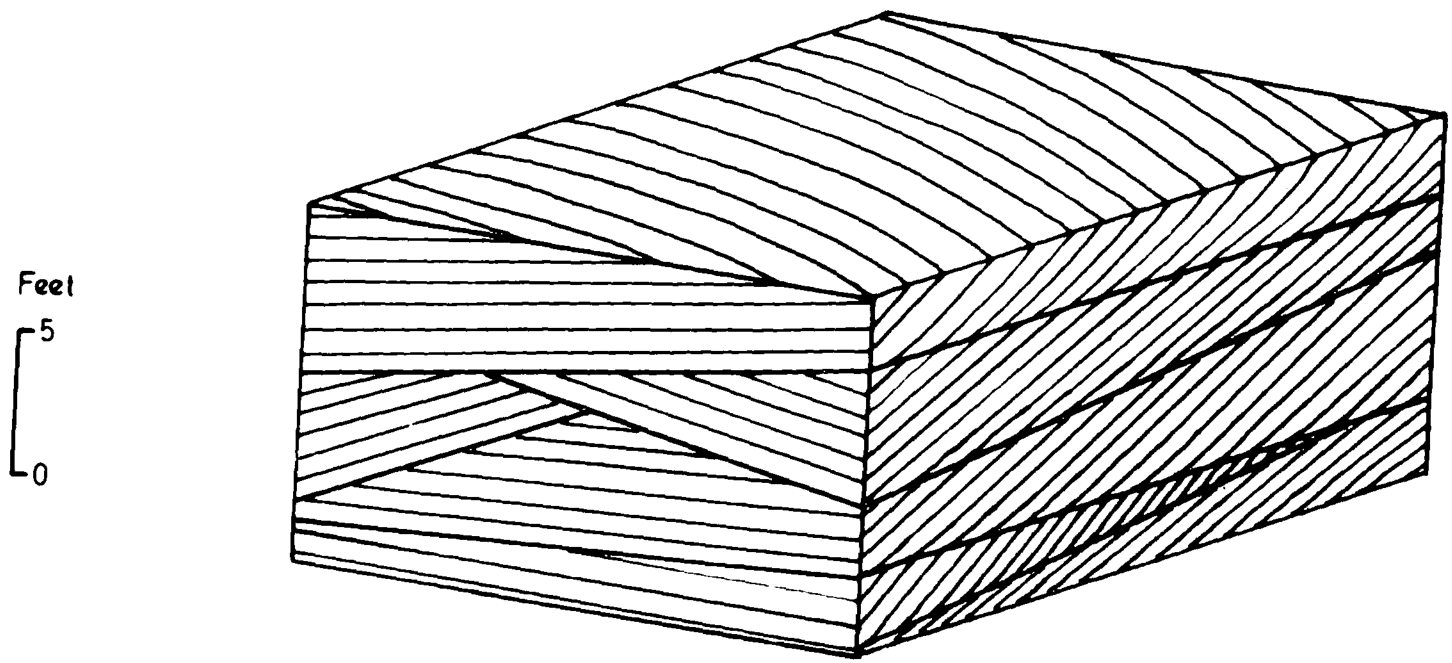
2) Large scale trough cross-stratification

Most commonly large scale trough cross-stratification is seen only in vertical sections which are governed to a large extent by jointing. In many cases, especially in the coarse lower layers of a channel deposit, the troughs are of such a width that they are rarely encompassed by the average outcrop. The troughs may,therefore, resemble in the field a series of planar sets as shown in Figure 15.6 and Plate 69. However, observation of many sets in differently orientated sections,a directional study if the cross-strata, and the presence of definite troughs of smaller dimension leave little doubt as to their true nature (Plates 70 to 72). Trough cross-stratification is equally common in coarse and medium sandstones in this facies, but, because the troughs tend to be smaller in the medium sandstones, they often appear to be more abundant.

The observed maximum thickness of the troughed sets ranges up to six feet. The present width of the troughs ranges from $1\frac{1}{2}$ to 6 feet, but this may only be a fraction of the original. The largest so far observed occurs in the Coalcleugh Transgression Beds and is described separately (p.234). The base of each set is strongly erosive and cuts across the underlying set at varying angles; in random sections through the troughs

Figure 15.6

LARGE SCALE TROUGH CROSS-STRATIFICATION IN THE LOW GRIT SILL



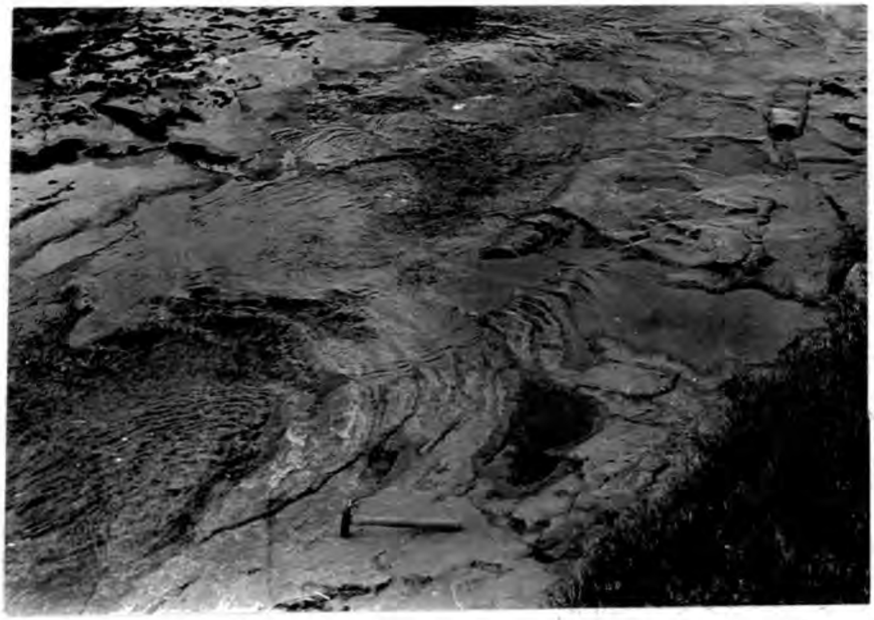


PLATE 71. Large scale trough cross-stratification, High Slate Sill. Beldon Burn.

PLATE 72. Large scale trough cross -stratification, Upper Limestone Group, near Howick, Northumberland.

each set appears to be markedly lenticular (Fig. 15.6). Stratification within the set in transverse section is always conformable with the base, but in longitudinal sections it approaches the asymptotic state (Plate 73). A corollary to this observation is the gradual thinning of individual beds as the base of the set is approached. In extreme cases, beds of micaceous sandstone may pass laterally into an unusual mica rock, which contains approximately 80% of mica. This results in the apparent anomaly of a highly turbulent environment depositing a great quantity of a flaky mineral, which normally would not settle under such conditions. Similar phenomen have been observed by Allen (1963a, p. 205), who states that the steep part of the cross-strata is produced by gravity slip of bed-load material. Jopling (1963) has confirmed this by experimental studies in a laboratory flume. He was able to show that upstream directed eddies occur below the jet-stream of the main flow, which not only have the effect of sorting the sediment as to grade, but also have the ability to deposit it as "toesets" (Fig. 15.7). This produces the concave upwards strata, tangential to the base, observed in most of the troughs.

Parting lineation may occasionally be seen on the cross-stratified beds and invariably the current direction indicated by this is parallel with the inclination of

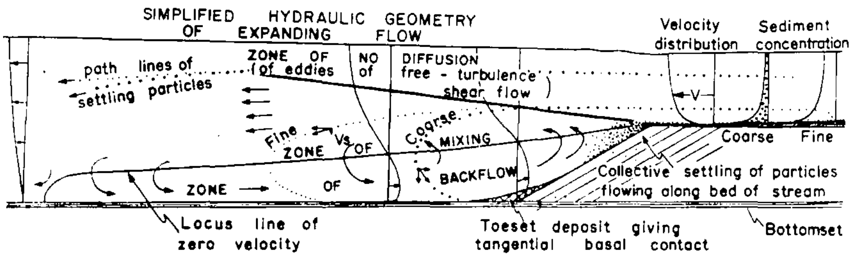


Fig.2. Zonal terminology for rapidly varied flow over the foreset slope of a small delta. Dotted lines represent idealized path lines of settling particlus. (Modified after JOPLING, 1961).

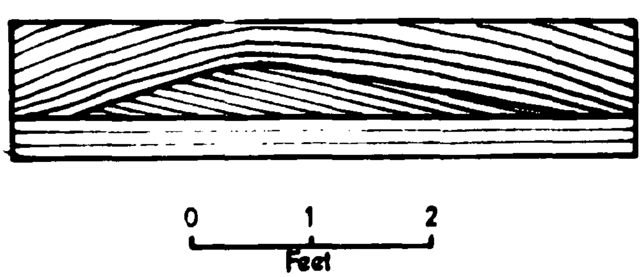
Figure 15.7

Hydraulic flow over foreset slope of small delta

(Jopling, 1963)

Figure 15.8

SOLITARY RIPPLE IN THE COALCLEUGH TRANSGRESSION BEDS



the cross-stratum itself. More active scour is indicated by the presence of actual troughs on the surface of some cross-strata, and again the current direction is parallel with the bedding inclination. These observations are at variance with Wright's contention (1959, p. 610) that fluvial currents produce cross-strata whose inclination is at right-angles to the current direction. On the other hand, rare examples may be found where small scale straight ripple lamination has been superimposed on large scale cross-strata. The current direction indicated by the ripples is approximately at right angles to that indicated by the cross-strata. This is believed to be due to minor fluctuations within the fluvial environment, and does not greatly affect the premise that cross-stratal inclination indicates local current direction.

A large scale trough in the Coalcleugh Transgression Beds

A series of photographs (Plates 74 to 77) serve to illustrate the salient features of a well-exposed trough in the Coalcleugh Transgression Beds of Sipton Cleugh. The trough is apparently 10 feet wide, though this may not be the true width; the cross-stratification indicates a probable trend of 290°, which is at an acute angle to the measured direction. The sandstone is well-bedded and, although the bedding has locally a definite trough-like shape, there is no evidence of erosion; the trough bedding

PLATE 73. Longitudinal section through large scale trough cross-stratification, Grindstone Sill. White Edge, Rookhope.

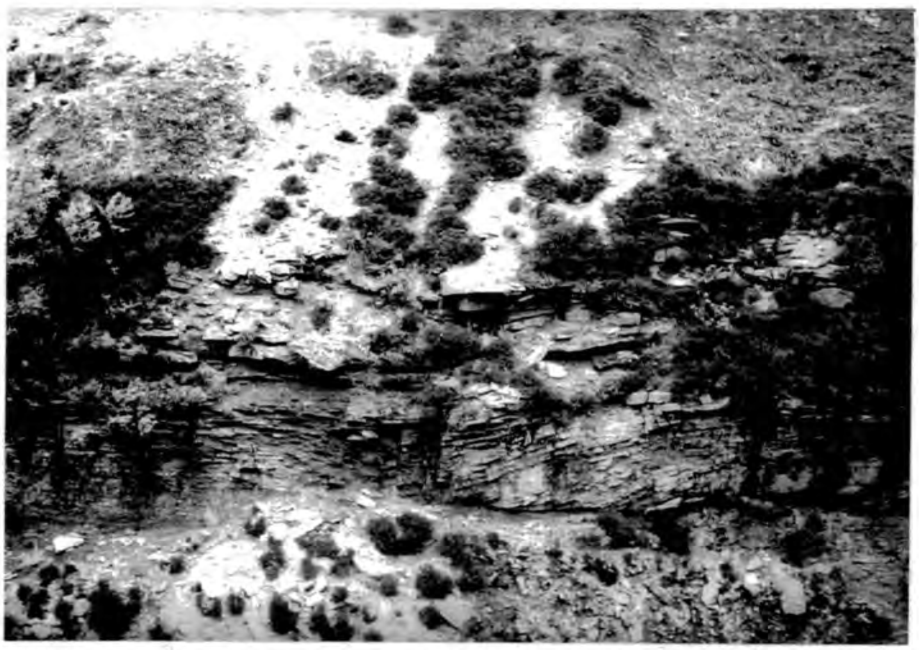


PLATE 74. Large scale trough structure in the Coalcleugh Transgression Beds. Sipton Cleugh.

PLATE 75. As for Plate 74, camera angle moved to the right.

PLATE 76. "Marginal facies" on south-west side of trough structure in Coalcleugh Transgression Beds, Sipton Cleugh.

is conformable with the underlying sediments on both sides (Plate 74). In both directions away from the trough the bedding passes laterally into near-horizontal bedding, but the relationship with underlying strata differs on either side. On the south-west side the sandstone passes gradually down into a series of sandy siltstones and sandstones (Plate 76) described elsewhere as "marginal facies" (p.239), and on the north-east side there is no apparent change in lithology, but an interesting change in bedding structure (Plate 75). Fortunately, a datum line is afforded by the thin coal seam which marks the irregular base of the Coalcleugh Transgression Beds washout channel as a whole. By application of the "Law of Superposition of Strata" it would appear that initially there were two areas of deposition separated by a zone of non-deposition. It is uncertain whether the two deposits were formed contemporaneously, for it is unusual that two completely dissimilar rock types be deposited at the same time in such close association.

The stratification of the lowermost sandy beds on the north-east side is interesting in that it is apparently convex upwards (Plate 75), as though the sand formed a low-lying bank on the bed of the channel. Within this "bank" the stratification is parallel to the base of the channel in its centre, but is disconformable near the inferred area of non-deposition (Plate 77). Undoubtedly,

PLATE 77. Allochthenous coal and "disconformable" relationship with overlying sandstone: base of Coalcleugh Transgression Beds, Sipton Cleugh.

