Stratigraphy and geochemistry of the Yoredale rocks between Shap and Appleby

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STRATIGRAPHY AND GEOCHEMISTRY OF THE YOREDALE ROCKS BETWEEN SHAP AND APPLEBY

by

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A thesis submitted to the
Faculty of Science in the University of Durham
for the degree of Doctor of Philosophy
January 1965

Grey College
Durham

ABSTRACT

Detailed mapping of the Carboniferous strata of Yoredale facies in north Westmorland has shown that the Middle Limestone Group succession comprises nine well developed cyclothems. The major limestones at their bases are clearly recognisable throughout the region but thin calcareous horizons, found within the clastic successions of four of the earliest cycles, are of more local distribution. Correlations of the limestones with those in the Westmorland Pennines are suggested and involve the equation of the Iron Post Limestone with the siliceous upper leaf of the Newby Mill (= Four Fathom) Limestone. The Upper Limestone Group sediments, lacking well marked calcareous horizons, cannot satisfactorily be divided into cyclothems. However, high in the sequence, the Bewley Castle Limestone has been shown to represent marine strata in the Crag Limestone cyclothem of the Pennines.

A decrease in the thickness of the Middle Limestone Group strata, of the order of 10%, has been detected in the western parts of the area as compared to the region east of the Lyvennet. This is consistent with the regional picture of minimal subsidence in west Cumberland and, taken in conjunction with the close similarity in the successions on either side of the Pennine Faults, it indicates that, at this time, a large part of northern England behaved as a distinct tectonic unit. In comparison with the rapidly subsiding trough to the north this was a stable region, to the whole of which the term 'Alston Block' may usefully be extended.Its structural unity was broken only after Carboniferous deposition ceased, by the initiation of the Pennine Faults; there is evidence that the latter had no earlier history as hinge-lines affecting deposition.

Of particular mineralogical interest are the Grayber Limestone, the upper leaf of which invariably is rich in glauconite, and the argillites which, irrespective of their position in the cycle, have kaolinite as a common component. This is a product of diagenesis and is believed to be due to the deep penetration of weathering under the tropical conditions of immediately post-Carboniferous times.

A comparison between pale and dark limestones suggests that finely divided pyrite has a greater influence upon colour than does organic carbon. Little mineralogical variation is present through the major limestones but certain trace elements, most notably manganese and strontium, are present in greatly varying amounts. Manganese is closely associated with iron- and magnesium-bearing carbonates and may total 1% in some dolomitised limestones. Studies of strontium variation in the Little Strickland Limestone strongly suggest that its distribution reflects primary differences in the proportions of aragonite and calcite accumulating on the sea floor. Such variation may prove to be a useful tool in aiding the understanding of the micro-environments of limestone deposition.

Chemical and mineralogical data support stratigraphical evidence which indicates that the bulk of the succession was laid down in relatively quiet shallow marine waters whose salinity varied from normal during times of limestone deposition to brackish at higher levels in most of the cycles. Only occasionally, where there is a sheet sandstone with a sharply erosional base, may a fluvial environment be said to have been dominant. A widespread tectonic control, probably depending ultimately upon isostatic forces, is considered to be the basic cause of the cyclic repetition.

Uplift in post-Carboniferous times led to strong erosion under a tropical climate which became increasingly arid. Its effects remain clearly recognisable in the reddening of the Carboniferous rocks which may extend to a depth of as much as 1000 feet below the New Red Sandstone unconformity. Two stages of reddening have been recognised; they were separated by a period of local dolomitisation consequent upon the extension into the Vale of Eden of the Zechstein Sea. It is postulated that the Vale underwent rapid sinking during the time of accumulation of the New Red Sandstone and that thick deposits did not spread far beyond their present limits. Deep wadi-like channels with a general northerly trend have been recognised and, in the vicinity of Appleby, upstanding remnants of Carboniferous strata, isolated by erosion from the main upland mass, can be proved to exist. The conclusion that this main erosion area lay to the south and west is supported by facies changes in the basal New Red Sandstone, Brockram giving way to pebbly Penrith Sandstone in a northerly and easterly direction.

ACKNOWLEDGEMENTS

The author would like to express his gratitude to Professor K.C. Dunham for his suggestion of the Vale of Eden as an area for study and to Dr G.A.L. Johnson for his supervision of the research. His help with fossil identification and in reading the manuscript is particularly welcomed.

The help of the following is greatly appreciated:-

Dr. D.M. Hirst for suggesting methods of approaching the chemical aspects of the work.

Mr. R. Phillips and Mrs. M. Kaye for demonstrating the use of the X-ray diffractometer and for advice in interpreting the results of the study.

Mrs. M.Kaye and Mr. P. Bradshaw for their assistance in the early stages of the work with the X-ray spectrograph.

Mr. R. Pattinson for useful discussions on sedimentation and Carboniferous stratigraphy.

Mr. R. Lambert for his help with the carbon determinations.

Mr. C. Chaplin and his technical staff for preparing thin-sections and producing the thesis illustrations.

The Department of Scientific and Industrial Research for their invaluable financial support.

Sincere thanks are also due to Mrs. O. Stubbs of Crosby Ravensworth and Mrs. J. Mason of Kings Meaburn for their kind hospitality during the many months of field-work.

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CHAPTER I

INTRODUCTION

A. REGIONAL SETTING

As a basis for the research, the rocks in an area of 42.5 square miles in north Westmorland have been studied in detail. This part of the county is relatively low-lying ground known broadly as the Vale of Eden, floored by rocks of Carboniferous and New Red Sandstone age and lying between the Lower Palaeozoic mountains of the Lake District on the west and the Carboniferous block of the Northern Pennines on the east.

Geologically, the Vale can be divided naturally into two parts – a north-eastern strip underlain by Permian and Triassic rocks, and a larger and topographically more varied part to the south-west, of Carboniferous strata. The boundary between the two, at Appleby, lies in close proximity to the Eden itself but strikes thence in a more westerly direction, approximately following the valley of the River Leith. The area studied is only a small part of a much larger region of Carboniferous rocks which, except south of St. Bees Head, encircle the older rocks of the Lake District. Strata from Tournaisian to Namurian age are present between Shap and Appleby but the bulk of the area is underlain by Visean rocks - a lower unit of thick limestones and an upper one of limestones, shales and sandstones, all dipping to the north east, where they are overlain unconformably by the basal conglomerates and sandstones of the New Red Sandstone. Attention has been largely confined to the Middle and Upper Limestone Groups (D2, P2 and E age) which show, as in the Pennines, a series of well-developed cyclothems. Mapping was, however, extended down to the top of the thick D1 limestones and up to include the lowest New Red Sandstone deposits. The formations occurring in the vicinity of Shap and Appleby are shown in Table 1 and Fig. 1.1.

The geology is partially reflected in the topography in so far as

TABLE 1

Period	Formation	Zone (Carboniferous)
Recent	Alluvium	
Pleistocene	Glacial drifts	
New Red Sandstone	Penrith Sandstone and Brockram	
	Upper Limestone Group	E1 ?E2
	Middle Limestone Group	D2 & P2
	Lower Limestone Group (Knipe Scar Limestone)	D1
Carboniferous	Knipe Scar Limestone (in part)	
	Ash Fell Sandstone	C1 to S2 (not mapped)
	Shap Limestones and Dolomites	

Formations in the Shap-Appleby region.

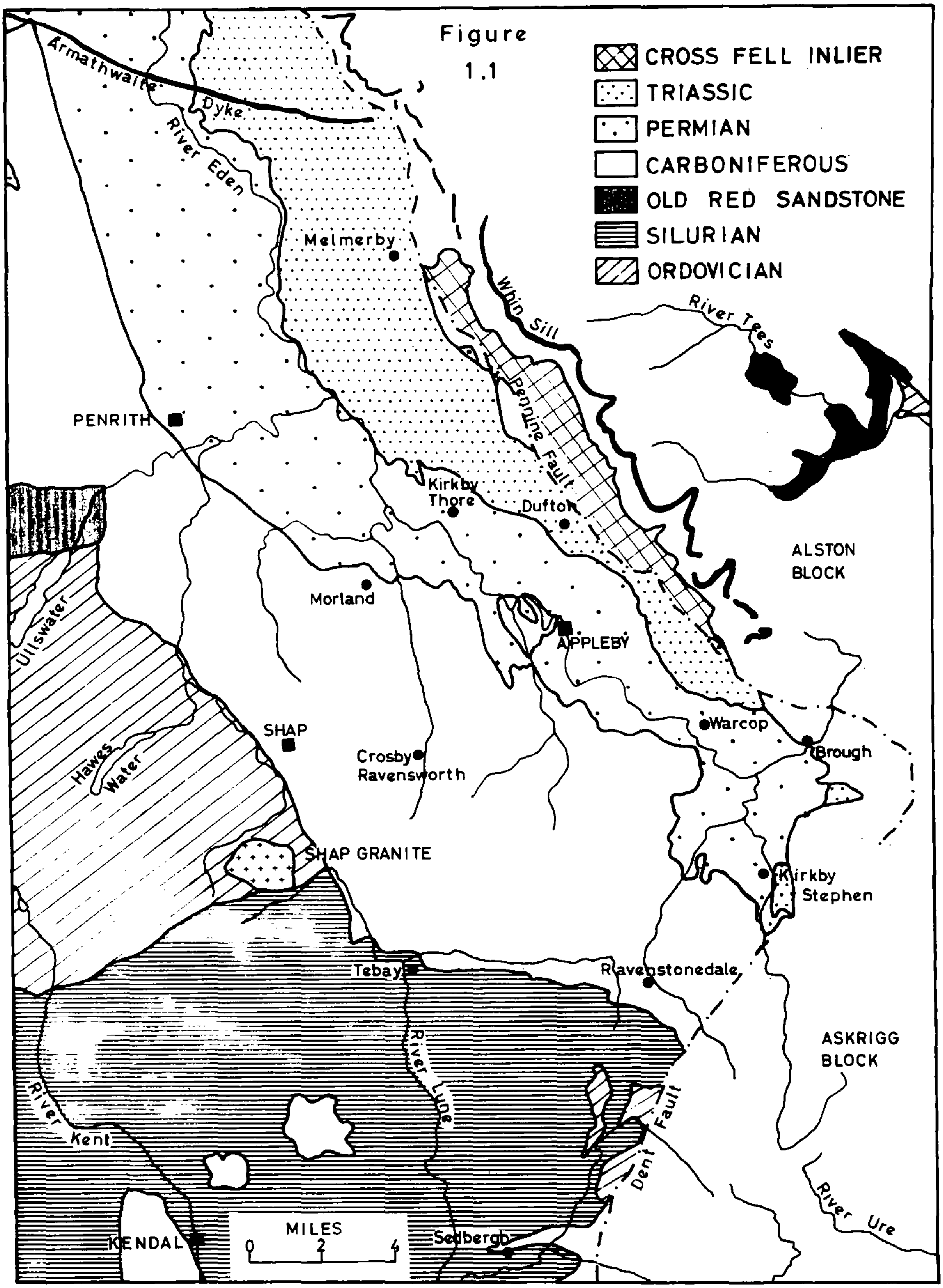


Figure
1.1
CROSS FELL INLIER
TRIASSIC
PERMIAN
CARBONIFEROUS
OLD RED SANDSTONE
SILURIAN
ORDOVICIAN
Armathwaite Dyke
River Eden
Melmerby
Whin Sill
River Tees
Pennine Fault
PENRITH
Kirkby Thore
Dufton
ALSTON BLOCK
Morland
APPLEBY
Ullswater
Warcop
Brough
SHAP
Crosby Ravensworth
Hawes Water
SHAP GRANITE
Kirkby Stephen
Tebay
Ravenstonedale
ASKRIGG BLOCK
River Lune
Dent Fault
River Kent
River Ure
MILES
0
2
4
KENDAL
Sedbergh

the limestones, and occasionally the sandstones, may give rise to westerly or south-westerly facing scarps separated by long gently falling dip slopes. This is best seen in the case of the thick Knipe Scar Limestone of D1 age, which forms a pronounced feature south from Shap village and eastwards to Orton and Ravenstonedale (Plate 1). The Yoredale Limestones form similar but much smaller and more broken features, well seen only where the cycle contains a thick, easily eroded shale sequence, especially on the higher ground, where glacial action has been erosional rather than depositional, so accentuating the scarp topography (Plate 2). The highest ground lies in the south-west of the area, reaching a maximum of 1166 feet on Harberwain Rigg and just over 1100 feet on Linglow Hill and Gaythorn Plain near the southern margin. Northwards and eastwards the ground falls gently with the dip of the rocks and most of the area lies between 1000 and 500 feet. Except in the south, relief is generally subdued and the lower ground often has a mantle of glacial drift and displays well developed drumlins. The best exposures are provided by the main streams, tributaries of the Eden, flowing northwards obliquely to the dip of the rocks in deep yet youthful valleys; they are, from west to east, the River Leith, Morland Beck, the River Lyvennet and Hoff Beck. These and other important streams together with the main settlements and hills are shown in Fig. 1.2.

The land is entirely enclosed except for an area, Gaythorn Plain, in the south adjoining the clint-covered extensive dip slope of the D1 limestones of Orton and Great Asby Scars. Settlement takes the form of small villages in, or adjacent to, the main valleys and as scattered farms, with Appleby, the county-town and marketing centre, on the Eden in the extreme east of the area. Farming, especially dairying, is the only major industry in the area studied although the latter does provide labour for the lime, granite and andesite quarries near Shap and the

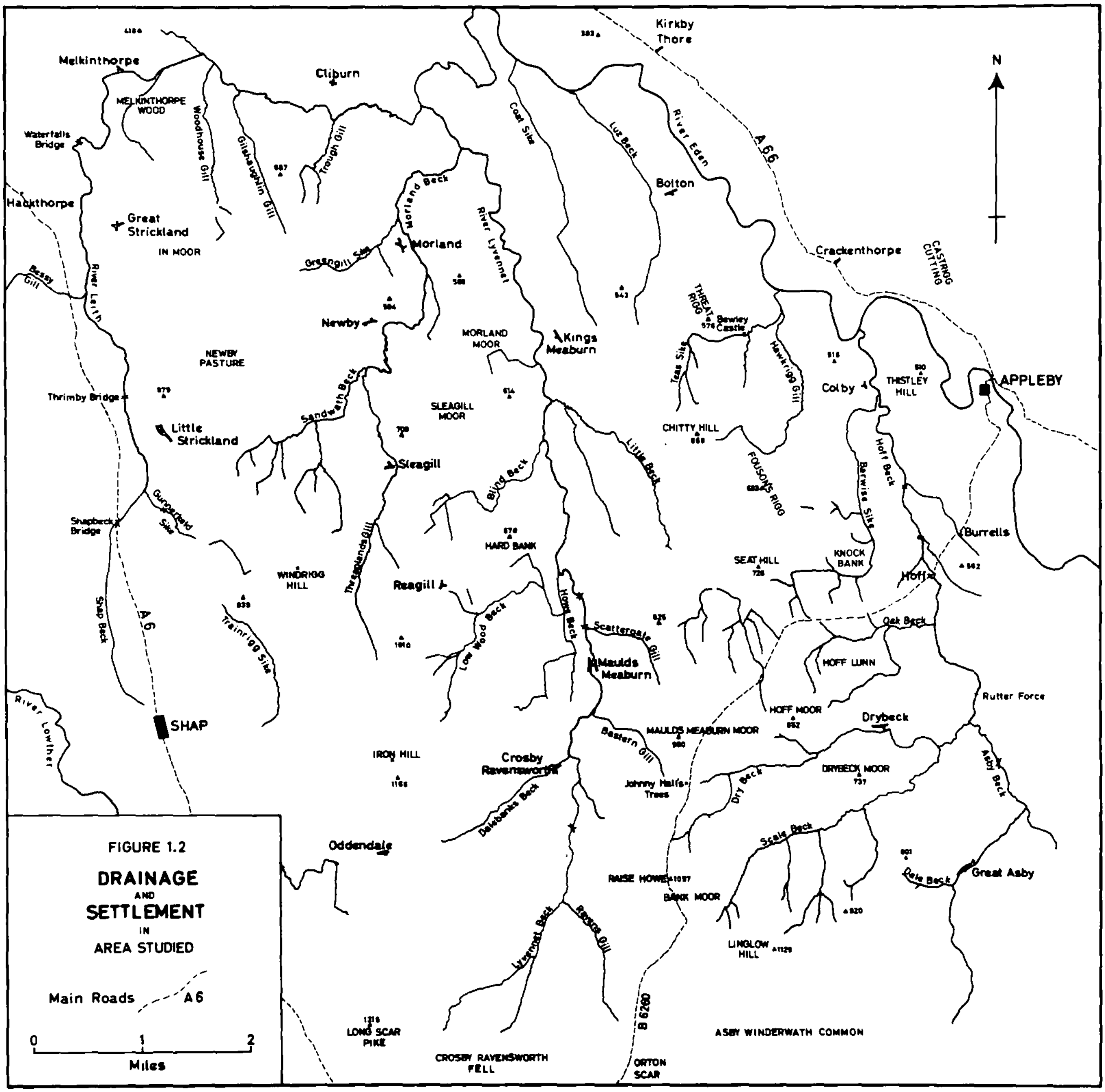


FIGURE 1.2

DRAINAGE AND SETTLEMENT IN AREA STUDIED

gypsum mines of Kirkby Thore.

PLATE 1. The Knipe Scar Limestone at Orton Scar.

PLATE 2. Scarp capped by the Maulds Meaburn Limestone, Raise Howe.

B. AIMS AND METHODS OF RESEARCH

Basically the aims of this research are threefold:-

1. Stratigraphy

Strata of the same age as those in the area studied are relatively well known in the Pennines and differ considerably from the equivalent rocks in west Cumberland, where the sequence is dominated by limestone. A primary aim, therefore, of the research was to build up a detailed picture of the stratigraphy in this intervening area so that comparisons which may elucidate the palaeogeography can be made with the neighbouring regions. More specifically, the possibility of defining a westerly limit to the Alston Block in Carboniferous times, comparable to that provided by the Stublick, Swindale and Lunedale faults, has been considered.

2. Depositional environment

With the object of obtaining more detailed information on the nature of the depositional environment special mineralogical and chemical studies have been made of selected parts of the succession; an attempt has been made to detect significant variations of components in what appear to be essentially uniform calcareous deposits.

3. Diagenetic changes

The New Red Sandstone unconformity cuts across a variety of horizons in the Carboniferous rocks which have been extensively altered immediately below it. The mineralogy and trace element content of some altered rocks has been studied in order to gain more information on the nature of the influences to which the Carboniferous strata were subjected during the following Permian Period, with special reference to the probable nature of the climate at that time.

Research has involved three main lines of investigation:-

1. Mapping

A compact region of rocks of Yoredale facies, east of Shap village and west of Appleby was selected for the construction of a litho-stratigraphic map. The area is bounded naturally on the north-east and south-west by the New Red Sandstone unconformity and the appearance of the Knipe Scar Limestone, respectively; the steep-sided valley of the River Leith, giving good stratigraphic control, was selected as a western limit but eastwards no well defined boundary occurs and, except in the north where the New Red Sandstone appears, an arbitrary limit was taken at the main Great Asby-Appleby road.

Little is seen of the shale horizons, and the sandstones, though often persistent, tend to vary considerably in lithology over short distances. The limestones are often well exposed, having been extensively quarried, and it is by using these as guide lines that the succession and structure have been determined. It has been found that there is some distinctive feature in the general aspect (lithology and bedding) of nearly all the limestones, so that after some experience, in most cases, they can be traced across the area reliably without much difficulty. In particular, several faunal marker bands occur through the succession and have proved very valuable in correlation.

Eleven important limestone horizons have been mapped and named in accordance with those used initially by the Geological Survey, with the exception of the limestone below the Great Strickland Limestone which, for consistency, has been given a local name - that used by Bland (1862). Bland's names do, in fact, have chronological precedence and in many cases are more suitable in that, in contrast to the Survey's alternatives, they indicate localities where the named horizons are well displayed. However it is the Geological Survey's terminology which has become established in the literature and its use will not be discontinued here. The names of the limestone horizons mapped are shown in Table 2, together with the nomenclature of other authors and their correlations.

2. Petrographical study

An understanding of the general compositional and textural characteristics of the rocks mapped has been gained by sampling all the main limestone, sandstone and shale horizons and examining these under the binocular microscope and in thin section, so enabling them to be classified. In some cases, minerals of unusual character or special interest, such as glauconite, have been studied further by means of X-ray powder photography.

3. X-ray study

A special study has been made of several series of carefully selected rocks, which were sectioned, powdered and examined using X-ray diffractometer and spectrograph techniques, to determine mineralogical and trace element variation. Samples were collected through the central parts of the Little Strickland Limestone at two separate localities which can be correlated at bedding-plane level (with additional samples from the base and the top), for the purpose of testing vertical and short range changes in mineralogy. Two similar sets of specimens were collected in the Great Strickland Limestone - one set where it is minimally altered and another where it directly underlies the New Red Sandstone unconformity. Another series is representative of the transition from a sandstone up into a limestone (the Maulds Meaburn Limestone) and specimens were also collected through a shale sequence, including nodules and their surrounding material. For a comparison a similar, but reddened, shale with nodules has been studied, though in this case, not from the same horizon as this proved impossible. Two samples representing very thin pale (possibly non-marine) shale and limestone have also been examined. Further information concerning the detrital fraction of the limestones has been gained by dissolving the carbonates in dilute acetic acids; in some of the samples organic carbon has been estimated.

C. HISTORICAL REVIEW

Although the neighbouring upland regions with their economically valuable mineral deposits received the early attention of geologists, notably John Phillips (1836) who first named the Yoredale limestones, it was not until the 1860's that work was initiated in the Vale of Eden by the Geological Survey. In fact, the first recorded study of a part of the region is that made by John Bland, a local naturalist, and published in the Transactions of the Manchester Geological Society for 1862 (Bland 1862). Though only aged 21 at the time, Bland also produced a map which received high praise, showing "how the limestone begins to be separated by coal measures", but was unfortunately not able to be published owing to lack of funds. This map is recorded as being preserved at Reagill, a village 5 miles west south west of Appleby, and still the home of the Bland family, in 1910 (Bland 1910), but extensive enquiries have only revealed that it has since vanished and, if not destroyed, at least is no longer in the possession of the family. This is a sad loss, for Bland, though trained only at two village schools, was a geologist of considerable ability as is shown by his paper which includes a succession needing little modification today. The names Bland gave to the rock units are not those of the Survey geologists but their descriptions are sufficiently reliable to equate the two (Table 2).

Shortly after the completion of Bland's work, the officers of the Geological Survey, working northwards from the Yorkshire and Lancashire coalfields, reached north Westmorland and completed the Appleby sheet (Old Series 102 SW) by 1875 though it appeared in its present form only in 1893. Similarly it was 1897 before the accompanying Memoir (Dakyns, Tiddeman and Goodchild) was published and, because the original surveyors

TABLE 2

PRESENT STUDY	BLAND 1862	GEOLOGICAL SURVEY 1897	MILLER AND TURNER 1931
Bewley Castle		Bewley Castle	Bewley Castle
Great Strickland	Morland	Great Strickland	Great Strickland
Newby Mill	Newby Mill	Undersett	Undersett
Grayber	Holesfoot	Grayber	Grayber
Brackenslack		Brackenslack } Lowther	Lowther (= Brackenslack)
Maulds Meaburn Edge	Blind Beck	Maulds Meaburn Edge } Lowther	Maulds Meaburn Edge } Reagill
Johnny Hall's Trees	Coday	Johnny Hall's Trees ?=Reagill	Johnny Hall's Trees } Reagill
Little Strickland	Greenriggs	Little Strickland	Little Strickland
Maulds Meaburn	Wickerslack	Maulds Meaburn	Maulds Meaburn
Bank Moor	Harberwain Rigg	Bank Moor	Bank Moor
Askham	Winter Tarn	Askham	Askham
Knipe Scar	Orton Scar	Knipe Scar	Knipe Scar

Names of the main limestone horizons

had either retired or died by this time, otherwise avoidable errors have appeared in the text.

The area has not yet been re-surveyed and, since the turn of the century, only two works, both however of considerable importance, have been directly concerned with the Yoredale strata themselves. The first was Garwood's classic work on the Lower Carboniferous of the North West Province (Garwood 1912) in which the first attempt to use palaeontology as an aid to stratigraphy and to produce a zonal scheme for northern England was made. Garwood divided the rocks of Yoredale facies on a faunal basis into two zones and recognised several persistent fossil bands, most notably the Girvanella Band which is still recognised as the D1 - D2 boundary. He was, however, more concerned with the pre-D2 thick "standard" limestones, having found many of the Yoredale limestones to be almost devoid of fossils and consequently, though he recognised the 11 distinct limestone bands of the Shap district, relatively little new information is provided about them. This gap in our knowledge was to some extent filled by the work of Miller and Turner (1931) who give short descriptions of the limestone horizons, suggest correlations with the North Pennine and Dent regions, and provide good faunal lists. They also give new data on the thicknesses of the different units and their variation and provide some new correlations within the area, modifying those of the Geological Survey, though the absence of an accompanying map is missed. The present study, whilst confirming the broad outlines of this previous work, modifies it in several important respects.

Works on other aspects of the Geology of the Vale of Eden are much more numerous and only a few, having a direct bearing on the present study, can be mentioned. Of particular interest is a paper by Trotter (1939) discussing the extensive reddening which may occur in the Carboniferous rocks below the New Red Sandstone unconformity. Because of the light they throw on the geological history of the region some of the studies of the basal Carboniferous conglomerates and of the New Red Sandstone deposits are worthy of mention. Early reference to the former was made by one of the Survey geologists, J.G. Goodchild, in 1874. He also made some observations on the classification of the New Red Sandstone (Goodchild, 1891) but perhaps his most important contribution was his study of the effects of the Pleistocene glaciation (Goodchild 1887) in which can be found ideas that became generally accepted only many years later. More recent and comprehensive studies of these subjects have been made by Capewell (1955) on the conglomerates below the marine Carboniferous, by Kendal (1902) and Versey (1939) on the Brockrams and Penrith Sandstone, and the glacial history of the area has been ably described by Trotter (1929) east of the Eden and in the Shap-Appleby region itself by Hollingworth (1931).

Works directly concerned with the geological history of the Vale of Eden include an early account by Goodchild (1889) where, again, some original ideas are advanced, and the paper on the Cross Fell inlier by Shotton (1935) in which an attempt is made to reconstruct the tectonic history of this complicated region. More general suumaries of the local geology have been produced at intervals, including works by Marr (1907) giving a good physiographic description and by Gilligan (1926); a particularly useful guide is the booklet "Geology of the Appleby District" written by Dr. Versey (1960).

Descriptions of neighbouring districts can be found in the Survey Memoirs - especially Eastwood _et al_. (1931) for the West Cumberland region, and for the Alston Block, Dunham (1948) and Johnson and Dunham (1962). Reference to works concerned with specific aspects of the study will be found in the appropriate sections of the thesis.

CHAPTER 2

STRATIGRAPHY

A. INTRODUCTION

i) Age

The most useful fossils for dating the succession, the goniatites, are uncommon in strata of Yoredale facies and no identifiable remains were found during the investigation. Little, therefore, can be added to the summaries of the evidence bearing upon the age of the rocks studied, which have been made by Rayner (1953, pp. 285-290), Dunham (1948, pp. 11-12) and Johnson (1959, pp. 96-99) who also discusses the Coral-Brachiopod zones. The important zonal boundaries are D1/D2, marked by a persistant horizon of algal nodules (the Girvanella Band, Garwood, 1912, p. 482), and P2/E1 (the Visean-Namurian junction), which Johnson, Hodge and Fairbairn (1962) have shown can most conveniently be taken as the base of the Great Limestone of the Pennines. In the Shap-Appleby area the best developed algal horizon low in the succession is that which occurs within the lowest thick limestone (the Askham) and this has been taken as the base of D2. The oldest rocks studied are probably, therefore, of late D1 age and, since the equivalent in this area of the Great Limestone is the Great Strickland Limestone, the succession continues into the E stage of the Namurian, though it is unlikely that strata younger than E1 are present, except in faulted outliers near Appleby.

The presence of Orionastraea in the Little Strickland Limestone, first recorded by Miller and Turner (1931) in the Shap district, has been confirmed, and, following Hudson (1938, p. 308) the upper limit of D2 is, therefore, placed above the Maulds Meaburn Limestone. Higher limestones have a fauna transitional to that characteristic of the Namurian but at present there is insufficient evidence on which to base any further subdivision of the Yoredale Series.