PLATE 78. Irregular, small scale trough cross -lamination, Low Slate Sill. Hawk Sike, Rookhope Burn.

these obliquely stratified beds are the principal cause of the ultimate formation of the trough-like stratification. As the bank increased in size by conformable increments of thin sandy beds the sand deposited in the "zone of non-deposition" had stratification which was conformable with the original shape of the depression, thus producing the structure now seen. Confirmation of this mechanism is to some extent confirmed by the observation of smaller convex-upwards bodies of cross-strata within the Coalcleugh Transgression Beds at this locality. They have the appearance of single ripples, with flat conformable bases and containing strongly cross-stratified bedding (Fig. 15.8). Schumm (1960, p. 183), in a study of modern rivers has observed that in wide sandy channels, with a width/depth ratio of approximately 280, the surfaces of deposition are convex upwards in a manner closely resembling that just described from the Coalcleugh Transgression Beds. It is highly possible that this may be the environment in which the Coalcleugh Transgression Beds were deposited in this region.

3) Small scale trough cross-stratification

Trough cross-stratification on a small scale occurs in the fine grained sandstones in the upper parts of the erosive sandstone facies. The average width of the troughs is approximately 2½ inches, and the depth approximately one inch. They appear to be essentially

PLATE 79. Small scale trough cross-lamination, Hipple Sill. Quickcleugh Burn.

PLATE 80. Convolute lamination in Grindstone Sill, Black Hill.

similar to the large scale troughs of the coarser sandstones, and differ but little from the small scale troughs described from Facies D (p. 197). The troughs may in fact become quite shallow, and, therefore, not sharply demarcated as in the typical examples of "rib and furrow" (Plate 58); this has often been referred to as "incipient" trough cross-stratification" in the field (Plates 78, 79). Thin beds of small scale troughcross-stratified sandstone are commonly interbedded with beds of planar cross-stratified sandstone, perhaps only three or four inches thick. This suite is apparently formed by the migration of trains of both straight and linguoid asymmetrical ripples (Allen, 1963a,b). Straight symmetrical and interference ripples are occasionally seen in this facies.

4) Convolute bedding

Large scale convolute bedding is not a particularly common feature of sandstones in this facies. The best example has been observed in the Grindstone Sill, where local overturning of the bedding planes occurs (Plate 80). The disturbed bed is 2½ feet thick and its observed length is 4 feet; it is overlain by flat-lying sandstone. The convoluted unit has the same general characteristics as deformational structures observed in modern river sands. Harms and his co-workers (1963, p. 577) considered that this type is typical of fluvial deposits, but Dzulinsky and Smith (1963, p. 626) are more reticent, and propose no correlation of type of convolute bedding with environment.

"Mixed facies"

This sub-facies is afforded separate treatment because, although it is essentially part of the erosional channel phase, it has rather different petrographical and structural features. As the name implies, and in the sense originated by Reading (1957), it is characterised by having a variety of rock types . The sub-facies is restricted to certain areas within the Coalcleugh Transgression Beds (Fig. 15.4).

The sequence generally comprises massive ganistroid sandstones, siltstones and ripple-laminated sandstones, and true ganister with siderite concretions. The ganistroid sandstone is medium grained with no trace of stratification, and contains stigmarian roots only in parts. The siltstone largely comprises well-sorted quartz grains, but finely disseminated carbonaceous material is abundant and is largely responsible for the finely laminated appearance. The laminae are irregular but cross-lamination is not pronounced, The fine grained ripple laminated sandstones contain abundant micaceous and carbonaceous material, and occasionally the ripples may be picked out by detrital siderite on certain bedding planes. Both straight symmetrical and linguoid asymmetrical ripples have been observed in this member. The topmost ganister usually rests directly on this sandstone. Evidence in Frazer's

Quarry, Rookhope (Fig. 8.3) that at least the top part of the siltstones and sandstones interdigitate with a coarse fluvial sandstone, and similar evidence in Beldon Burn (Fig. 8.4), suggests a possible mode of formation of this sub-facies as an inter-fluvial flood plain deposit.

"Marginal facies"

A certain suite of rocks occurring in lenticular masses at the base of, and marginal to, fluvial channels, has been observed in the Coalcleugh Transgression Beds (Fig. 8.2) and the Low Grit Sill (Figs. 7.4, 7.5). The rocks are considered as part of the erosive sandstone member because they occur above the plane of erosion of this facies, although of different petrographical type. The suite essentially comprises black sandy shale or siltstone interbedded with dark grey, micaceous sandstones. The actual scale of the units differs in the two instances, but their general properties are similar. The whole series has fine, uniform lamination, and although horizontal annelid-type burrows are present they disturb the sediments but little (Plate 76). In the Low Grit Sill example thin beds of coarse sublitharenite occur which die out completely in only a few yards. Towards the north-east the deposits appear to become generally coarser and to contain quite large plant stems in position of growth. Small siderite concretions are present in the siltstones, which may have well-preserved leaves and lamellibranchs of possible fresh-water habitat. The base of this sub-facies is inferred to have a sharp, eroded contact with marine beds in each case, and the top is conformable with the overlying fluvial sandstone, into which there is a rapid transition (Plate 76). The marginal position and the general properties of this sub-facies suggest that it may be the representative of a levee environment.

C Fossil content

Fossil material in the erosive sandstone member is largely restricted to plant fragments, although occasional worm burrows and trails may be observed in the medium grained sandstone. The plant fragments areof various sizes, from finely fragmented stems to large logs of Lepidodendron over six inches in diameter; Calamites is also recorded. They usually occur as drifted remains on the bedding surfaces, but in the "marginal facies" they do occur in situ occasionally. U-shaped burrows filled with argillaceous material occur in the medium grained sandstones and sandy shales of the upper parts of the main series; sinuous trails of uncertain origin also occur.

D Lithological relationships

Characteristically, the basal member of this facies, be it coarse conglomeratic sandstone or medium sandstone, lies above a strong plane of erosion. Most examples occur as well-marked channels, some of which may be traced for quite considerable distances. Only one horizon, the Low Slate Sill, has a sheet-like form: it still has an erosive base and retains all the petrographic features of the shoestring or channel sandstones. When observable in detail, the base of the channel is extremely irregular and in places the erosive contact may be sub-vertical (Fig. 7.3). Smaller washout channels may, however, have smooth regular bases (Plate 11). In other cases the plane of erosion is hardly discernible and can only be inferred by general lithological relationships (p. 68). Within this facies there is invariably a systematic decrease upwards in grain size, which may eventually lead to a thin development of fine clastics at the top.

The uppermost beds of this facies pass gradually into either a seatearth or a shell bed facies. The seatearth, which may be either a fireclay or ganister or both, is never very thick. In rare instances no seatearth is present, but the top is marked by an impure coal. The passage into the shell bed facies may take place through a postulated beach or coastal bar facies (p. 205), or through a complex series of argillaceous sandstones and siltstones of uncertain origin. In either case there is no intervention of marsh or swamp facies.

E Possible environment

All of the features of the previously described series indicate a fluvial environment of deposition; the main factors are summarised below:-

1) the universal occurrence of an erosive base to the series;
2) the commonly observed channel or shoestring nature of the facies;
3) the contained sediments gradually become finer grained upwards;
4) the presence of cross-stratification of fluvial aspect;
5) the preponderance of plants of presumed terrestrial origin, and the complete absence of marine fossils.

Many of these points are self-explanatory, or have been sufficiently elaborated in the preceding text, but some of them are worth considering in greater detail. Although not a single one of these attributes, if taken by itself, could be said to indicate conclusively a fluvial environment, the presence of all five is convincing.

The concept of a fining upward cycle has often been emphasised in the text with reference to Upper Limestone Group sandstones of this facies. Exactly the same phenomenon has been described from many modern river channels (Fisk and McFarlan, 1955, Fig. 2, p. 281; Dunbar and Rodgers, 1957,

p. 32; van Straaten, 1960, p. 419; Schumm, 1963, p. 1096). In the Mississippi Quaternary flood plain, Fisk and McFarlan (1955) consider that the passage upwards of the fluvial facies into their finer "deltaic plain" facies is due to the rise of sea level after the Quaternary glaciation. The same feature may also be produced during aggradation of a river system (van Straaten, 1960; Schumm, 1963).

Sedimentology has recently seen important advances in our knowledge of the stratification of sediments deposited by rivers. It is generally agreed that most deposition in meandering streams takes place on point bars on the insides of meanders (Dunbar and Rodgers, 1957, p. 31; Wright, 1959, p. 611; van Straaten, 1960, p. 419). Wright (ibid.) maintained that point bar deposition would result in planar sets formed at right angles to the principal current direction. However, three recent papers on modern point bar deposits (Frazier and Osanik, 1961; Lane, 1963; Harms et al., 1963), indicate that stratification is mainly of "trough-type" with subordinate "planar-type". Furthermore, the cross-strata are orientated parallel with the local stream flow and not at right angles to it. More general aspects have been studied by Allen (1963a,b) in a series of papers on the origins and classification of cross-stratification types. The overall conclusions of these several workers are much in agreement, and will be briefly summarised below in relation to the Upper Limestone Group examples.

Trough cross-stratification of various scales is a common feature of fluvial sandstones in the Upper Limestone Group of the area surveyed (p. 229). The nature of these troughs is exactly similar to those observed in modern river sands, and there is therefore good reason to postulate an essentially similar origin; there may not, however, be a unique mode of formation. Frazier and Osanik (ibid., p. 135) and Allen (1963a,b) have shown that trough cross-stratification may form as a result of the contemporaneous erosion and deposition inherent in the migration of a train of sand waves or large scale linguoid asymmetrical ripples. Harms and his co-workers (1963, p. 574) have suggested another mechanism in view of the absence of sand waves or large linguoid ripples from the vicinity of the Red River point bar which they studied. They postulate local turbulence in the form of vortices moving with the current flow which scours out a spoon-shaped trough. This is subsequently filled with sediment by an unspecified process. The whole sequence of erosion and deposition is believed to represent one continuous process (ibid., p. 574). One important point of difference between the trough stratified sands in the Red River point bar and the Locksite point bar is that the latter are believed to form entirely below water (Frazier and Osanik, 1961, p. 136), whereas the former are periodically exposed and are only covered by the river for approximately six months of the year (Harms et al, 1963, Fig. 3, p. 569).

The thin beds of planar cross-stratified sandstone found in the Upper Limestone Group in association with trough cross-stratification also have their counterpart in modern fluvial sands. Harms and his co-workers (1963, p. 576) record thin sets of planar cross-strata, some three to four inches thick, but reaching two feet in thickness on occasions. They are the deposits of migrant "sand waves" or, in Allen's terminology (1963a), large scale straight asymmetrical ripples. In the Old River Locksite point bar, planar cross-stratification was nowhere observed.

X Directional studies in fluvial sandstones

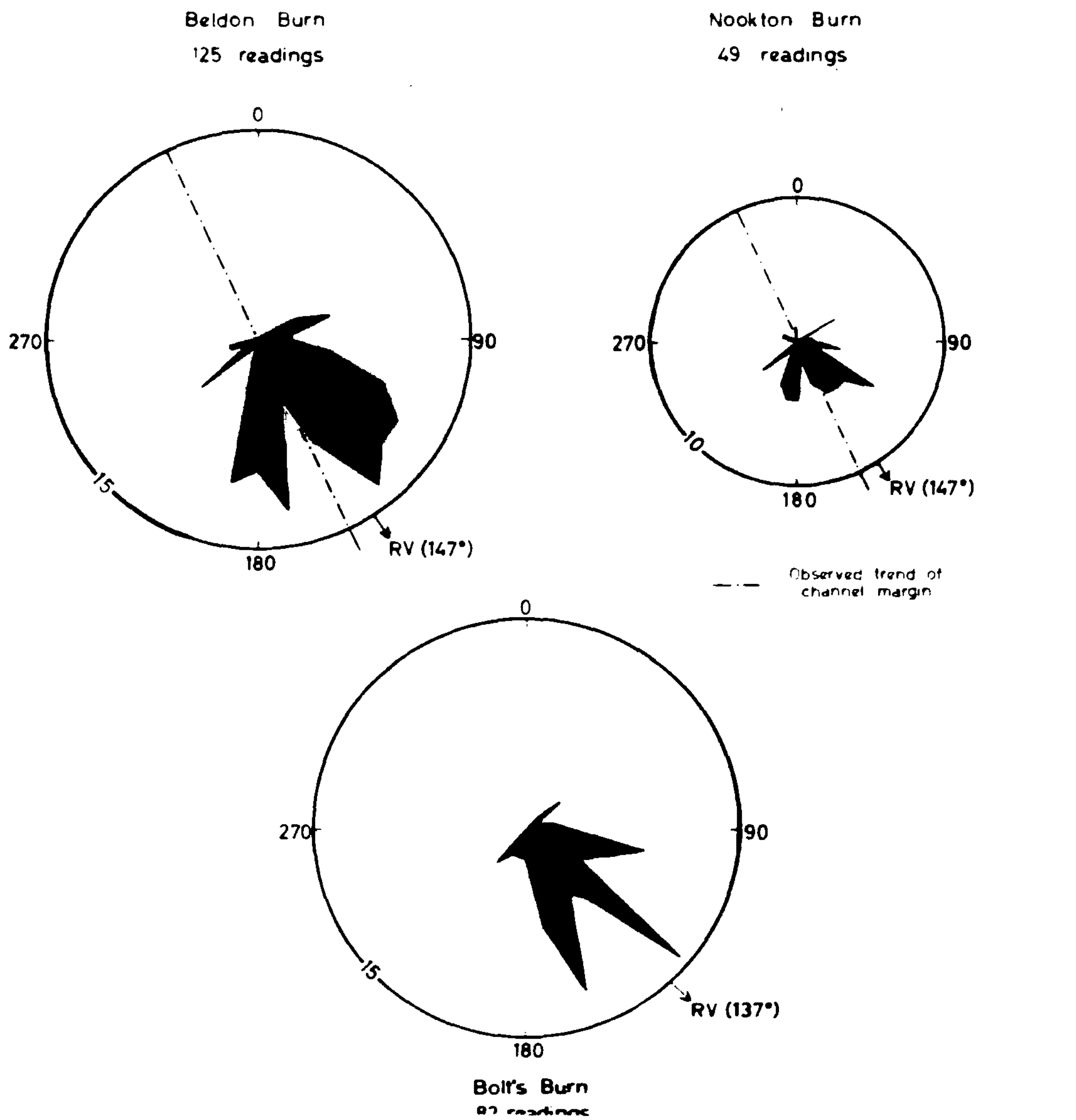
A study of the directional properties of the fluvial sandstones in the area to the east of the Burtreeford Disturbance was undertaken during the course of the routine mapping. Poor exposure limited the usefulness of these data except in the case of two horizons, the Low Slate Sill (and its equivalent the Low Grit Sill), and the High Grit Sill. Most of the measurements were made in the tributaries of the River Derwent and Rookhope Burn where exposure is good; a few measurements were also obtained in East Allendale. Time unfortunately did not allow use to be made of several good exposures to the west of the Burtreeford Disturbance.

A Method

Exposures in the field rarely allow discrimination to be employed in the collection of the directional data from cross-stratified sandstones. Normally, as many observations as possible were made at any outcrop, but readings were limited to one per set of cross-strata. Azimuths were measured with a prismatic compass to the nearest 5°, and inclinations were measured with a clinometer level. The structural dip is difficult to measure at outcrop because of the cross-stratification, but it averages 5 or 6°; thus, no correction of the cross-stratification data for tectonic dip was considered necessary. As a precaution, readings with strata inclination less than 10°

Figure 15.9

FREQUENCY OF CROSS-STRATIFICATION AZIMUTHS IN THE ROGERLEY CHANNEL



were discarded (Tanner, 1955, p. 2472). The data were subsequently plotted as rose diagrams with a 10° azimuthal separation (Fig. 15.9), and statistically analysed using the Curray method (1956). In this way, both the aximuth and magnitude of the resultant vector may be calculated: the resultant vector magnitude (in percent) gives a measure comparable with standard deviation (*ibid.*, p. 120). The significance of the result is checked by using the Rayleigh test, for which Curray gives a graph relating total number of measurements and vector magnitude (*ibid.*, Fig. 4, p. 126). The probability level accepted in this thesis is 0.10. This indicates that there is a 90% probability that the resultant vector actually does represent the distribution employed in the calculation and is not merely due to chance. It does not indicate the probability that the resultant vector represents the *actual* directional field at that locality. The method of calculating the resultant vector is given below, and the results are summarised in Tables 11 and 12.

Calculation of resultant vector

(from Curray, 1956)

North-south component $= \sum n \cos \theta$

East-west component $= \sum n \sin \theta$

$$\tan \bar{\theta} = \frac{\sum n \sin \theta}{\sum n \cos \theta}$$

$$r = \sqrt{(\sum n \sin \theta)^2 + (\sum n \cos \theta)^2}$$

$$L = \frac{r}{n} \cdot 100$$

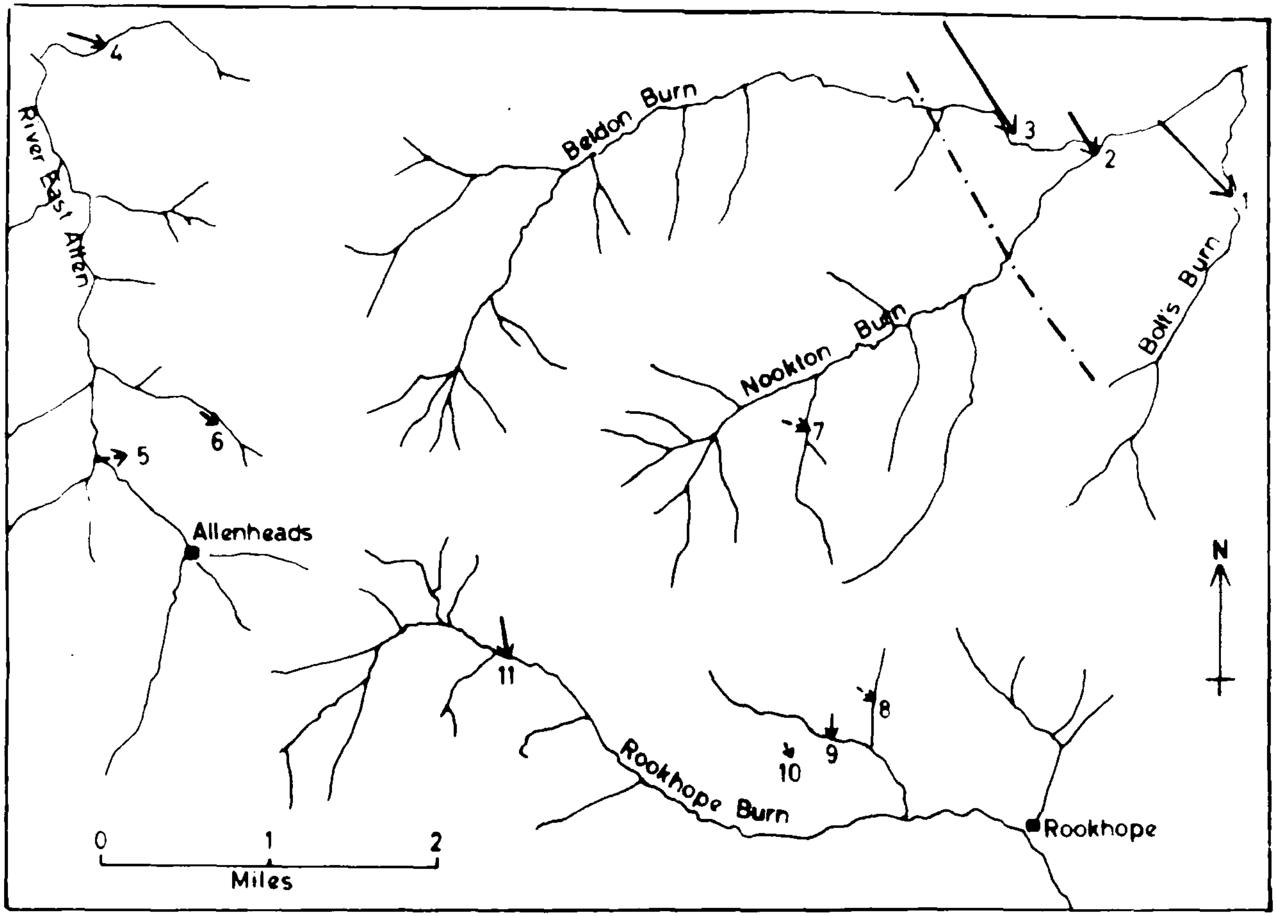
T A B L E 11

Data on resultant vectors of cross-stratification azimuths in Low Slate Sill

Locality	n	r	Az.	L(%)	R_t
1	82	24.3	137	29.6	0.01
2	49	11.6	147	23.67	0.05
3	125	33.0	147	26.4	10^{-3}
4	36	9.06	108	25.17	0.05
5	27	6.79	82	25.15	0.10
6	11	5.0	126	45.45	0.05
7	16	5.48	110	34.25	0.10
8	15	5.57	129	37.12	0.10
9	17	6.24	182	36.73	0.05
10	6	2.83	156	47.13	0.10
11	35	9.64	171	27.54	0.05

Figure 15.10

CROSS-STRATIFICATION DIRECTIONS IN THE LOW SLATE/GRIT SILL



—·—· Western limit of Rogerley Channel

→ Resultant vector at the > 0·5 probability level
-→ Resultant vector at the 0·10 probability level

} length ∝ magnitude

Numbers refer to data in Table 11

where θ = azimuth from 0° to 360° of each observation or group of observations

$\bar{\theta}$ = azimuth of resultant vector

n = observation vector magnitude, or, in the case of grouped data of unit vectors, it is the number of observations in each group

r = magnitude of resultant vector

L = magnitude of resultant vector in percent

B The Rogerley Channel

The existence of a channel of considerable magnitude, represented by the Low Grit Sill, was first demonstrated by Dunham in 1948. He observed (ibid., Fig. 4, p. 38) that the trend of the channel was approximately NNW-SSE around Hunstanworth, but becoming N-S through Stanhope in Weardale. This is confirmed so fas as is possible by recent mapping: the trend of the western edge of the channel in the Hunstanworth area was found to be 155° (Fig. 15.10). A total of 256 cross-stratification azimuths were measured in three traverses along Beldon, Nookton, and Bolt's Burns; the results are summarised in Table 11 and Figure 15.9. The azimuths of the resultant vectors in Beldon and Nookton Burns are both 147°, which agrees well with the observed trend of the channel in that area. In

Bolt's Burn the resultant vector has a bearing of 137°, which presumably indicates a slight change in the orientation of the channel. Analogous directional studies by Frazier and Osanik (1961) and Harms <u>et al</u>. (1963) on recent fluvial sands lend conviction to the belief that vectorial analysis of cross-stratification directions truly indicate current flow.

The results of the Old River Locksite observations (Frazier and Osanik, 1961) are perhaps less useful in the present context because the authors do not make clear how many cross-stratification directions were measured in each trough; it would seem that only one was measured as a general rule (<u>ibid</u>., Fig. 11, p. 134). Their quoted average dip direction presumably indicates more or less the orientation of the troughs, assuming that the measurements were made near the trough axis. The correspondence between the postulated direction of current flow and the actual local channel alignment is very high. The results of a similar study on a Red River point bar (Harms <u>et al</u>., 1963) are more comprehensive, and produce two important conclusions (<u>ibid</u>., p. 573):-

1) resultant vectors of trough axes closely parallel local stream flow directions
2) resultant vectors of included cross-stratal inclinations also parallel local stream flow

directions, but a few tens of observations are required for comparable accuracy.

In studying the directional properties of ancient rocks it is often impossible to measure directly the trough axis; restrictions provided by natural exposures are the major inhibiting factor. In the present study, therefore, directional observations have been made entirely on randomly selected beds. The resultant vector has already been shown to supply a satisfactory value for the preferred orientation of a given distribution, but it is interesting to speculate on the actual nature of the distribution produced by such an analysis of trough cross-stratified beds. It is significant that all three rose-diagrams illustrating cross-stratification directions in the Rogerley Channel are polymodal (Fig. 15.9). Furthermore, there is a certain consistent symmetry about the modes which suggests that they are not fortuitous, but are reproducible phenomena requiring an explanation. In particular, it is apparent that the rose-diagrams from Beldon and Nookton Burns are closely comparable. By and large, they have two major modes approximately bisected by the trend of the channel itself, and two subsideary modes at right angles to the channel trend. The rose-diagram from Bolt's Burn shows both of these features, but differs in the presence of a strong central mode close to the direction of the resultant

Figure 15.11

V-shaped point bar deposit in the Brazos River, Texas.

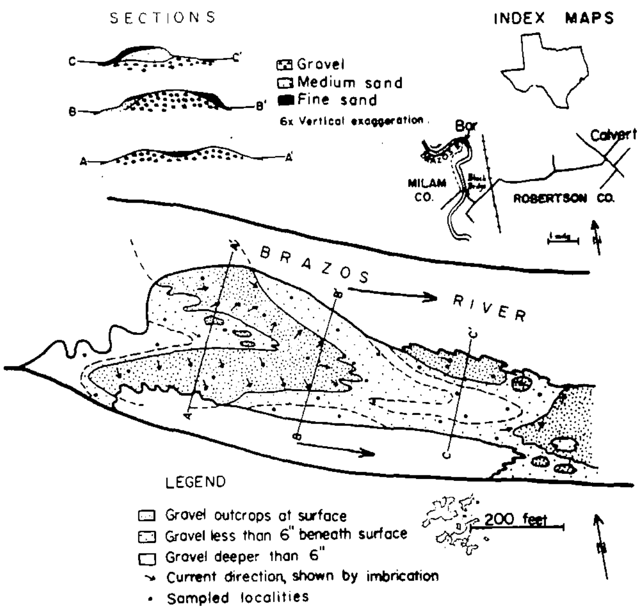
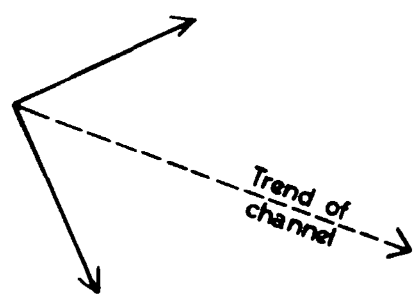


Fig. 1.—General features of the bar. Sandy pebble gravel forms the foundation of the bar, and outcrops as a V-shaped area pointing downstream.



Local current directions over the Brazos River bar

Figure 15.11

vector. The question to be resolved is whether these modes are significant in terms of the genesis of the cross-stratification, or whether they merely represent a peculiarity of the sampling technique.