Fig. 2.1 shows the position of the succession in the goniatite and coral-brachiopod zonal schemes.

ii) Use of fossils

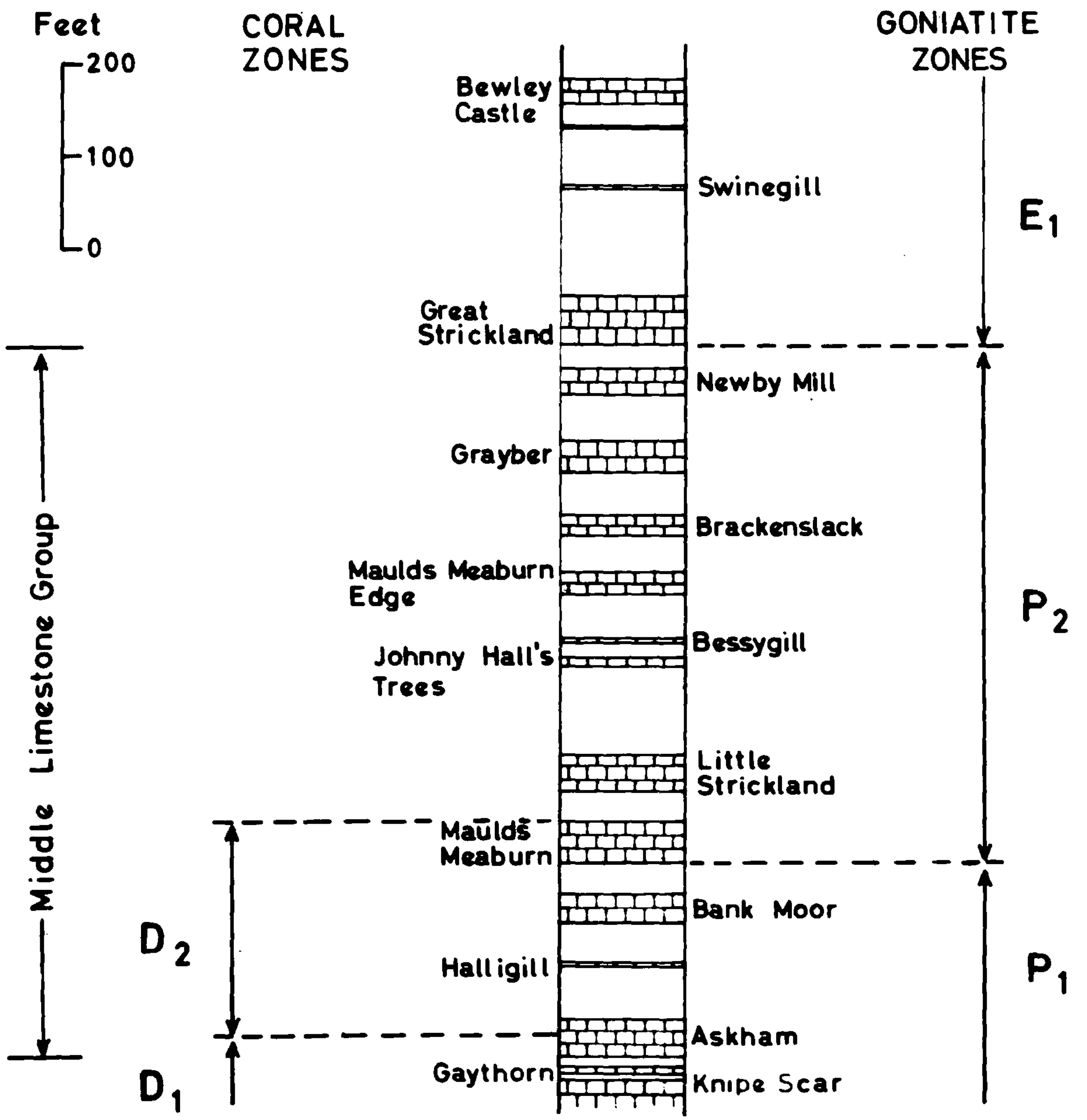
Detailed palaeontological work on the rocks has not been attempted, though adequate material is present and would undoubtedly repay study. Instead attention has been focussed on marker horizons containing an abundance of one particular type of organism, which are relatively easily recognised in the field and so are a considerable aid to mapping. Such biostromes occur in many of the limestones; the more important are listed below.

ASKHAM LIMESTONE The Girvanella Band (D1/D2) occurs at an estimated position of 17 feet below the top of the limestone.

BANK MOOR LIMESTONE There is a horizon very rich in Lithostrotion junceum in the middle of the Limestone; though the density of the corals varies, it is remarkably persistent.

MAULDS MEABURN LIMESTONE A bed with Giganteid Productids occurs at about 12 feet 6 inches above the base of the Limestone; it has been found everywhere that this horizon is exposed.

Figure 2.1



ZONAL POSITION OF THE SUCCESSION

LITTLE STRICKLAND LIMESTONE Two distinct bands with abundant Saccamminopsis fusulinaformis are present — not one as suggested by Garwood (1912, p. 494). The Lower Saccammina Bed is 18 feet above the base, and the Upper Saccammina Beds are about 6 feet below the top, of the limestone but horizons rich in Foraminifera are also present between these two.

JOHNNY HALL'S TREES LIMESTONE The Limestone contains ferruginous cavities which are possibly partly of organic origin but cannot be ascribed with confidence to the Erythrospongia lithodes Bed of Hudson (1929) and said to be present in this area by Miller and Turner (1931).

MAULDS MEABURN EDGE LIMESTONE Abundant Lithostrotion junceum occur near the base of the Limestone at the western edge of the district but have not been found elsewhere.

GRAYBER LIMESTONE The upper part has a very common Bryozoan which in the west of the area is particularly abundant in a bed 18 feet above the base of the Limestone.

NEWBY MILL LIMESTONE Simple conical corals occur quite commonly near the base of the Limestone, though nothing comparable with the Dibunophyllum band of other districts (Turner, 1956) has been found.

GREAT STRICKLAND LIMESTONE At some localities, colonial corals occur a short distance above the base of the Limestone forming a biostrome comparable to the Chaetetes band (Johnson, 1958, pp. 149 and 150), though Chaetetes itself was not found at this horizon.

BEWLEY CASTLE LIMESTONE The Limestone is characterised by an abundance of large anchoring spines of the sponge Hyalostelia.

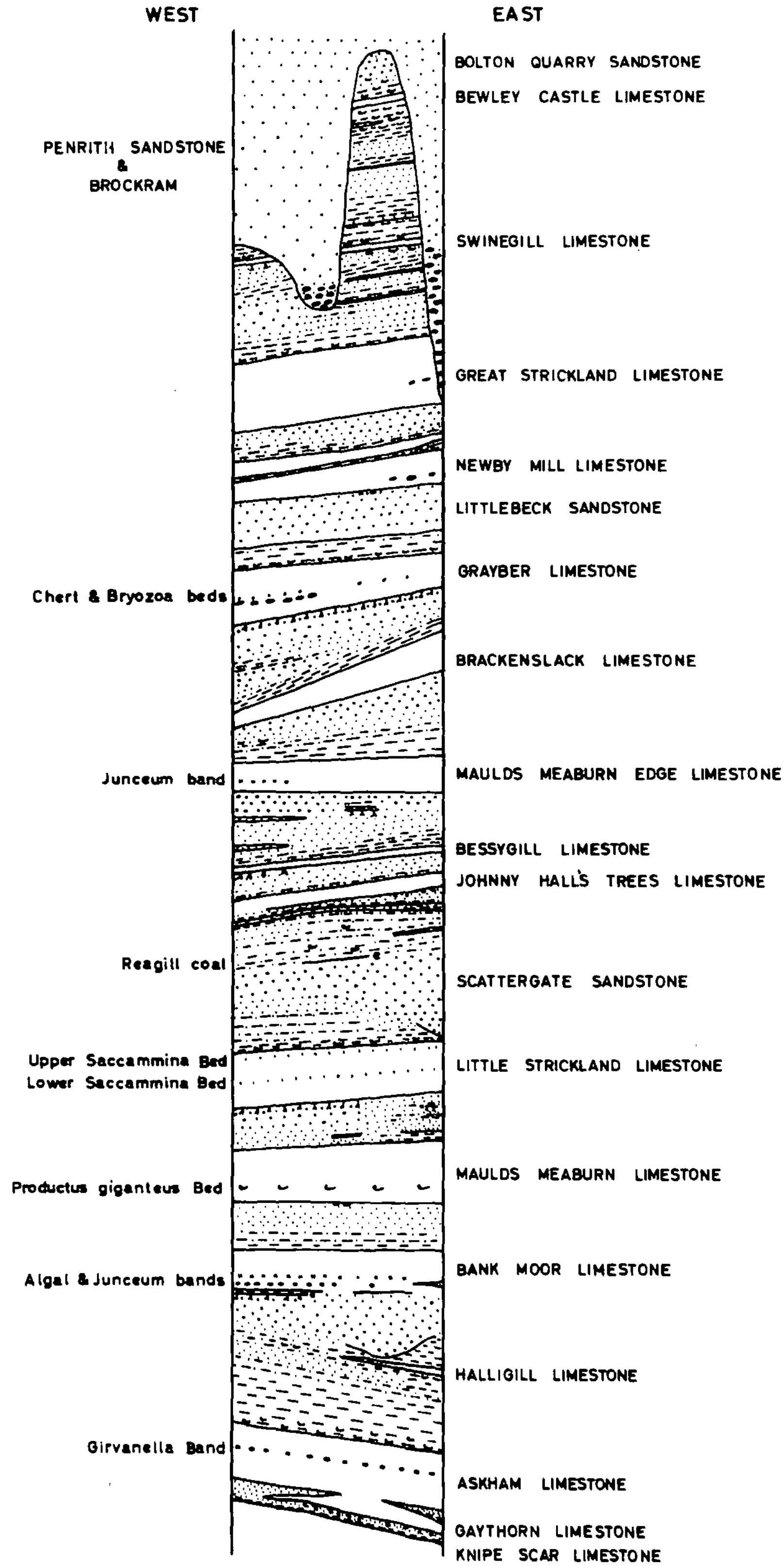
iii) Rhythmic nature of the succession

The most striking feature of all but the top part of the succession is the reccurrence of thick limestones through several hundreds of feet of rock. The thickness of these limestones is generally of the order of 30 feet and they are separated by rather thicker strata, mostly having a terrestrial source, which normally coarsen upwards and are followed by the next limestone usually without any appreciable fining. The succession is, therefore, basically rhythmic (of the form ABCABC) rather than cyclic (with an ABCBA pattern), though each unit, following common usage, has been termed a cyclothem, a word first coined by Weller (1930).

In the subsequent section each of the 11 main cycles is described separately, a summary of the features of special importance being followed by a more detailed account, first of the major limestone member and secondly of the strata up to the succeeding limestone. The latter have, for convenience, been termed the clastic part of the succession though, of course, they may include lesser amounts of non-clastic components. Even the limestones may not be strictly non-clastic in the sense that they often contain transported and broken shell material but the term is used here to denote detrital components of extra-basinal origin. The essential features of the stratigraphy are illustrated in Fig. 2.2 and Fig. 2.4 is a key to the symbols used in the vertical sections.

Figure 2.2

DIAGRAMMATIC SECTION THROUGH THE STRATA IN THE SHAP - APPLEBY DISTRICT



B. STRATIGRAPHIC DETAILS

For ease of reference and clarity, where necessary, the stratigraphy is described, for each cyclothem, in a series of sub-areas. These have been named after their most important settlements and are, from west to east,

1. Strickland.
2. Reagill-Morland.
3. Meaburn.
4. Drybeck-Asby.
5. Appleby.

All contain a fairly full succession except sub-zone 5, which is underlain by the New Red Sandstone and the top part of the Carboniferous. Fig. 2.3 shows the limits of the sub-areas.

i) Knipe Scar Cyclothem

The Knipe Scar Limestone, a very thick limestone of S2 and D1 age lying beneath the Yoredale Series and having therefore not been closely studied, will be mentioned only briefly. It probably can itself be divided into cycles of the type described in the equivalent Great Scar Limestone by Schwarzacker (1958).

a. SUMMARY

The top of the Knipe Scar Limestone is marked by the incoming of a wedge of clastic material which appears to be present over the whole of the area and, though very thin, (probably never more than

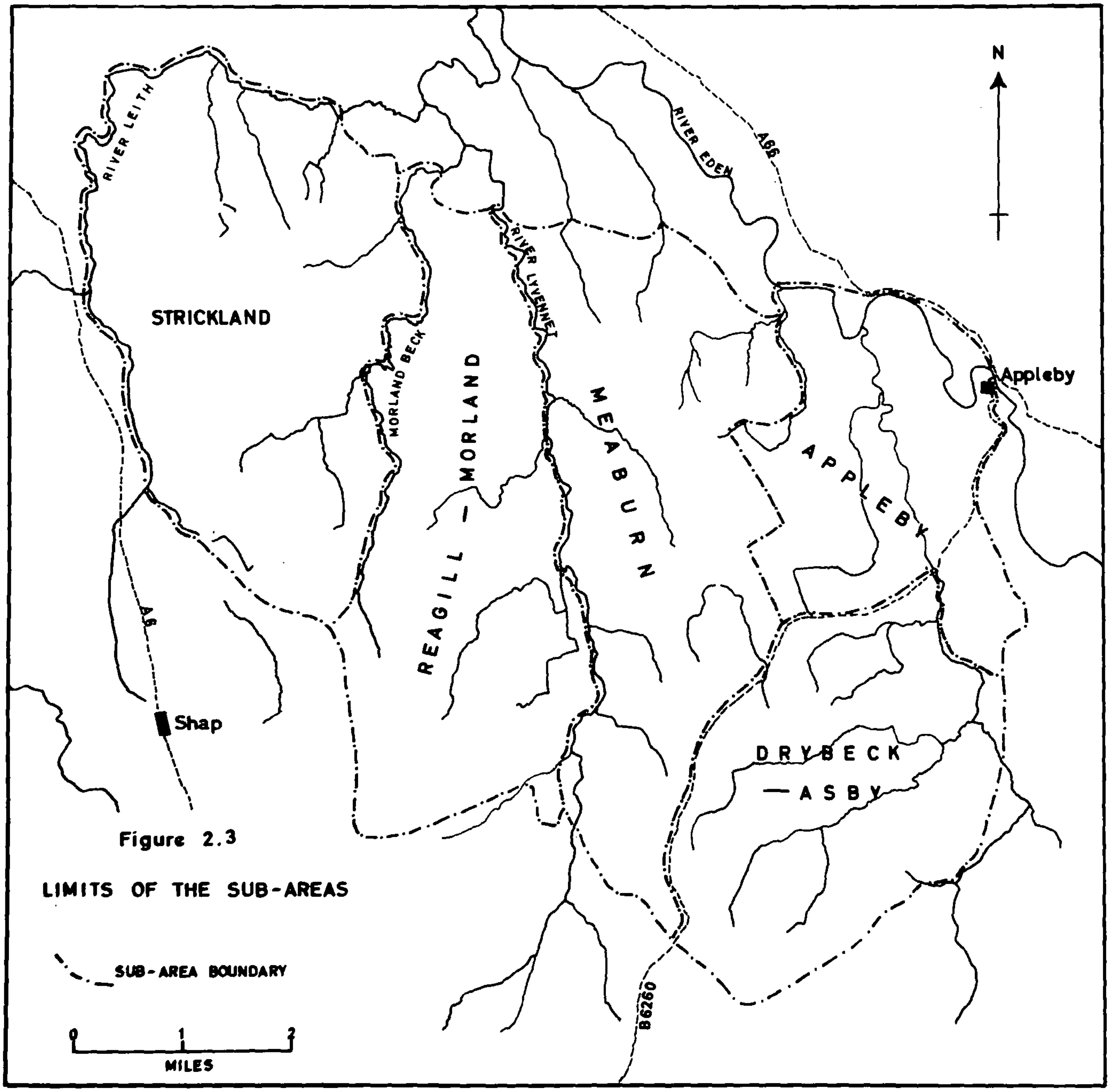


Figure 2.3

LIMITS OF THE SUB-AREAS

25 feet) effectively separates this Limestone from the first of the main Yoredale Limestones (the Askham). Fine sandstone, often with ganister, forms most of the unit though some shale occurs and, wherever the beds are well seen, there is evidence of the presence of a thin limestone within the clastics. This has been called the Gaythorn Limestone, from the locality, Gaythorn Plain, where it is best seen. It appears to unite with the overlying Askham Limestone in the headwater region of Scale Beck and is probably absent in the north-west of the area, where the unit is slightly thinner, averaging about 15 feet.

b. THE KNIPE SCAR LIMESTONE

The Limestone forms the top part, and extensive dip slope, of the major escarpment which faces westwards to Shap and then follows an easterly course overlooking Orton and the Lune valley above Tebay. Vast areas of clint occur, notably at Orton Scar and Great Asby Scar, and over the whole of this upland region the Limestone is very well exposed. Perhaps the best section is that provided by the upper part of Lyvennet Beck and its tributaries. The main westerly tributary rises in D1 limestones but cuts steeply down to produce an inlier of S2 beds. The top of these is marked by the Bryozoa Band of Garwood (1912, p. 473) which can be examined near the confluence with the King's Well tributary. The gradient of the stream then lessens and it crosses increasingly younger limestones, initially of calcite mudstone type, to the north, before finally reaching the top of the D1 strate just downstream from Holme Bridge, Crosby Ravensworth.

In this succession many lithological variants are exposed including both pale and dark micrites and very fossiliferous horizons though pale-grey limestone with lenticular horizontal joints, many shell and crinoid fragments and often tiny limonite-coated molds is the commonest. Complete corals and brachiopods (especially

Productids) are also common although they tend to occur in beds separated by limestone in which they are rare. Pseudo-brecciated horizons (Garwood, 1912, p. 477) can be found in Ravens Gill and over much of the limestone dip slope of Orton Scar and Asby Winderwath Common. Here too, reddish flecks are present locally in the Limestone; they may result from weathering in pre-New Red Sandstone times.

Eastwards, a small inlier of the Limestone occurs where the three headwater streams of Scale Beck unite and can be seen in the bed of the easterly tributary, where it is shelly, sometimes pinkish, and becoming impure near the top. At the eastern edge of the area near Great Asby the Limestone is well seen in Dale Beck, where it is unusual in that it becomes quite dark- and nodular-weathering for perhaps 20 feet at the top. Lower down it is paler and thick-bedded, and has abundant brachiopods and corals which are thought to represent the Davidsonina (=Cyrtina) septosa Band described by Garwood (1912, p. 479) from near the top of D1.

North-west of the Lyvennet, the upper part of the Limestone maintains its thick-bedded, pale, and very fossiliferous nature and is seen in many large quarries before it reaches the limit of the area mapped near Gunnerwell Farm. Here, in a series of small quarries at the south end of the wood south-west of the farmhouse, the highest beds of the Limestone are seen and are of particular interest on account of their lithology. They are fine grained with glassy calcite and have occasional plant stems in growth positions, testifying to the extremely shallow nature of the water at the time of deposition and the virtual absence of currents. By this time, sedimentation, though still producing rocks of a calcareous facies, had reached sea-level and current-swept seas had given way to marshy lagoons.

c. THE KNIPE SCAR CLASTICS

The unit is poorly exposed except in the highest parts of the area, as in Gaythorn Plain, where glacial action has served to accentuate the features rather than to bury them. Here the clastics form the lower part of a small but well-marked escarpment which is capped by the lower beds of the Askham Limestone (Plate 3). They are indicated by a clear vegetation change, the short grass of the Knipe Scar Limestone giving way in the feature to long tufty yellow grass and heather; even the very thin Gaythorn Limestone in the middle may give rise to its own thin belt of short green grass. The base of the unit is further marked by a well developed line of swallow holes where water draining from the feature has descended into the Knipe Scar Limestone. Such sinks can be traced across Gaythorn Plain and towards Great Asby, becoming particularly large in the vicinity of Whitewall Farm.

The feature is similarly developed at intervals northwards to Crosby Ravensworth and near Oddendale, but elsewhere the position of the unit is often difficult to locate exactly.

The Lower Knipe Scar Clastics

Drybeck-Asby sub-area

The easterly headwater stream of Scale Beck shows the only good section of the beds below the Gaythorn Limestone, though even this is incomplete (Fig. 2.5). The lowest visible horizon is a blue-grey silty micaceous shale with a few carbonaceous patches on bedding-planes, and just upstream in the right bank and a small fall is a bed of fairly soft sandstone with plant remains, becoming hard and ganister-like at the top. This rock forms the bed of the stream for a short distance and occurs in similar fashion in the central of the three tributaries where it has a pinkish surface. In the westerly stream, however, the plant remains are absent and there are small exposures of medium grained, orange speckled, buff sandstone.

The main outcrop of these beds is to the south, curving across Gaythorn Plain, where numerous small exposures occur in the sides of sinks which have developed underground in the Knipe Scar Limestone and caused a collapse of the strata above. Only one shows loose shale but several examples of thin-bedded, slightly micaceous and carbonaceous

Figure 2.4

SYMBOLS USED IN MEASURED SECTIONS

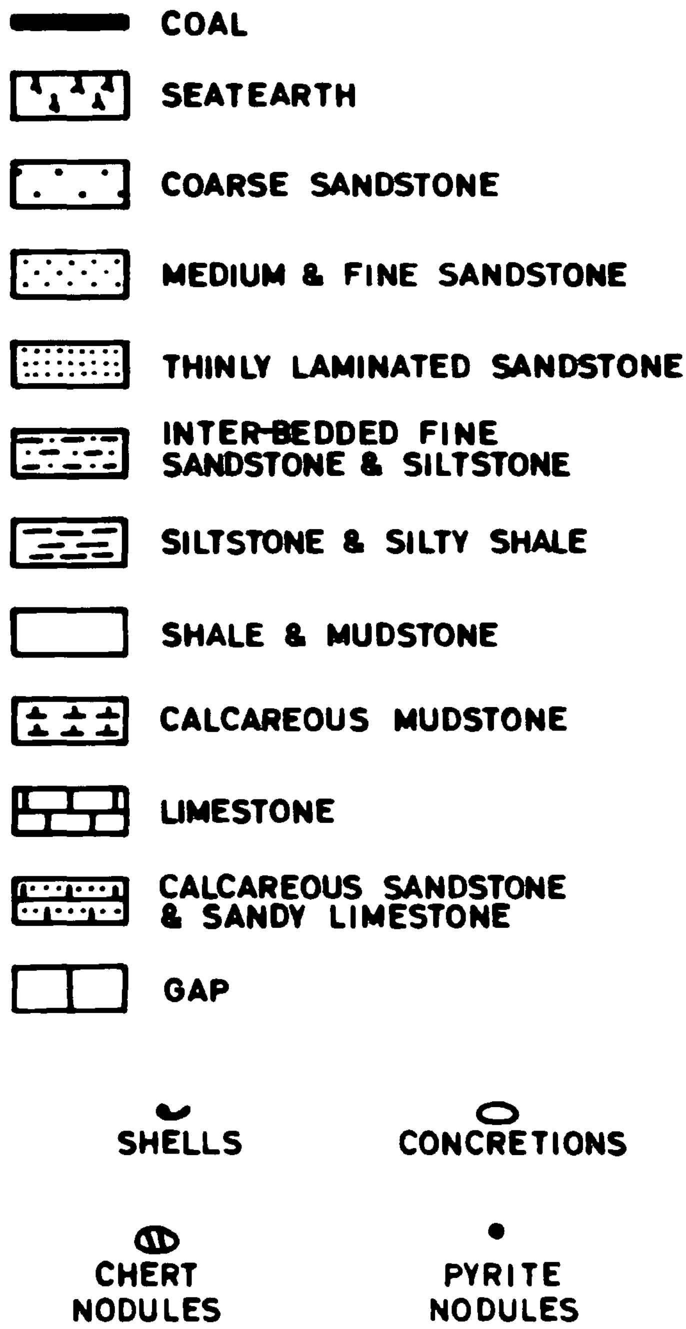
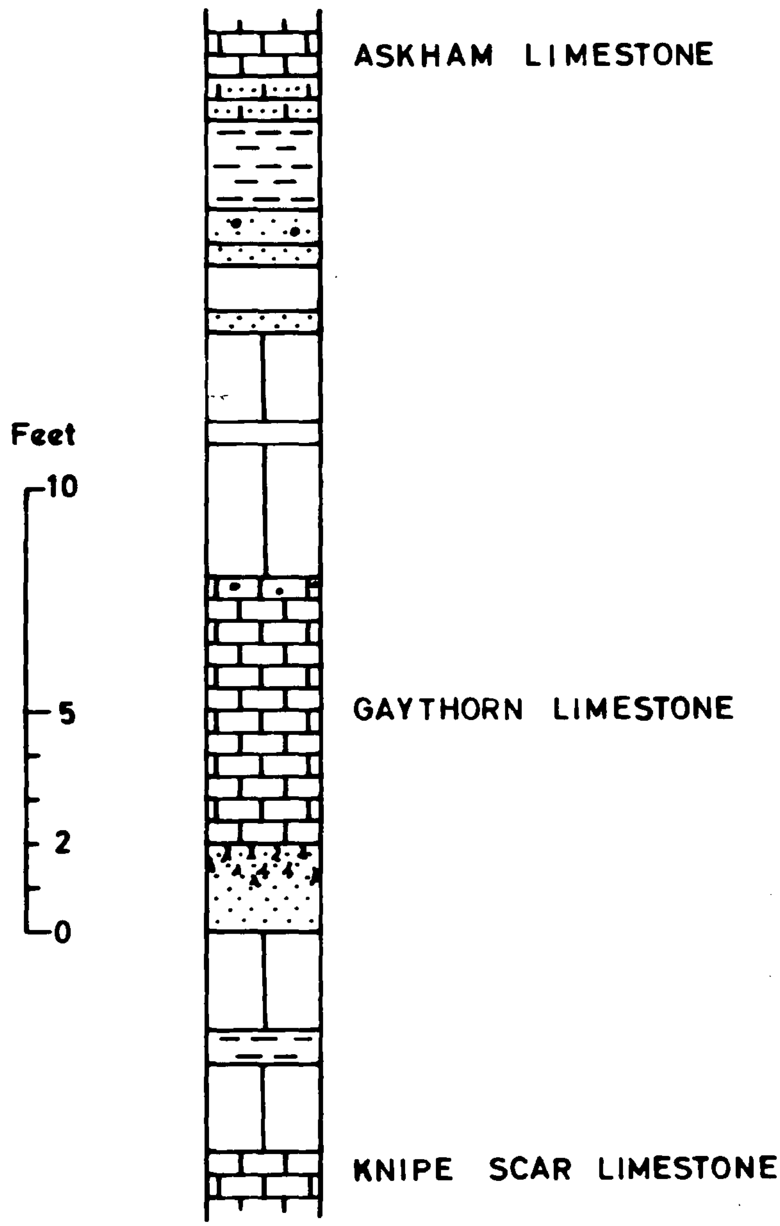


Figure 2.5

MEASURED SECTION IN THE KNIPE SCAR CYCLOTHEM



Upper Scale Beck

pale sandstone occur and a deep sink, 400 yards south-east of the most easterly of the small faults, shows the upper part of the sandstone. Here, massive medium-grained slightly micaceous yellow sandstone is overlain by a bed of ganister of yellow-orange colour, with thin brown streaks representing plant roots. At the top, immediately below the Gaythorn Limestone, are tiny molds of shell fragments. Along much of the outcrop are scattered large loose blocks, probably belonging mostly to this sandstone; all show the massive nature, with in-situ plant roots common, and having a pale purple or white colour though often strongly ferruginous stained.

The beds are not seen between Gaythorn Plain and Great Asby.

Meaburn sub-area

No exposures occur north-westwards from Gaythorn Plain until east-north-east of the prominent house known as Hill Crest where small quarries show fine-grained pale buff sandstone with some faint traces of in-situ plant roots. Loose ganister is also visible, nearer Crosby Ravensworth, in the feature south-east of Woodfoot Farm.

Reagill-Morland sub-area

Except, possibly, north of High Dalebanks, where loose sandstone is visible associated with limestone debris, this sub-division cannot be differentiated east of Oddendale. Here, north of the farms, the feature, including a minor change of slope at the Gaythorn Limestone, reappears, although it does not persist far to the north.

Strickland sub-area

Due to the apparent absence of the Gaythorn Limestone in this region, the sub-division cannot be separated from the rest of the unit, though an equivalent pale very hard fine grained sandstone occurs in a small feature just above the Knipe Scar Limestone quarries south-south-west of Gunnerwell Farm.

The Gaythorn Limestone

Drybeck-Asby sub-area

In the sides of the eastern headwater stream of

Scale Beck (Fig. 2.5) the Limestone is about 6 feet thick. At the base it is dark with abundant fragments of crinoids and brachiopods but becomes paler upwards and, at the top, is an unusual bed distinguished by its amber weathering and cavities. It contains traces of pyrite and the cavities appear to be due to the weathering of small pyrite nodules. The Limestone is also seen in the central tributary where it is ferruginous weathering with an argillaceous top, and again in a small quarry adjacent to the westerly stream. Here its very shelly nature and brownish-grey weathering is maintained and it displays an ochreous speckle and thin bedding.

The biggest exposure of the Limestone is in the steep valley side east of the eastern tributary where a long scar showing a minimum of 7 feet occurs and the Limestone appears to thicken to the north at the expense of the beds above. It is very poorly bedded, various shades of grey but dark and bituminous-smelling with pyrite towards the top, and ferruginous-weathering with quite large Productids lower down. Unfortunately the scar is not continous with the quarry by the side of Scale Beck 200 yards to the north but there is little doubt, from the dip of the beds and the similarity in lithology, that the same strata are here represented. There are 6 feet 6 inches of poorly bedded palish fossiliferous limestone which becomes darker at the top. These same beds occur in the stream itself to the north; at first they are medium grey and very fossiliferous with Lonsdaleia, brachiopods and trilobites but then the dark bituminous-smelling limestone above appears and is exposed continuously to where scars of undoubted Askham Limestone with Lithostrotion junceum is seen in the right bank. The clastics separating the Gaythorn Limestone from the Askham Limestone have therefore disappeared altogether, in spite of being 12 feet thick only $\frac{1}{4}$ mile to the south.

Across Gaythorn Plain, the Limestone is often exposed, usually in sinks, or is clearly indicated by a change of slope in the feature, the appearance of short green grass, or the occurrence of pale orange-brown soil. Sometimes the sinks mark its upper boundary but more often they tend to penetrate right through to the Knipe Scar Limestone. Though the Limestone may vary in thickness, there seems little doubt that it is present at least as far as the Great Asby road but north-westwards no further evidence for its existence occurs and here, too, it may have united with the Askham Limestone.

Meaburn sub-area

The shelly, thin-bedded Limestone gives rise to a small feature east and north-east of Hill Crest and again south-east of Woodfoot, where a small excavation shows pale-medium grey limestone with ferruginous speckles and molds of shell fragments.

Reagill-Morland sub-area

West of the Lyvennet exposures of the Limestone are restricted to the south-west part of the area and elsewhere it is probably absent, either not having been deposited or having become continuous with the Askham Limestone in a northerly and easterly direction. However, because of the paucity of exposure, except in the south and west, some doubt must remain on this point. Thin-bedded brown weathering limestone is present from Oddendale to west of Iron Hill but northwards, including the whole of the Strickland sub-area, no further trace occurs.

The Upper Knipe Scar Clastics

Drybeck-Asby sub-area

The only section is in the eastern headwater tributary of Scale Beck (Fig. 2.5), where, though less than 12 feet thick, a very varied succession is displayed:

Askham Limestone		(7' visible)	
Flaggy, sandy and carbonaceous limestone		1'	0"
Poorly bedded yellow and grey soft crumbly siltstones		2'	0"
Hard white sandstone with mica, carbonaceous dust and pyritic nodules		0'	9"
Orange-mottled, calcareous, ferruginous sandstone		0'	6"
Soft, pale grey, crumbly shale		1'	0"
Hard, thin-bedded, silty grey sandstone		0'	6"
Break; some shale visible	c.	5'	6"
Gaythorn Limestone			
Total		11'	3"

The sub-division is present throughout Gaythorn Plain where it can be seen in sinks or is indicated by a belt of tufty yellow grass and heather. Tiny molds of shell fragments may be present and there is some evidence of thickness variations.