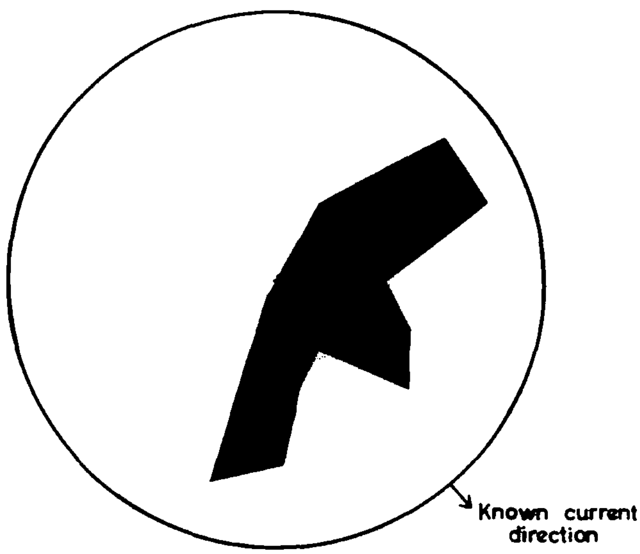
The field observation were not sufficiently comprehensive to include detailed descriptions of all cross-strata measured, so it is unfortunately impossible to tell whether a particular mode is related to a particular type of cross-stratification. However, it is demonstrable that this type of distribution can be explained in terms of a specific sedimentological mechanism, leaving aside for a moment considerations as to the feasibility of such an explanation. Folk and Ward (1957) have described a V-shaped bar occurring in the Brazos River, Texas. The bar is situated on a strong meander, and is in fact a point bar deposit; the open end of the "V" points upstream (Fig. 15.11). It is, in effect, a large solitary linguoid ripple (Allen, 1963a). An interesting feature of the bar is the orientation of local current flow over it in relation to the general flow of the stream: the local flow is at approximately 45^{o} to the trend of the channel (ibid., p. 4). Although this bar is composed of gravel showing imbrication, a sand bar of similar shape would contain cross-stratification directions indicating a similar flow pattern. A systematic plot of cross-stratification directions in this bar would result in the approximate distribution shown in Figure 15.11, which is closely comparable with the two major modes of the Nookton and Beldon rose-diagrams. Trains of irregularly distributed V-shaped bars or lingoid ripples are known to occur in nature (Allen, 1963a, Fig. 8, p. 201), and it is believed that cross-stratification within such deposits could produce an essentially bimodal distribution.

The minor modes, occurring at right angles to the observed trend of the Rogerley Channel (Fig. 15.9), may also be explained as primary sedimentological phenomena. Reference to the Brazos River Bar (Fig. 15.11) shows that subsidiary currents may be orientated approximately at right angles to the river bank. Similarly, on a point bar on the Santiam River, Oregon, local currents are directed away from the main channel towards the bank (Byrne, 1963, Fig. 1, p. 468). These currents are strong enough to produce imbrication in pebbles and should also be capable of producing cross-stratification in sands. It cannot be proved that this is in fact the origin of these minor modes, but careful study of the type of cross-stratification associated with each mode may produce significant information.

The presence of three major modes in the Beldon Burn data (Fig. 15.9) may be explicable in several ways. The additional central mode may be a peculiarity of sampling and more apparent than real, although this is extremely doubtful. The fact that the Bolt's Burn section involves the whole thickness of the Rogerley Channel, whereas the other two are more or less restricted to the same level within the Low Grit Sill, may involve the introduction of another factor into the Bolt's Burn data. This factor could be an increase in the relative importance of planar cross-stratification, or some other change in the sedimentary processes of the river. Alternatively, there is a possibility that all of the modes in the distribution have no genetic significance, and are merely functions of random sampling of trough cross-stratified beds. This is the next point which must be considered.

A rigorous study of random sampling in cross-stratified beds is clearly needed if the full significance of directional data in natural occurrences is to be appreciated. The only evidence in this connection known to the writer is a rather inelegant treatment of a theoretical linguoid ripple pattern investigated by Allen (1963a, p. 216). Allen measured assumed cross-stratal dip directions at randomly selected positions on his model of the surface features of the ripples and not on their internal features. The two are not necessarily the same, and it is the internal features which are usually preserved in ancient sandstones. However, it may be assumed that an analysis of both external and internal features of the ripples would give similar

Figure 15.12



Frequency distribution pattern produced by measurements on randomly selected orientations of ripple crests (after Allen, 1963a).

results. Allen (ibid., Fig. 16D, p. 216) plotted as a histogram the deviation of the ripple-crest orientation from the assumed mean current direction. It is interesting to observe that this random selection gives a strongly trimodal distribution, with an approximately central mode flanked almost symmetrically by two larger modes (Fig. 15.12): this distribution has astrong superficial resemblance to the cross-stratification distribution in Bolt's Burn. The fact that the two major modes in Allen's data deviate strongly from the actual current direction is not important because they are based on theoretical shapes of linguoid ripples, which may not be borne out by naturally occurring examples. An important question yet to be resolved, is whether this argument can be regarded as proof that the modes in the directional data from the Rogerley Channel are merely a product of random sampling of trough cross-stratified sandstones. With the present state of knowledge a positive answer cannot be given; many investigations need to be undertaken before the important question of the significance of modes in cross-stratified fluvial sandstones can be resolved.

C Low Slate Sill

Directional data are known from the Low Slate Sill at widely scattered localities, but little is known in the immediate vicinity of the Rogerley Channel; the slight change in sandstone type and the lack of exposure in upper Nookton and Beldon Burns are the main factors responsible. However, the resultant vectors of cross-stratification azimuths over the remainder of the area, with probability over 0.10, lie in the south-east quadrant, indicating derivation from the north-west. Moore (1960, p. 227) found that sheet sandstones in the Middle Limestone Group were derived from neighbouring channel sandstones by multiple crevassing. The Low Slate Sill is a sheet sandstone, but one with an erosional base: the available directional data do not suggest a similar origin, but rather one under the same fluvial regime as deposited the Low Grit Sill in the Rogerley Channel. It is believed, therefore, that the very coarse deposits of the highly erosive Rogerley Channel constitute the initiation of the fluvial phase in this area. Subsequent aggradation of the channel was accompanied by lateral migration of the river system, which involved an essentially erosive stage followed by typical fluvial sedimentation. Cross-stratal orientations from the Low Slate Sill in East Allendale indicate a dominant westerly component in that area (Fig. 15.10).

D High Grit Sill

The orientations of the resultant vectors from the High Grit Sill in Nookton Burn show an apparent two-fold origin of the sediments involved. It can be seen from

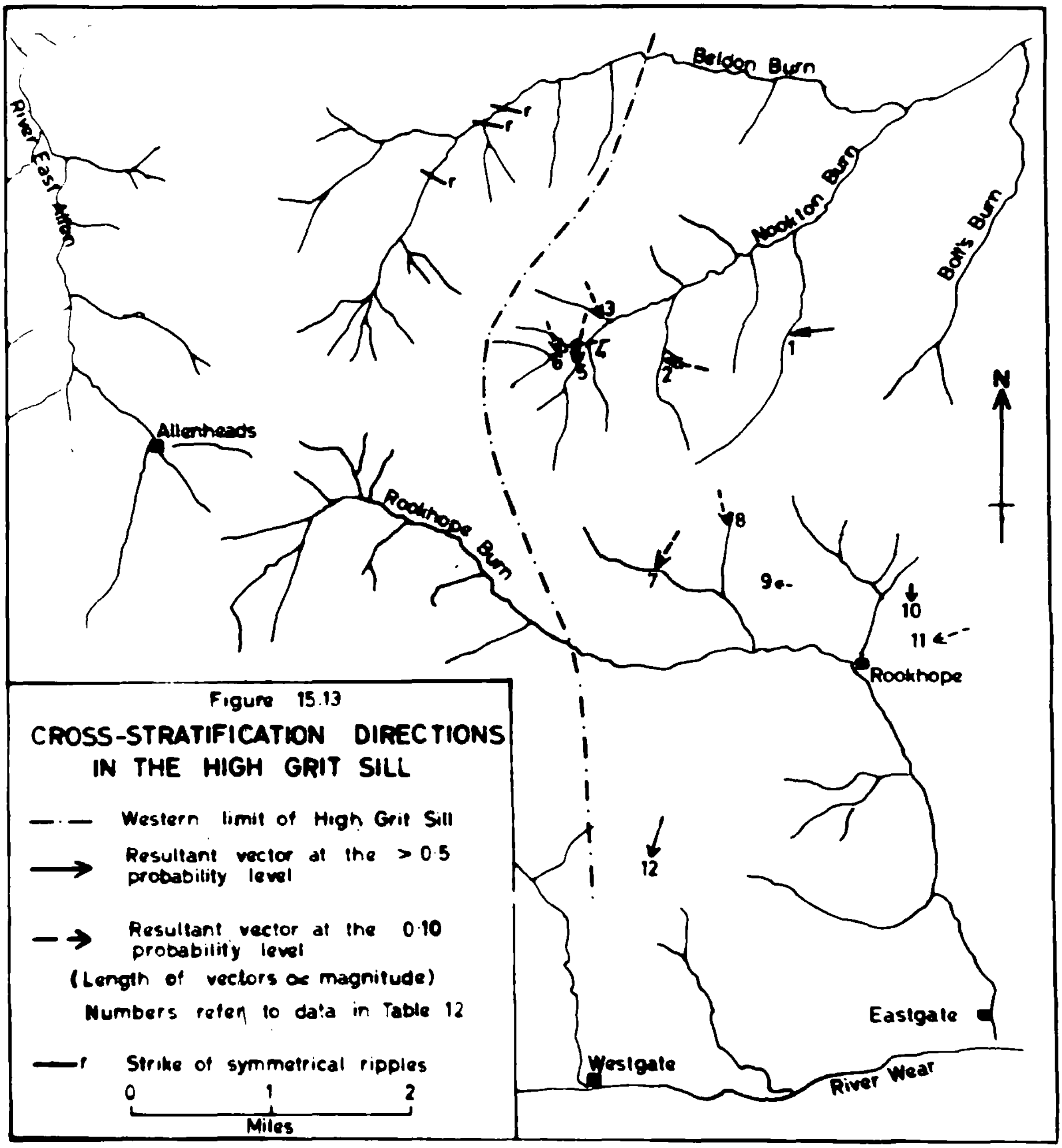


Figure 15.13

CROSS-STRATIFICATION DIRECTIONS IN THE HIGH GRIT SILL

TABLE 12

<u>Data on resultant vectors of cross-stratification azimuths in High Grit Sill</u>

Locality	n	r	Az.	L(%)	R_t
1	21	7.28	261	34.67	0.05
2	26	6.63	287	25.5	0.10
3	15	5.39	155	35.90	0.10
4	17	5.39	262	31.68	0.10
5	27	7.55	195	27.96	0.10
6	8	4.00	158	50.00	0.10
7	23	6.56	215	28.51	0.10
8	14	5.29	168	37.79	0.10
9	3	1.73	277	57.73	0.10
10	5	3.31	180	66.28	0.05
11	14	4.69	247	33.5	0.10
12	16	6.48	201	40.5	0.05

Figure 15.13 that sediment derivation is from the east except at Nookton head where the vectors indicate a northerly source. Indeed, at Nooktonhead both easterly and northerly vectors are present in a small area, but it is evident from field observations that the easterly vector refers primarily to the lower beds in the High Grit Sill, and the northerly vector to the upper beds. Similar changes in sedimentation patterns in a single sandstone member have been observed in the Grindstone Sill of the present area, and also in the Rough Rock of Yorkshire (Shackleton, 1962, p. 114). Directional data from the High Grit Sill in Rookhope Burn confirms the general conclusion that sedimentation is essentially from the north-east (Fig. 15.13). The orientation of the ripple marks in the Coalcleugh Transgression Beds (the lateral equivalents of the High Grit Sill) of Upper Beldon Burn, further indicates the possible influence of northerly depositional factors.

XI Concluding remarks

It is self-evident that not all cyclothems in the Upper Limestone Group reach the same stage of development. In the area studied, many contain no evidence of terrestrial sedimentation and are considered to be entirely marine in origin. This type, often culminating in the lagoonal shell bed phase is at least as abundant as the type usually regarded as "typical" of Yoredale cyclothems, which has a seatearth facies as its uppermost member. The occasional formation of a marshy seatearth facies from the topset tidal flat sandstones may be observed, and usually produces widespread ganisters (e.g. the Firestone ganister and the Hipple ganister). The seatearths found in the fluvial environment are usually less persistent (e.g. in the Slate Sills Formation) with the possible exception of the one which ends the fluvial episode (e.g. that below the Coalcleugh Coal).

Broadly, therefore, the Upper Limestone Group sediments may be regarded as being deposited in a marine environment in which the principal controlling factor was deltaic. The intimate association of marine and terrestrial conditions is evident in many parts of the succession. Occasionally the fluvial environment of the deltaic sequence becomes dominant in the area, and deposited sediments of an essentially terrestrial aspect. The mechanism producing the repetition of the cyclothem sequence is beyond the scope of this work. Either the type of sedimentological control envisaged by Moore (1958) or some kind of eustatic change suggested by Wells (1960) and Hallam (1963) could produce the sedimentary sequence observed in the Upper Limestone Group.

REFERENCES

ALBEE, A.L., 1962. Relationships between the mineral association, chemical composition and physical properties of the chlorite series. Am. Miner., 47, 851-870.

ALLEN, J.R.L., 1963a. Asymmetrical ripple marks and the origin of water-laid cosets of cross-strata. Liv. and Manch. Geol. Journ., 3, 187-230.

ALLEN, J.R.L., 1963b. The classification of cross-stratified units with notes on their origin. Sedimentology, 2, 93-114.

BANNISTER, F.A., 1939. in HALLIMOND, A.F., HARVEY, C.O., and BANNISTER, F.A., The relation of chamosite and daphnite to the chlorite group. Miner. Mag., 25, 441-465.

BANNISTER, F.A., 1952. see WHITEHEAD et al., 1952.

BATHURST, R.G.C., 1958. Diagenetic fabrics in some British Dinantian limestones, Liv. and Manch. Geol. Journ., 2, 11-36.

BEALES, F.W., 1958. Ancient sediments of Bahaman type. Am. Assoc. Pet. Geol.,Bull., 42, 1845-1879.

BISAT, W.S., 1924. The Carboniferous goniatites of the north of England and their zones. Proc. Yorks. Geol. Soc., 20, 40-120

BLACK, M., 1928. "Washouts" in the Estuarine Series of Yorkshire. Geological Magazine, 65, 301-307.

BLATT, H, and CHRISTIE, J.M. 1963. Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. Journ. Sed. Pet., 33, 559-579.

BORCHERT, H., 1960. Genesis of marine sedimentary iron ores. Bull. Instn. Min. Metall., 69, 261-279.