Reagill-Morland sub area

No definitely in-situ rock is seen in the Meaburn sub-area, but it appears in the steep northern valley side of Dalebanks Beck in the vicinity of Haber and above High Dalebanks. Here, small quarries and excavations for the newly-installed electricity line, show pale yellow, slightly micaceous and often orange-speckled, medium or fine-grained sandstone. Fine-grained sandstone, just below the Askham Limestone, is also visible at the old limekiln near the Oddendale Fault, where molds of shell fragments occur in the top 5 inches but are associated with traces of plant roots which continue to a few inches below.

Strickland sub-area

The unit is poorly exposed but sandstone can be seen in the small escarpment on the opposite side of the road from Wintertarn Quarries, and locally at the base of the Askham Limestone feature south-south-east of Gunnerwell Farm, where some is strongly iron-stained. Sandstone can also be found in the wood south-west of the farm, but northwards it is obscured by glacial deposits.

ii) Askham Cyclothem

a. SUMMARY

The cycle starts with the oldest of the major Yoredale Limestones which maintains a fairly constant thickness of about 40 feet throughout the area and, in its upper part, contains an algal horizon which may be the equivalent of the Girvanella Band of the Pennines. The Limestone is well exposed, the lower beds frequently forming a distinct feature, backed by a wide bench and ending in a line of sinks, above which is the steep escarpment of the overlying clastic beds. These, averaging 100 feet, include the thickest shale sequence in the region and often two sandstone horizons, although the lower one is only poorly developed. To the south-east, a thin ferruginous limestone, the Halligill, is present in the middle of the unit but seems to have a very restricted distribution. There is evidence that the overlying sandstone can have an erosional base, and on Linglow Hill, at the southern margin of the area, it appears to have cut down almost to the level of the Halligill Limestone.

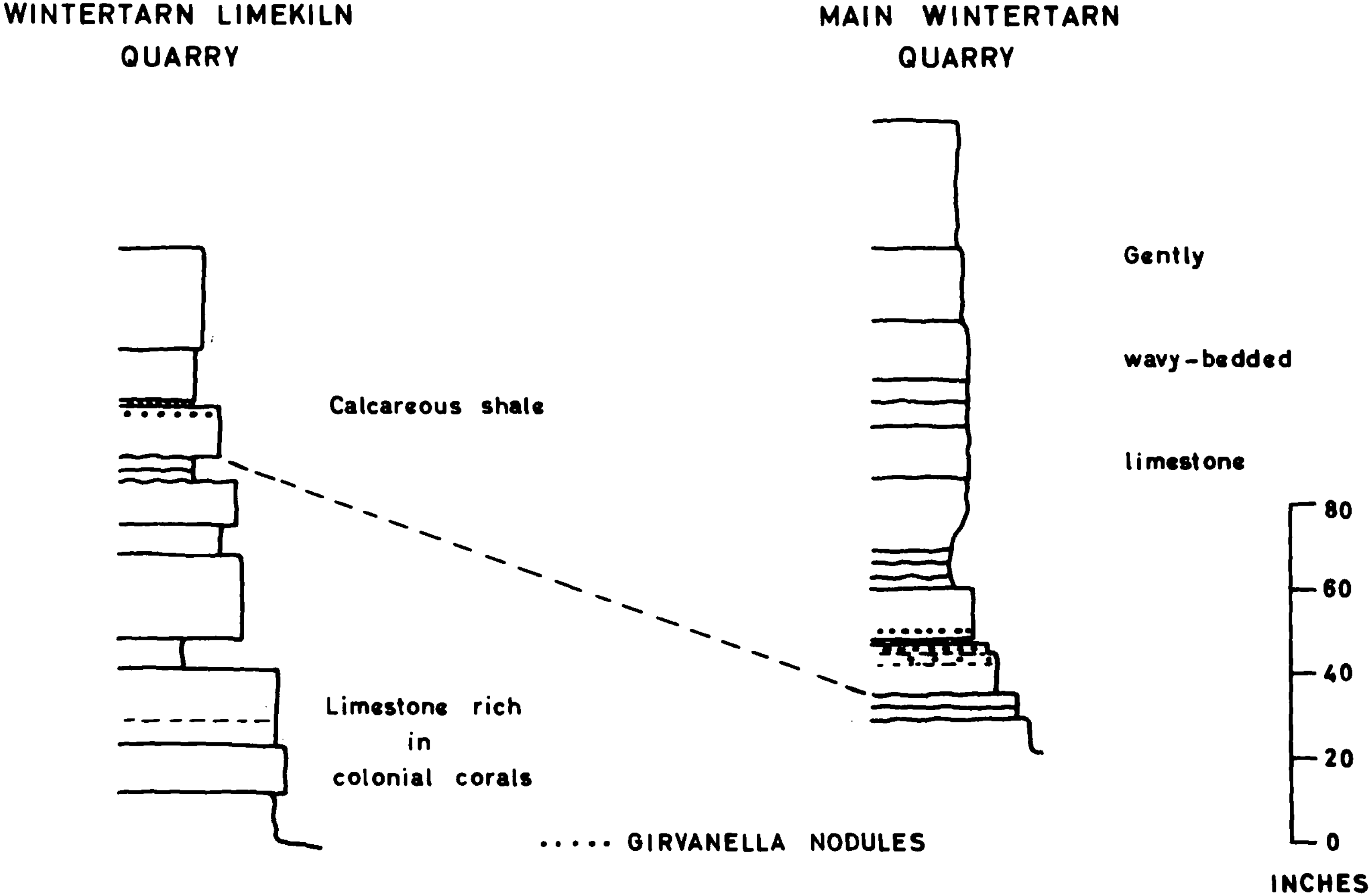
b. THE ASKHAM LIMESTONE

Strickland sub-area

A good section of the Limestone is seen in the Wintertarn Quarries where a band of Girvanella nodules is well developed; the details of the succession are shown in Fig. 2.6. The Limestone is pale-weathering and medium- and thick-bedded with fairly even major bedding-planes. It is medium grey and quite fossiliferous, being especially rich in colonial corals near the base. The algal band occurs high in the quarry adjacent to the limekiln but low in the succession in the main quarry to the east and is easily recognised because it lies on either side of an in-weathering shale horizon. Here the limestone over a distance of about 10 inches has abundant Girvanella nodules, though of rather sporadic distribution, which are dark in colour on fresh surfaces but can best be seen where weathered, since the pyrite they contain produces a pale red-brown stain which has a distinct concentric structure.

Small quarries nearer Wintertarn Farm show the coral and algal horizons but further north-west only occasional swallow-holes indicate the position of the Limestone and a thick mantle of glacial

Figure 2.6

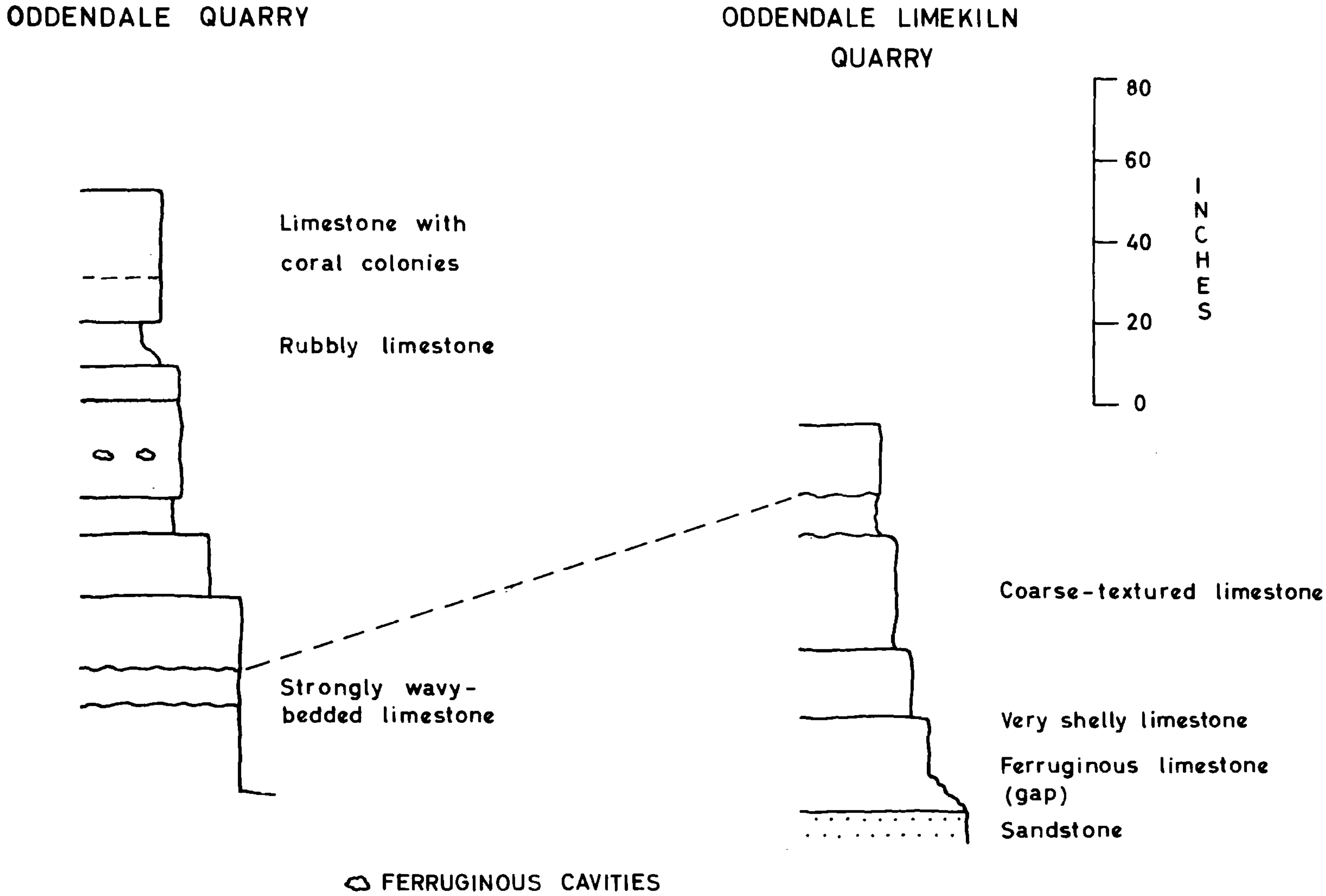


MEASURED SECTIONS IN THE ASKHAM LIMESTONE material obscures the solid geology until Gunnerwell is approached, when the Limestone is visible in a distinct feature. It also occurs north-west of the farm and by the strong spring at Gunner Keld where, in both cases, limestone rich in a large species of Lithostrotion can be seen. Several small quarries in the banks of Gunnerkeld Sike show the same Limestone which is often mottled, rather nodular-weathering and frequently fine-grained. North of Edgebrow Bridge, no exposures occur, although several strong springs suggest that the top of the Limestone approaches river-level near the confluence of Shap Beck with Gunnerkeld Sike, and limestone in the nearby railway-cutting is almost certainly from this horizon.

Reagill-Morland sub-area

Eastwards from Wintertarn the outcrop is covered by drumlin-like masses near Broadslack and at Plover Rigg but the highest bed is visible in Plover Sike. It is hard, dark-grey and sometimes slightly ferruginous-weathering with crinoid and shell fragments, becoming softer and paler upwards and passing into a poorly-bedded dark crinoidal shale. To the south, the Limestone seems to occupy a large area west of Wyebourne, and south of the Shap-Crosby Ravensworth road, it lies near the surface, producing a small scarp feature and with a line of sinks marking its upper boundary. They can be traced to near Oddendale where quarries show thick-bedded medium- or pale-medium-grey limestone with scattered colonial corals, to a height of about 16 feet above the base (Fig. 2.7). Near the old limekiln the lowest limestone is seen and, at about 4 feet above the base, is a characteristic bed of pale, coarse-textured limestone, which can be found at intervals along the whole length of the Askham Limestone outcrop. The Girvanella band does not occur in this succession so that 16 feet is a minimum value for its height above the base; also, since the succession does not compare with that at Wintertarn Quarry (Fig. 2.6), the suggestion is that the latter may lie entirely above the top limestone seen here, hence making the Girvanella band at least 24 feet above the base of the Askham Limestone. However, the highest beds form scars for a considerable distance on either side of the quarry, showing pale and rather rubbly-

Figure 2.7



MEASURED SECTIONS IN THE ASKHAM LIMESTONE weathering limestone with quite large Lithostrotion colonies, and throughout the area a bed with these characteristics occurs in this position. Because it seems to be a particularly coral-rich horizon, it possibly is equivalent to the base of the Wintertarn succession, thus making the Girvanella band about 22 feet 6 inches above the base.

The base of the Limestone can be traced north of Oddendale hamlet and down to Dalebanks by a series of small exposures showing quite thin-bedded, often mottled limestone, with occasional excavations at higher horizons and a line of sinks at the top. These then die out but several exposures, notably in Blind Beck and along the Oddendale road as scars of medium- and quite dark-grey limestone just above Dalebanks Beck, show that the Limestone dips down to reach the Lyvennet Valley in the neighbourhood of Crosby Ravensworth. No rock is seen here but strong springs at Crosby Hall Farm suggest that the top of the Limestone is nearby.

Meaburn sub-area

The Limestone is seen in many small quarries between Crosby Ravensworth and the Orton-Appleby road but no large section occurs. In the Lyvennet, about 11 feet of the lower beds are seen as bluffs in the right bank, where the pale coarse-textured limestone can be recognised. This bed is also seen in the woods on either side of the Howarcles Fault and along the feature to the south above Hill Crest; in all cases the pale limestone passes up into medium-grey, fairly fine-grained limestone. A second feature showing slightly higher beds is present above Hill Crest where they have a pale crumbly nature similar to the pseudo-breccias described by Garwood (1912, p.477). Higher horizons are only poorly seen but a quarry south-east of Howarcles shows dull, medium-grey limestone which contains slightly ferruginous-weathering, darker nodules, almost certainly of algal origin. From its apparently high position, it is likely that it is not the time-equivalent of the Girvanella band found at Wintertarn.

Drybeck-Asby sub-area

A large area of Gaythorn Plain consists of the dip slope of the Askham Limestone (Plate 4) and shows much limestone pavement with excellent development of pseudo-breccias in beds from the middle of the Limestone; fossils generally are not very evident. From the Plain the outcrop runs down towards Gaythorn Hall and, beyond the inlier of older rocks, forms the bed of Scale Beck as far as the wood north of the farm. Downstream, drift and alluvium covers the Limestone but it reappears to the east in Halligill Beck (Fig. 4.15) where the top part forms a series of falls at the north end of the gorge. Thick-bedded, fairly fine-grained, mostly medium-grey limestone is visible and the lowest 6 inch bed, about 14 feet below the top, has small dark markings which appear to be algal in origin. Above is medium-bedded limestone of darker colour, with a horizon rich in pyrite and containing a few spherical white bodies which are more abundant just below and appear to be foraminifera. Pyritic and argillaceous limestone can also be found in sinks at the top of the Limestone around Linglow Hill.

The base of the Limestone is visible in the scars at the head of the eastern tributary of Scale Beck where it is of semi-transitional nature lying on a bed of sandy carbonaceous limestone from which it is separated by a distinct bedding-plane. The Limestone is hard, rather impure and poorly-bedded, breaking into angular blocks - a characteristic feature of these lowest beds. They are also well seen in the feature which curves across Gaythorn Plain, where a horizon with abundant colonial corals, especially Diphyphyllum, is present. At the eastern end of this feature, by the Asby road, the coarse-textured limestone with irony spots is again visible and is overlain by medium- pale grey limestone with a pseudo-breccia band and many corals including Lithostrotion and Chaetetes. Another coral-rich horizon, but higher in the limestone, occurs 200 yards south-west of the bungalow near Gaythorn Tilery where Lithostrotion martini and Lonsdaleia floriformis can be found as well as large simple corals.

Beds in the upper half of the Limestone are seen in a series of small quarries around Hollin Stump, which show fairly thin- and wavy-bedded medium-grey limestone. Only doubtful algal traces occur except in the quarry nearest to the Asby road where, in the middle, is a bed of fine-grained darker limestone with small Girvanella nodules. Its height relative to the base cannot be estimated but, from the position of the

PLATE 3. Small escarpment in the lowest Yoredale strata on Gaythorn Plain.

PLATE 4. Dip slope of the Askham Limestone at Gaythorn Plain and the Marksclose Wood outlier.

outcrop, it may be rather higher than the algal band at Wintertarn, though it is not, of course, necessarily the same horizon. More weight is lent to this possibility by the occurrence of dark algal-like markings in the quarry 200 yards south-west of the Tumulus which must be at a lower level.

The outcrop of the Limestone is obscure north-east from Gaythorn Plain probably due to a drift cover until, $\frac{1}{4}$ mile north of Whitewall, sinks appear and a large quarry shows beds in the upper part of the succession. In the lowest few feet of the limestone dark algal traces and coatings of crinoid debris are common. The Limestone can be traced to below Stannerstones where very large sinks mark the position of its top but nearer Great Asby glacial material again covers the solid rocks and it is not seen west of Asby Beck.

c. THE ASKHAM CLASTICS

Drybeck-Asby sub-area

The unit is very well exposed, especially in the southern tributaries of Scale Beck, of which the gorge of Halligill Beck provides the most continuous section (Fig. 4.15). The Askham Limestone passes up by alternation into fossiliferous shale, the lower part having predominant brachiopods and crinoid fragments with bands of hard, argillaceous, crinoidal limestone but passing up into dark crumbly shale with abundant thin-shelled brachiopods, small crinoid ossicles, lamellibranchs, bryozoa and with numerous large septarian nodules. The fossils die out rapidly upwards and the shale becomes more compact and blocky, splitting easily on joints and what appear to be curved bedding-planes. Concretions still occur but are smaller and less common, sometimes with unusual tube-like internal structures, and the shales tend to weather with a ferruginous stain; near the base thin, branching, gently curved, yellow-brown or grey-green streaks of unknown origin are characteristic. These beds, which are over 40 feet thick, are exposed, though mostly inaccessible, in the gorge to the south and get gradually more silty upwards, often having mica and plant debris on bedding-planes; small concretions may still occur. Impersistent thin fine sandstones and

and silty sandstones which are quite carbonaceous and micaceous with a tendency to ferruginous-weathering lie high in the succession. However, the beds fine again upwards and immediately below the Halligill Limestone are 10 feet of micaceous, carbonaceous, silty shales and laminated siltstones.

The stream has cut down to a fairly constant horizon not far above the top of the fossiliferous shales which appear mid-way along the gorge and again at its south end. Here the nodular argillaceous limestone bands also occur indicating that the Askham Limestone is only a few feet below. At the heads of small side gullies, especially the westerly ones, the Halligill Limestone can often be seen. It is an impure limestone, often silty and reddish-weathering at the base with large Productids common, and occurs as thick-bedded blocks. Good sections do not exist, but it seems to be between 3 feet and 5 feet thick, and is overlain by ferruginous-weathering, finely cross-bedded, silty shales. Above, palish ferruginous shales, sometimes with a few irony nodules, seem to continue to at least 24 feet above the Limestone and there is no evidence of any sandstone in this interval.

Only small exposures occur in Scale Beck itself but the thick shale and siltstone sequence is also well displayed in Shale Gill, to the east, though it does not cut down as far as the fossiliferous shales. Nor, in the gorge, is the Halligill Limestone seen, though many loose blocks of amber-weathering limestone at its upper end and upstream south of the wood, indicate that it lies not far above the exposed rock. A four-inch, parallel-bedded horizon of very fine-grained grey sandstone and a one-inch, wavy-laminated sandstone above, are the only sandstones seen, so that the succession is finer than at Halligill Gorge; this westward-coarsening trend is continued in the stream west of Halligill Beck where rather more sandstone is visible. Here, well below the Halligill Limestone, at least 4 feet of sandstone is present, resting on shales with silty laminations and having soft irony nodules at the base. The sandstone is silty and in even $\frac{1}{2}$- to 1-inch beds at the base with much mica and plant material on bedding planes, but becomes thicker bedded upwards with wavy laminations and broad curved trails on some bedding surfaces. At the top the beds get thinner and more silty again, with some straight or broadly curved ripples. The fining is continued upwards and a series of dull, olive-grey shales capped by regularly striped palish grey silty shales intervenes before the Halligill Limestone. Marine fossils, though rare, were found between 1' 6" and 2' 6" below the Limestone. The latter is here well seen as jointed blocks in the stream bed (and its western tributary) at the top of some rapids, where 2' 6" occur. It is dark, hard and amber-weathering with many shell and crinoid fragments, a few coral colonies, and again, large complete Productids are characteristic of the lowest bed. At the base it becomes very impure and orange-weathering and the basal-surface is covered with shell molds (ribbed and smooth brachiopods and trilobites).

The Halligill Limestone is not well exposed elsewhere but its position can be traced by means of numerous sink-holes around most of Linglow Hill and across to Halligill Gorge. East of the gorge, its exact position is generally less certain, though its thickness is probably maintained to the south-east since it gives rise to sinks on the hill east of the headwaters of Shale Gill. In Scale Beck it appears as about 1 foot of hard, medium-grey, well-jointed limestone which is strongly reddened, and this may be close to its true thickness since it does not appear anywhere along the north side of Scale Beck and may die out in a northerly direction. An unusual feature of its distribution is the apparent absence from the south-west side of Linglow Hill for, although little <u>in situ</u> rock is visible, vegetation and features give a good indication of the geology. The upper part of the Hill is in sandstone, whose lower limit is marked by a change from heather to long, tufty, yellow grass together with a distinct bench feature and several springs and seepages. Below this, neither the slope nor the vegetation suggest that any limestone occurs before the Askham Limestone is reached. It could be argued that because of the dip of the beds into the hillside no spring-line would be expected and glacial drift might obscure any influence on vegetation. However, the hill presents a fairly steep slope well above 1000 feet where drift deposition is unlikely - and the sandstone workings show that it is absent just above. The Halligill Limestone can, in fact, be traced by means of a series of sink-holes as far as the westerly and south-easterly stone walls on the hill, making its apparent absence from the slope between more difficult to understand unless the overlying sandstone has a locally erosive base and the Limestone was removed prior to its deposition. That this is a definite possibility is shown by the following measurements:

Thickness between the Askham and Halligill Limestones at Halligill Gorge	51' - 55'
Height from the top of the Askham Limestone to the base of the Halligill Limestone by the west wall of Linglow Hill	52'
Height from the top of the Askham Limestone to the base of the sandstone feature by the south-west wall of Linglow Hill	54'

Clearly the base of the sandstone seems to occur at about the same height above the Askham Limestone as does the Halligill Limestone elsewhere. Some doubt must remain since these measurements do not take into account any additional thickness between these horizons due to the dip - a factor which is too variable, both in direction and amount, to estimate with any accuracy. Because of this it is still possible that the Limestone is present, but obscured, some way below the sandstone feature but there is little doubt that the sandstone must cut to a lower horizon than it does to the east, and is consequently appreciably thicker here. This mass of resistant sandstone and the local synclinal dips, probably largely account for the existence of the hill, an outlier of considerable size.

This upper sandstone, though undoubtedly a persistent band, is not well exposed except for the top part which is seen in several small workings and is pale-purple or buff in colour with some pockets of mica. On Linglow Hill itself, it has been extensively quarried and can be traced to the north and north-east on either side of Marksclose Wood with the aid of small outcrops and vegetation of an acid-loving type, to the hill, west of Halligill Gorge, which it caps. In general, lower horizons tend to be quite thin-bedded, micaceous and orange-speckled but upwards beds are thicker, often showing cross-laminations and may be of medium-grain size.

Eastwards, above Great Asby at Stannerstones, the clastics reach a maximum estimated thickness of 115 feet. The shales are seen in a stream south-west of the buildings, otherwise the beds below the highest sandstone are not exposed. The latter, however, is well seen in a series of quarries, and is often calcareous for varying thicknesses at the top.

This calcareous sandstone has gently wavy beds and may pass laterally into a non-calcareous rock, possibly suggesting that at least part of the calcification is not a primary depositional feature.

The sandstone is not exposed in Scale Beck, having been cut out by a large north-westerly trending fault. Just west of the fault, some shales with brachiopods and crinoid fragments occur in the stream; presumably they belong to the shale sequence above the Halligill Limestone, although similar beds have not been found elsewhere. North of Scale Beck the clastics are only rarely seen but large excavations, long-since abandoned, were made in the shales when the Gaythorn Tilery was in production.

Meaburn sub-area

Only scattered exposures occur in the steep feature which marks the outcrop of this unit most of the way from Bank Moor to the Lyvennet, and is especially well developed south of the Howarcles Fault where an estimated thickness of 96 feet of clastics is present. Here, a spring issues from the base of the main sandstone and further north, south of Bell Foot, this horizon is clearly marked by a long belt of water seepage and small springs. These form a stream which, just north of the end of the line of seepage, shows shale passing up into carbonaceous sandstone, and is of interest because of the absence of any limestone. It stongly suggests that there are here no calcareous beds equivalent to the Halligill Limestone to the south. Beds lower down in the cycle are seen in the steep right bank of the Lyvennet where they consist of sandstone, siltstone and shale in rhythmically-bedded units averaging about 2' 6" in thickness. No exposures occur in the river itself, which has produced a wide alluvial flood-plain, north of Crosby Ravensworth, in the softer horizons.

Reagill-Morland sub-area

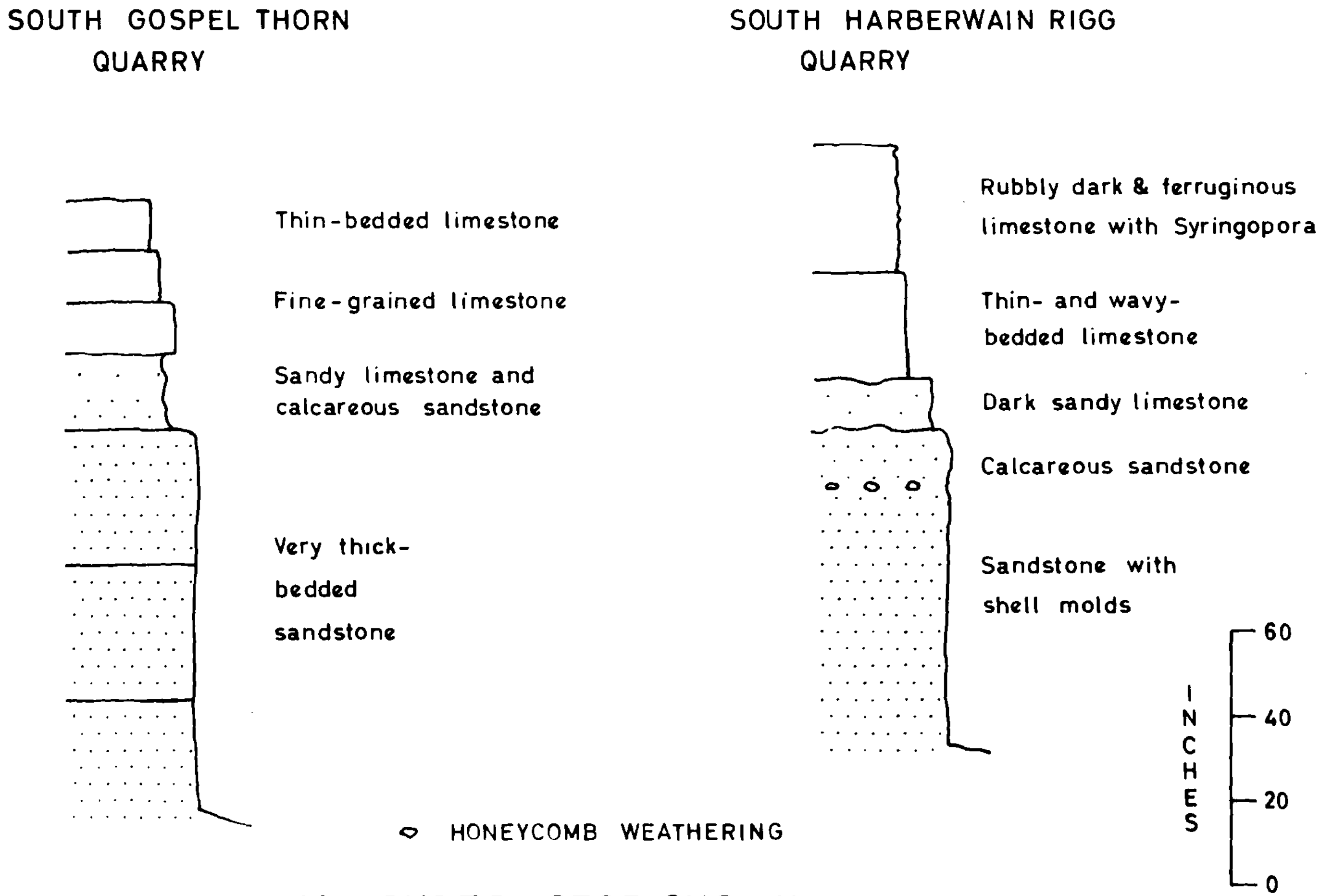
Continuous sections are absent though many small exposures occur and the unit, because of the easily eroded shales at the base, again produces a large feature throughout the area. Scattered flaggy, orange and brown spotted sandstone and shale exposures are seen above High Dalebanks in the sides of three deeply-incised streams and are probably from the lower sandstone horizon. The north-easterly one is of particular interest because, near its source, in the left valley side, is some pale but orange-mottled calcareous sandstone which weathers to a deep uniform orange colour and then shows tiny molds of fossil fragments and occasionally complete brachiopod impressions. Although the rock is loose, much occurs and is probably almost in situ; it represents the only evidence for closely-marine conditions in the centre of the cycle outside the area where the Halligill Limestone is developed, but may be rather nearer the base of the Bank Moor Limestone than the latter.

The highest part of the top sandstone is seen in the quarries south of Gospel Thorn (Fig. 2.8) where it is very thick bedded with well developed and approximately parallel bedding-planes separating apparently structureless pale purple or yellow sandstone. There is a thin transitional zone of calcareous sandstone with molds of shell fragments before the Bank Moor Limestone, the zone being separated from the underlying sandstone by a distinct bedding-plane. This is not the relationship seen further west, south of Harberwain Rigg (Fig. 2.8), where there is a continuous transition from fairly parallel-bedded sandstone, through calcareous sandstone with honeycomb weathering, to the sandy grey and maroon-mottled base of the Bank Moor Limestone (Plate 49). All but the lowest few inches of sandstone contain molds of shell fragments though these are very small and scarce low down, and although a clear bedding plane occurs high in the calcareous sandstone, it separates beds of identical nature.

To the north, no large exposures occur before Plover Sike where fossiliferous shales and argillaceous limestone are visible to about 9 feet above the Askham Limestone. The top bed of limestone passes up into poorly bedded, dark, crinoidal shale, followed by shale with iron-stained fossils including very small crinoid fragments, bryozoa, lamellibranchs and brachiopods. At about 5 feet above the Askham Limestone is a hard, dark, red- or orange-weathering, 5" argillaceous limestone similar to those in Halligill Beck. Very weathered fossiliferous shale with irregular shaped septarian nodules occurs above.

The sandstone immediately below the Bank Moor Limestone is seen at

Figure 2.8



MEASURED SECTIONS IN
THE ASKHAM SANDSTONE AND BANK MOOR LIMESTONE

several places in the steep valley sides of Threaplands Gill near the old bridge. The highest part is poorly exposed but includes a sandstone bed with better developed in situ plant remains than is seen anywhere to the south-east, and which appears to be overlain by 3 feet of soft shale which, at the base, is very dark and carbonaceous; the Bank Moor Limestone follows immediately. Up to 10 feet of sandstone below is seen above the path on the right bank, only in the top 2' - 3' massive part of which do in situ plant remains occur, though carbonaceous material is found in pockets in the underlying sandstone which is more markedly cross-bedded than that seen elsewhere at this horizon. A steep-sided washout can be recognised but some of the major bedding-planes are so irregular that post-depositional movement must have produced over-steepening. Estimated thicknesses of 100 feet in Plover Sike and 90 feet at Harberwain Rigg suggest that the unit shows little variation throughout its outcrop, though the latter narrows slightly to the north-west where there may be some reduction in thickness.

Strickland sub-area

All except the upper part of the unit is poorly exposed in the district, although steep features continue to mark its outcrop. Small exposures in the steep valley side south of Towcett cross-roads show that sandstone in the middle of the cycle maintains its flaggy, buff, and orange-speckled character with mica and plant debris on bedding-planes, and to the north-west, above Marthergill, the thickest development of ganister at the top of the sandstone is visible in a long series of workings. The ganister is hard, medium-grained, buff coloured often with orange speckles and is without mica; bedding-planes are absent and it reaches a maximum of just over 4 feet at one locality. A few ochreous nodules now mostly weathered to oxides are present, but occasionally spherical ones can be found in which the original pyrite is preserved.

iii) Bank Moor Cyclothem

a. SUMMARY

The cycle is amongst the thinnest of those studied, averaging about 65 feet and changing little in thickness throughout the region. The Limestone member is visible in many quarries but sections in the beds above are uncommon. They often form steeper ground below the bench due to the Maulds Meaburn Limestone but, because of their thinness (30 to 35 feet) and the absence of much shale, the feature is rarely very pronounced. The Limestone, characterised by strongly ferruginous beds at the base and by a band in the middle in which Lithostrotion junceum is very well developed, is about 30 feet thick and generally produces a distinct flat area above the steep feature of the Askham clastic succession.

b. THE BANK MOOR LIMESTONE

Drybeck-Asby sub-area

The Limestone takes its name from the upland area west of the headwaters of Scale Beck but is here only poorly exposed. Sinks clearly mark its upper boundary across Bank Moor, in some of which, argillaceous, yellowish-weathering limestone is visible and is capped by a 4 inch bed of calcareous mudstone with large Productid shells. A vegetation change occurs at the bottom of the Limestone in the same area, and it, too, is locally marked by sinks due to streams draining from the Askham clastics forming the high ground to the south. They show limestone typical of this horizon with medium-bedding, dull grey colour and abundant shell and crinoid fragments. To the north-east, along the north side of Scale Beck, the

Limestone can be seen by a small spring, north-west of Gaythorn Hall, where it contains Syringopora and between the Harding's Wood and Drybeck Moor Faults where it forms a very pronounced feature, along which angular blocks of very hard, medium-grey, slightly bituminous-smelling limestone are common; it is here approximately 32 feet thick. No further exposures occur north of Scale Beck and because of the Scalebeck Fault it does not appear in the stream. However, three outliers occur on the hills to the south of the stream, the localities being, from south-west to north-east, Marksclose Wood, Halligill and Stannerstones.

The Marksclose Wood outlier (Plate 4) is fairly well exposed and occurs on the down-dip side of Linglow Hill. There is no doubt that the mapping of this horizon as the Maulds Meaburn Limestone by the Geological Survey is in error, both because of its position relative to the Askham and Halligill Limestones and because of its lithology including the presence of the Lithostrotion junceum Band. The Limestone produces an even-topped, gently sloping hill but with scarps on the west and east sides having several small quarries, two of which, east of the wood, show colonies of Lithostrotion junceum and much loose material suggests that a band was once exposed; large simple corals, brachiopods and Syringopora can also be found.

The boundaries of the Halligill outlier are mainly conjectural, the Limestone only being seen at and around the farmhouse where it is thick-bedded, medium-pale-grey in colour and with some colonial corals visible in the quarry in the small wood. This is also true of the northern part of the faulted Stannerstones outlier, where the Limestone is nowhere seen but on thickness grounds must occur round the hill west of the Scalebeck Fault and north of Twins Cottage. However, in the vicinity of Stannerstones, several quarries provide good exposures of its lower part, which here is anomalous in having a 4 foot sandstone horizon at about 6 feet above the base. This is best seen at the top of the quarry south of the fieldhouse lying west of the buildings, where it is medium- and thin-bedded, micaceous, and with wavy bedding-planes; it lies on soft, very micaceous, silty sandstone. The limestone below is massive and fine-grained with some shell and crinoid fragments and Syringopora. At the base there is a transitional zone of sandy limestone and calcareous sandstone of purple and pale green colour and often having honeycomb-weathering like the equivalent beds on Harberwain Rigg.

The base of the lower limestone is visible in the quarry just south of the buildings and again east of the sheepfold but the quarry further to the north-east, because of its relatively high position, is thought to show the base of the main limestone body resting again on calcareous sandstone. The Limestone has not been recognised nearer Great Asby, having been cut off by the Scalebeck Fault, but it is thought to be responsible for the large sink-hole in the valley $\frac{1}{4}$ mile east of Stannerstones.

Meaburn sub-area

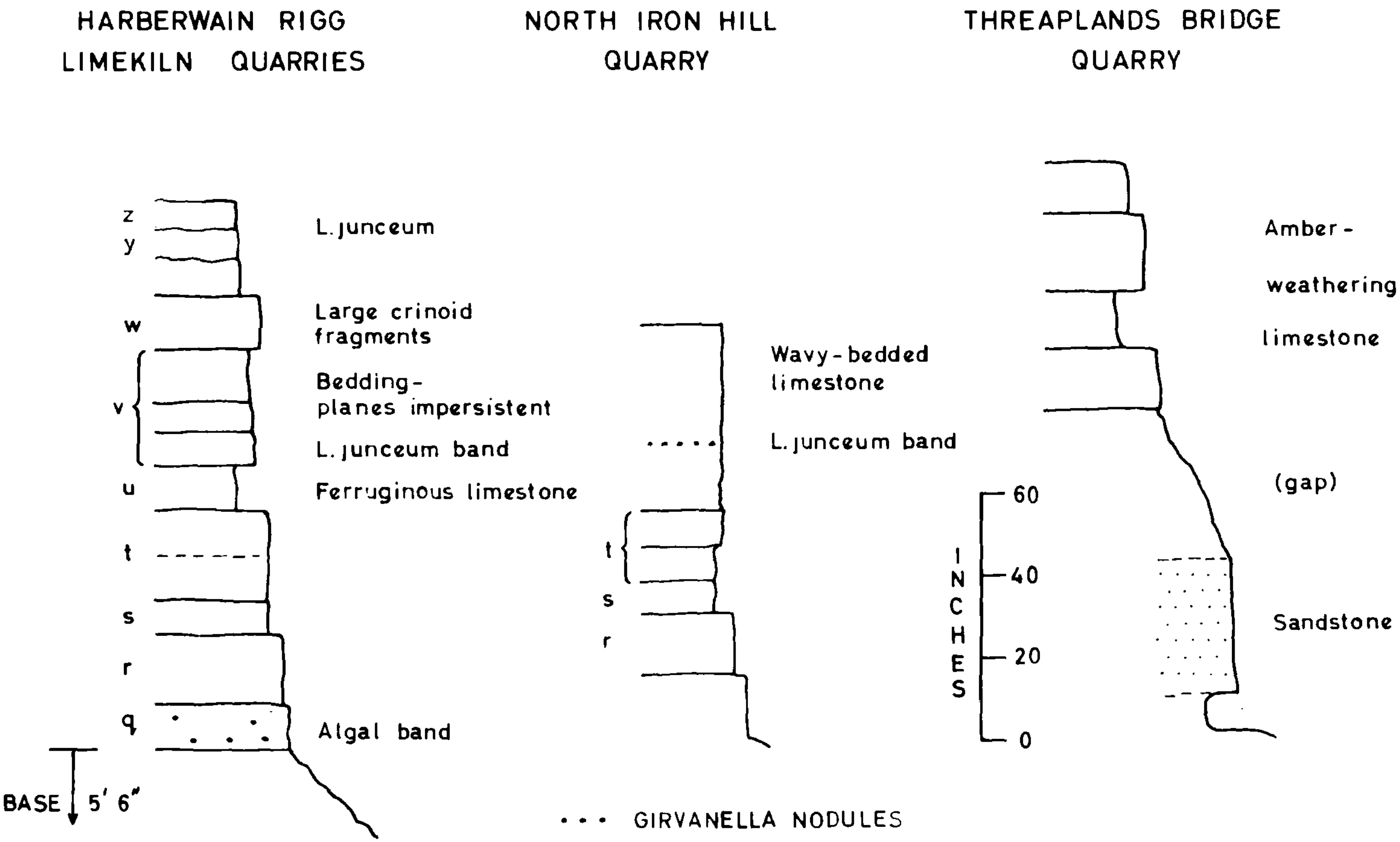
North-west from the Appleby-Orton road, the Limestone forms a bench above the feature due to the Askham clastics, at first occuring in the upper part of this feature but further north-west having its base at the change of slope. Possible algal nodules were found at this horizon on the north-west edge of Bank Moor.

The Howarcles Fault clearly displaces the Limestone to the west on the north side, and just beyond it, a long quarry shows its base. It is rubbly-weathering, mottled and very shelly with a ferruginous zone at the base in which corals in overturned positions occur. Northwards, the sink-holes, which had marked its upper limit, die out and it cannot be traced accurately except below Bank Head Quarries where a spring rises at its base. Neither the Limestone nor the clastics above are seen in the Lyvennet.

Reagill-Morland sub-area

The middle and lower part of the Limestone is very well exposed in several quarries south of Harberwain Rigg whose details are shown in Figs. 2.8 and 2.9. A total of 16$\frac{1}{2}$ feet of limestone is visible in which the most important horizons are, an algal band (bed q) 5' 6" above the base which is below all but the quarry near the old limekiln, and the <u>Lithostrotion junceum</u> Band (bed v, lower part) which is very well developed in all the quarries and lies 11' 3" above the base of the Limestone. Individual beds, varying little in thickness, can be easily correlated between quarries and recognised as far as the Shap road

Figure 2.9



MEASURED SECTIONS IN THE BANK MOOR LIMESTONE to the north and Haber to the east. Particularly distinctive are three beds of approximately equal thickness in the middle of the succession (beds s and t, t often being split in the middle), and a strongly in-weathered ferruginous horizon (u) just below the Coral Band. The limestone is medium- and fairly even-bedded, medium to dark grey and weathers to a dull slightly yellowish-grey colour.

Similar features are seen in the series of quarries in the small feature north from Iron Hill (Fig. 2.9) and to the east in the quarries south-east of High Haber. The former clearly shows the Lithostrotion junceum Band with, locally, larger colonial corals, crinoids and brachiopods 1' 3" higher (bed w), and low in the latter, by the old limekiln, is the most easterly locality where the algal horizon can be recognised, with the possible exception of one exposure on Bank Moor.

Throughout this well-quarried area, the top of the Limestone is clearly shown by the presence of numerous sinks, in some of which the Limestone is visible. It is brownish grey and contains thick-shelled brachiopods, occasional Lithostrotion colonies and possibly some algal markings. The sinks die out east of High Haber and no evidence for the position of the Limestone exists apart from the probability that Howe Beck rises from a strong spring at its top.

Just north of the Shap road, quarries occur in the lower beds of the Limestone and sinks allow it to be traced east of Wyebourne to Threaplands Gill where it is visible in a quarry at the west end of the bridge (Fig. 2.9) and in the steep valley sides. The lowest bed is a distinctive pale limestone with ferruginous areas and dark markings, weathering with a sandy texture; it is poorly-bedded but followed by thick beds of dark, impure, very hard limestone which has molds of shell fragments and weathers to an amber colour. Upwards it gets less ferruginous and long scars in the east valley side show medium- and even-bedded, quite dark limestone in which the Lithostrotion junceum Band can still be recognised. The Limestone is here 29 feet thick, which is not significantly less than that above Scale Beck.

Strickland sub-area

The Limestone is poorly exposed and, apart from small quarries in the east near Edge where loose Lithostrotion junceum represents the most north-westerly occurrence of the Band, only beds near the base are seen. A long quarry at the top of a feature north of Wintertarn Farm is mostly overgrown but the algal horizon near the base of the Limestone can be distinguished. As in the quarries at Harberwain, the irony-weathering, dark nodules are most abundant at the base of the bed in which they occur; though irony patches are sometimes seen above, they are more irregular in shape and usually smaller. Colonial corals are present both in the bed above the algal horizon and in the ferruginous limestones below it.

To the north, the only exposures are of the ferruginous lower beds in the wood above Marthergill where Lithostrotion martini can be found, but its position is indicated at a few places by orange-brown soil and, at the western margin of the area, it is seen in the River Leith at Thrimby Grange.

c. THE BANK MOOR CLASTICS

Drybeck-Asby sub-area

Only small scattered exposures, mostly of the sandstone at the top of the clastics, occur. Sandstone with carbonaceous streaks is seen in the stream below Scale Beck Quarries and upstream, where it is pale-purple and micaceous and has strong dips due to the proximity of the Scalebeck Fault. The dip brings the Maulds Meaburn Limestone into the stream for a short distance downstream but then it cuts down to produce an inlier of the Bank Moor clastics which are visible east of the road-bridge. Immediately below the Limestone is fairly fine-grained sandstone which becomes thin bedded lower down and has very micaceous bedding-planes with plant remains and, sometimes, regular asymmetrical ripple-marks.

Westwards, in the north valley side of Scale Beck, little is seen of the unit until, at the large quarry north of Gaythorn Hall (Fig. 2.10), 4 feet of yellow, medium-fine-grained, micaceous sandstone with faint in situ plant traces is visible and capped by 6 inches of very ferruginous sandstone with small fossil molds. The only exposure of lower horizons is in a sink-hole on Bank Moor, where 1' 3" of crumbly shales lie on the

Bank Moor Limestone and within 6 feet flaggy, fine-grained sandstone associated with pale-grey shale, occurs.

Meaburn sub-area

North-west from the Orton-Appleby road, the clastics, having an estimated thickness of 34 feet, form a small but well developed feature in which sandstone is visible and up to 2 feet of thin-bedded crumbly shale with pale orange ferruginous nodules is seen in sinks at the base. The only large exposure in the whole region lies further north at the quarries west of Bank Head Farm (Plate 5), where about 17 feet of massive and thick-bedded sandstone with thin shale partings is visible and passes up, via calcareous sandstone, into the Maulds Meaburn Limestone. The sandstone is probably mostly cross-bedded but the laminations are not usually very apparent, and the major bedding-planes are often quite parallel. Some have shale horizons up to a few inches, but generally less than one inch, thick and into these (occasionally into sandstones too) some of the sandstone beds cut in broadly lenticular fashion. One such bed has, in its lower part, numerous pellets of plastic, khakhi-coloured clay (though of only small lateral extent) which are unlike the dark grey, micaceous shale below. The sandstone is of varying lithology and colour, being purple, lilac, pink and white and often has a ferruginous speckle; upwards, it becomes yellow and has specks of carbonaceous material. Shale partings are thicker to the south where 3" to 5" horizons occur and include some sandy silts. Northwards, massive sandstone just below the Maulds Meaburn Limestone is seen at Bell Foot but beyond, no further exposures occur.

Reagill-Morland sub-area

Beds high in the unit are seen west of the Lyvennet near Crake Trees where the usual transition from sandstone to limestone does not occur. Above the main sandstone body are alternations of soft, very thin-bedded, grey or ferruginous, silty sandstone with mica and plant material on bedding-planes, and thicker grey sandstone with patches of pyrite. Between these and very ferruginous impure limestone, a shale horizon intervenes.

No further exposures occur to the west until the sinks at Harberwain Rigg are reached, where dark, crumbly shales, pale-grey, micaceous and carbonaceous, poorly-bedded siltstone and medium-bedded, flaggy, orange-speckled sandstone are seen in slumps within a short distance of the top of the Bank Moor Limestone. Here too, sandstone rich in pyrite can be found, apparently only 1 foot above the Limestone. At Iron Hill (Fig. 4.10 and Plate 47), a transitional relationship between the sandstone and the Maulds Meaburn Limestone again occurs. The sandstone, which is buff or yellow with carbonaceous specks and some mica on bedding-planes, is superficially massive but weathering reveals thin and medium beds of considerable lateral extent and many gently-wavy laminations. Above, sometimes with a bedding-plane between but not separating beds of different lithology, it passes into a pale pinkish-amber calcareous sandstone which is harder at the top and contains an increasing number of crinoid and small shell fragments upwards.

A little sandstone is seen at intervals northwards to the Shap road but no exposures then occur until, in the steep east valley side of Threaplands Gill, the transitional junction and the sandstone immediately below is again visible. The unit remains about 34 feet thick.

Strickland sub-area

The clastics are very poorly exposed but their position can be estimated from that of the Maulds Meaburn Limestone which often has been quarried as far north as Edge Brow. North of Wintertarn are old sand excavations just below the Maulds Meaburn Limestone in which pale brown calcareous sandstone is visible and the sandstone below is of interest because it contains orange-brown tube-like markings which are almost certainly the remains of plant roots, a feature not commonly seen where the calcareous, fossiliferous sandstone occurs above. North from Edge Brow to the River Leith, the position of the unit is entirely conjectural, and, in the river itself, it is only represented by a little buff sandstone seen just downstream from the Maulds Meaburn Limestone exposures near Thrimby Bridge.

iv) Maulds Meaburn Cyclothem

a. SUMMARY

The cycle is thicker than the underlying Bank Moor cyclothem, averaging 80 feet, but is probably less than 70 feet in the north-west and may be up to 90 feet in the south owing to variations in the thickness of both the Limestone and the clastics. The Limestone is very well exposed in quarries and in natural scars, which are characteristically white-weathering and have a rubbly appearance. It is a medium-grey, fairly even-bedded limestone with a persistant horizon of calcite mudstone overlying the Gigantoproductus Band about 12 feet above the base of the Limestone. Corals, which tend to occur in bands, especially in the middle of the Limestone, are common. In general, fossils are probably more abundant in this Limestone than in any of the other Yoredale Limestones studied. The overlying clastics are noteworthy for the presence of only minor shale horizons, and for their great lithological variability, sandstones, ganisters, shales, coals and impure limestones, all occuring within the space of a few feet.

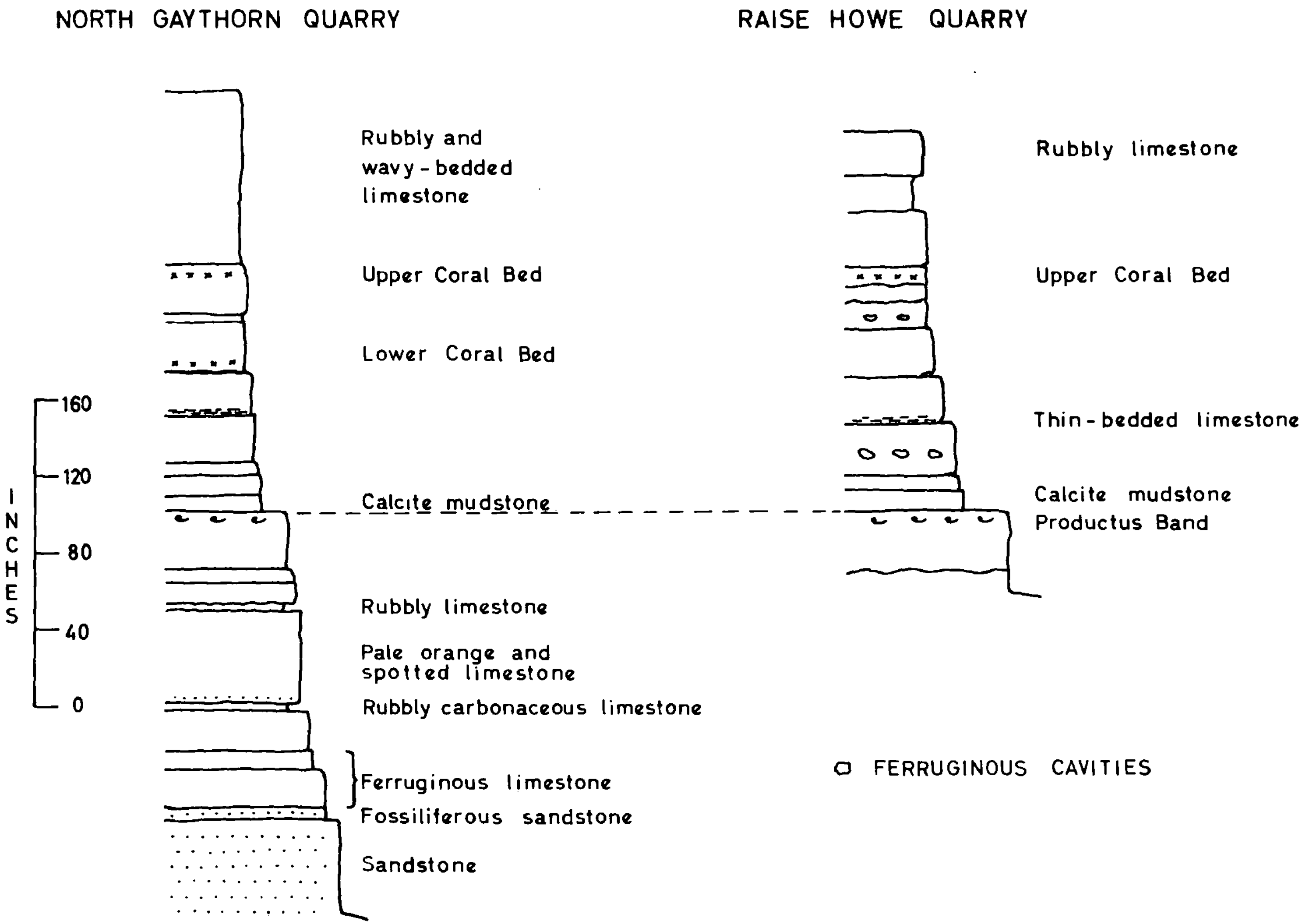
b. THE MAULDS MEABURN LIMESTONE

Asby-Drybeck sub-area

Several quarries give excellent exposures of the Limestone which has a wide outcrop across Bank Moor and can be traced along the north side of Scale Beck to the Drybeck-Great Asby road. Those at Raise Howe and $\frac{1}{3}$ mile north of Gaythorn Hall provide the best sections, showing 20 feet and 31 feet respectively, the details of which are illustrated in Fig. 2.10. They show evenly-bedded limestone,

Figure 2.10

MEASURED SECTIONS IN THE MAULDS MEABURN LIMESTONE



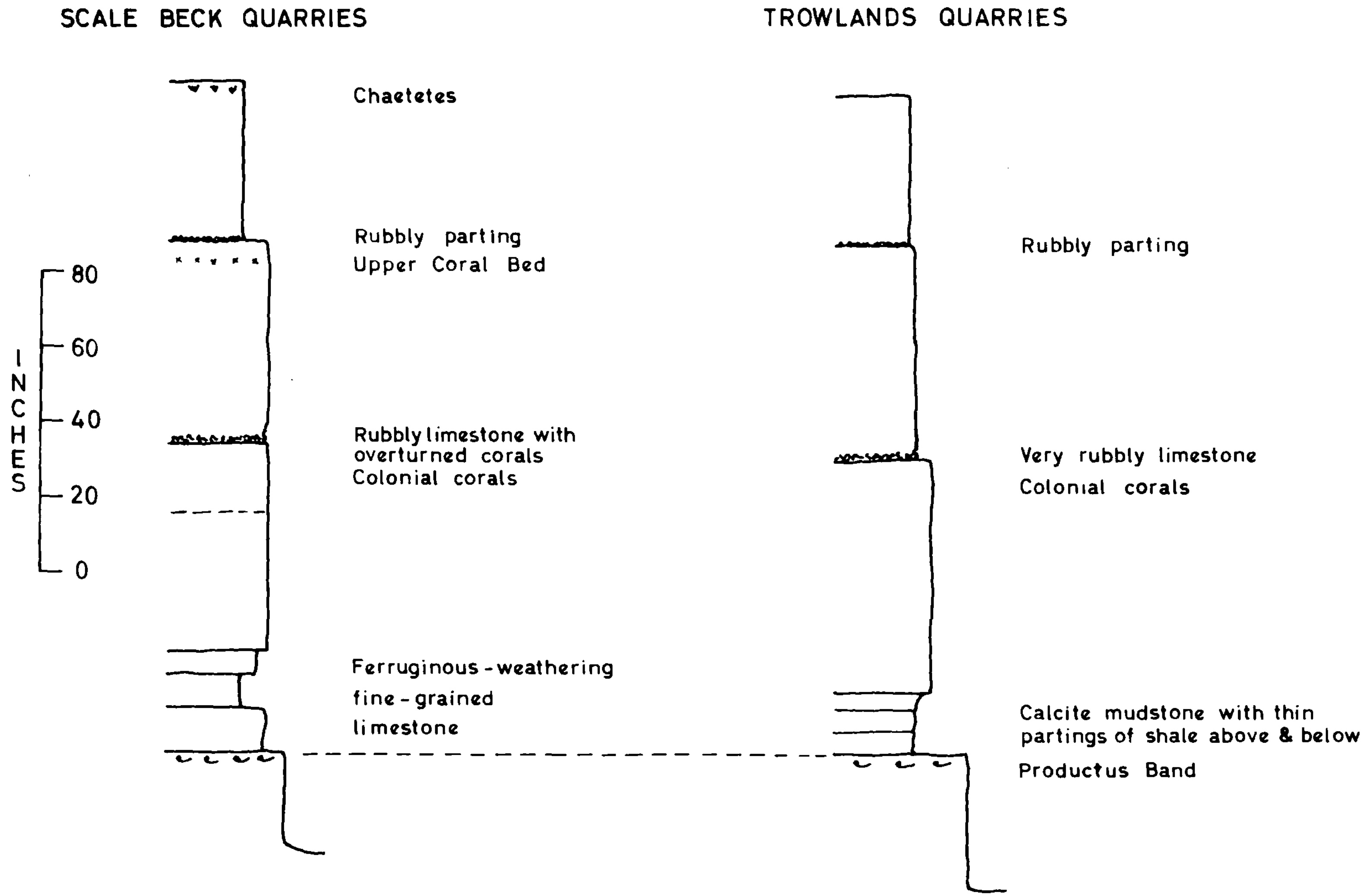
weathering to an unusually dark-grey colour at Raise Howe, in beds between 1' and 2' 6" thick which contain a prolific fauna, especially of corals, though brachiopods are very common; thin, rubbly-weathering horizons, often containing corals, occur at intervals through the Limestone. The Gigantoproductus Band is in the shaly top of a thick bed of limestone at a height of 12' 6" above the base, in which many well preserved specimens are visible, mostly with their concave sides uppermost. This is generally considered to be an indication of little current action but the shells are so large that quite strong currents would probably be necessary to overturn them, and, in fact, the corals at higher horizons often are not in growth positions perhaps indicating, then at least, the presence of currents of some strength. Overlying the Gigantoproductus Band are quite thin-bedded and often ferruginous-weathering calcite-mudstones up to 2 feet thick which become slightly darker in colour upwards and pass into even, quite thick limestone beds, some weathering with large irony cavities (dolomitic patches). Colonial and simple corals are common and become especially abundant in a 7" to 13" bed at about 10 feet above the Gigantoproductus Band (The Upper Coral Bed) where species of Lithostrotion, in particular, abound. The highest part of the Limestone is poorly exposed but is usually quite pale, wavy-bedded, rubbly-weathering limestone, though medium-dark-grey, thin-bedded limestone also occurs.

These horizons, and often individual beds, can be traced throughout the sub-area making it possible to detect a slight but definite thickening (of the order of 8%) of the limestone from the base of the calcite-mudstone to the top of the Upper Coral Bed in a north-easterly direction.

The Limestone outcrop can be followed east-north-east from Raise Howe by means of numerous quarries and sinks and is affected by four faults all down-throwing to the east. The first, at Maskriggs Wood, has a very small displacement and that at Harding's Wood Fault is only a little greater, but the two easterly ones are more significant, the Scalebeck Fault having a throw of at least 80 feet. It brings the Limestone almost down to the level of Scale Beck, adjacent to which it has been quarried (Fig. 2.11), and produces the first definite exposures of this Limestone south of the stream around Scalebeck Farm, although

Figure 2.11

MEASURED SECTIONS IN THE MAULDS MEABURN LIMESTONE



thickness considerations suggest that it also caps the hill just west of the fault, $\frac{1}{4}$ mile south-west of the farm. Downstream from the road-bridge the Limestone can be traced for a short distance and two strong springs may indicate where its top reaches river-level. However, owing to important north-north-west trending faults, it reappears to the east and is well seen in a series of quarries near Trowlands Farm (Fig. 2.11) and again above Bowbridge House. The reddened crinoidal limestone occuring in Asby Beck at Bow Bridge is also probably from this member though it is further below the scars above the house than would be the base of the Limestone (given the normal thickness) and another fault is likely. Although the Limestone can be followed, rising southwards from Scalebeck Farm, to high above Great Asby and seems to occupy a large area north of the town, the exact disposition of the outcrop at the south-east edge of the area mapped is uncertain due to the extensive faulting and the cover of glacial-drift. In nearly all these south-eastern exposures the Limestone has been reddened, though often just in small discrete patches, due to the fracturing having produced an easy means of access for oxygenating fluids.