BOTT, M.H.P., 1961. A gravity survey off the coast of North-east England. Proc. Yorks. Geol. Soc., 33, 1-20.

BRINDLEY, G.W., 1949. Mineralogy and structure of chamosite. Nature, 164, 319-320.

BRINDLEY, G.W. (Ed.), 1951. X-ray identification and crystal structures of clay minerals. The Mineralogical Society, London, 336 pp.

BRINDLEY, G.W., 1951. The crystal structure of some chamosite minerals. Min. Mag., 29, 502-525.

BRINDLEY, G.W., 1961, see BROWN, G. (Ed.), 1961.

BRINDLEY, G.W., and GILLERY, F.H., 1954. A mixed layer kaolin-chlorite structure. Clays and Clay Minerals: Natl. Research Council Pub. 327, 349-353.

BRINDLEY, G.W. and ROBINSON, K., 1950. X-ray studies of some fireclay and shale deposits. Trans. Leeds. Geol. Assoc., 6, 75-94.

BRINDLEY, G.W. and YOUELL, R.F., 1953. Ferrous chamosite and ferric chamosite. Miner. Mag., 30, 57-70.

BROWN, G. (Ed.), 1961. The X-ray identification and crystal structure of clay minerals. Mineralogical Society, London, 514 pp.

BURST, J.F., 1959. Post-diagenetic clay mineral environmental relationships in the Gulf Coast Eocene. Proc. 6th. Nat. Conf. on Clays and Clay Minerals. 327-341.

BYRNE, J.V. 1963. Variations in fluvial gravel imbrication. Journ. Sed. Pet., 33, 467-469.

CARRUTHERS, R.G., 1925. Summ. Prog. Geol. Surv. Gt. Brit., for 1924, 85.

CARRUTHERS, R.G., 1938. An adventure in stratigraphy. Proc. Yorks. Geol. Soc., 23, 236-253.

CAYEUX, L., 1922. Les minerais de fer oolithiques de France Fasc. II. Minerais de fer secondaires. Paris, 1051 pp.

CHANDA, S.K., 1963. Cementation and diagenesis of the Lameta Beds, Lametaghat, M.P., India. Journ. Sed. Pet., 33, 728-738.

CRAIG, G.Y., 1954. The palaeoecology of the Top Hosie Shale (Lower Carboniferous) at a locality near Kilsyth. Quart. Journ. Geol. Soc., 110, 103-119.

CROOK, A.W., 1960. Classification of arenites. Amer. Journ. Sci., 258, 419-428.

CURRAY, J.R., 1956. The analysis of two-dimensional orientation data. Journ. Geol., 64, 117-130.

DEANS, T., 1934. The spherulitic ironstones of west Yorkshire. Geol. Mag., 71, 49-65.

DEANS, T., 1936. Some oolitic ironstones from the Coal Measures of Yorkshire. Trans. Leeds Geol. Soc., 5, 161-187.

DICK, A. 1856. The iron ores of Great Britain: Part I: the northern and north-midland counties of England. Mem. Geol. Surv., p. 95.

DODSON, M.H amd MOORBATH, S., 1961. Isotopic ages in the Weardale Granite. Nature, 190, 900.

DUFF, P. McL. D. and WALTON, E.K., 1962. Statistical basis for cyclothems: a quantitative study of the sedimentary succession in the East Pennine Coalfield, Sedimentology, 1, 235-255.

DUNBAR, C.O. and RODGERS, J., 1957. Principles of stratigraphy. Wiley, New York. 317 pp.

DUNHAM, K.C., 1948. Geology of the Northern Pennine Orefield, vol. I. Mem. Geol. Surv., London. 344 pp.

DUNHAM, K.C., 1950. Lower Carboniferous sedimentation in the Northern Pennines (England). Rept. XVIII Int. Geol. Congress, Pt. IV, 46-63.

DUNHAM, K.C., 1952, see WHITEHEAD, T.H., et al., 1952.

DUNHAM, K.C., 1958. Non-ferrous mining potentialities of the Northern Pennines. Proc. Symp. on Future of Non-ferrous Mining in Gt. Brit., Instit. Min. Metall., 115-145.

DUNHAM, K.C., 1960. Syngenetic and diagenetic mineralisation in Yorkshire. Proc. Yorks. Geol. Soc., 32, 229-284.

DUNHAM, K.C., 1961. Black shale, oil and sulphide ore. The Advancement of Science, 18, 1-15.

DUNHAM, K.C., BOTT, M.H.P., JOHNSON, G.A.L., and HODGE, B.L., 1961. Granite beneath the Northern Pennines. Nature, 190, 899-900.

DUNHAM, K.C. and JOHNSON, G.A.L., 1962. Subsurface data on the Namurian strata of Allenheads, South Northumberland. Proc. Yorks. Geol. Soc., 33, 235-254.

DZULINSKY, S. and SMITH, A.J., 1963. Convolute lamination, its origin, preservation and directional significance. Journ. Sed. Pet., 33, 616-626.

EDWARDS, W., 1951. The concealed coalfield of Yorkshire and Nottinghamshire. Mem. Geol. Surv., London (3rd. Ed.), 285 pp.

ELIAS, M.K., 1937. Depth of deposition of the Big Blue (Late

Paleozoic) sediments in Kansas. Bull. Geol. Soc. Amer., 48, 403-432.

ENGELHARDT, W. von, 1942. Die Strukturen von Thuringit, Bavalit, und Chamosit und ihre Stellung in der Chlorit-gruppe. Zeit. f. Krist., 104, 142-159.

EYLES, V.A., SIMPSON, J.B., MACGREGOR, A.G., 1949. Geology of Central Ayrshire. Mem. Geol. Surv., Edinburgh, 160 pp.

FALCON, N.L. and KENT, P.E., 1960. Geological results of petroleum exploration in Britain, 1945-57. Mem. Geol. Soc. London, No. 2, 56 pp.

FISK, H.N. and McFARLAN, E., 1955. Late Quaternary deltaic deposits of the Mississippi River. Geol. Soc. Amer., Spec. Paper 62, 279-302.

FOLK, R.L., 1954. The distinction between grain size and mineral composition in sedimentary rock nomenclature. Journ. Geology, 62, 344-359.

FOLK, R.L., 1959. Practical petrographic classification of limestones. Amer. Assoc. Pet. Geol. Bull., 43, 1-38.

FOLK, R.L., 1961. Petrology of sedimentary rocks. Hemphill, Austin. 154 pp.

FOLK, R.L. and WARD, W.C., 1957. Brazos River Bar : a study in the significance of grain-size parameters. Journ. Sed. Pet., 27, 3-26.

FORSTER, W., 1821. A treatise on a section of strata from Newcastle-upon-Tyne to the mountain of Cross Fell; with remarks on the mineral veins in general. Alston (2nd. Edition) 410 pp. (1st Ed. 1809).

FRANK-KAMENETSKY, V.A., 1960. A crystallochemical classification of simple and interstratified clay minerals. Clay Min. Bull. 4, 161-172.

FRAZIER, D.E. and OSANIK, A., 1961. Point-bar deposits, Old River Locksite, Louisiana. Trans. Gulf Coast Assoc. of Geol. Socs., 11, 121-137.

GEORGE, T.N., 1958. Lower Carboniferous palaeogeography of the British Isles. Proc. Yorks. Geol. Soc., 31, 226-312.

GILBERT, C.M., 1954: see WILLIAMS, H., TURNER, F.J., and GILBERT, C.M., Petrography. Freeman, San Francisco, 406 pp.

GOODCHILD, J.G., 1890. An outline of the geological history of the Eden Valley or Edenside. Proc. Geol. Assoc., 11, p. 271.

GREEN, R., 1954. The Upper Limestone Group, "Millstone Grit", and Lower Coal Measures of the Lower Tyne Valley. Ph.D. Thesis, Newcastle-upon-Tyne, 343 pp.

HALLAM, A., 1963. Eustatic control of major cyclic changes in Jurassic sedimentation. Geol. Mag., 100, 444-450.

HARBORD, N.H., 1962. Mineralogy of Yoredale Series rocks in Upper Teesdale with special reference to clay minerals. Ph.D. Thesis, Durham.

HALLIMOND, A.F., 1925. Iron ores : bedded ores of England and Wales. Spec. Rep. Min. Res., Mem. Geol. Surv., 29.

HALLIMOND, A.F., HARVEY, C.O., and BANNISTER, F.A., 1939. On the relation of chamosite and daphnite to the chlorite group. Min. Mag., 25, 441-465.

HAMBLIN, W.K., 1961. Micro-cross-lamination in upper Keweenawan sediments of northern Michigan. Journ. Sed. Pet., 31, 390-400.

HARMS, J.C., MACKENZIE, D.B., and McCUBBIN, D.G., 1963. Stratification in modern sands of the Red River, Louisiana. Journ Geol. 71, 566-579.

HEY, M.H., 1954. A new review of the chlorites. Min. Mag. 30, 277-292.

HEY R.W., 1956. Cherts and limestones from the Crow Series near Richmond, Yorkshire. Proc. Yorks. Geol. Soc., 30, 289-299.

HUDSON, R.G.S., 1924. On the rhythmic succession of the Yoredale Series in Wensleydale. Proc. Yorks. Geol. Soc., 20, 125-135.

HUDSON, R.G.S., 1941. Mirk Fell Beds of Tan Hill, Yorkshire. Proc. Yorks. Geol. Soc., 24, p. 259.

INMAN, D.L., 1949. Sorting of sediments in the light of fluid mechanics. Journ. Sed. Pet., 19, 51-70.

JOHNSON, G.A.L., 1960. Palaeogeography of the Northern Pennines and part of north-eastern England during the deposition of Carboniferous cyclothemic deposits. Rept. Int. Geol. Congress, XXI Session, Pt. XII, 118-127.

JOHNSON, G.A.L., 1961. Skiddaw Slates proved in the Teesdale Inlier. Nature, 190, 996-997.

JOHNSON, G.A.L. and DUNHAM, K.C., 1963. The geology of Moor House. Mon. Nature Conservancy, No. 2, London, 162 pp.

JOHNSON, G.A.L., HODGE, B.L., and FAIRBURN, R.A., 1962. The base of the Namurian and of the Millstone Grit in north-eastern England. Proc. Yorks. Geol. Soc., 33, 341-362.

JONES, H.Ll., 1956. Stratigraphy and structure of the area between Middleton-in-Teesdale and Woodland. Ph.D. Thesis. Durham.

JOPLING, A.V., 1963. Hydraulic studies on the origin of bedding. Sedimentology, 2, 115-121.

KRYNINE, P.D., 1940. Petrology and genesis of the Third Bradford Sand. The Penn. State College Mineral Industries Expt. Sta. Bull., 29, 134 pp.

LANE, D.W., 1963. Cross-stratification in the San Bernard River, Texas. Journ. Sed. Pet., 33, 350-353.

LAZARENKO, E.K., 1959. Nomenclature and classification of the clay minerals, Clay Min. Bull., 4, 67-68.

LEBOUR, G.A., 1886. Outlines of the geology of Northumberland and Durham. Lambert, Newcastle-upon-Tyne (2nd. Ed.), 145 pp.

MAGRAW, D., CLARKE, A.M., and SMITH, D.B., 1963. The stratigraphy and structure of part of the south-east Durham Coalfield. Proc. Yorks. Geol. Soc., 34, 153-208.

MILLER, H., 1887. The geology of the country around Otterburn and Elsdon. Mem. Geol. Surv., London, 147 pp.

MOORE, D., 1958. The Yoredale Series of Upper Wensleydale and adjacent parts of north-west Yorkshire. Proc. Yorks. Geol. Soc., 31, 91-148.

MOORE, D., 1960. Sedimentation units in sandstones of the Yoredale Series (Lower Carboniferous) of Yorkshire, England. Journ. Sed. Pet., 30, 218-227.

MOORE, D.G., and SCRUTON, P.C., 1957. Minor internal structures of some recent unconsolidated sediments. Bull. Amer. Assoc. Pet. Geol., 41, 2723-2751.

MOSELEY, F., 1954. The Namurian of the Lancaster Fells. Quart. Journ. Geol. Soc., 109, 423-454.

MURRAY, M.H., and HARRISON, J.L., 1956. Clay mineral composition of Recent sediments from Sigsbee Deep. Journ. Sed. Pet., 26, 363-368.

McBRIDE, E.F., 1962. The term greywacke (Discussion) Journ. Sed. Pet., 32, 614-615.

McBRIDE, E.F., 1963. A classification of common sandstones. Journ. Sed. Pet., 33, 664-669.

MACKENZIE, R.C., 1959. The classification and nomenclature of clay minerals. Clay Min. Bull., 4, 52-65.

McKEE, E.D., 1954. Report on studies of stratification in modern sediments and in laboratory experiments. Office of Naval Research, Project No. 164 (00), 61 pp.

NELSON, B.W., and ROY, R., 1958. Synthesis of chlorites and their structural and chemical constitution. Am. Miner., 43, 707-725.

ORCEL, J., HENIN, S., and CAILLERE, S., 1949. Layer silicates of oolitic iron ores. Compte Rendue Acad. Sci., 229, 134-135.

OWENS, B., and BURGESS, I.C., in press. The stratigraphy and palynology of the Upper Carboniferous outlier of Stainmore, Westmoreland. Bull. Geol. Surv., Gt. Brit.

PACKHAM, G.H., 1954. Sedimentary structures as an important feature in the classification of sandstones. Am. Journ. Sci., 252, 466-476.

PETTIJOHN, F.J., 1957. Sedimentary rocks. Harper, New

York, (2nd. Edition), 689 pp.

PHILLIPS, J., 1836. Illustrations of the geology of Yorkshire, Part II, the Mountain Limestone. London, 253 pp.

POWERS, M.C., 1959. Adjustment of clays to chemical change and the concept of the equivalence level. Proc. 6th. Nat. Conf. on Clays and Clay Minerals, 309-326.