Meaburn sub-area

The Limestone can be accurately mapped throughout the sub-area, where its estimated thickness is 46 feet, from the Orton-Appleby road down to the Lyvennet south of the village from which it takes its name. The lower beds occur high in the feature due to the Bank Moor clastic succession and a second, parallel, feature often occurs showing horizons in the middle of the Limestone. They are offset $\frac{1}{4}$ mile south of Bank Head Farm, indicating the position of the Howarcles Fault, here with a throw of just over 30 feet, and producing a small fault-scarp in which rather mottled and red-stained limestone can be seen. Similar irregularly mottled limestone, but mostly in shades of grey with minor iron-staining, is characteristic of the top part of the Limestone exposed low in the feature east of Bank Head Farm, and, to the west, the basal ferruginous beds, resting on calcareous sandstone, are visible in a long series of exposures above the Bank Head sandstone quarries. The Limestone is not seen north of Bastern Gill (Fig. 2.15) where the Gigantoproductus Band can be found, though it must reach the Lyvennet in the vicinity of Flass House.

Reagill-Morland sub-area

West of the Lyvennet the outcrop is at first covered by glacial material, often in drumlin form, but small exposures and sinks can be found in the vicinity of Micklebank Sike and south of Prickly Bank Wood where a large area is underlain by limestone, there being big tracts where the slope of the ground approximates to the dip of the beds. Southwards, the outcrop entirely surrounds Crake Trees Hill and the adjoining ridge to the south-west, limestone being visible both above the Crake Trees ruin and at Wickerslack hamlet. It unites to form the extensive, gently sloping ground north-east of Harberwain Rigg, which is partly drift-covered but has limestone very close to the surface along the southern and western margins. Several quarries show the lower part of the Limestone in the south-facing feature overlooking Dalebanks Beck and one, on Harberwain Rigg, exposes the Gigantoproductus Band and beds which are closely comparable to those seen at Raise Howe Quarry, including a coral bed, with Diphyphyllum, 5' 6" above the Gigantoproductus Band. Here, the Band extends upwards into the base of the brownish grey calcite-mudstone and appears now to be within 10 feet of the base of the Limestone. The basal beds, again resting on calcareous sandstone, are well displayed at Iron Hill (Fig. 4.10 and Plate 47) where a strongly ferruginous-weathering band is clearly visible near but, unlike in exposures to the south-east, not right at, the base. Directly overlying it is a thin bed of carbonaceous, sandy, wavy-bedded, pale-yellow limestone with crinoid fragments, at almost exactly the same height above the base as similar sandy limestone seen in the large quarry north of Gaythorn Hall (Fig. 2.10), suggesting that there was a sandy incursion of more than local significance. The upper part of the bed immediately overlying this is interesting in having well defined and usually very regular darker spots in a pale matrix and can be recognised in several exposures to the north, as can the bed above which has colonies of Lithostrotion. In this direction the Limestone becomes less well exposed, though numerous sinks occur in and south of Wyegill Plantation, and it forms a long, narrow inlier in the headwaters and upper part of Low Wood Beck. Here, corals can be found right at the top of the

Limestone which is rubbly-weathering and has a mottled texture.

North from Wyegill Plantation, the Limestone at first forms a distinct feature in which it has been quarried, but towards Cow Pasture Plantation this diminishes and only a few sinks remain to mark its top. These continue to the west of Threaplands where small quarries reappear and show both the coral-rich horizons and the ferruginous bed nearer the base, now without the thin sandy bed above. In the steep valley sides of Threaplands Gill, the ferruginous bed can again be seen to be not directly above the calcareous sandstone, and the most north-westerly exposure of the Gigantoproductus Band is visible. Calcite-mudstone continues to overly it and an outcrop of the beds above is notable for the presence of abundant Lithostrotion junceum and a very large Orthoceras. Again, the Gigantoproductus Band seems to be only about 10 feet above the base of the Limestone, the total thickness of which, at 37 feet, has undergone slight reduction from its maximum development to the south-east.

Strickland sub-area

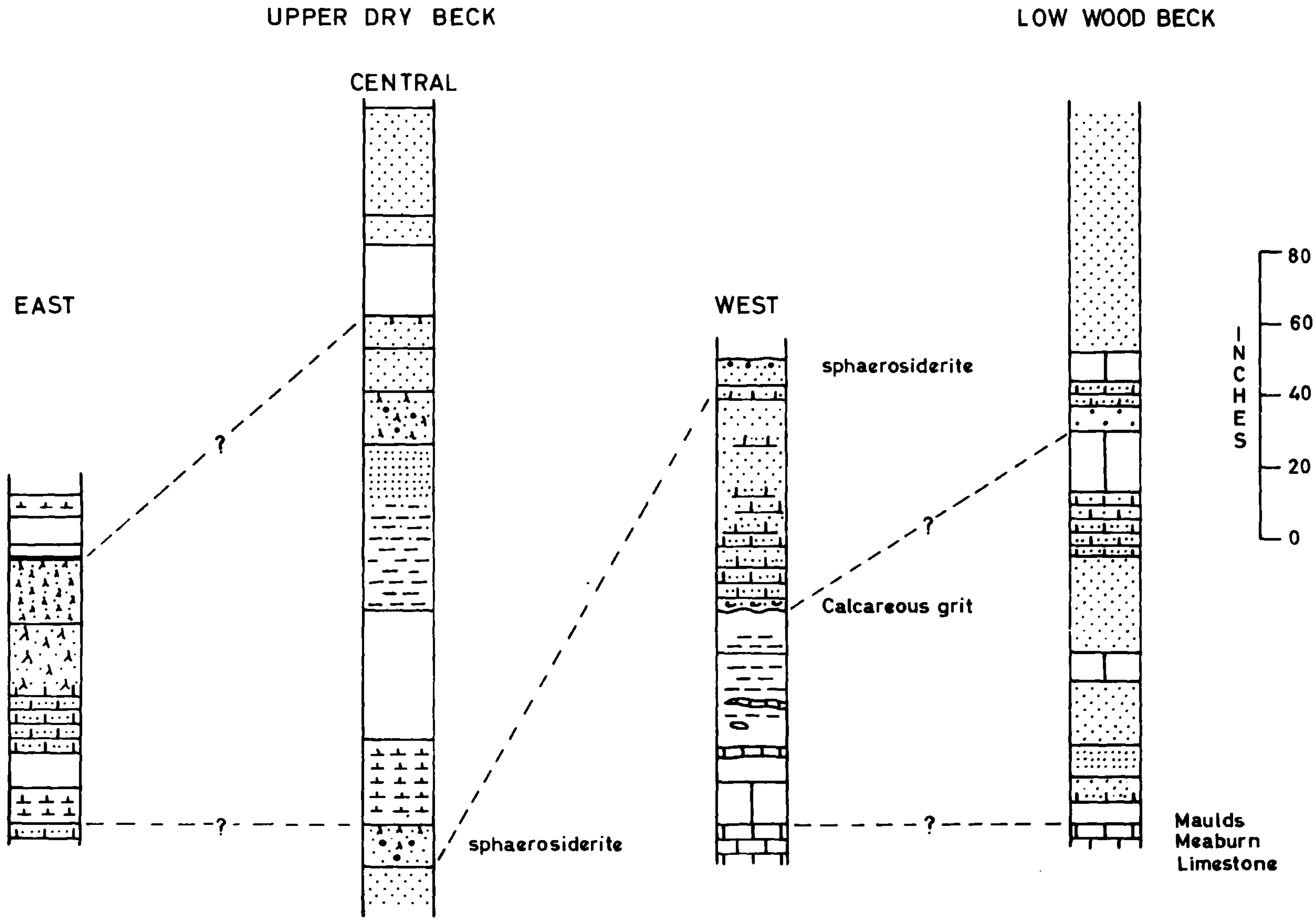
Westwards from Threaplands Gill the outcrop of the Limestone can be traced round Windrigg Hill by means of small excavations and sinks, but is then obscured until, west of Towcett, it is seen in a series of small quarries at the summit of the steep feature overlooking Gunnerkeld Sike. From the width of the outcrop, further thinning of the Limestone seems to have occured and, northwards, it is not seen before the coral-bearing outcrops which appear in the River Leith 130 yards south of Thrimby Bridge.

c. THE MAULDS MEABURN CLASTICS

Drybeck-Asby sub-area

The most complete exposures of the unit in the region occur in Dry Beck which, for most of its length, cuts through beds at this level in the succession, allowing lateral facies variations to be closely followed (Fig. 2.12). The lowest beds visible occur in

Figure 2.12 MEASURED SECTIONS IN THE MAULDS MEABURN CLASTICS



the core of a faulted anticline where it crosses the stream about 700 yards north of Highfield Farm, and are argillaceous limestones with very abundant brachiopod shells overlain by pale-grey silty shales with bands of nodular, irony-weathering limestone but without fossils. The lowest horizon is so fossil-rich that it seems likely that it represents a shell-bed at the top of the Maulds Meaburn Limestone itself and that this is, therefore, a small faulted inlier of the Limestone. The shales are dark at the top and are abruptly overlain (Plate 6) by a calcareous coarse sandstone with scattered small pebbles and, often, well preserved brachiopod shells. It passes up into finer-grained, very hard, calcareous sandstone with small-scale cross-laminations (Plate 7) and has, at its top, which shows strong undulations, occasional small irony spheres. These horizons are visible both upstream and downstream, in which direction the coarse gritty sandstone becomes less fossiliferous and the beds above include, as lenticles, non-calcareous but still quite hard, fine, quartzose sandstone with plant remains. The disposition of outcrops suggest that the bed varies considerably in thickness and is probably of strongly lenticular form. It is overlain by hard, calcareous mudstone and softer shales which pass up into thin sandstones and ganisters, often with pyrite nodules, and separated from more sandstone by a thin horizon of very carbonaceous shale. These beds are seen at several places downstream, mostly in the left bank, and as small waterfalls. One, showing what is thought to be the top of the lenticular sandstone bed, is of particular interest in that here, the ferruginous spheres are better developed and appear to be weathered sphaerosiderite. Due to the intermittent nature of the exposure, the close coincidence between the dip of the rocks and the slope of the stream, and the possibility of faulting, correlation along the length of exposures is hazardous, but it is thought that the same horizons are seen nearer Drybeck village. Here ganister is again visible in the left bank, though the shales below have thinned considerably and the underlying sandstone has become a fine sandy limestone with thin, black _in situ_ plant remains. These pale impure limestones and hard, buff, cross-laminated calcareous sandstones are characteristic of the unit and can be found, not only by Fieldhouse Wood higher up Drybeck, but also throughout much of the region.

PLATE 5. Maulds Meaburn Limestone (below wall) and Bank Moor Sandstone, Bank Head Quarries.

PLATE 6. Abrupt base of coarse fossiliferous sandstone above Maulds Meaburn Limestone, Dry Beck.

Small-scale cross-bedded fine sandstone from low in the unit is visible south-west of the Scalebeck-Asby road but the main outcrop from Drybeck Moor to Maskriggs Wood is entirely obscured by a thick mantle of drift and the upper part is nowhere seen. There are, however, about 28 feet visible in Dry Beck and the total thickness, allowing for the sandstone which occurs above, cannot be less than 40 feet.

Meaburn sub-area

At the north side of Bank Moor, the sandstones low in the unit give rise to a small but distinct heather-covered feature on the broad dip slope of the Maulds Meaburn Limestone and also to a strong spring near the Howarcles Fault, as well as considerable zones of seepage to the north. As it is traced northwards along the side of the Lyvennet valley, the unit appears to thin slightly, being estimated at 34 feet thick. Calcareous sandstones and pale sandy limestones with in situ plant remains but also fossils, near the middle of the cycle are visible in the vicinity of Hulls and in situ plant remains also occur at the top of the main sandstone member in the few exposures where it is seen. To the north the only outcrop is of a little of the sandstone at the top of the unit in Bastern Gill (Fig. 2.15) where ripple-marks are well developed.

Reagill-Morland sub-area

Although the clastics underly large tracts of country, especially on Wickerslack Moor, sections are limited to a few rather inaccessible exposures by Reagill Grange and in Low Wood Beck. At the latter locality (Fig. 2.12) sandstones, having a basal layer with a few crinoid fragments, much carbonaceous matter and worm-burrows, follow the Maulds Meaburn Limestone after an interval of only 6 inches of shale. As in Dry Beck, calcareous sandstone and impure limestone, though with only faint carbonaceous traces, occurs and one bed, which if feldspathic, quite coarse and has a strong vermillion colour, may be the lateral equivalent of the gritty bed of that locality. Above, up to 10 feet of sandstone, which is massive or gently cross-bedded and of medium-grain size with a brown or purple speckle, is visible in the steep valley sides and stream bed north-eastwards to the edge of the plantation.

Beds low in the unit, comprising micaceous and carbonaceous wavy-bedded sandstone, often very ferruginous-weathering and with fossil molds, are seen in several of the tributaries of Low Wood Beck and 15 feet of the sandstone at the top is well exposed in the ravine by Reagill Grange. It is medium- or thick- bedded, with gentle cross-laminations, and low down is quite ferruginous with some hard calcareous layers. There is a well developed ganister at the top capped by fine sandstone with coaly lenticles and, higher, some shell fragments.

Southwards the clastics form outliers south and east of Wickerslack and spread over a large area of Wickerslack Moor where, however, their exact limits are impossible to define because of a partial drift cover. Although the occurrence of large deep sinks shows that the Maulds Meaburn Limestone is not far below the surface, loose sandstone in their sides and extensive overgrown workings on the Moor, bear witness to the existence of in situ higher beds.

Strickland sub-area

No exposures exist, though sandstone at the top of the clastics was once quarried in a small feature 300 yards south of Longlands Farm and loose sandstone with in situ plant remains is visible on ploughed land at Windrigg Hill and by Towcett Cottages. The width of outcrop suggests that the unit is thinner, perhaps less than 30 feet, than in the south-east, and at the westerly edge of the region it is entirely absent in the River Leith, having been cut out by the Little Strickland Fault.

v) Little Strickland Cyclothem

a. SUMMARY

The cycle is not only the thickest, at 140' to 150', but also the most complex of those studied. The major Limestone at its base shows little variation, averaging 38 feet, and being characterised by the occurrence of Orionastraea and the foraminifera, Saccamminopsis fusulinaformis, which is particularly abundant at two horizons, one in the middle and one near the top of the Limestone. The overlying clastics maintain a fairly constant thickness of just over 100 feet which can be divided into two parts. There is a normal coarsening-upwards lower unit, at the top of which a quite extensive workable coal, the Reagill Coal, is developed, and an upper unit of considerable lithological variety which includes shales, sandstone (both frequently fossil-bearing), ganisters, thin coals and some impure limestone.

b. THE LITTLE STRICKLAND LIMESTONE

Reagill-Morland sub-area

The Limestone is very well exposed in a series of quarries of which Greenrigg and that north of Threaplands Farm (Fig. 4.1) give the fullest successions. The lowest beds, seen in Threaplands Gill and, partially, at the base of these quarries, are fairly even-bedded, medium-dark coloured, often bituminous-smelling limestones, culminating, about 16 feet above the base, in a thin but persistent horizon of calcareous shale. The succeeding limestones are paler and wavy-bedded and, near their base, include a 10" to 12" horizon containing abundant Saccamminopsis fusulinaformis - the Lower Saccammina Bed. Five feet above this, there occurs a very distinctive bedding-plane having strong undulations (Plate 34), which is of wide lateral extent and is overlain by limestones with sporadic Saccamminopsis, becoming locally more abundant and there termed the Middle Saccammina Bed. Darker, more even-bedded limestones then reappear before an upper unit of wavy-bedded, medium-grey limestone containing another foram-rich horizon - the Upper Saccammina Bed. Its base is 34 feet above the base of the Limestone and, nowhere, is more than 5 feet of limestone seen above it so that 40 feet is probably a close approximation to the total thickness of the Limestone. The highest part, visible in the easterly tributary of Threaplands Gill and a sink-hole north of Greenrigg Quarry, is again of dark colour, having a considerable admixture of argillaceous material and with a tendency to ferruginous-weathering.

The Saccammina Beds are often crowded with foraminifera, which appear as white, spherical or lozenge-shaped bodies on weathered surfaces, or, more commonly, as glassy patches on broken surfaces and joint planes. The Upper and Lower Beds are remarkably similar in lying just over 2 feet above a distinct in-weathering horizon of calcareous shale which, in both cases, marks the top of even-bedded, darker limestone containing a few algal nodules and coatings around crinoid and shell fragments, from which they are separated by limestone with four distinct bedding-planes. Their appearance is so similar that only prolonged study proved that they are, in fact, two separate horizons; in general, the in-weathering calcareous shale is less well marked below the Upper Bed, which tends to be nearer 30 inches above it rather than the 26 inches of the Lower Bed, and which shows a gradually increasing number of foraminifera upwards and so is less sharply differentiated from the beds below.

A small exposure by the roadside, 300 yards north-north-west of Greenrigg Quarry, is of interest in that it is one of the few localities where Orionastraea has been found. Here, it occurs as small colonies resting on limestone very rich in large fragments of crinoids and brachiopods.

East of these exposures, the Limestone can be traced to Reagill Grange, where the lower part is seen in the ravine, and is sandy and ferruginous-weathering at the base. It must form an outlier on the opposite side of Low Wood Beck stretching to Prickly Bank Wood, and is seen intermittently in the steep north-west valley side before finally disappearing below the drumlins of the Lyvennet valley in the neighbourhood of Morland Bank.

Strickland sub-area

Westwards from Threaplands Gill, the Limestone can be followed easily by means of numerous quarries and sinks to Windrigg

Hill, which it caps, and thence to the north-west via Longlands and Towcett hamlet to Towcett Cottages (Fig. 2.13). The horizons found to the south-east are still easily recognisable but, though the Lower Saccammina Bed is, in particular, well seen in nearly all the quarries, the Upper Saccammina Bed is only visible in the large quarries at, and north-west of, the Cottages. In the vicinity of the cross-roads, south of the village which bears its name, the width of outcrop of the Limestone is considerably thinned by a fault, though it can still be found in the village at, and south-east of, the Green. However, further north, with one possible exception, the Limestone is not seen and it is absent from the River Leith due to the effect of the strike-fault mentioned above, which increases its throw in this direction.

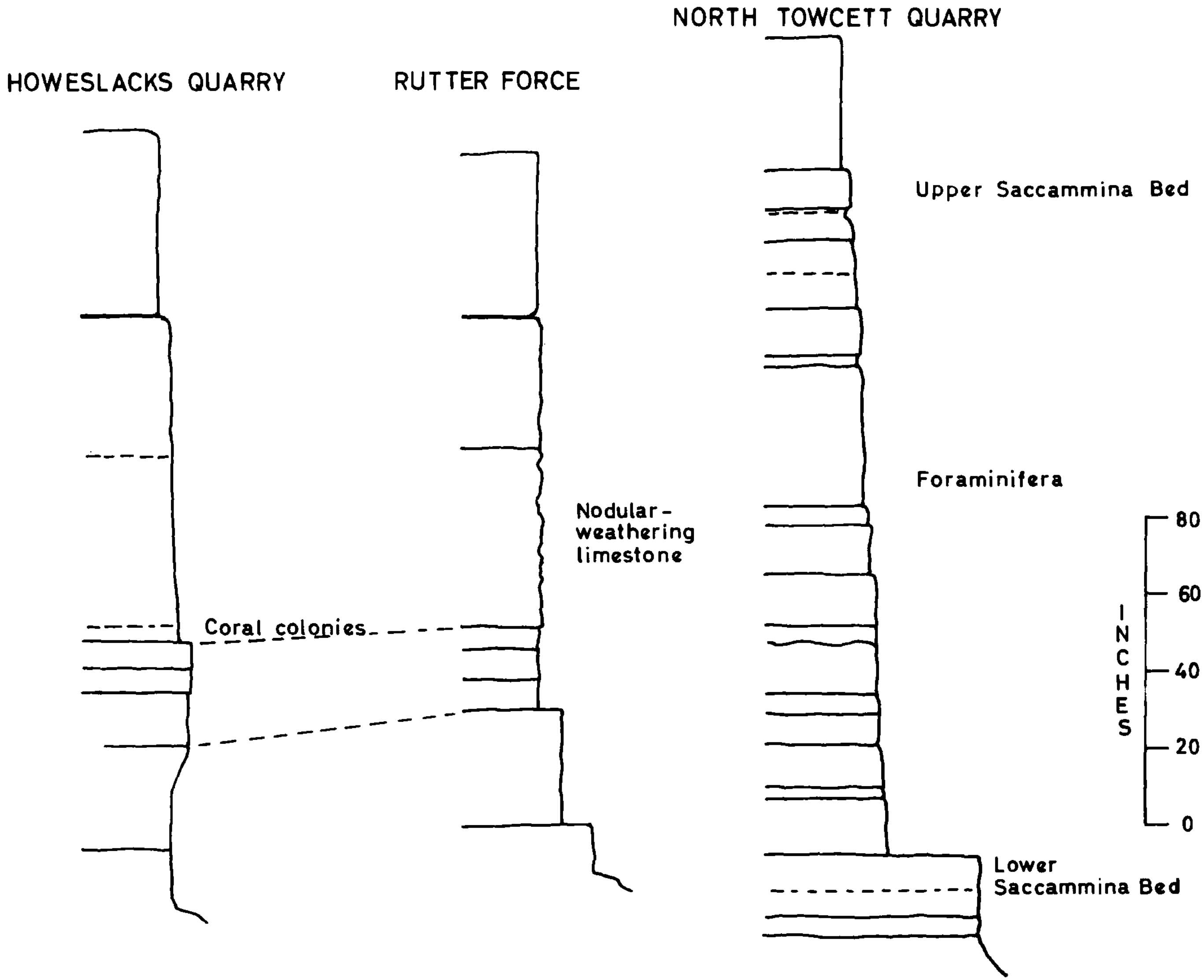
Meaburn sub-area

The Limestone must cross the Lyvennet at the north end of Maulds Meaburn village near Low Bridge, but it is not seen before Bastern Gill, where it produces a series of small waterfalls (Fig. 2.15). It has been quarried at Hulls and, to the south, where it underlies a widening area, are many exposures in some of which the Lower Saccammina Bed, now a 9" bed capped by a 3" bed but still 26" above the shaly parting, can be found. The Middle Saccammina Bed is also locally well developed and, by the track east of Bank Head Farm, Orionastraea occurs. The line of continuation of the Howarcles Fault is clearly indicated by the offsetting of the feature due to the Limestone, and by the linear series of sinks south-east of Allan's Ling Wood.

Drybeck-Asby sub-area

The Limestone can be traced in sinks and quarries north-east from the Orton-Appleby road down to the broad flat area adjacent to the sharp easterly bend in Dry Beck, where it has been affected by both the Howarcles and Harding's Wood Faults. The former gives rise to a marked linear series of swallow-holes and still has a throw of over 30 feet. A horizon with foraminifera can be found but it is not possible to correlate it confidently with any of the Saccammina Beds seen to the north-west, and now the Limestone has some thin

Figure 2.13



MEASURED SECTIONS IN THE LITTLE STRICKLAND LIMESTONE argillaceous partings. There is little to indicate its position on Hoff Moor but north of Drybeck village it has been extensively worked and, in the middle of the succession, there is a rather distinctive 1 foot bed of fine-grained, pale-grey limestone with locally abundant colonial corals and overlain by limestones containing foraminifera. Wavy-bedding remains a feature of the limestone, most of which is still quite fine-grained and of medium-grey colour but, here, is characterised by an abundance of crinoid fragments, some of which are very large.

To the south-east, the Limestone is difficult to map accurately owing to the thick cover of drift and much faulting, but it appears to be faulted down into Dry Beck south-east of the village where it forms the bed as far as the wood, and probably occupies a large area of Drybeck Moor bounded by the Drybeck Moor and Scalebeck Faults to the north-west and south-west respectively. Having been thrown up by the Long Moor Fault, it again appears at Howeslacks Quarry, above Dry Beck, where horizons quite high in the Limestone are visible (Fig. 2.13). Corals, especially colonial species, can be found at most levels but no foraminifera, to permit a correlation with the Limestone to the north-west, have been found. Although bedding-planes can be traced along the whole length of the exposure, these, too, cannot be matched with the sequence elsewhere except to the north-east where, at Rutter Force (Fig. 2.13), the Limestone can last be identified with certainty in the area mapped.

c. THE LITTLE STRICKLAND CLASTICS

Strickland sub-area

In the River Leith, only the top part of the unit is well exposed, though the main body of sandstone (the Scattergate Sandstone) is visible at several places in the vicinity of Thrimby Mill, where it is buff and medium-grained with occasional mud-flakes, some irregular trough-bedding and horizons of calcareous sandstone. Above, horizons at the level of the Reagill Coal are not seen, though large excavations at the south end of Towngill Wood may have been for the coal, and beds just below the Johnny Hall's Trees Limestone are visible further downstream at and north of the weir (Fig. 2.14). Here 8' 6" below the Johnny Hall's Trees Limestone is a thin, ferruginous limestone resting on pale, carbonaceous shale and overlain by micaceous shale and wavy-bedded sandstone. Above, a well developed ganister passes up via very hard, pale-buff sandstone with faint tube-like structures (possibly worm-burrows) into the Limestone.

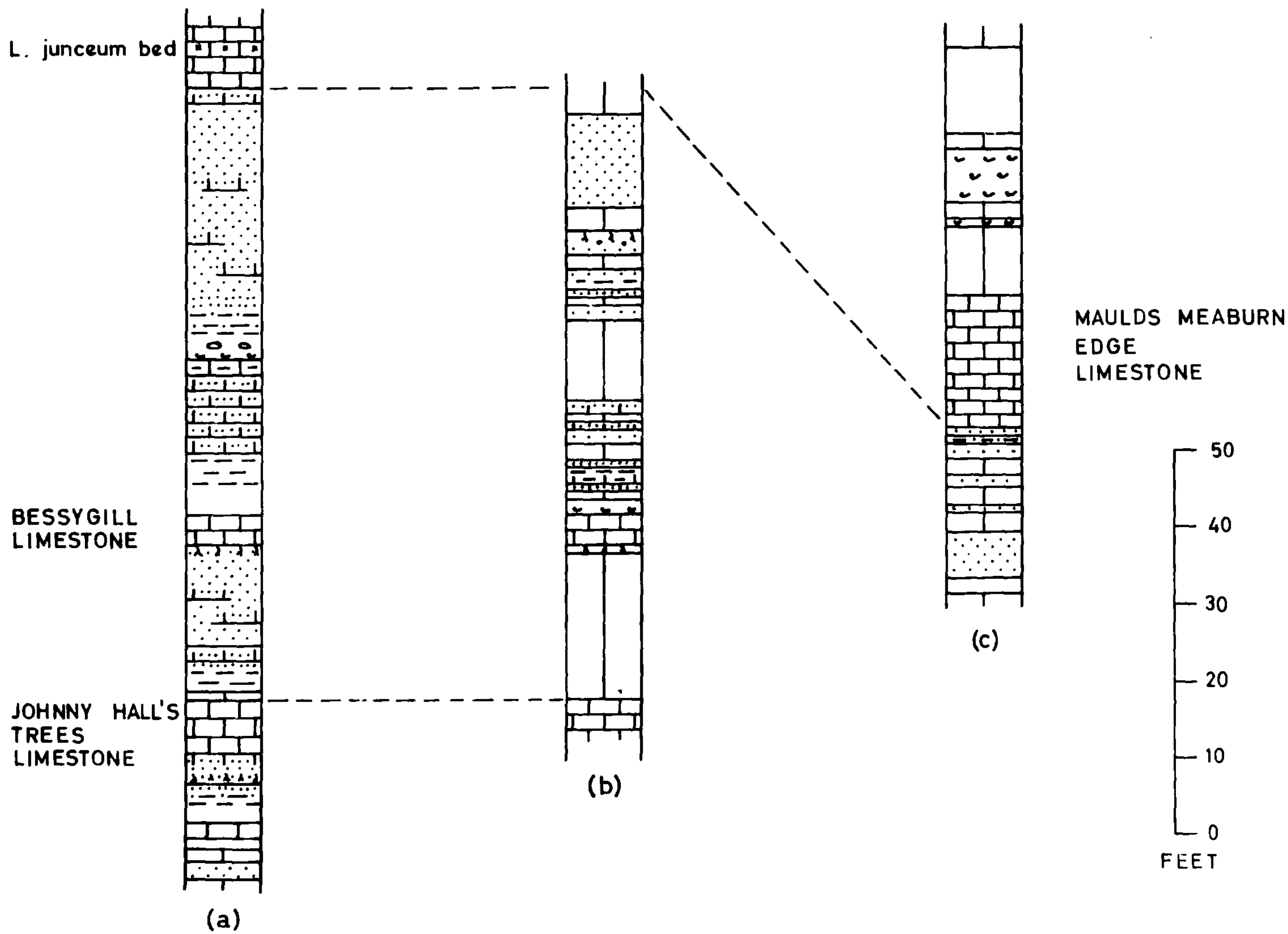
Southwards, the main sandstone body is visible in several exposures in the steep slope overlooking the Thrimby Bridge-Little Strickland road, where a large quarry shows massive sandstone overlain by beds with some good planar cross-laminations. To the south and east, though the unit underlies a large area drained by Long Sike and Gillmoor Sike, little in the way of in situ rock occurs, but evidence for the existence of a workable coal in the series is abundant. Starting at Bedlands Gate Farm and passing by way of Birks Plantation, Low Murber and Sleagillhead Plantation to Threaplands Gill south of Sleagill village is a series of spoil-heaps resulting from mining operations which must have almost completely worked-out the Reagill Coal. They vary in size according to how much of the overlying beds had to be removed and provide the only exposures, though of course loose, of these horizons, which include thin micaceous and carbonaceous sandstones and shales, often ferruginous with some concretions, and having occasional fossils, usually thin-shelled lamellibranchs; thin, vitreous-looking coals are probably also part of the sequence. A trial-shaft for coal was bored north of Brown Howe Farm but was unsuccessful, having apparently been sited too low in the series and must soon have entered the Scattergate Sandstone, of which loose pieces can still be found around the shaft. Its upper part, often of deep yellow colour and with in situ plant remains is also seen as an inlier in the gill by Birks Plantation, but it is not exposed to the east.