PULFREY, W., 1933. The iron ores and pisolites of North Wales. Quart. Journ. Geol. Soc., 89, 401-430.

RASTALL, R.H., and HEMINGWAY, J.E., 1939. Black oolites in the Dogger of north-east Yorkshire. Geol. Mag., 76, 225-233.

RASTALL, R.H., and HEMINGWAY, J.E., 1940. The Yorkshire Dogger: I The Coastal Region. Geol. Mag., 77, 177-197, 257-275.

RASTALL, R.H., and HEMINGWAY, J.E., 1941. The Yorkshire Dogger; II Lower Eskdale. Geol. Mag., 78, 351-370.

RASTALL, R.H., and HEMINGWAY, J.E., 1943. The Yorkshire Dogger: III Upper Eskdale. Geol. Mag., 80, 209-230.

RASTALL, R.H., and HEMINGWAY, J.E., 1949. The Yorkshire Dogger: IV Rosedale and Farndale. Geol. Mag., 86, 201-225, 265-277.

RAYNER, D.H., 1953. The Lower Carboniferous rocks in the north of England: a review. Proc. Yorks. Geol. Soc., 28, 231-304.

READING, H.G., 1957. The stratigraphy and structure of the Cotherstone Syncline. Quart. Journ. Geol. Soc., 118, 27-52.

ROBSON, D.A., 1956. A sedimentary study of the Fell Sandstones of the Coquet Valley, Northumberland. Quart. Journ. Geol. Soc., 112, 241-258.

ROBERTSON, T., and HICKLING, H.G.A., 1948. Guide to Excursion C9, North-east Coast. Int. Geol. Congress, XVIII Session, 26 pp.

ROGERS, J.J.W., KRUEGER, W.C., and KROG, M., 1963. Sizes of naturally abraded materials. Journ. Sed. Pet., 33, 628-632.

ROWELL, A.J., and SCANLON, J.E., 1957a. The Namurian of the north-west quarter of the Askrigg Block. Proc. Yorks.,Geol, Soc., 31, 1-38.

ROWELL, A.J., and SCANLON, J.E., 1957b. The relation between the Yoredale Series and the Millstone Grit on the Askrigg Block. Proc. Yorks. Geol. Soc., 31, 79-89.

RUSNAK, G.A., 1960. Sediments of Laguna Madre. Recent Sediments, North-western Gulf of Mexico, Am. Assoc. Pet. Geol., 153-196.

SCHUMM, S.A., 1960. The effect of sediment type on the shape and stratification of some modern fluvial deposits. Am. Journ. Sci., 258, 177-184.

SCHUMM, S.A., 1963. Sinuosity of alluvial rivers on the Great Plains. Geol. Soc. Am. Bull., 74, 1089-1100.

SCRUTON, P.C., 1960. Delta building and the deltaic sequence. Recent Sediments, north-western Gulf of Mexico, Am. Assoc. Pet. Geol., 367 pp., 82-102.

SHACKLETON, J.S., 1962. Cross-strata of the Rough Rock (Millstone Grit Series) in the Pennines. Liv. and Manch. Geol. Journ., 3, 109-118.

SHEPARD, F.C., 1960. Mississippi delta : marginal environments, sediments and growth. Recent Sediments, northwestern Gulf of Mexico, Am. Assoc. Pet. Geol., 56-81.

SHEPARD, F.P., and MOORE, D.G., 1960. Bays of Central Texas Coast. Recent Sediments, northwestern Gulf of Mexico, Am. Assoc. Pet. Geol., 117-152.

SHIROZU, H., 1958. X-ray patterns and cell dimensions of chlorites. Miner. J., 2, 209-223.

SHROCK, R.R., 1948. Sequence in layered rocks. McGraw Hill, New York.

SIEVER, R., 1962. Silica solubility, 0-200°C and the diagenesis of siliceous sediments. Journ Geol., 70, p. 141.

SOPWITH, T., 1833. An account of the mining districts of Alston Moor, Weardale, and Teesdale. Alnwick, 183 pp.

STEAD, J.E., 1910. Cleveland ironstone and iron. Proc. Cleveland Instn. Engrs., (Session 1909-10), 75-117.

STRAATEN, L.M.J.U. van, 1959. Minor structures of some recent littoral and neritic sediments. Geol. en Mijnb., 21, 197-216.

STRAATEN, L.M.J.U. van, 1960. Some recent advances in the study of deltaic sedimentation. Liv. and Manch. Geol. Journ., 2, 411-438.

TANNER, W.F., 1955. Paleogeographic reconstruction from cross-bedding studies. Am. Assoc. Pet. Geol. Bull., 39, 2471-2483.

TAYLOR, J.H., 1949. The Mesozoic Ironstones of England : Petrology of the Northampton Sand Ironstone Formation. Mem. Geol. Surv., 111pp.

TAYLOR, J.H., 1951. Sedimentation problems of the Northampton Sand Ironstone. Proc. Yorks. Geol. Soc., 28, 74-85.

TROTTER, F.M., 1951. Sedimentation facies in the Namurian of north-western England and adjoining areas. Liv. and Manch. Geol. Journ., 1, 77-102.

TROTTER, F.M., and HOLLINGWORTH, S.E., 1927. On the Upper Limestone Group and "Millstone Grit" on north-east Cumberland. Summ. Prog., Geol. Surv. for 1926, 98.

TROTTER, F.M., and HOLLINGWORTH, S.E., 1932. The geology of the Brampton district. Mem. Geol, Surv, London, 183 pp.

TRUEMAN, SIR A., (Editor), 1953. The coalfields of Great Britain. Arnold, London, 381 pp.

VIVALDI, J.L.M., and GALLEGO, M.R., 1961. Some problems in the identification of clay minerals in mixtures by X-ray diffraction: 1. Chlorite-kaolinite mixtures. Clay Min. Bull., 4, 288-292.

WALLACE, W., 1861. The laws which regulate the deposition of lead ore in veins. Stanford, London, 248 pp.

WANLESS, H.R., 1958. Pennsylvanian faunas of the Beardstown, Glasford, Havana, and Vermont Quadrangles, Illinois. Rept. of Investigations 205, Illinois State Geol. Surv.

WANLESS, H.R., and WELLER, J.M., 1932. Correlation and extent of Pennsylvanian cyclothems. Bull. Geol. Soc. Amer., 43, p. 1003.

WARSHAW, C.M., and ROY, R., 1961. Classification and a scheme for the identification of the layer silicates. Bull. Geol. Soc. Amer., 72, 1455-1492.

WELLER, J.M., 1930. Cyclical sedimentation of the Pennsylvanian Period and its significance. Journ. Geol., 38, p. 97.

WELLS, A.J., 1960. Cyclic sedimentation : a review. Geol. Mag., 97, 389-402.

WELLS, A.J., 1955. The development of chert between the Main and Crow Limestones in north Yorkshire. Proc., Yorks. Geol. Soc., 30, 177-196.

WENTWORTH, C.K., 1922. A scale of grade and size terms for clastic sediments. Journ. Geol., 30, 377-392.

WHITEHEAD, T.H., ANDERSON, W., WILSON, V., and WRAY, D.A., 1952. The Liassic Ironstones : the Mesozoic Ironstones of England; with contributions on the petrography. Mem. Geol. Surv., London, 211 pp.

WHITTAKER, A., 1963. The geology of the Namurian and Lower Coal Measures of the Tyne Valley and adjacent areas. Ph.D. Thesis, Newcastle-upon-Tyne.

WHITTARD, W.F., and SCOTT SIMPSON (Editors), 1960. Lexique stratigraphique international, vol. 1, Europe, Fasc., 3a. Paris, 365 pp.

WILLIAMSON, W.O., 1946. Some grits and associated rocks in the Etruria Marls of North Staffordshire. Geol. Mag., 83, 20-32.

WILSON, AA. and THOMPSON, A.T., 1959. Marine bands of Arnsbergian age (Namurian) in the south-eastern portion of the Askrigg Block, Yorkshire. Proc. Yorks. Geol. Soc., 32, 45-64.

WILSON, A.A., 1960a. The Carboniferous rocks of Coverdale and adjacent valleys in the Yorkshire Pennines. Proc. Yorks. Geol. Soc., 32, 285-308.

WILSON, A.A., 1960b. The Millstone Grit Series of Colsterdale and neighbourhood, Yorkshire. Proc. Yorks. Geol. Soc., 32, 429-446.

WINCH, N.J., 1817. Observations on the geology of Northumberland and Durham. Trans. Geol. Soc., London, 4, p. 60.

WRIGHT, M.D., 1959. The formation of cross-bedding by a meandering or braided stream. Journ. Sed. Pet., 29, 610-615.

YODER, H.S., and EUGSTER, H.P., 1955. Synthetic and natural muscovites. Geochim. Cosmochim. Acta, 8, 225-280.

A P P E N D I C E S

APPENDIX I

LIMESTONE PETROGRAPHY

I Little Limestone

In hand specimen the Little Limestone is dark to medium grey in colour and usually contains abundant crinoid columnals; very little fine grained material can be observed. Other macrofossils are not common and tend to occur in thin bands. Stratification is ill-defined and irregular, but there is a thin sand-rich zone at the base which has a sharp upper boundary. Saucer-shaped dolomitic structures of problematic origin are apparently peculiar to the Little Limestone (p. 275).

Limestone type:- Generally crinoid biomicrite with subordinate amounts of crinoid biosparite.

A Framework constituents

Allochems The allochem constituents in the Little Limestone are predominantly of organic origin; crinoid columnals are by far the most abundant of the allochems. Crinoid fragments are always present, but the relative proportion of foraminifera, shell fragments, and bryozoa is extremely variable. Many of the crinoidal fragments are marginally replaced by sparry calcite in the matrix, so that their outlines become irregular; this feature is common in all the limestones

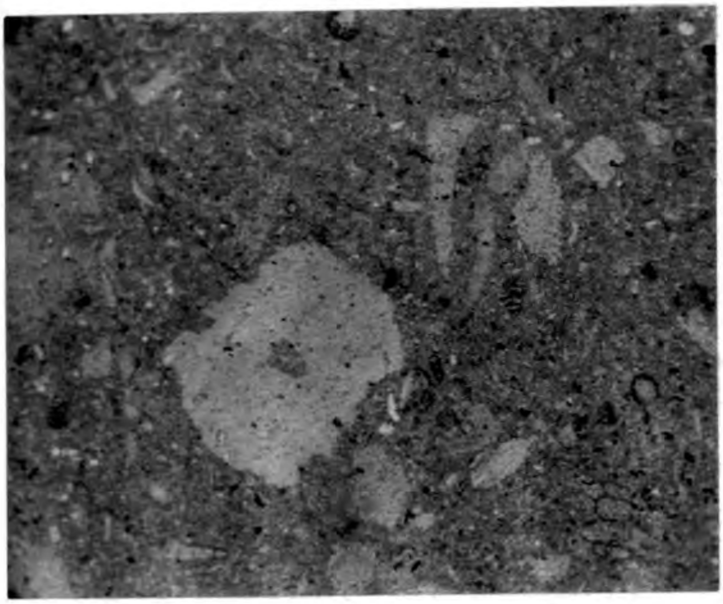


PLATE 81. Microspar corroding crinoid columnal, Upper Felltop Limestone. (x 30)

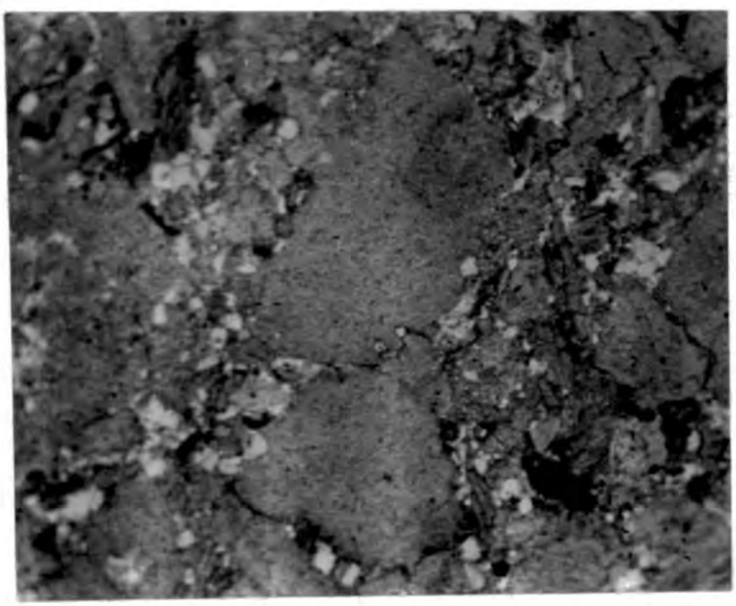


PLATE 82. Pressure solution between contiguous crinoid fragments, Upper Felltop Limestone. (x 30)

studied in the Upper Limestone Group (Plate 81). The foraminifera may occasionally be partially replaced by pyrite. Intraclasts occur but rarely in the Little Limestone and generally comprise rounded fragments of micrite, sometimes containing supposedly faecal pellets. Some intraclasts are in fact rounded crinoid columnals whose multiple origin is betrayed by the presence of a black organic pigment.

Quartz. The basal sandstone contains moderately well-sorted sand grains of all three crystalline types (p. 114). There is generally no carbonate matrix now, so pressure solution and authigenic overgrowths are common. Percentage of quartz falls off rapidly above the true sandstone layer, and generally comprises less than 5% of the limestone. The quartz grains are usually very fine grained and angular.

B Matrix

An interlocking mosaic of medium sized calcite crystals constitutes the matrix of most of the specimens studied from the Little Limestone. This is not a sparite of Folk's classification (1959), because the crystalline calcite is believed to be of organic origin: the majority of the calcite is dusty or clouded in appearance, a feature typical of crinoid columnals. The irregular nature of the contact between adjoining grains suggests pressure solution

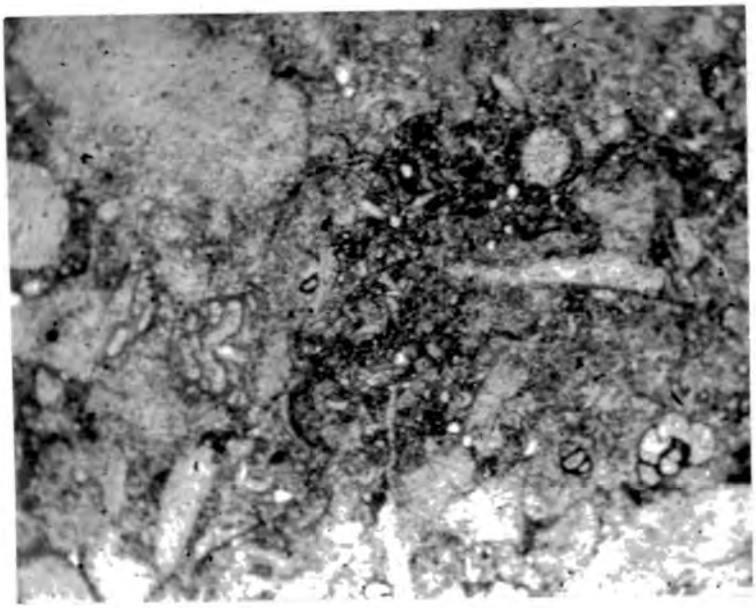


PLATE 83. Patchy micrite matrix, Little Limestone.
(x 30)

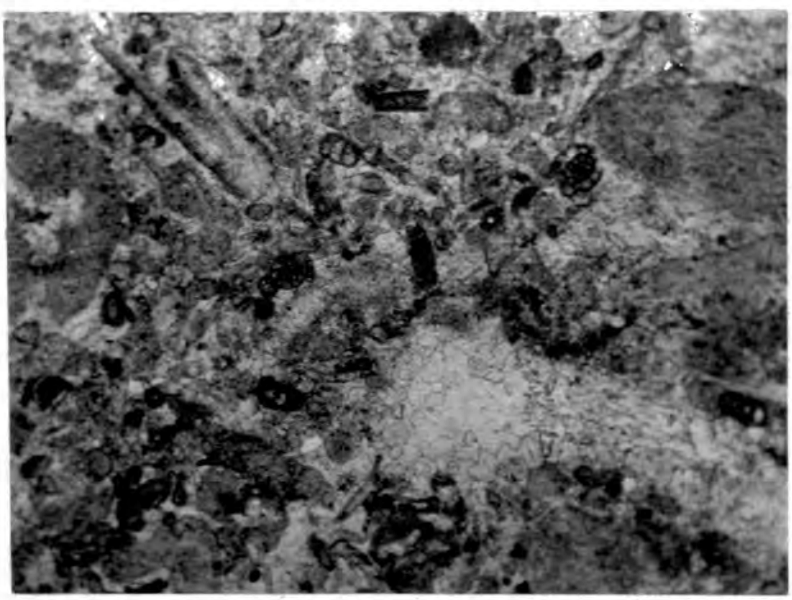


PLATE 84. Patch of sparry calcite in Little Lime-
stone. (x 30)

(Plate 82) rather than growth in a drusy cavity or recrystallisation. The majority of the crystalline calcite in the matrix, therefore, is believed to be much reworked crinoidal material.

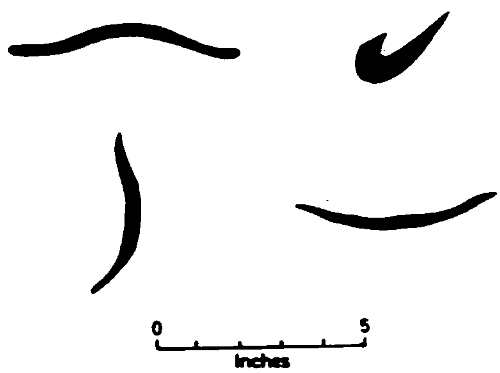
Micrite occurs in irregular patches, but never constitutes more than 15% of the limestone (Plate 83). Authigenic calcite may grow into the micrite with well-developed crystal faces. True sparite, comprising large crystals of clear calcite, does occur in one sample of the Little Limestone (Plate 84). It may grow in optical continuity with neighbouring crinoid columnals. The sparite exhibits syntaxial growth and increases in size towards certain centres, which Bathurst (1958, p. 15) interprets as being due to growth in a drusy cavity.

C. Problematic structure

The general appearance of this structure is illustrated in Figure A.1 and Plate 85. In thin section, the essential petrographic feature is the interlocking coarse crystals of ferruginous dolomite (Plate 86): the identification is based on an X-ray analysis kindly done for the writer by Mrs. M. Kaye. There is a sharp contact with the enclosing rock, yet there are apophyses of the host rock extending into the structure (Plate 86). The country rock is itself only partly calcitic, and contains many perfect rhombs of dolomite which have nucleated on crinoid columnals (Plate 87).

Figure A.1

VERTICAL CROSS-SECTIONS THROUGH THE DOLOMITE STRUCTURE IN THE LITTLE LIMESTONE



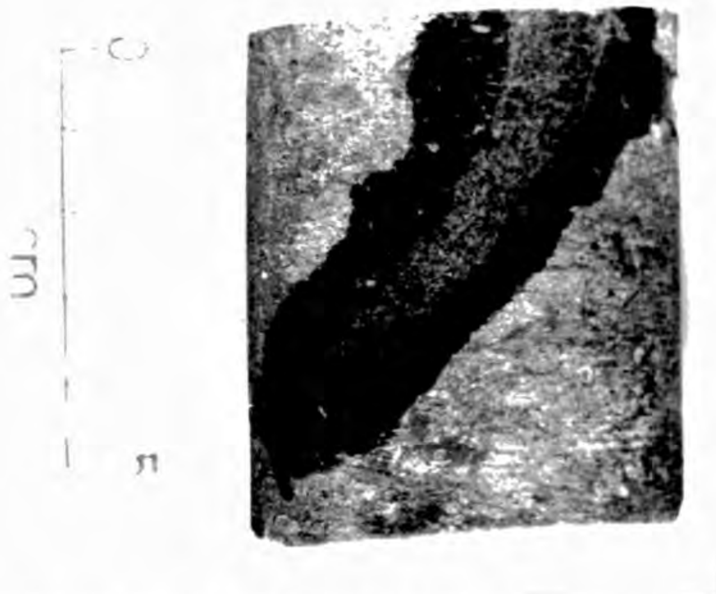


PLATE 85. Dolomite structure in Little Limestone. Note sharp margin, but with apophyses of dolomite (light coloured) in country rock. (Dark streak is simply wetted limestone).

PLATE 86. Photomicrograph of contact between dolomite structure and host limestone. (x 30)

Diagenesis has clearly played a major part in producing this structure, but the exact time of diagenesis in relation to the formation of the rock as a whole, is uncertain. The sharp boundary to the structure and its different petrography suggest a different origin from the bulk of the rock, and, as such may be regarded as a primary sedimentological feature. It is uncertain whether it represents a reworked dolomite deposit which subsequently dolomitised the limestone in its immediate vicinity, or some other type of carbonate deposit which was later dolomitised itself, perhaps by solutions from the many veins in the area. There is no evidence of intensive veining in the Little Limestone, however, so the latter explanation is not favoured.

PLATE 87. "Limestone" adjacent to dolomite structure, showing dolomite crystals nucleated on crinoid columnals. (x 30)

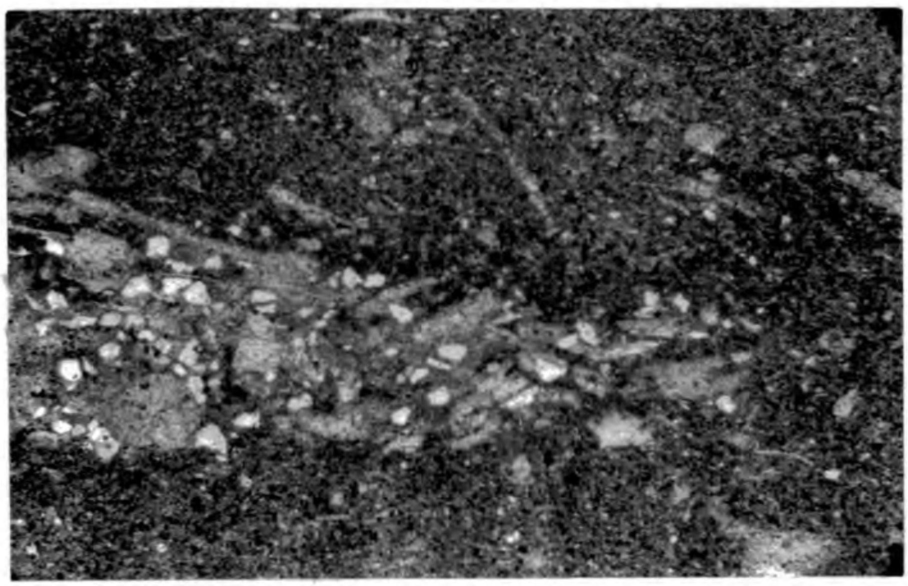


PLATE 88. Crag Limestone, showing variability in petrography. (x 30)

II Crag Limestone

In the area studied this is a dark grey to black sandy limestone weathering limonite brown. Finely divided mica may be observable in hand specimen and crinoid and shell fragments are common. Whole fossils are quite abundant and occur scattered throughout the rock.

Limestone type:- Sandy biomicrite

A. Framework constituents

Allochems. Organic detritus constitutes the dominant part of the allochem content of the Crag Limestone. Crinoid columnals and medium sized calcite crystals of organic origin are abundant. The proportion of foraminifera is variable and ranges from almost absent to prolific. Fragments of brachiopods and lamellibranchs are occasionally common. The petrography of the limestone is extremely variable, even over a few millimetres, and quite different limestone types occur in close association.

Quartz. The Crag Limestone always contains a certain amount of sand which may amount to as much as 35%. Thin sand-rich laminae are frequently observed which may die out completely within the compass of a thin section (Plate 88). The quartz usually occurs in association with allochem constituents. Quartz grains may also occur sporadically, throughout the rock and are moderately well-sorted and usually angular,

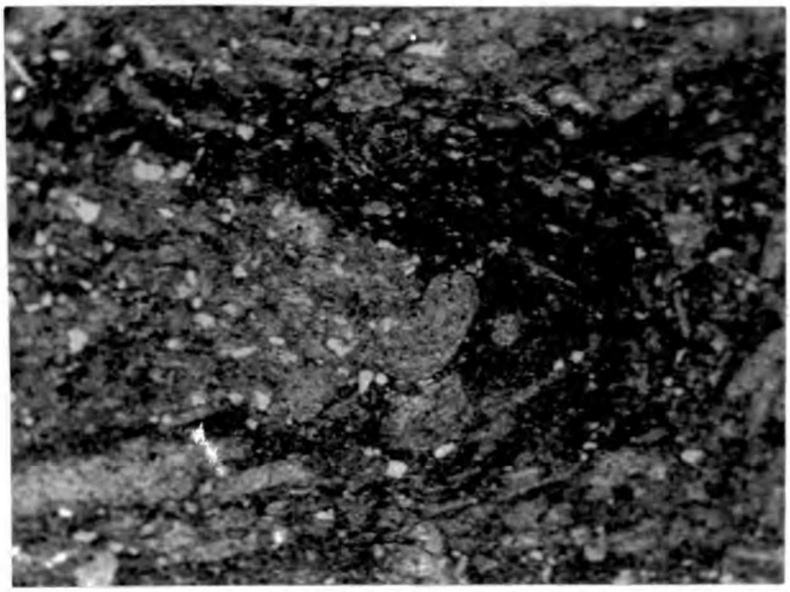


PLATE 89. Vertical cross-section of "caudagalli".
(x 30)

PLATE 90. Micritic matrix in Crag Limestone.
(x 30)

though some are well-rounded. Quartz plus sparry calcite occasionally occur in elongate and curved bands due to the action of burrowing organisms (Plate 89).

B. Matrix

The characteristic matrix is dark brown micrite which is apparently highly carbonaceous (Plate 90). Commonly it may be recrystallised to microsparite (Folk. 1959) which is pale yellow in colour. The micrite may occur as discrete bands in which there are virtually no allochem constituents, or it may occur in the interstices between detrital calcite, crinoid columnals and quartz.

PLATE 91. Osagia encrusting shell fragment, Lower Felltop Limestone. Sipton Cleugh. (x 30)

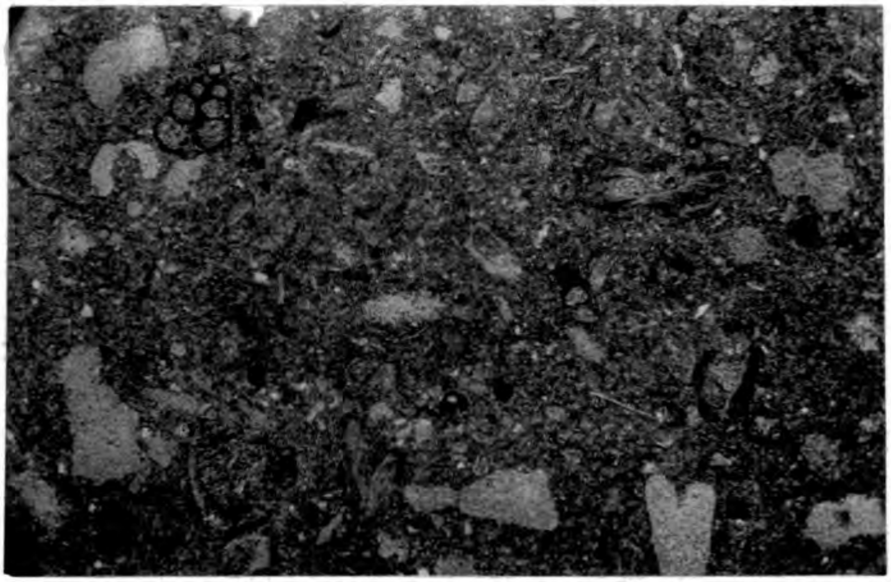


PLATE 92. Bryozoal limestone, Upper Felltop Limestone. (x 30)

III Lower Felltop Limestone

Macroscopically, the Lower Felltop Limestone may be either light grey or dark grey to almost black in colour, but always contains abundant crinoidal fragments. Algal coatings, ascribed to the form-genus Osagia, a symbiotic growth of algae and foraminifera, occur on shell fragments within the limestone and are typical of this horizon. Stratification is commonly "wavy" (Plate 18).