Reagill-Morland sub-area

The unit is not exposed in Threaplands Gill but the main easterly tributary shows fossiliferous shale overlying the Little Strickland Limestone, becoming silty and unfossiliferous upwards, as well as even- or wavy-bedded, often carbonaceous and micaceous sandstone with some pyrite, below the Reagill Coal whose position is again

Figure 2.14

MEASURED SECTIONS IN
THE RIVER LEITH (a) GILLMOOR SIKE (b) AND OAK BECK (c)



clearly marked by the spoil-heaps. These provide an extremely useful mapping guide and, when very small, that is at their southern and western limit, indicate the outcrop position of the coal which can, therefore, be mapped with some accuracy except where the spoil-heaps have been removed to allow cultivation. By this means, the coal can be traced right across the sub-area, passing east of Threaplands Farm, through Pithills Plantation to just south of Reagill School and thence east and north-east, high above Low Wood Beck, towards Hard Bank where the spoil-heaps end. Some here, as well as showing the usual thin-shelled, ribbed lamellibranchs, are very fossiliferous with, in addition, crinoid fragments and bryozoa. Excavations between the Morland Bank drumlin and that to the west show no rock but are dissimilar in form to the coal-workings and are probably at the horizon of the Scattergate Sandstone.

Strata above the coal are nowhere seen in situ although, between Reagill and Sleagill, large pieces of argillaceous limestone with shell and crinoid fragments, derived from the spoil-heaps, can be found, suggesting the continuation into this district of the thin limestone below the Johnny Hall's Trees Limestone or, possibly, an even lower calcareous horizon. As is the situation to the north-west, where there is evidence for a thick coal, the Scattergate Sandstone seems less well developed as a massive unit and is seldom seen. Thus, only thin sandstone and shales are visible in the stream above Reagill Grange and in that north of Prickly Bank Wood.

Meaburn sub-area

The River Lyvennet meanders across a broad flood-plain where it flows over the easily eroded upper part of the unit which is not exposed but, south of Dairy Bridge, the valley is narrow and the Scattergate Sandstone occurs in the right bank. It is buff or yellow and fine-medium-grained with small scale cross-laminations and is often characterised, as to the south, by an orange or brown speckle. It can be traced upstream along the valley side where small workings occur but is only poorly exposed in Scattergate Gill and the adjacent quarry (Fig. 2.15). In the Gill, thin-bedded, micaceous sandstone and grey, silty, carbonaceous shale, estimated as starting about 25 feet above the Little Strickland Limestone, are capped by thick-bedded, orange-speckled sandstone which seems less than 10 feet thick, and at the top of which is the presumed horizon of the Reagill Coal though it is not now exposed. Above, the coal-series is quite well seen and includes, only a few feet above the sandstone, a distinctive limestone horizon which has a sandy-weathering base with molds of complete lamellibranchs and broken brachiopods but is hard and argillaceous at the top. It rests on, and is capped by, pale-grey and yellowish silts with abundant plant debris, above which is sandstone with delicate cross laminations and with a bed of unusual slump structures near the base (Plate 44). Shales, siltstones, sandstones and, at the top, ganister, continue above and include a horizon of very ferruginous sandstone containing a few small molds of fossils, which, from its position, may be the lateral equivalent of the impure limestone seen in the Leith.

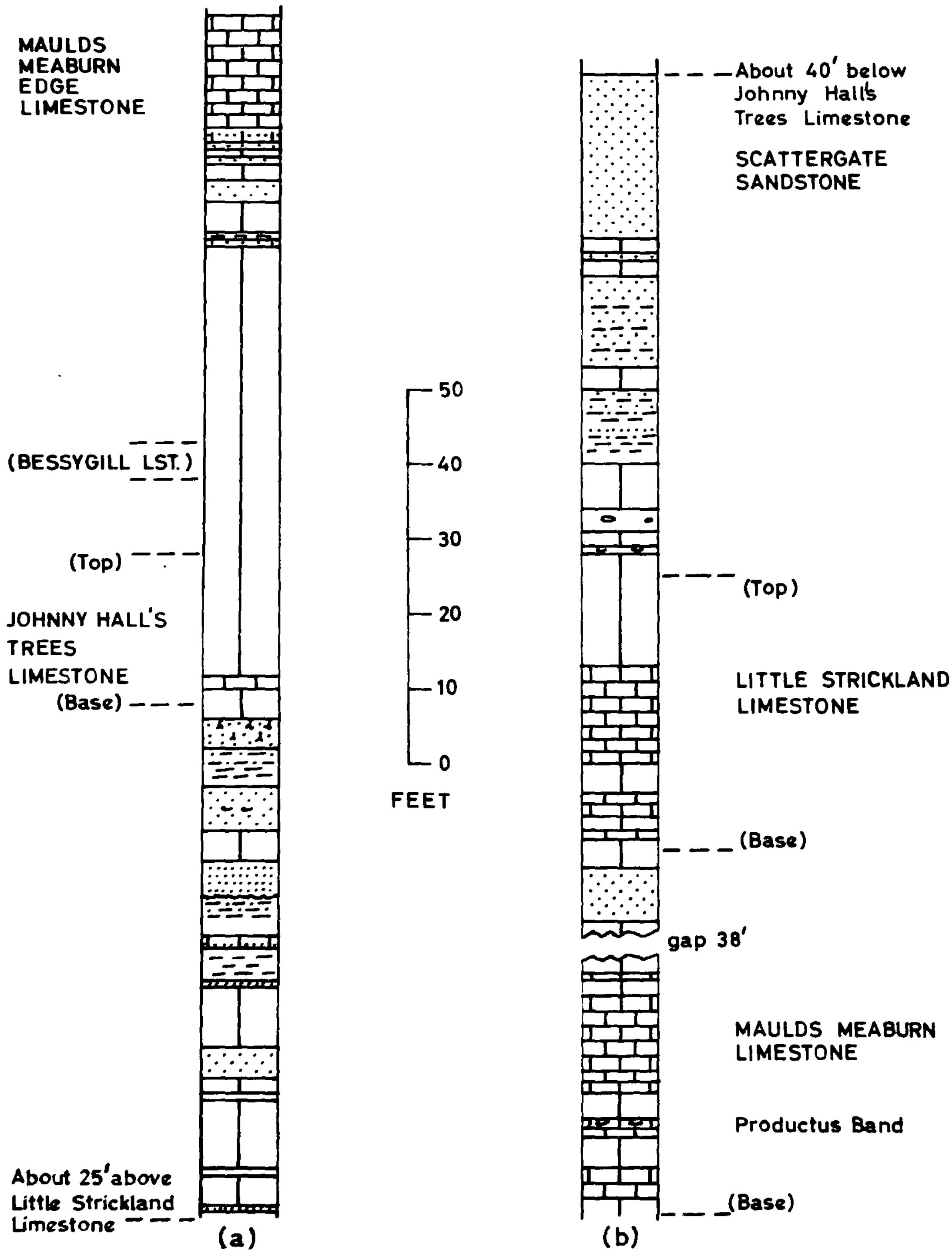
In Bastern Gill, to the south, the lower part of the succession is well exposed in a gorge (Fig. 2.15) and is much sandier than in Scattergate Gill. Fossiliferous shales are overlain by micaceous shales with a few ironstone nodules. These soon give way to alternations of sandstone siltstone and shale, the former becoming increasingly abundant upwards and culminating in a thick-bedded, buff, orange-speckled sandstone (the Scattergate Sandstone), now about 22 feet thick. Just above are excavations which may have been for coal but, apart from a little micaceous and ferruginous sandstone and carbonaceous shale, no in situ rock occurs and southwards the line is continued in a series of sandstone quarries owing to the Scattergate Sandstone having been thrown up by the small Bastern Fault.

Drybeck-Asby sub-area

East of the Orton-Appleby road, on the upthrow side of the Howarcles Fault, shale and sandstone close above the Little Strickland Limestone is visible in large sink-holes and the same horizons are very well exposed on the opposite side of the fault in a tributary of Dry Beck. Here the Scattergate Sandstone, over 30 feet thick, is medium- to coarse-grained at the base but becoming finer upwards. It is mostly thick- and strongly cross-bedded with much mica,

Figure 2.15

MEASURED SECTIONS IN SCATTERGATE GILL (a) & BASTERN GILL (b)



some feldspar, and is buff or purple in colour often with a brown speckle. It has a few mud-flakes at the base and rests on thinner-bedded sandstone passing down into dark-grey shales within 10 feet of the top of the Little Strickland Limestone. To the north-east, beyond the small Harding's Wood Fault and on the upthrow side of the Howarcles Fault, a small stream, flowing from the north, shows fairly coarse sandstone with carbonaceous specks now within 5 feet of the top of the Little Strickland Limestone, suggesting that the base of the Scattergate Sandstone is here erosional and has removed several feet of shale and thin-bedded sandstone. There is no evidence for the extension of the Reagill Coal into this sub-area, although exposures of the upper part of the cycle are restricted to a few outcrops of sandstone with molds of shell fragments, just below the Johnny Hall's Trees Limestone.

The Scattergate Sandstone is also recognisable in the steep feature overlooking Drybeck village, both in the east by Drybeck Hall and near the road at the west end of the village, where it is medium-coarse-grained, feldspathic and salmon coloured with black specks. It remains close to the top of the Little Strickland Limestone and characteristically gives rise to a red-brown soil. Similar reddened soil, with some loose sandstone, occurs further east in the small tributary of Scale Beck flowing from Mill Lane and is thought to be from this horizon, though lack of exposure and faulting make correlation uncertain.

The same is true of Hoff Lunn where again, however, members of this unit are thought to be exposed on the upthrow side of the major north-north-westerly trending fault (the Barwise Fault) in both Oak Beck and its main southerly tributary. In Oak Beck, exposures at and west of Hofflunn Farm are thought to belong to the upper part of the unit and consist of alternations of shales, first with ferruginous nodules, and thin sandstones with, in the middle, a bed of ganister capped by a thin reddened limestone. This has caudagalli markings on its upper surface and is overlain by a little shale before more reddened limestone with Productids and crinoid fragments occurs. The rocks seen in the upper part of the tributary south-west of Brown Hills, near the southern edge of Hoff Lunn, seem also to belong to this unit but may be from a lower horizon. Here, upstream from the fault which cuts off a thick cross-bedded sandstone, are many small outcrops of very altered purple and yellowish, soapy-feeling, shaly mudstone. These beds appear to be more than 10 feet thick and are unlikely to represent shales at the base of the unit and so probably overly the Scattergate Sandstone. A quarry in the left bank shows that they are overlain by a pale-buff, micaceous and cross-bedded sandstone and, upstream, a hard 9 inch greenish ganister appears from below them and is separated from more greenish and purple sandstone by 1' 3" of nodular-weathering very reddened shale.

vi) Johnny Hall's Trees Cyclothem

a. SUMMARY

The succession is imperfectly known due to lack of exposures but appears to undergo considerable changes, including a marked thinning of the clastics, from west to east, to some extent compensated for by a thickening of the main Limestone. This is seldom visible but easily recognised because of its characteristic appearance, most notably its pale colour and tendency to ferruginous-weathering with large irregular cavities (Plate 8). It is less than 10 feet thick to the west but probably doubles its thickness in the centre of the area, perhaps thinning again further east. An even thinner Limestone, the Bessygill, is present in the west of the area a short distance above the Johnny Hall's Trees Limestone, and, in the absence of any definite evidence to the contrary, has been mapped as an independent unit throughout the area. The overlying clastic beds are notable for the development of thick calcareous sandstones and impure limestones towards the west.

PLATE 7. Cross-laminated calcareous sandstone, Dry Beck.

PLATE 8. Cavernous-weathering Johnny Hall's Trees Limestone at Dry Beck.

b. THE JOHNNY HALL'S TREES AND BESSYGILL LIMESTONES

Strickland sub-area

The Johnny Hall's Trees Limestone appears in the bed and left bank of the Leith at the old ford where the track from Sheriff's Park Farm once crossed the river. It is ferruginous-weathering and quite coarsely crystalline but becoming pale and fine-grained with strong brown and purple mottling upwards, where however, it is cut off by a small fault, only to reappear as a long inlier downstream at the south end of Sheriff's Park Slip. It is most clearly exposed by the weir to the south, where the full thickness (here 8' 6") is seen in the right bank (Fig. 2.14). Here again it is pale with crinoid fragments and quite large irony flecks and patches, which sometimes are cavernous; at the top, it becomes less pure and is strongly ferruginous-weathering.

Twenty feet above this Limestone, in the Leith, is the Bessygill Limestone, taking its name from the nearby wood and railway cutting in which it is well exposed. It forms the bed of the Leith towards the north end of Sheriff's Park Slip where corals can be found, and upstream 4 feet are visible in the right bank, the coral horizon being at the base of the top bed. Here it is fairly even-bedded and quite fine-grained; though medium-grey in colour it is strongly ferruginous-weathering and has a sandy base.

To the south, there is no evidence for the position of the Limestones until, at Bedlands Gate, loose limestone can be found and, to the east, a sink probably marks the top of the Johnny Hall's Trees Limestone. Nearby, spoil-heaps contain much coral rock and must have penetrated the Bessygill Limestone, which, medium-dark-grey in colour with crinoid fragments, is also seen at the head of a small tributary of Long Sike west of Dead Tree Bank. In Long Sike itself the Johnny Hall's Trees Limestone is visible south-east of the farm where it forms small rapids and the higher Limestone, with abundant Lithostrotion junceum, crinoid and shell fragments and complete brachiopods, occurs further downstream in the bed and left bank.

Both Limestones are again recognisable in Gillmoor Sike below the confluence with Town Head Gill. The Johnny Hall's Trees Limestone occurs for some distance in the stream bed where it is pale, fine-grained and with much characteristic darker grey, buff and purplish irregular mottling, and, about 75 yards beyond, the Bessygill Limestone appears as a hard, dark rock with abundant caudagalli markings. It is more clearly exposed to the south in Town Head Gill where 3' 6" occurs in three beds, the lowest having abundant shells including large Productids, the middle being in-weathering with coral colonies and the upper having, again, caudagalli markings.

Reagill-Morland sub-area

The Limestones are exposed neither in Threaplands Gill nor southwards as far as the village of Reagill but, 600 yards east of the school, a small quarry by a fieldhouse shows pale-grey crinoidal limestone with strong ferruginous mottling and cavities which is undoubtedly the Johnny Hall's Trees Limestone or, as it has been called west of the Lyvennet, the Reagill Limestone. This Limestone appears to occupy a large area to the north and north-west, in the vicinity of the village and, though no exposures are visible, the Limestone can be examined in many stone walls where it invariably shows all the characteristics of the Johnny Hall's Trees Limestone. A few grassy hollows which were probably excavations for the Limestone are recognisable east of the village, but scarcely seem large enough to have provided all the stone used, much of which has probably been obtained from the shafts sunk in search of coal. Because of the broad area occupied by the Limestone, it seems probable that its thickness is now considerably greater than it is to the west, and it may even have united with the Bessygill Limestone, of which no exposures occur unless a thin limestone seen further north in Blind Beck (p. 64) is its attenuated representative.

The Johnny Hall's Trees Limestone produces a series of sink-holes in the dry valley west of Hard Bank, but it cannot be followed to the east.

Meaburn sub-area

The Johnny Hall's Trees Limestone does not occur in the

Lyvennet and only reappears in the steep slope north of Scattergate Lane, Maulds Meaburn, where it forms a slight feature covered with loose brownish limestone. It can again be found by the side of the lane itself where it is very hard, brown weathering and with crystal-filled cavities, and as blocks in the banks of Scattergate Gill. To the south, above Bastern Gill, it caps a marked feature and is then displaced slightly by the Bastern Fault, just south of which a series of sinks may show the position of the top of the Limestone. More sinks allow the outcrop to be traced to the south and at Johnny Hall's Trees itself, although no limestone is visible, irregularities in the ground suggest that there may once have been quarries. The Bessygill Limestone is nowhere seen but, if it is still an independent unit, it may be responsible for some of the sink-holes otherwise attributable to the Johnny Hall's Trees Limestone.

Drybeck-Asby sub-area

The outcrop of the Johnny Hall's Trees Limestone runs north-eastwards from the B6260 road to the Harding's Wood Fault and thence in an easterly direction to the Hoff Moor Fault. Locally, it gives rise to small scarp and bench features, when occasional outcrops of amber-brown, cavernous-weathering limestone, above sandy limestone, occur. Above the most south-westerly outcrop of the Limestone are sinks at two different levels, lending slight support to the suggestion that the Bessygill Limestone still remains a separate bed. More sinks, probably at the top of the Johnny Hall's Trees Limestone allow the Limestone to be traced across Hoff Moor, but it is then obscured by glacial deposits until it is possibly seen in the bed of Oak Beck in Hoff Lunn. Here, just upstream from the confluence with the Nag's Head tributary, is a little, very reddened, calcareous sandstone with both mica and crinoid fragments, and probably appearing from below it beyond the bridge is 1 foot of reddened hard crinoidal limestone. Still further upstream, more red, micaceous, calcareous sandstone occurs and has only a few small shell-molds. It probably lies above the calcareous beds described and is overlain by some pale-grey, soapy-feeling, silty shales, above which is more massive calcareous sandstone with very large crinoid fragments. These beds may represent the top of the Johnny Hall's Trees Limestone with some of the Bessygill Limestone, now of sandier facies, above; equally they may overly the latter Limestone, but the exposures are too few and the possibilities of faulting too great to allow any definite conclusions.

c. THE JOHNNY HALL'S TREES CLASTICS

Strickland sub-area

Beds immediately overlying the Johnny Hall's Trees Limestone are seen in the right bank of the Leith at either end of the inlier of the Limestone (Fig. 2.14). Shale and dull purple siltstone pass up into wavy-bedded sandstone, followed by medium-bedded, pale, brown-speckled sandstone, some of which is calcareous. At the top, ganister is well developed and is exposed in the river bed just upstream from the Bessygill Limestone. To the south, the sandstone member, here pale amber, hard and fine-grained, is faulted against the Johnny Hall's Trees Limestone and can then be traced in the steep right bank, a short distance above the Limestone, where it is gently cross-bedded and often calcareous.

A little shale overlies the Bessygill Limestone but this soon gives way to very hard, maroon, fine-grained calcareous sandstone, seen at the fords north of the wood, and culminating in grey and maroon, silty limestone with small crinoid fragments (Fig. 2.14). This is overlain by purple and grey fossiliferous shales with brachiopods near the base and two bands of deep purple-brown oxidised iron carbonate, as well as some flat calcareous concretions. The shale gets more micaceous upwards and passes into sandstone, again often calcareous and wavy-bedded but sometimes, especially at the top of the unit, non-calcareous and medium-fine grained. In Sheriff's Park Wood the upper part of the sandstone is well exposed; it is broadly lenticular bedded, some has a calcareous cement, and near the top are what appear to be altered *in situ* plant remains, though having an unusual regularity of form.

This succession is also partially exposed at many places in the very steep valley side known as Sheriff's Park Slip where an estimated 79 feet of rock occurs between the top of the Johnny Hall's Trees

Limestone and the base of the Maulds Meaburn Edge Limestone, and in the deep gully in Towngill Wood, but the outcrops are too overgrown and scattered to build up a detailed succession. At the top, there is a transition to the Maulds Meaburn Edge Limestone via calcareous sandstone with crinoid fragments.

To the south, a little of the sandstone just above the Johnny Hall's Trees Limestone is visible high in the steep valley side east of Thrimby Bridge, and fine-grained, pale sandstone and ganister, close to the base of the Maulds Meaburn Edge Limestone, outcrops north-east of Little Strickland village. Exposures are then absent until Long and Gillmoor Sikes cut deep valleys through the succession, which is very similar to that seen in the Leith. In Long Sike, the ganister below the Bessygill Limestone is well exposed, with a little thin-bedded sandstone and shale below, and overlying the Limestone some of the calcareous sandstone is seen before, downstream as far as Gillmoor sike and in quarries in both banks, exposures of cross-bedded, medium and fine-grained sandstone occur. In Gillmoor Sike, the ganister below the Bessygill Limestone is again visible and the succession above this Limestone is almost continuously displayed (Fig. 2.14). Blocky, finely micaceous and slightly carbonaceous shale with a few small shell imprints overlies the Limestone and is followed by calcareous siltstones and gently cross-laminated, fine-grained sandstone, often hard and calcareous with plant debris on bedding planes, before the thick, massive sandstone exposed in Blenkingship Wood. This is bedded in a series of lenticles within which more regular, unidirectional cross-lamination sets are sometimes visible. The same sandstone can be recognised to the south-east at Sleagill Green Farm, where it contains some unusual red elongated markings which, like those in Sheriff's Park Wood, may be the altered remains of the plant roots.

Reagill-Morland sub-area

At Sleagill, a little sandstone is seen in the stream just below the Maulds Meaburn Edge Limestone, and similar sandstone, with <u>in situ</u> plant roots, occurs in Blind Beck before it disappears down a sink in the Limestone west of Brocks Brow. Upstream, towards Main Ing, wavy-bedded, micaceous and carbonaceous sandstone and some shale, from a lower horizon, is visible and horizons probably just below these occur in Blind Beck south-west of Main Ing. Here, ganister in the stream bed is overlain by carbonaceous sandstone with crinoid fragments and then a 3 inch impure crinoidal limestone, getting shaly and darker upwards before passing into a dark pyritic shale with rare fossil traces at the base. This 1 foot shale becomes slightly micaceous and carbonaceous towards the top, heralding the incoming of thin wavy-bedded sandstone and very carbonaceous silty sandstone before hard, yellowish, fine-grained sandstone completes the minor rhythm. It is possible that the marine horizon is the attenuated equivalent of the Bessygill Limestone but the exposure is only 1 mile east of the outcrop in Town Head Gill where the Limestone is as well developed as in the Leith, a further 2½ miles to the north-west. More probably it represents a higher calcareous horizon of that section.

Upstream in Blind Beck, from below this thin limestone, there appears some hard pinkish calcareous sandstone with quite common crinoid fragments and brachiopods, and loose micaceous sandstone visible upstream is thought to be from a still lower horizon. South-eastwards from Blind Beck, the clastics must form much of Hard Bank but appear to be obscured by glacial material and are not seen west of the Lyvennet.

Meaburn sub-area

Beds underlying the Maulds Meaburn Edge Limestone are well exposed in the river-cliffs of the Lyvennet south of Barnskew, and are notable for an increased proportion of shale as compared to western exposures, the thick sandstone at the top not being developed. About 20 feet of sandstones and shales, usually micaceous and with abundant carbonaceous material on bedding-planes, are here visible and of which almost 25% is shale. The contrast with their equivalents in the Leith is further maintained by the absence of calcareous sandstone, accompanied by a general thinning of the unit, an estimated thickness of 55 feet at Maulds Meaburn contrasting with that of 79 feet to the west.

The unit occupies the upper part of the steep slope overlooking

Maulds Meaburn Hall, where the sandstone passes up via sandy limestone into the Maulds Meaburn Edge Limestone. The same transitional relationship is displayed in Scattergate Gill (Fig. 2.15) but further south in situ rock is rarely seen. At Johnny Hall's Trees the width of outcrop suggests that the beds above the Limestone have thinned still further, probably to less than 40 feet.

Drybeck-Asby sub-area

The clastics can be traced across Maulds Meaburn and Hoff Moors (where they may be even thinner) with the aid of a few small sandstone quarries, but their outcrop position is uncertain in Hoff Lunn before Oak Beck where there is a good section in the bed and right bank (Fig. 2.14). A 6 feet thick body of red-speckled sandstone is present but the succession is again notable for the frequent occurrence of shales, separated by thinner sandstone horizons. If the calcareous beds below, of uncertain horizon, are omitted (p. 61) probably little more than 30 feet of strata now separate the Johnny Hall's Trees and Maulds Meaburn Edge Limestones. Sandstone, partly strongly vermillion-stained, seen in the tributary which rises at the Nag's Head, is thought to be from below the Maulds Meaburn Edge Limestone but to the east the unit has not been recognised.

vii) Maulds Meaburn Edge Cyclothem

a. SUMMARY

The cyclothem shows an unusually large variation in thickness from about 45 feet in the west to almost double that figure near the eastern margin of the region. The Limestone at the base is thinner than all the major Limestones below it except for the Johnny Hall's Trees Limestone, being usually between 20 and 25 feet thick, but it frequently produces good features and is well exposed. It is thick- and usually wavy-bedded with much pale and fine-grained limestone, often having abundant crinoid fragments and, near the base in the west of the area, a horizon with colonies of Lithostrotion junceum. The overlying clastics are here only 25 feet thick and include beds with marine fossils, but eastwards they greatly expand and include a thick, massive sandstone at the top.

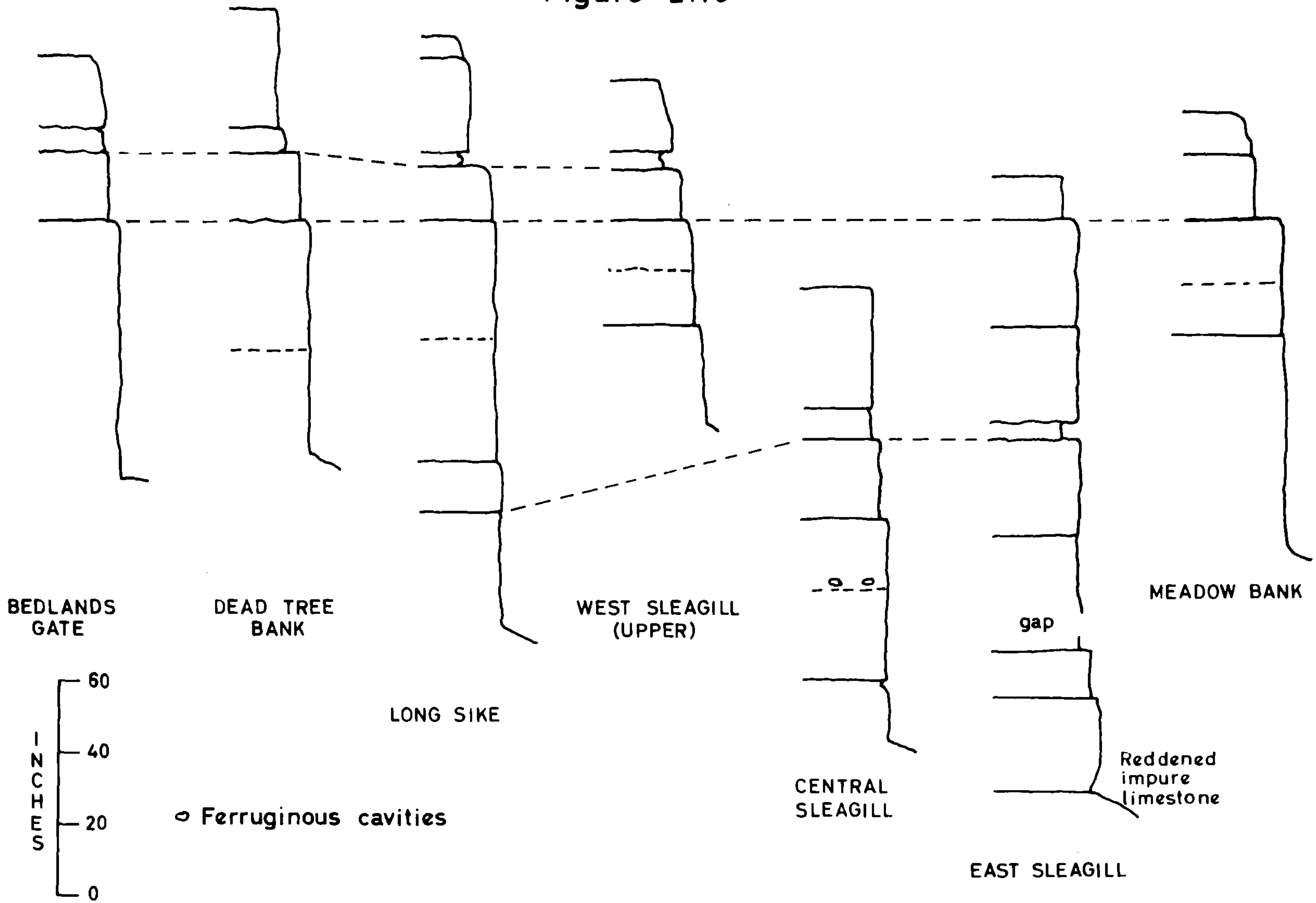
b. THE MAULDS MEABURN EDGE LIMESTONE

Strickland sub-area

The Limestone occurs in the bed of the River Leith just north of Sheriff's Park Wood, and the lower part is well exposed in a cliff on the right bank in the wood itself. Here, the Limestone has a sandy base succeeded by dull-purple-stained limestone and then paler grey, irregular blocky-weathering limestone with slightly wavy minor bedding-planes, abundant crinoid fragments and, about 5 feet above the base, a bed with Lithostrotion junceum. The Limestone rises rapidly to the south so that, in Sheriff's Park Slip, it occurs at the top of the very steep valley side where the lower part, with the Lithostrotion junceum Bed up to 2' 3" thick and especially well displayed, is almost continuously visible as far as Towngill Wood. Its position west of the Little Strickland-Great Strickland road is indicated by some large hollows and, at the road itself, several small quarries again show the Lithostrotion junceum Bed which has not, however, been found any further to the south and east. Numerous quarries (Fig. 2.16), showing up to 10 feet of fairly pale-grey crinoidal limestone, allow the unit to be traced past Field House and Dead Tree Bank to Long Sike, east of the confluence with Gillmoor Sike, where it forms the river-bed for 75 yards. In most of these exposures, especially in the quarries north-west of Dead Tree Bank, the Limestone has small, glassy, sub-spherical bodies which may be Saccamminopsis fusulinaformis, though never as abundant as in the Little Strickland Limestone.