Limestone type :- Biomicrite

A. Framework constituents

Allochems. Crinoid columnals, foraminifera, and shell fragments are abundant constituents of the Lower Felltop Limestone. The crinoidal detritus is now being marginally replaced by microspar calcite. Most of the shells are disarticulated but a few whole ones occur in which clear, sparry calcite has crystallised. Osagia is seen in thin section as a dark, micritic layer of varying thickness coating shell fragments, and, more rarely, crinoid columnals (Plate 91). It is not known whether Osagia thus shows a preference for living on shell fragments or whether this merely illustrates the multiple origin of the limestone components. The layers around crinoid fragments are invariably thinner than those around shell fragments and are often incomplete. Girvanella tubules may be seen in some sections of Osagia to average 15 microns in diameter.

B. Matrix

Microspar forms the dominant matrix component in the Lower Felltop Limestone, but varying amounts of sparry calcite also occur. The microspar averages 10 microns in diameter, and the micrite from which it may have crystallised (Folk, 1959) may still be observed as small, irregular patches. Clear, sparry calcite also occurs up to about 80 microns in irregular segregations which are believed to form by grain growth (Bathurst, 1958, p. 24) rather than by crystallisation in drusy cavity. Thus, there appears to be a gradual process of "recrystallisation" from the original micrite matrix to a sparite matrix; only the intermediate microsparite stage has been reached here.

IV Upper Felltop Limestone

A medium to dark grey limestone which is brown weathering at outcrop. Crinoid columnals are usually much in evidence in the hand specimen, and quartz may also be obvious. Quartz content varies from almost nil to about 50%, but, because of incomplete exposure, it is usually impossible to observe the position of a particular sample in the limestone as a whole. In common with most other limestones in the Upper Limestone Group the proportion of sand is probably greatest at the base and decreases upwards.

Limestone type:- Bryozoal biomicrite

A. Framework constituents

Allochems. The proportions of the allochem constituents are variable, but crinoid columnals, foraminifera, and bryozoa are the most common (Plate 92). Broken shell material occurs sporadically, but only locally becomes abundant. Crinoidal fragments commonly exhibit marginal attack by the microspar matrix (Plate 81), but in highly crinoidal examples pressure solution and sutured contacts between contiguous crystals are common (Plate 82). Collophane is occasionally observed to replace partially some crinoid columals. Micritic intraclasts and nebulous detrital calcite also occur.

Quartz. Much of the Upper Felltop Limestone contains less than 5% of quartz, but amounts up to 50% have been recorded.

In the relatively quartz-free examples the sand is very fine grained and occurs only in small pockets. It is commonly very angular as a result of carbonate corrosion, but some is well-rounded.

B. Matrix

Recrystallised micrite (microspar) or micrite form the matrix of the Upper Felltop Limestone. Only one sample in fact, has a true micrite matrix, with average grain size below 4 microns; this contains very little sparry calcite. Most samples have a microspar matrix in which the grain size is fairly constant and averages 8 microns. Occasional patches of sparry calcite occur in the microspar but this is rather cloudy and not of the drusy mosaic type.

V Shell Beds

Many so-called shell beds in the Upper Limestone Group are in fact ironstones because of their high siderite and chamosite content: these are described elsewhere (Chapter 14; pp. 208-220). Many of the non-ferruginous shell beds fall into the category of limestone, for they contain over 50% of calcareous material. The following description is a summary of the petrographic properties of eleven shell bed samples taken from the Pattinson Sill, the Firestone Sill, the Knucton Shell Beds and the Rookhope Shell Beds. Modal analyses of four of them are given in Table 13.

TABLE 13

Sample	Quartz	Sparry Calcite matrix	Organic calcite	White mica	Access.
80	33.9	45.5	17.6		1.0
225	35.1	55.4	8.6		0.9
313	35.9	60.6		1.9	1.6
355	43.8	56.0			0.2

A. Framework constituents

Allochems. Shell fragments and crinoid columnals are the most abundant members of this group, although the actual proportions vary quite considerably; some shell beds are very largely composed of abraded shell fragments, and other "shell beds" contain dominant crinoid material. In the particularly quartz-rich varieties shells may occur in local pockets only.

Other major components. Quartz is generally the most abundant non-calcareous constituent of the shell beds, although there are some in which it is virtually absent. In the extremely sandy shell beds all three mineralogical types of quartz (p. 114) may be observed. Mostly, the quartz is rather poorly sorted and shows corrosion by calcite.

White mica and degraded biotite may occasionally be present in the shell beds. The one sample containing biotite is noteworthy for the fact that calcite is seen to invade the biotite along its cleavage. This process ultimately results in the disruption of the biotite.

Carbonaceous material is commonly present, and may be in the form of carbonaceous flecks, small grains, or rounded fragments of vitrain.

B. Matrix

A wide range of matrices is known in the shell beds from the Upper Limestone Group. Many have a microspar matrix, but sparry calcite is also quite common, especially in those limestones containing large fragments of abraded shells. The sparry calcite here occurs as large clear, interlocking crystals which is poikilitic to the smaller constituents in the rock. Microspar in the matrix of other shell beds contains only small, irregular patches of sparite. Siderite may form a small percentage of the matrix in some samples.

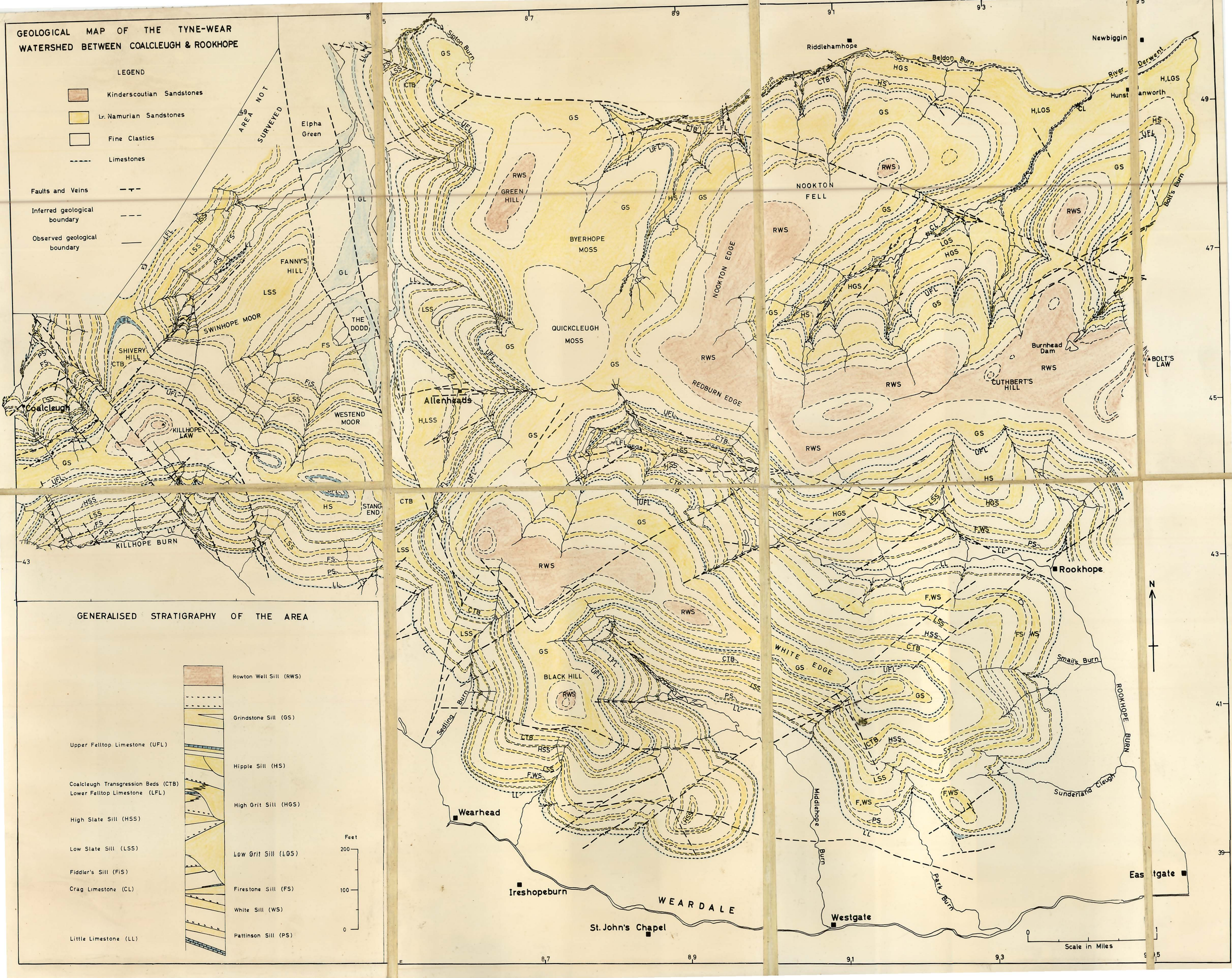
APPENDIX II

LOCATION OF SAMPLES QUOTED

Sample Number	Geological Horizon	Location
7	Low Grit Sill	Gibraltar Banks, Nookton Burn
16	Low Grit Sill	Gibraltar Banks, Nookton Burn
20	Firestone Sill	Nookton Wood, Nookton Burn
47	Marginal facies, Low Grit Sill	Wagtail, Nookton Burn
51	Low Grit Sill	Nookton Wood, Nookton Burn
57	Marginal facies, Low Grit Sill	Wagtail, Nookton Burn
70	Firestone Sill	Near Nookton Farm, Nookton Burn
80	Firestone Sill	Smithy Cleugh, Nookton Burn
93	Low Grit Sill	Nookton Burn
94	Low Grit Sill	Nookton Burn
96	Fiddler's Sill	Coal Crag, Nookton Burn
123	Low Slate Sill	Eastend Burn, East Allendale
133	Lr. Rookhope Shell Beds	Rookhopeburnhead
135	Coalcleugh Ganister	Lower Northgrain Qy., Rookhope
139	Lr. Rookhope Shell Beds	Rookhopeburnhead
142	High Slate Sill	Shorngate Sike, Rookhope Burn
145	Low Slate Sill	Woodhead Qy., East Allendale
173	High Slate Sill	Grove Rake, Rookhope Burn

192	Pattinson Sill	Wolfcleugh, Rookhope Burn
225	Knucton Shell Beds	Sipton Cleugh, East Allendale
286	Base, Crag Limestone	Smithy Cleugh, Nookton Burn
305	Grindstone Sill	Great Espey Sike, Nookton Burn
310	Grindstone Sill	Nookton Burn
313	Knucton Ironstone	Westerley Sike, Nookton Burn
317	Knucton Ironstone	Red Braes, Beldon Burn
321	Pattinson Sill	Craig Nook, Rookhope Burn
326	Firestone Sill	Rookhope Burn
327	Pattinson Sill	Rispey Sike, Rookhope Burn
330	Firestone Sill	Hawk Sike, Rookhope Burn
355	Up. Rookhope Shell Beds	Middlehope Burn, Weardale
369	Low Grit Sill	Bolt's Burn, Derwentdale
374	Grindstone Sill	Ferney Gill, Bolt's Burn
375	Rowton Well Sill	Burnhead Dam, Bolt's Burn

DURHAM UNIVERSITY SCIENCE 12 JUN 1964 SECTION LIBRARY


GEOLOGICAL MAP OF THE TYNE-WEAR WATERSHED BETWEEN COALCLEUGH & ROOKHOPE
LEGEND
Kinderscoutian Sandstones
Lr. Namurian Sandstones
Fine Clastics
Limestones
Faults and Veins
Inferred geological boundary
Observed geological boundary
AREA NOT SURVEYED
GENERALISED STRATIGRAPHY OF THE AREA
Rowton Well Sill (RWS)
Grindstone Sill (GS)
Upper Felltop Limestone (UFL)
Hipple Sill (HS)
Coalcleugh Transgression Beds (CTB)
Lower Felltop Limestone (LFL)
High Grit Sill (HGS)
High Slate Sill (HSS)
Low Slate Sill (LSS)
Low Grit Sill (LGS)
Fiddler's Sill (FiS)
Firestone Sill (FS)
Crag Limestone (CL)
White Sill (WS)
Little Limestone (LL)
Pattinson Sill (PS)
Feet
200
100
0
Scale in Miles
Coalcleugh
Allenheads
Rookhope
Eastgate
Westgate
Wearhead
Ireshopeburn
St. John's Chapel
WEARDALE
Riddlehamhope
Newbiggin
Hunstanworth
Elpha Green
QUICKCLEUGH MOSS
BYERHOPE MOSS
NOOKTON FELL
NOOKTON EDGE
REDBURN EDGE
WHITE EDGE
BLACK HILL
GREEN HILL
FANNY'S HILL
SHIVERY HILL
SWINHOPE MOOR
WESTEND MOOR
KILLHOPE LAW
KILLHOPE BURN
THE DODD
STANG END
CUTHBERT'S HILL
Burnhead Dam
BOLT'S LAW
ROOKHOPE BURN
Sunderland Cleugh
Smail's Burn
Middlehope Burn
Park Burn
Sedling Burn
Sipton Burn
Beldon Burn
River Derwent
Bolt's Burn
N