Between the quarries at Dead Tree Bank and in the north valley side of Long Sike (Fig. 2.16), a distance of less than $\frac{1}{2}$ mile, there is a thickness reduction of 16% between two bedding-planes which can be

Figure 2.16



MEASURED SECTIONS IN THE MAULDS MEABURN EDGE LIMESTONE correlated with certainty. The Long Sike quarry is of particular interest in that it includes a 4-inch bed near the top which has in-weathering shaly horizons on either side and can be correlated with a similar but slightly thicker bed to the east, thereby providing a link with the westerly exposures where the shaly horizons are absent and making it possible to demonstrate the persistence of this thin bed (never exceeding 8 inches) over a distance of more than 6 miles.

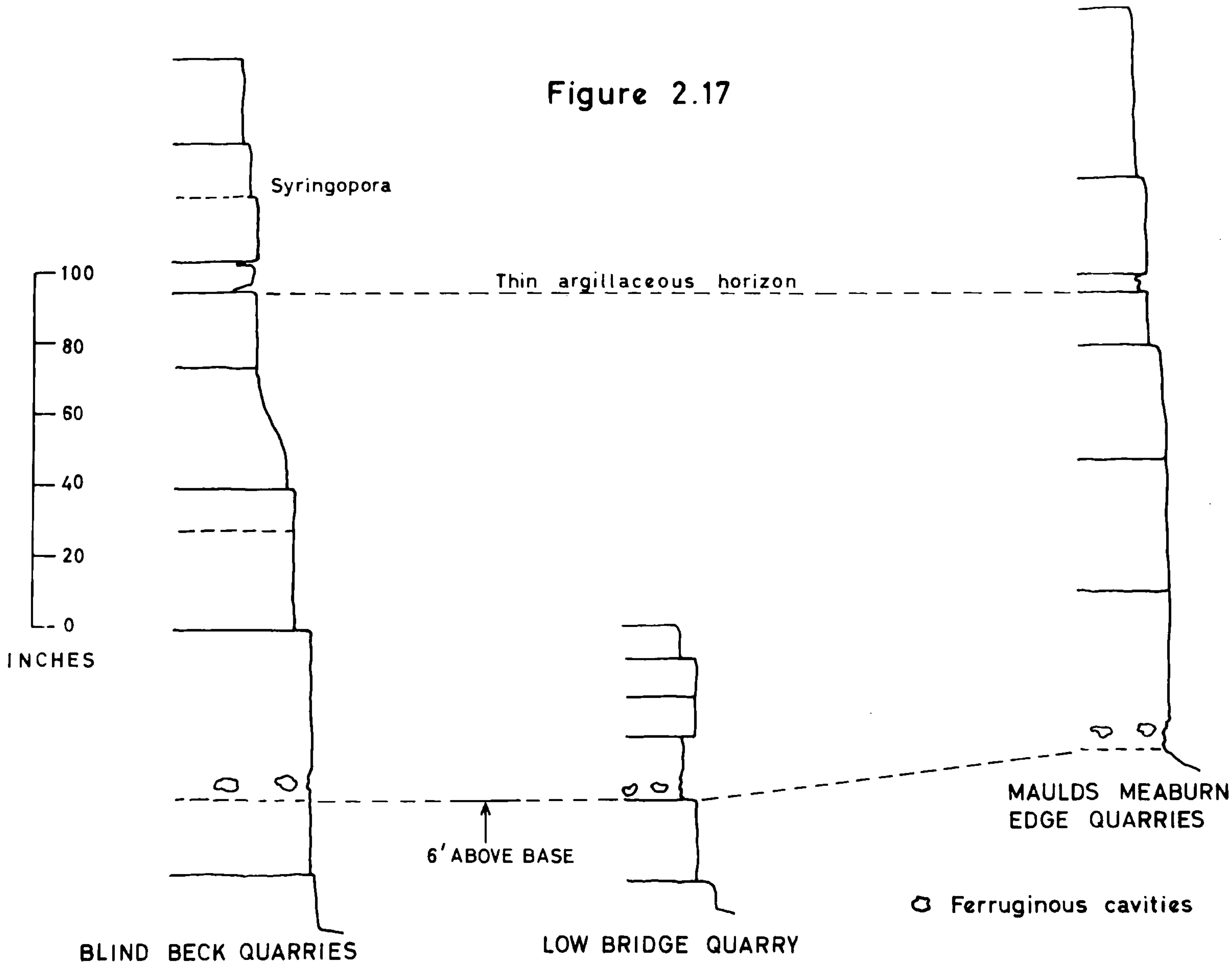
The Limestone rises southwards from Long Sike but its position is only indicated by sink-holes until, at Sleagill village, which is built on the Limestone, several large quarries occur (Fig. 2.16). The most westerly, at the foot of the steep slope opposite the school, show what is thought to be the laterally persistent thin argillaceous bed near the top and, low down, is a horizon with very poor indications of large irregular irony cavities, which may be the most westerly exposure of a horizon well seen near the Lyvennet. This bed is also visible low down in the large quarry in the centre of the village but cannot be recognised to the east on the opposite side of the road, though the large exposures are undoubtedly of the lower part of the Limestone, since, at the base, it is reddened and impure and overlain by dark limestone becoming paler upwards. It is possible that the cavernous bed lies between the limestone exposed in the lower and in the upper parts of the quarry but, though correlations with nearby quarries are suggested in Fig. 2.16 they are rather uncertain and, clearly, bedding-planes are not uniformly persistent at all levels in the Limestone.

Reagill-Morland sub-area

Long exposures occur in the bed of Sleagill Beck and it is again seen $\frac{1}{4}$ mile south-east of Meadow Bank (Fig. 2.16) where the middle part of the Limestone is visible. As to the west, major bedding-planes are uncommon and the limestone again contains rare foraminifera. Towards the north-east the outcrop is obscured by drift but numerous sinks indicate its position north of Main Ing, and it is very well exposed by the Reagill road junction in Blind Beck and adjacent quarries (Fig. 2.17). Here, near the base of the succession, the horizon which weathers with large irregular ferruginous hollows is well seen, as is the persistent thin argillaceous bed near the top; in

MEASURED SECTIONS IN THE MAULDS MEABURN EDGE LIMESTONE

Figure 2.17



the limestone just above it Syringopora is unusually abundant. The stream itself goes underground where it reaches the Limestone but the upper part is visible downstream, beyong the road, where its bed is of fine-grained, medium-grey limestone with some pyrite and a few darker patches which may be algal markings. Glacial deposits then obscure the solid rock in the deep valley but where it opens out to the east, several sinks indicate that the Limestone still lies just below the stream.

Meaburn sub-area

The Limestone is visible in the bed and left bank of the Lyvennet at Barnskew, where again it is often fine-grained and medium-dark-grey with abundant crinoid fragments, but cannot be recognised to the south, in the east side of the valley, before Maulds Meaburn where it caps the steep feature overlooking Low Bridge and the horizon with large ferruginous cavities is recognisable 6 feet above the base (Fig. 2.17). Good exposures occur adjacent to Brackenslack Lane, in Scattergate Gill (Fig. 2.15) and at Maulds Meaburn Edge itself where a series of large quarries show all but the basal and top parts of the Limestone (Fig. 2.17). It here totals about 27 feet, with the thin argillaceous bed clearly seen throughout; the ferruginous-weathering cavernous horizon can be found right at the base. A few irregular crinoidal shale partings are present and appear to sharply follow massive crinoidal limestone but to grade up into the next massive limestone. Bedding-planes, here showing little variation in their distances of separation, can be traced throughout the quarries and picked up again on Maulds Meaburn Moor, near the B6260, where the Limestone underlies a broad area and produces numerous swallow-holes.

Drybeck-Asby sub-area

Just east of the Appleby-Orton road a large quarry shows the upper part of the Limestone, which then can be easily traced to Hoff Moor by means of an almost continuous line of sink-holes, marking its upper boundary and showing that it is affected by three minor faults. The Limestone appears to be thinning in this direction and, after being obscured by drift in Hoff Lunn, reappears in the upper reaches of Oak Beck (Fig. 2.14) where it seems to be only about 20 feet thick and has been strongly dolomitised with, in addition, some reddening.

On the downthrow side of the Barwise Fault the Limestone is thought to be that which occurs in a small quarry south of the deep valley by Brown Hills, and, to the south, it may be indicated by sinks near the junction of Blind Lane and Mill Lane. Elsewhere, it has not been recognised with certainty owing to the scattered nature of the exposure and the extensive drift cover, though it may be present in Hoff Beck. Here, downstream from the last of the Little Strickland Limestone seen in the bed north of Rutter Force there are several exposures of limestone up to the confluence with Oak Beck, which on lithological grounds could belong to this member. They are of fine-grained, medium-grey limestone with crinoid fragments, some of which is strongly reddened and, showing variable dips, has clearly been affected by faulting, the nature and position of which cannot, however, satisfactorily be discerned. Because of this, the possibility remains that the exposures are of upthrown Little Strickland Limestone, of Brackenslack or even higher Limestones, or, of course, all these horizons. In Oak Beck too, just east of Hoff Lunn Farm, some quite steeply dipping limestone, reddened and slightly dolomitised at the base, occurs in the stream bed and is possibly the Maulds Meaburn Edge Limestone lying between two branches of the Barwise Fault. It rests on sandstone but the reddened argillaceous limestone, a few yards to the west, has little dip and is thought to belong to the Little Strickland clastics on the upthrow side of the fault.

c. THE MAULDS MEABURN EDGE CLASTICS

Strickland sub-area

Almost the full thickness of the clastic sequence is seen in the right bank of the River Leith, north of Sheriff's Park Wood, where they are probably little more than 20 feet thick; the following succession is exposed:-

Sandstone	6' 3"
Siltstone with sandy lenses	4' 3"
Fine sandstone with fossil bands	1' 10"
Siltstone	0' 10"
Mudstone	1' 4"
Total	14' 6"

Blocky, dull-purple and green mudstone with small dark spheres of unknown origin occurs in the stream and passes up, via parallel bedded siltstone into hard, fine sandstone which has thin bands containing molds of shell fragments and is overlain by pale siltstones with purple laminations indicating small lenses of wavy-bedded, very fine sandstone. Horizontal thin tube-like bodies of sandstone (probably worm-burrows) occur, and there is also a lens of less fine-grained sandstone having a few fossil molds. Above, is a thick sandstone body which splits into thin sheets at the base showing, on some bedding surfaces, many trails and also circular pits which may have been produced by escaping gas. The upper sandstone is exposed in this bank nearly to the weir and again in the bed of the river a little further to the north, where it is overlain by the Brackenslack Limestone, but the unit is nowhere else visible west of Sleagill Beck.

Reagill-Morland sub-area

Although not visible in the stream itself, in the east valley side of Sleagill Beck just north of the village, some small excavations show massive pale-buff sandstone not far below the Brackenslack Limestone. It is medium-fine-grained with only rare mica and some has dark markings which may be the remains of _in situ_ plant roots. Judging from the width of its outcrop, the unit appears to be thicker than in the Leith section, and may thicken further to the east but remains unexposed.

Meaburn sub-area

In the right bank of the Lyvennet at Barnskew, shale with small siderite nodules, passing up into siltstones and thin, gently cross-laminated sandstones with a little flaggy sandstone at the top, overlies the Maulds Meaburn Limestone to a height of about 25 feet. Since the main sandstone member intervenes before the Brackenslack Limestone, the whole unit must be considerably thicker than in the Leith, and at Maulds Meaburn Edge, to the south, it has an estimated thickness of 50 feet of which the lowest 10 feet appear to be mostly shale and is overlain by a thick pale or slightly purple medium-fine grained sandstone. It is seen in several small workings west of the junction of the Maulds Meaburn road with the B6260, on Maulds Meaburn Edge, and north-west of Brackenslack Farm and, in most cases, is rather friable and with very little mica.

Drybeck-Asby sub-area

Passing eastwards from the Orton-Appleby road, the clastics probably thicken still further and occupy a large part of Maulds Meaburn and Hoff Moors, where however, except in the west, solid rock rarely outcrops. Here, many shallow excavations show the massive-looking, pale purplish sandstone, and a little blue-grey crumbly shale, sometimes with ferruginous nodules, is visible in the sinks at the top of the Maulds Meaburn Edge Limestone. In Hoff Lunn, the deep gorge of Oak Beck is cut through the clastics, which now must reach a thickness of over 60 feet. About 10 feet of fossiliferous shale with crinoid fragments and molds of brachiopods but mostly with small pieces of shell appear to overlie the Limestone and are followed by at least another 15 feet of predominantly argillaceous beds before thin-, wavy-bedded, maroon and grey siltstones and sandstones occur, the latter getting thicker-bedded upwards. This part of the unit is well displayed towards the top end of the gorge where trough-bedding, ripple-marks and worm tracks are common features of the micaceous sandstones and silty sandstones.

Further down Oak Beck, just beyond the Barwise Fault, what are thought to be more exposures of strata from this unit occur. Here, steeply dipping reddened shale, siltstone and micaceous sandstone appear to have been thrown down to the level of the limestone visible upstream, and must themselves be separated by a fault from the shales in the beck to the south-east. These are maroon and green-grey with ferruginous concretions and a few traces of gastropods and ribbed shells and must, if they belong to the same unit, have been upthrown with respect to the steeply dipping beds, and probably also with respect to the limestone seen to the east by the gamekeepers' house. Overlying them in the right bank are unfossiliferous, silty shales and massive, slightly reddened, cross-bedded sandstone. Similar horizons are also thought to occur in the main southern tributary of Oak Beck, being well displayed in the deep valley west of Brown Hills. Due west of the buildings, purple and slightly greenish crumbly shale passes up into finely laminated silty shales with very small-scale cross-bedding and these, in turn, pass into the laminated siltstones and delicately cross-bedded sandstones characteristic of this horizon. These thin- and medium-bedded sandstones are seen downstream, where trough-bedding and various sole-markings occur, as well as a horizon with a few decalcified fossil fragments. These beds are overlain by a more massive, medium-grained, cross-bedded sandstone which is well exposed higher up the stream before being cut off by the Barwise Fault, and is also seen in the steep slope south-south-east of Brown Hills where it is strongly purple-stained.

iix) Brackenslack Cyclothem

a. SUMMARY

The cycle is very poorly exposed throughout the area but everywhere appears to be about 75 feet thick. The Limestone member, in the Leith, is very thin and the overlying clastics contain two thick sandstone bodies, but towards the south and east the proportion of limestone in the cycle greatly increases until it probably reaches a thickness comparable to that of the clastics on

Maulds Meaburn Moor. Further east, however, the shales and sandstones may expand again and certainly include a very thick body of sandstone at the top. The Limestone is nowhere completely exposed but is, in general, a hard, dark-grey rock with crinoid and a few shell fragments but appears to have no characteristic fossil bands.

b. THE BRACKENSLACK LIMESTONE

Strickland sub-area

The Limestone is visible in the right bank of the Leith at the weir south of Strickland Mill, and in the river bed just to the north where about 10 feet of reddened limestone occur and probably represent almost the whole of the member. It is fine-grained with crinoid fragments and brachiopods as well as occasional small glassy spheres which, if they are Saccamminopsis fusulinaformis, are at the highest horizon at which this fossil has been found.

To the south, there is little evidence for its position until, north-west of the Shap-Newby road it produces a well defined feature in which scattered pieces of quite dark, hard, fine-grained limestone can be found. The outcrop then follows an easterly course towards Sleagill Beck but the only indication of its exact position is the loose pinkish limestone ploughed up in a large field west-north-west of Whitestone and big sink-holes, west and just east of the farm.

Reagill-Morland sub-area

Slabs of impure, dark, slightly purple, fine-grained limestone with crinoid fragments and some large bryozoa occurring in the right bank of Sleagill Beck 100 yards south of Ironshaw, are thought to be at the top of the Limestone, which is nowhere exposed to the south-east, though it gives rise to a series of sinks in the dry valley just south of the Sleagill-Low Moor road. In the valley west of Turnbank, several strong springs appear at the base of the Limestone which, again, is not visible, there probably being an appreciable cover of glacial drift.

Meaburn sub-area

The absence of the Limestone from stream sections is again apparent and the River Lyvennet does not produce any exposures. In the sides of the track from Roans to Grayber, where it is sunk deeply into the ground, a little quite dark-grey, fine-grained, crinoidal limestone is visible and has been assigned to the Brackenslack Limestone on account of its similarity with the limestone exposed on Maulds Meaburn Moor. At Brackenslack Farm itself, it forms a small feature but only a little ferruginous limestone at the base of the member is seen, just north of the road. However a series of deep hollows above Maulds Meaburn Edge clearly show its position, and to the east on the Moor, the outcrop widens considerably, being marked by numerous sinks and quarries in and near the wood at the junction of the B6260 with the road to Maulds Meaburn, and the Limestone may now reach 30 feet in thickness. It is medium-dark-grey, fine-grained, with crinoid fragments and occasional dark algal-like markings. The ground to the north-east has a thick mantle of drift but the Limestone can be traced, via large sinks, to the dry valley $\frac{1}{2}$ mile south of Dryevers, where a little dark, hard limestone is visible, and to the east, the largest exposure of the limestone in the whole region (7' 6") occurs west of the junction of the B6260 with the road to Drybeck. Here, it is a thick- and slightly wavy-bedded, hard, amber-yellow-weathering, dark and finely crystalline limestone with a few crinoid fragments; dark, possibly algal, patches occur near the base which is finer-grained.

Drybeck-Asby sub-area

At the western margin of Hoff Lunn by the Drybeck junction, the Limestone was once quarried; sinks marking its top lie in the wood to the east and loose reddened crinoidal limestone, visible in the stream rising at the Nags Head, is perhaps referable to this member but no definitely in situ rock occurs west of the Barwise Fault.

On the downthrow side of this fault, what is thought to be the Brackenslack Limestone, rich in very small crinoid fragments, partly reddened, and thick-bedded, is visible in a quarry by Oak Beck just west of the gamekeepers' house in Hoff Lunn, and red limestone in the stream, east of the house, belongs to this horizon. The same may, perhaps, also be said of the reddened limestone present in Hoff Beck where it is joined by Oak Beck.

c. THE BRACKENSLACK CLASTICS

Strickland sub-area

In the River Leith, blocky purple-stained shales are visible above the Brackenslack Limestone and some of the overlying beds, though absent from the river except for a little pale sandstone just below the Grayber Limestone, are well exposed in the cliff by the mill-race, south of Strickland Mill. Here, about 2 feet of thin- and medium-bedded, purplish, micaceous siltstones with intercalations of fine, cross-bedded sandstone at the top, are overlain by an 8 feet thick bed of massive, pale-brown, medium-fine-grained sandstone. Planar cross-bedding can sometimes be recognised, and mica, common at the base, becomes rare upwards where the grain size increases and feldspar becomes more clearly visible; deep purple mud-flakes are present. Above, about 4 feet of pale purple and maroon crumbly shale occur, having sandstone intercalations upwards and passing into medium-bedded sandstone. The succession above this is not exposed but is probably mostly sandstone, the top of which, a medium-fine-grained, hard, pale and purplish rock with *in situ* plant roots becoming very common at the top, is visible in Strickland Mill Quarry just to the east.

This same horizon, is the only one which is well exposed to the south where very hard siliceous sandstone or ganister can be found on the top of the feature which crosses Thrimby Mill Plantation. To the east, except for a little pinkish medium-fine-grained sandstone in a small stream near the road at Newby Pasture, exposures are absent.

Reagill-Morland sub-area

A little shale and much of the overlying sandstone is visible in Sleagill Beck where it flows in the deep valley at Ironshaw. The lowest sandstone is pale, thin-bedded and with almost parallel or gently wavy laminations covered with mica, but more massive-looking buff sandstone is present at higher levels, though it often still weathers with purplish discontinous wavy laminations. Eastwards, sandstone just below the Grayber Limestone is visible south-east of Low Moor Farm where old excavations show intermittent exposures of mostly massive medium-grained sandstone often with big mica flakes on the irregular cross-laminations, extending over a height of 16 feet.

Meaburn sub-area

Massive sandstone from the unit occurs in the Lyvennet section north of Turnbank, and southwards can be traced between High and Low Lankaber to west of Grayber by means of several small quarries. Up to 12 feet of cross-bedded, medium or medium-fine-grained sandstone with a little feldspar and often large mica flakes on bedding-planes, may be visible. Usually bedding is obscure but seems to be generally in thick lenticles with, rarely, some planar cross-bedding present in units of the order of 2 feet thick.

An inlier of the clastics occurs in Little Beck, just north-west of Brackenslack Lane, where 6 inches of dark purple and white, mottled and altered ganister, having a few molds of shell fragments at the top, is visible. The ganister is again seen to the south of Holesfoot, where the westerly headwater streams of Little Beck enter a sink in the Grayber Limestone, and the sandstone below occurs in the stream at the plantation to the south-west and again, by the same stream further south, where a very large part of the north of Maulds Meaburn Moor in underlain by the unit. A strong spring appears from the base of this thick sandstone member 750 yards south of Dryevers and it was extensively quarried at the south end of Long Rigg near the Kings Meaburn junction on the B6260, though now only a little dark-red, very micaceous sandstone is visible.

Drybeck-Asby sub-area

At the north-west edge of Hoff Lunn a series of quarries show up to 10 feet of the red and purple, medium-grained, cross-bedded sandstone. What is thought to be approximately the same horizon on the downthrow side of the Barwise Fault is seen in a northern tributary of Oak Beck, where the sandstone is planar-cross-bedded, with much mica and feldspar visible and is stained deep vermillion. It is medium-grained at the top but very coarse near the base of the member below which dull-purple shales are seen a few yards downstream. It is also possible that the thick-bedded, medium-grained, micaceous and strongly reddened sandstone visible in the left bank and bed of Hoff Beck, 150 yards north of the confluence with Oak Beck, belong to this unit.

Appleby sub-area

In the south-west part of the district, a large inlier of the thick sandstone at the top of the unit is present on the upthrow side of the Barwise Fault. Just north of the B6260, by the Nag's Head, are several quarries in the cross-bedded sandstone which is brownish-purple, medium-coarse-grained, with some small flat irony nodules and, locally, with large concretion-like reddened masses which must have been siderite-cemented patches. One of the headstreams of Barwise Sike rises to the west of the Nag's Head and shows a little of the same massive sandstone, with small irony nodules and some deep-purple-brown or yellow mudflakes; it is well displayed in the gorge at Barwise Hall. To the south, in the wood, two large quarries show up to 26 feet of the sandstone of purplish or pale yellow colour with much mica, often in large flakes, and generally medium- or medium-fine-grained but with lenses of coarser sandstone too; feldspar is not apparent, even in the coarsest rock. The same sandstone is also seen in the stream at the southern margin of the wood but is cut off eastwards by the Barwise Fault, adjacent to which it is purple-stained and appears to be dipping steeply.

A possible inlier of the clastics is present in Barwise Sike between the Hall and Rainbow Plantation. Underlying what is thought to be the Grayber Limestone some hard, mottled ganister, very similar to that seen in Little Beck, occurs and upstream further sandstones, usually wavy-bedded and medium-fine-grained, and silty shales are visible. There is, however, some doubt about this correlation since the beds appear to be quite close to the base of the Grayber Limestone and yet no sign of the thick sandstone seen at Barwise Hall occurs; either they must overly this sandstone or, more likely, the main sandstone body has been faulted out.

ix) Grayber Cyclothem

a. SUMMARY

The Grayber cycle, which has a persistent relatively thick shale horizon above the Limestone and a well developed sandstone member, is the best exposed of the higher Yoredale cycles and averages 75' to 80' throughout the region. The clastic part of the succession probably thins to the north-west but this is compensated for by a considerable expansion of the Limestone to about 40 feet in the River Leith. Here, in the middle of the Limestone, is a bed with abundant bryozoa and some simple corals which is not recognisable to the east, although corals and scattered specimens of the bryozoan can still be found. Westwards, also, chert nodules make their appearance in the lower part of the Limestone and, in the Leith valley, occur in four distinct bands. The Grayber Limestone is of particular interest in that it is characterised throughout the area by the presence, towards the top, of many small specks of glauconite. This mineral has been discovered in abundance at only two other levels in the succession, at the base of the Little Strickland Limestone and in the Newby Mill Limestone, but in neither case is it as common as in the Grayber Limestone. It allows this Limestone to be identified with certainty and has proved invaluable for correlation purposes in a part of the succession where lack of exposures would otherwise have made interpretation difficult. The overlying sandstone member, named the Littlebeck Sandstone, is also quite distinctive, being characterised by large-scale cross-bedding, sometimes of planar type, and horizons where the grain size is coarse with feldspar clearly present. It is also unusual in having frequently an erosive base, the sharp contact with the underlying shale and siltstone contrasting with the passage by alternation exhibited by almost all other sandstone bodies in the Middle Limestone Group of the region studied.

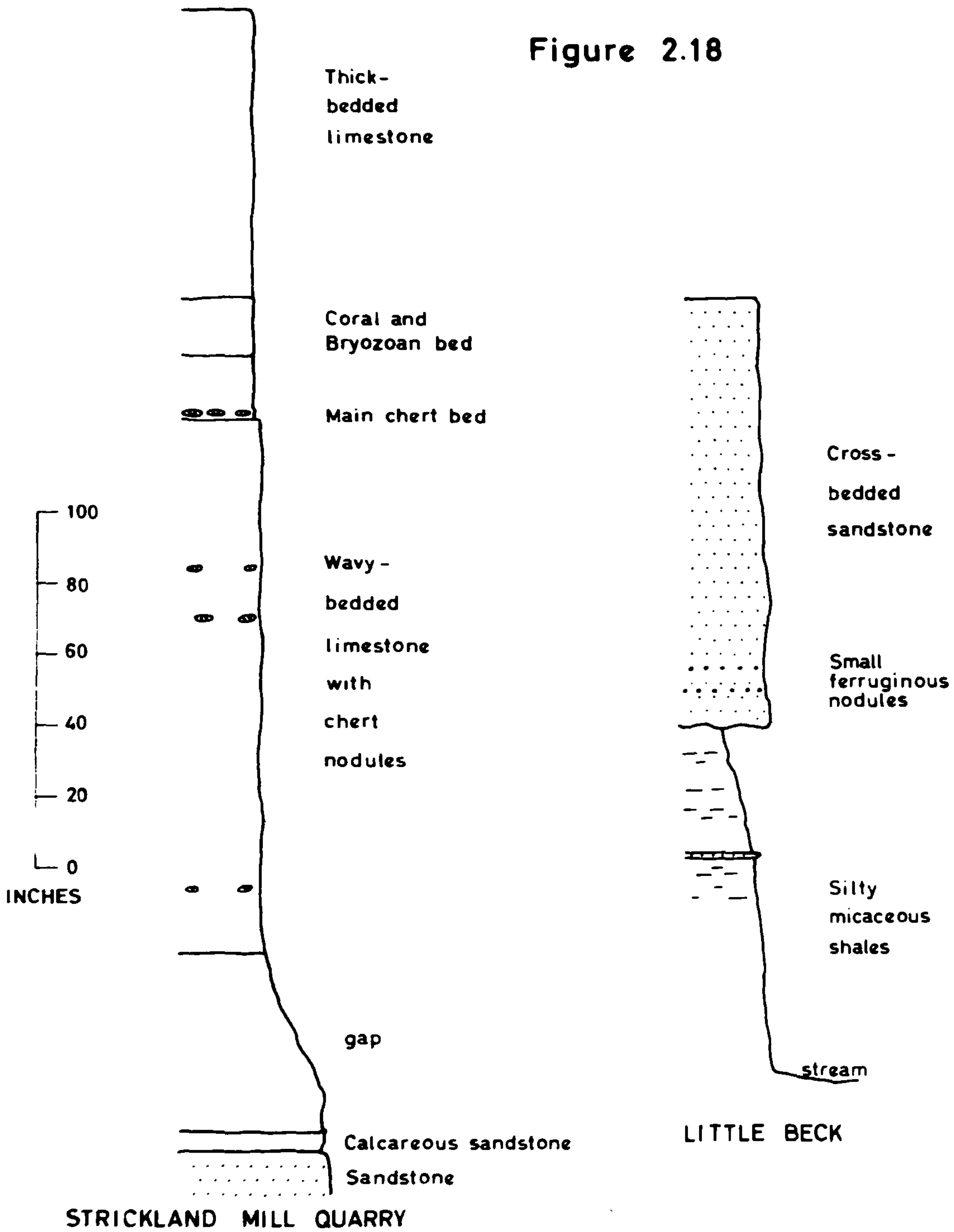
b. THE GRAYBER LIMESTONE

Strickland sub-area

The largest exposure of Grayber Limestone in the region is at Strickland Mill Quarry where it is visible to about 26 feet above the base (Fig. 2.18) and includes four horizons with yellow or pink chert nodules, the highest and best developed of which is shortly overlain by the bryozoa bed. The Limestone is thick- and medium-bedded but weathers with thin wavy laminations and, near the base, is slightly reddened. Crinoid fragments, often large, are abundant throughout but the limestone, having a very finely granular "powdery" texture and a buff colour low down, changes upwards to a more compact and often quite pale, fine-grained rock. Glauconite was not found at this quarry but is recognisable, though in lesser abundance than to the south-east, where the Limestone reaches the River Leith in the cliff north of Strickland Mill. Here all but the top of the Limestone is visible and shows rather frequent reddening.

MEASURED SECTIONS IN THE GRAYBER CYCLOTHEM

Figure 2.18



The Limestone can be traced easily to the south-east with the aid of several quarries mostly showing the lower part which is medium-pale-grey or pink-stained with a rough fragmental texture weathering to a "peppery"-looking rock and having common cherty horizons, though, south-west of Great Strickland Vicarage, some of the overlying beds containing glauconite are seen. It passes just north of Moorriggs and is exposed in quarries between Sandriggs and Lodge, where it is thin- and wavy-bedded, often pink or purple-brown-stained but with glauconite still locally visible. Southwards, the position of the outcrop is initially obscure but must skirt Kirkbridge Hill Plantation and can be picked up again on Newby Pasture where numerous sinks indicate its upper limit, and several small excavations show pale- or medium-grey but often brown- or purple-stained limestone, apparently here without glauconite. Eastwards, the Limestone is nowhere exposed, though it gives rise to three large sink-holes between Thorney Croft and Sandwath Bridge.

Reagill-Morland sub-area

In situ limestone is not present in Sleagill Beck, and is not seen west of the Low Moor cross-roads, although it can be locally traced by means of sink-holes north of Weathery Crook and west of White Stone. An extensive quarry south-west of the junction of the Morland-Maulds Meaburn road with that to Sleagill shows the lower part of the Limestone, here considerably reddened. Again weathering has produced irregular, thin wavy-bedding and the limestone is very rich in crinoid debris which is characteristically of white colour but with a reddened centre to the ossicles.

The quarry to the north-east, near Low Moor Farm, shows rather more of the Limestone and from higher horizons. The lowest beds seen are of very fragmental texture, purple-tinted, with abundant and often large crinoid fragments, a few simple abraded corals and with occasional chert nodules. Higher up it is medium-bedded and pale-medium-grey, with fewer crinoid fragments and has abundant small granules of glauconite. This glauconitic limestone is separated from the lower beds by a distinct erosion surface which is of channel shape, although of only very gentle relief (p.141 and Fig. 3.4).

Meaburn sub-area

A little reddened limestone from near the base of the member occurs in the Lyvennet south of the ford at High Whitber, but to the south there is no indication of the position of outcrop before a sink north-north-west of the farm from which it takes its name, though a strong spring near Littlebeck, in the stream, probably appears at the top of the Limestone. It is no longer exposed at Grayber but loose glauconitic limestone can be found north-west of the farm and, to the south, the outcrop widens to cover a very large area around Trainlands, although the thickness, estimated at 25 feet, is now much decreased. Beds near the base of the Limestone were once exposed by the track from Grayber to Brackenslack but the main outcrops are seen in and near Little Beck, to the north-east, where nearly all of the Limestone is visible. The lowest beds, seen just north of Brackenslack Lane above the sandstone inlier, are dull-purple-brown or yellow-stained, finely crystalline limestone, which can also be found in the stream bed and banks to the north-west. Above, is medium-bedded, fairly fine-grained limestone with small crinoid fragments, wispy dark markings, and maroon flecks, in which glauconite is always present and frequently quite common. The bryozoan (Stenopora), so abundant at this horizon to the west, can often be found, as can occasional simple corals and, closely associated with the glauconite, is pyrite, at times very abundant. The top bed, well seen in the stream, is slightly ferruginous-weathering with caudagalli markings on the surface which continue into the fresh limestone as dark streaks; glauconite as small green specks is still present.

South-east of Brackenslack Lane, the glauconitic part of the Limestone is again well seen in the dry bed of Little Beck and in adjacent quarries. The basal beds, again of amber-yellow-weathering limestone, appear near the fieldhouse south-west of Holesfoot but, to the east, glacial deposits obscure the solid geology and the Limestone nowhere outcrops.

Appleby sub-area

The Limestone is thought to extend into the north-west margin of the Drybeck-Asby sub-area in Hoff Lunn at the south end of

Long Rigg and, though there not exposed, is seen just to the north near the head of the stream 330 yards west of the Nag's Head, where it contains glauconite. To the north-east, the orange-red thin and slightly wavy-bedded crinoidal limestone on which Barwise Hall is built is thought to be the Grayber Limestone which, thickness considerations suggest, probably also occurs as an outlier west of the Barwise Fault at Mount Pleasant. The yellow and pink dolomitised limestone thrown against the Brackenslack sandstone member in the stream south of Barwise Wood and isolated between branches of the fault may also be from this horizon.

On the downthrow side of the Barwise Fault, the position of the Limestone is largely uncertain but it is thought to appear as the reddened limestone just south of the fault in Rainbow Plantation. The outcrop must then extend southwards but no in situ rock is seen, although large blocks of glauconitic limestone in the stream 450 yards east-north-east of Mount Pleasant, and red limestone in Hoff Beck south of Douglas Ing, may indicate its approximate position.

c. THE GRAYBER CLASTICS

Strickland sub-area

The clastics are only poorly exposed in the River Leith where, in the left bank 700 yards north of Strickland Bridge, 7' 6" of pale, fine-grained and wavy-bedded sandstone is visible. This is probably because they have been partially cut out by the Great Strickland Fault, but also it seems likely that there has been some thinning of the medium- and coarse-grained sandstone which elsewhere forms such distinct features. Just to the south, for example, at Great Strickland vicarage, the outcrop is relatively narrow and estimates suggest that it is unlikely that the unit is as much as 40 feet thick, in contrast to the 55 feet estimated to the east. At Newby Pasture the sandstone has, perhaps, begun to thicken and can be found in the valley ½ mile east of Lodge and by the track north-west of Thorneycroft Plantation. Certainly, it develops a coarser facies in this direction, and this is well seen in the steep left bank of the stream north-east of Thorney Croft Farm where it shows large-scale cross-bedding, often of planar type, is medium-coarse-grained with feldspar visible and characteristically gives rise to deep red-brown-soil. It does, however, probably have a transitional base in this district, for, in the stream north-east of Birks Plantation, purple shales and silty shales have intercalations of thin- and wavy-bedded, fine sandstone at the top, above which loose coarser feldspathic sandstone can be found.

Reagill-Morland sub-area

The unit is well exposed in Newby Beck, where the Littlebeck Sandstone, now probably having a sharp lower boundary, gives rise to river cliffs showing up to 20 feet of mostly medium-grained sandstone in broadly lenticular beds but with a very coarse or conglomeratic strongly cross-bedded facies developed locally. It is also visible in the river towards Newby, where it has altered plant remains at the top and is overlain by a bed of buff calcareous siltstone just below the Newby Mill Limestone. Upstream, the underlying purple shales, having thin seams of small ferruginous nodules and becoming silty at the top, are occasionally visible. Near the sharp bend where the river turns to the north they have obscure fossil traces and contain strongly vermillion-stained bands of very hard calcareous mudstone with large orange crinoid fragments and small molds of shell fragments.

South-eastwards, overlooking the stream which flows to Newby End, the Sandstone produces a steep escarpment in which medium-grained sandstone apparently passes laterally within a very short distance into the coarser rock; both facies are again closely associated at White Stone Farm. It does not outcrop on Sleagill Moor although it must underlie a broad area around Habers and Milbers Plantations and is visible in the lower part of Swair Gill. Just to the north by the old mill, a quarry shows about 24 feet of medium and coarse-grained sandstone, here characterised by widely separated (about 3 feet) essentially parallel bedding-planes.

Meaburn sub-area

The Littlebeck Sandstone is almost continuously exposed in the bed of the Lyvennet south of the Welltree Ford at Kings Meaburn and as vertical cliffs in both banks. It is mainly medium-grained with decomposed feldspar and often large mica flakes, but with thin bands of coarse and conglomeratic quartz. Southwards, it forms the steep right bank of the Lyvennet and then of Little Beck, where, east of High Whitber, large quarries show medium- and coarse-grained pale sandstone with major bedding-planes of such strong relief that some movement subsequent to deposition must have locally taken place. Below, in the stream bed, a little of the underlying purple-stained shale and siltstone occurs and upstream, beyond the ford, silty shale can be seen giving way to the overlying sandstone here estimated at 35' to 40' in thickness. At the top, it becomes finer-grained, and micaceous, very thin-bedded, greenish-grey siltstone and maroon silty sandstone with faint indications of plant remains underly the Newby Mill Limestone.

The unit can be traced southwards to above High Lankaber, where purple sandstone outcrops in a steep scarp and is of particularly coarse, often conglomeratic, facies with much feldspar, mica, and some small irony nodules, before it skirts Grayber and reappears in Little Beck. Here, blue-grey fossiliferous shale with brachiopods and crinoid fragments overlies the Grayber Limestone but within 2' 6" only orange streaks and specks remain as possible fossil traces, though the latter seem to be small weathered area of pyrite. Above, dark shale with large septarian nodules containing calcite and pyrite appears and passes up via slabby, silty shale and impersistent ferruginous-weathering, carbonate-cemented horizons into micaceous, dark, shaly siltstones. They are well seen downstream where they contain ferruginous nodules at the top and are sharply overlain by the Littlebeck Sandstone (Fig. 2.18). This may have a conglomeratic base with, locally, large elongated hollows which contain sticky red clay; they presumably represent spaces once filled by mud pellets which have shrunk subsequently to deposition. The basal bed is sometimes without mica which does, however, soon appear upwards where the sandstone gets less coarse and has two layers of abundant small red-brown nodules, often sausage-shaped and with hollow centres. Downstream the dip brings mostly medium-grained sandstone into the stream and a variety of depositional feature can be seen including irregular trough-bedding, faint ripples, and large-scale troughs and swells. The top of the Sandstone appears in the stream where it is crossed by the track from Crabstack to Sideway Bank and is overlain by about 5 inches of pale-grey shale with plant remains passing up into 6" to 8" of darker carbonaceous shale with four very thin coal seams, though the upper two locally unite. Thin, calcareous siltstones and silty sandstones capped by 2" of purple and buff calcareous siltstone with crinoid fragments and, occasionally, poorly preserved brachiopods separate the coal from the Newby Mill Limestone.

Appleby sub-area

West of the Barwise Fault, the unit has not been recognised but at Rainbow Plantation on the downthrow side of the fault, beds at the top can be seen in Barwise Sike underlying the Newby Mill Limestone. It is a pale, medium-fine-grained sandstone becoming slightly coarser below where it is more micaceous, but is then faulted against the Grayber Limestone, although a little crushed shale is visible in the right bank. Small quarries also give exposures of sandstone, thought to belong to this unit, on either side of the Rainbow Plantation Fault just north-west of the stream. The underlying shales are thought to be those exposed in the stream rising near Mount Pleasant east of where it crosses the Barwise Fault. They are blocky, purple and greenish, with oxidised ferruginous nodules at the base but become dull-purple, finely micaceous and silty upwards, with fine sandstone laminae at the top. Above, fine, wavy-bedded sandstone appears and it is likely that the Littlebeck Sandstone no longer has a sharp base. Downstream sandstone shale and altered limestone are visible but no clear succession can be recognised since the strata have all been affected by branches of the fault.

Eastwards, lack of exposure makes the position of the clastics impossible to determine but the conglomeratic, cross-bedded, very feldspathic sandstone seen in a small feature 350 yards west-south-west of Lookingflatt Farm, on account of its lithology, has been mapped as the Littlebeck Sandstone.

x) Newby Mill Cyclothem

a. SUMMARY

The cyclothem remains between 55 and 65 feet thick throughout the area but, whereas in the east it contains a thick massive sandstone body at the top, to the west only thin- and wavy-bedded sandstone are present and the Limestone becomes the dominant member. It is often characterised by a pale lilac or pink colour and a finely granular "powdery" texture, with occasionally a few grains of glauconite and some chert nodules. In Little Beck, shales separate it from hard, siliceous and very fossiliferous limestone, but to the north and west they become thinner, passing into a bed of calcareous mudstone above which the impure limestone is expanded and often contains glauconite.

b. THE NEWBY MILL LIMESTONE

Strickland sub-area

The Limestone appears in the River Leith at Oak Gill Wood, having been thrown down by the Great Strickland Fault, and is then exposed almost continuously in the bed through Rowland's Lum with the upper siliceous beds in the east bank as far as Waterfalls Bridge. It is quite fine-grained and of lilac or pink colour, sometimes with a powdery texture, and above a 3 feet thick horizon of thin- and slightly wavy-bedded calcareous mudstone are at least 12 feet of thick- and medium-bedded, powdery-textured and siliceous limestone. This is often stained pink or shades of purple but pure white limestone also occurs and these horizons are characterised by an abundance of large crinoid fragments and, locally, many specks of glauconite.

To the south-east, the Limestone is not seen before Great Strickland vicarage where a quarry by the road shows up to 6 feet of pink-orange crinoidal limestone with lenticular horizontal joints, near the base of the member. It can then be traced by means of several sink-holes past Blands to the northern edge of Newby Pasture, and to Carr Bank.

Reagill-Morland sub-area

Although not exposed, the Limestone must pass south of Newby village and its base is seen in the Beck 90 yards south of the bridge at the sharp easterly bend, where it is pink, fine-grained and with a deep red speckle. No further exposures occur in the stream bed but in the steep left bank at the wood just to the north, lilac, medium-bedded limestone is visible with the powdery texture characteristic of the higher horizons of the Limestone. Strong springs between Newby End and Ivy Cottage indicate the position of the top of the Limestone, and it gives rise to sink-holes north of White Stone and at the south end of Morland Moor but no more outcrops occur west of the Lyvennet.

Meaburn sub-area

The Limestone is visible in the banks of the Lyvennet south of the ford at Welltree where it is fine-grained and medium-grey, becoming paler with crinoid fragments, brachiopods and occasional simple corals upwards. These horizons are not visible in the river bed which does, however, north of Welltree, provide excellent exposures of the top part of the Limestone, much of which is again pale-lilac and powdery-textured and is often rich in fossils, especially brachiopods and lamellibranchs. Crinoid fragments, usually large and brown- or orange-stained are characteristic of the highest purplish impure limestones and calcareous mudstones, the top-most of which has distinctive ferruginous patches which have weathered to a deep vermillion colour, and is easily recognised in the stream where it occurs for some distance in, and north of, Barnholme Wood.

Southwards, the outcrop is lost beneath glacial drift until it is seen in Little Beck west-south-west of Peaslands where, towards the base, simple corals and trilobites can be found and a cherty horizon is present about 5 feet above the base. It is then again obscured but must pass southwards towards Grayber before turning north and reappearing higher up Little Beck between Crabstack and Sideway Bank. Here the Limestone, again often pink and lilac and with a powdery texture, is almost completely exposed and, east of Crabstack, can be seen to be overlain by shales which are almost certainly the equivalent of the calcareous mudstone band in the westerly parts of the region. They are poorly-bedded and very dark-grey at the base with red patches and streaks and some poorly preserved fossils, including brachiopods and trilobites. They become unfossiliferous upwards but the succession is badly exposed until, perhaps 10 feet above the Limestone, there appears some very fossiliferous, dark-purplish, hard, calcareous mudstone which is especially rich in brachiopods but with lamellibranchs and crinoids also present. It appears to be about 3 feet thick but a further 6 feet of medium-bedded, argillaceous and siliceous, fine-grained crinoidal limestone, some of which has delicate pale- and darker-grey banding, occurs above after a short interval of silty mudstone and thin sandstone.

The Limestone floors the dry valley south of Sideway Bank, in the sides of which it is exposed in small excavations and, near the top, a few glauconite grains can be found. Grey and brown-grey beds just above the base, with some impure sandy horizons and chert nodules, are visible in a small quarry near Brackenslack Lane and a large sink-hole near the Kings Meaburn road indicates the position of the top of the Limestone.

Appleby sub-area

Large sink-holes mark the position of the Limestone north-west of Seat Hill but otherwise, on the upthrow side of the Barwise Fault, its outcrop is obscured by a series of drumlin-like ridges. It does, however, reappear east of the fault at several places in Rainbow Plantation, where a river cliff shows the lower 12 feet of the Limestone. It has a strongly reddened base with yellow rather granular dolomitised limestone above and is full of molds of small brachiopods and some crinoid fragments; also, many large Productids and a few simple corals can be found. It is cut off to the south by the Rainbow Plantation Fault, which here may have a throw of over 50 feet, but can probably be recognised again in Hoff Beck where the dolomitised crinoidal limestone seen in the right bank at Douglas Ing, south-east of Hoff village, is thought to be from this horizon.

c. THE NEWBY MILL CLASTICS

Strickland sub-area

In the River Leith, a little of the sandstone member is visible below the scars of the Great Strickland Limestone at the north-west end of Short Wood, where it is medium-fine-grained, lilac coloured and poorly-bedded with possible _in situ_ root traces at the top. Downstream, the Great Strickland Limestone appears but, due to the southerly sweep of the river which is slightly against the dip, a small inlier of the sandstone occurs before the Limestone is again seen at the Otter Stones. Small exposures also occur to the south in the steep east valley side below the limestone scars of Rowland's Lum, where the unit has an estimated thickness of 20 feet. Thin-bedded sandstone lies only a short distance above the cliffs of Newby Mill Limestone so that the cycle has, here, only a very thin shale member. Upwards, loose material covers the outcrop until just below the Great Strickland Limestone which has a calcareous sandstone bed at the base, overlying a 6-inch in-weathering horizon of soft micaceous siltstone and fine, micaceous, purple sandstone with a bed of mottled micaceous shale. Below is some quite hard, fine ganister, lying on siltstone and wavy-bedded sandstone, there being little massive sandstone present.

Thin-bedded sandstone is also seen in Oak Gill Wood but further south the clastics are almost entirely cut out by the Great Strickland Fault, although adjacent to the fault-plane in Maudy Lane, Great Strickland, 5 feet of medium- and thin-bedded sandstone and loose siltstone occurs; variable dips are due to the close proximity of the fault.

Reagill-Morland sub-area

A little thin- slightly wavy-bedded sandstone and loose shale from the unit is visible in the very steep north bank of Newby Beck east of the village where, with an estimated thickness of 22 feet, the clastics are scarcely thicker than to the west. However, to the east there undoubtedly is an increase in thickness which is accompanied by the development of a thicker-bedded sandstone at the top. This is first seen below the Great Strickland Limestone at Byesteads Quarries where up to 6 feet of massive and purplish sandstone is visible and has an in-weathering horizon of shale near the top, capped by about 1 inch of pale and greenish sandstone which passes up rapidly into the limestone, here without the calcareous sandstone horizon. This again appears, however, at Morland where, below the waterfall under the road-bridge, is a small inlier of the clastics and it can be seen to overly medium-fine-grained, purplish sandstone with in situ plant remains near the top. Apart from a small amount of thin-bedded sandstone near Ivy Cottage, the unit is not exposed to the east on Morland Moor.

Meaburn sub-area

Thin-bedded micaceous siltstone, sandstone and shale, within a few feet of the top of the Newby Mill Limestone, are visible in the steep left bank of the Lyvennet at the south end of Barnholme Wood, and grey-lilac coloured shale, with oxidised ironstone nodules but apparently without fossils, lying directly on the top bed of the Limestone, is visible intermittently in the river bed and banks to the north. The massive sandstone below the Great Strickland Limestone is only poorly seen in the river at Kemplee, but has been quarried at several places in the steep valley sides to the south where it is overlain by a 3-inch shale band and purple calcareous sandstone, below the Limestone (Fig. 5.1). This calcareous sandstone varies from 6 inches to 2 feet thick at Jackdaw's Scar, where the most complete exposures occur. Here, the clastics have expanded to about 30 feet and, low in the unit, thin-bedded, very micaceous sandstone, often with meandering trails, is visible in the steep valley side north of Welltree Cottage. This becomes very thick-bedded and often medium-grained above where 12 feet of irregularly maroon-stained sandstone are present at the base of the Scar. It shows, except at the base where it is delicately cross-bedded and colour-banded, large-scale, sometimes planar cross-stratification and has thin horizons of soapy-feeling mudstone and very micaceous fine sandstone. Near the top, a few small irony concretions occur and above it has a dark mottle which may be altered and redistributed carbonaceous material. There is a greenish tint at the top above which is a thin band of dark shale, which here contains occasional shell-traces; more greenish sandstone, becoming calcareous with increasing crinoid fragments upwards, intervenes before the harder sandy beds at the base of the Great Strickland Limestone.

To the south, the sandstone was once exposed in excavations west-south-west of Peaslands and near the track to Crabstack where a gully shows 11 feet of thinly-laminated, micaceous sandstone. Also, south-east of Sideway Bank in the feature below the Great Strickland Limestone, is massive sandstone becoming thin-bedded and silty below.

Appleby sub-area

The clastics are nowhere exposed west of the Barwise Fault, but the small excavations in purple-stained and yellowish-brown sandstone at, and east of, Knock Bank are thought to be from this unit. The thick-bedded sandstone at the top, now expanded to more than 15 feet, is well exposed to the east at the large quarries in the escarpment between Hoff and Lookingflatt Farm. Near the south-east end, where the maximum thickness is visible, it occurs in beds between 2' 0" and 3' 9" thick, in which there is very little indication of cross-laminations. Much is pure white in colour but is locally stained yellow, purple, and red, with quite common mica. The top seems a fairly even plane and is abruptly overlain by the Great Strickland Limestone which, although sandy, has no basal horizon of calcareous sandstone. The massive sandstone is also well seen in Rowley Wood where it is notable for the remarkably regular and persistent purplish-pink and white colour-banding through a thickness of 15 feet of rock, (Plate 9).

xi) Great Strickland Cyclothem

a. SUMMARY

The Great Strickland Limestone, averaging about 50 feet throughout the region, is the thickest of the Limestones mapped and is well exposed, having been extensively quarried for lime and building-stone. Except for a few feet at the base, it is pale- or medium-pale-grey, fine-grained limestone with abundant small shell and crinoid fragments. Major bedding-planes are widely spaced though, in between, weathering reveals wavy minor bedding-planes and lenticular horizontal joints. Coral colonies occur locally near the base, otherwise complete fossils are uncommon. At the eastern margin of the region, the Limestone lies immediately below the New Red Sandstone unconformity and is considerably dolomitised, having a yellow colour and many cavities. Elsewhere, it is never very far below the unconformity (Fig. 2.23) and, though little affected by dolomitisation, it often has red flecks and a strongly reddened zone extends above the base for a short but varying distance (Plate 10). The overlying clastics are visible, like the rest of the Upper Limestone Group, in only a few isolated exposures, so that a reliable succession cannot be built up. The equivalent of the Upper Little Limestone of the Pennines has not been identified with certainty and

PLATE 9. Colour-banding in sandstone below the Great Strickland Limestone, Lookingflatt.

PLATE 10. Strongly reddened zone at the base of the Great Strickland Limestone, Lookingflatt.

consequently the thickness of the clastics is unknown, although estimates suggest that they may be as much as 100 feet, and they contain more than one sandstone member and possibly two thin impure limestones.

b. THE GREAT STRICKLAND LIMESTONE

Strickland sub-area

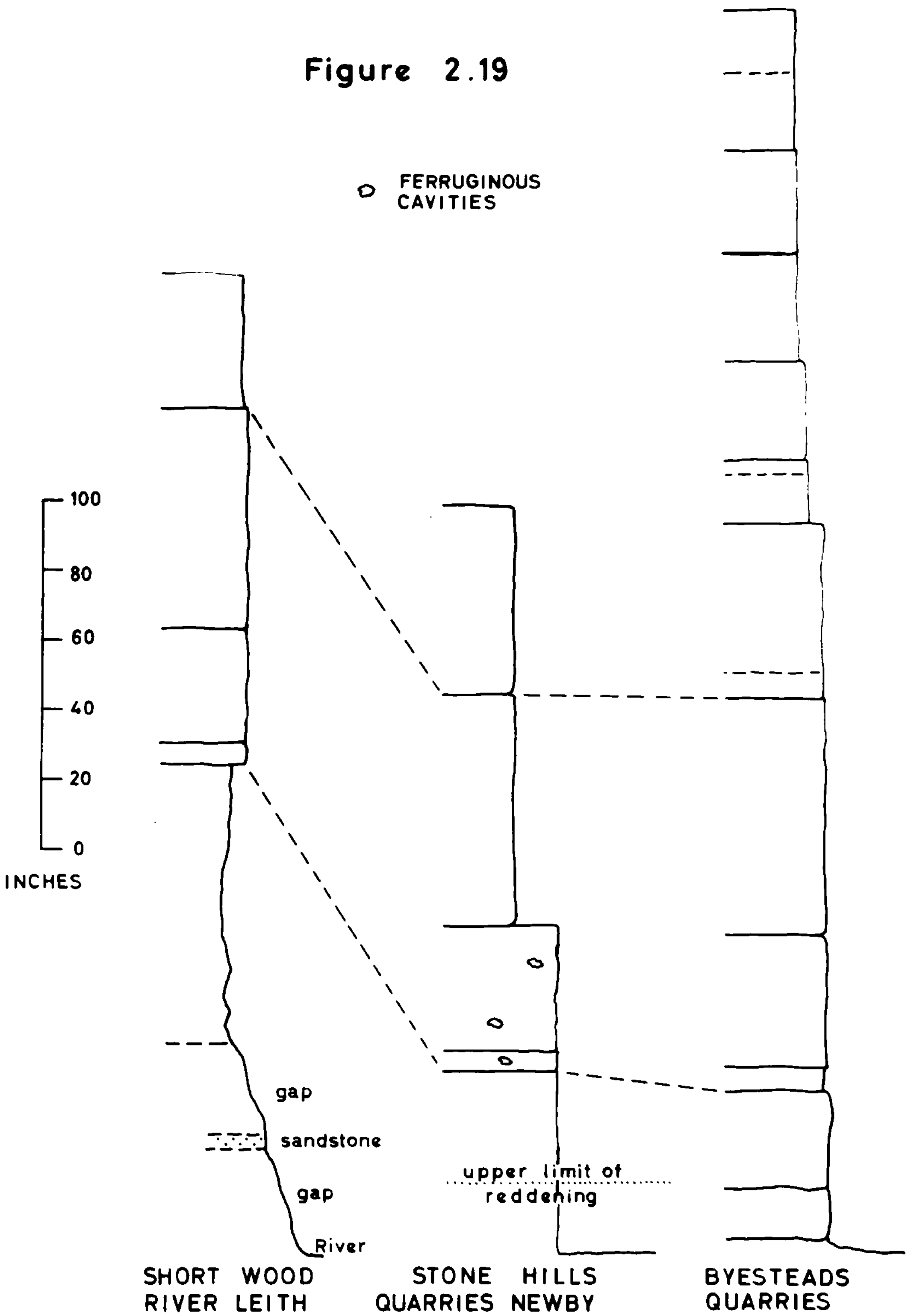
The Limestone occurs in the River Leith just downstream from Waterfalls Bridge, beyond the inlier of sandstone at the Otter Stones (Plate 11) and for ¼ mile towards Burnbank Dubs, becoming impure and rather reddened at the top. Up to 30 feet are visible in the scars on both banks at Short and Oldscar Woods (Fig. 2.19) where, at from 6' 8" to 7' 0" above the base, is a 6-inch bed which can be traced across the area to south of Kings Meaburn, a distance of 5 miles. In the Leith, and throughout the region, the base is sandy and with a maroon stain but upwards the sand soon dies out and the stain becomes paler and mottled before being reduced to occasional flecks in the otherwise pale-grey and often fine-grained limestone.

Upstream, the Limestone is well exposed in scars high in the right bank where the base, reddened to between 1' 6" and 4' 0" is again visible, and large quarries occur just south-west of Waterfalls Bridge and on both sides of Airygill Lane, especially at Bowberthill where at least 24 feet is present. Here, beds in the middle of the succession, which can be identified 3½ miles to the south-east at Byesteads Quarries, have slightly thickened (by 8.3%) and contrast with lower horizons which, between Byesteads and the River Leith, have become thinner by about 9.4%. The overall effect, therefore, of these changes is negligable.

To the south, a few sink-holes indicate the position of the top of the Limestone but no exposures occur before the fault scarp north-west of Great Strickland, where rather altered-looking pale and yellowish limestone is visible. The village itself is largely built on the Limestone which, though here poorly exposed, can be traced to the east and the south-east by means of several sink-holes to Brackenber and Dallan

MEASURED SECTIONS IN THE GREAT STRICKLAND LIMESTONE

Figure 2.19



Bank, where it has again been quarried. Sink-holes also clearly mark the top from the Head of Woodhouse Gill south-eastwards below Jubilee Plantation to near Lansmere where a series of large quarries known as Stone Hills give excellent exposures (Fig. 2.19) continuing almost to Newby. This village, too, is sited on the Limestone which can be seen at many places, including Newby Head and high above Newby Beck at the east end of the village. Eastwards, the Limestone is obscured for a short distance but reappears in the west valley side of Morland Beck south of Town Head Bridge, Morland, and occurs as large slabs in the bed of Greengill Sike north-west of the village. The limestone is here of a slightly darker colour than usual, the beds exposed being almost at the top of the member.

Reagill-Morland sub-area

Morland, like Great Strickland and Newby, lies on the Great Strickland Limestone which is scarcely absent from the bed or banks of the Beck from west of Byesteads to near Powdonnet Well, a strong spring rising near the top of the Limestone. It is very well exposed to 32' 6" above the base south-east of the village at Byesteads Quarries (Fig. 2.19) and a few exposures occur to the east for a short distance but it is nowhere seen across Morland Moor, reappearing only at Kemplee in the Lyvennet valley.

Meaburn sub-area

The Limestone is visible in the River Lyvennet from Chapel Bridge downstream for 250 yards but is best exposed in the many vertical scars in the right valley side to the south, culminating in Jackdaw's Scar just west of Kings Meaburn village where more than 30 feet is visible (Fig. 5.1 and Plate 12). Bedding-planes which can be traced as far as the Leith are present but some are, apparently less persistent although the chance effects of weathering cannot be neglected. Kings Meaburn, like Great Strickland, is probably only partly built on the Limestone but it here has a thick cover of boulder-clay and the exact position of the top is uncertain.

PLATE 11. The Otter Stones (Great Strickland Limestone), River Leith.

PLATE 12. River Lyvennet at Jackdaws' Scar, Kings Meaburn (Great Strickland Limestone).

In a south-easterly direction, the Limestone can be easily followed to the south end of Wickerfield Plantations and occupies a wide fairly flat area in which numerous quarries give good exposures (Fig. 2.20), the largest being Hart Quarry, near Wormpotts and Peaslands, and at Sideway Bank. The former once showed coral-bearing rock, including Chaetetes, on its floor (Johnson, personal communication), being the lateral equivalent of the Chaetetes Band of the Pennines (Johnson 1958) and indicating a position near the base of the Limestone. The quarries north of Wormpotts give the best exposures of beds high in the Limestone which here have a rather crystalline appearance with abundant crinoid fragments, and are poorly and very irregularly bedded, whilst those around Sideway Bank and Peaslands are of interest in that abraded simple corals are here scattered through the Limestone. Also, in a quarry west of the road near Sideway Bank, low in the Limestone, the only colonial corals, outside the Appleby sub-area, in this Limestone were found. South from Wormpotts, via Wickerfield and Hardpot, the top of the Limestone is clearly indicated by a line of well developed sink-holes, one of which, at the latter locality, shows a little reddened, impure limestone.

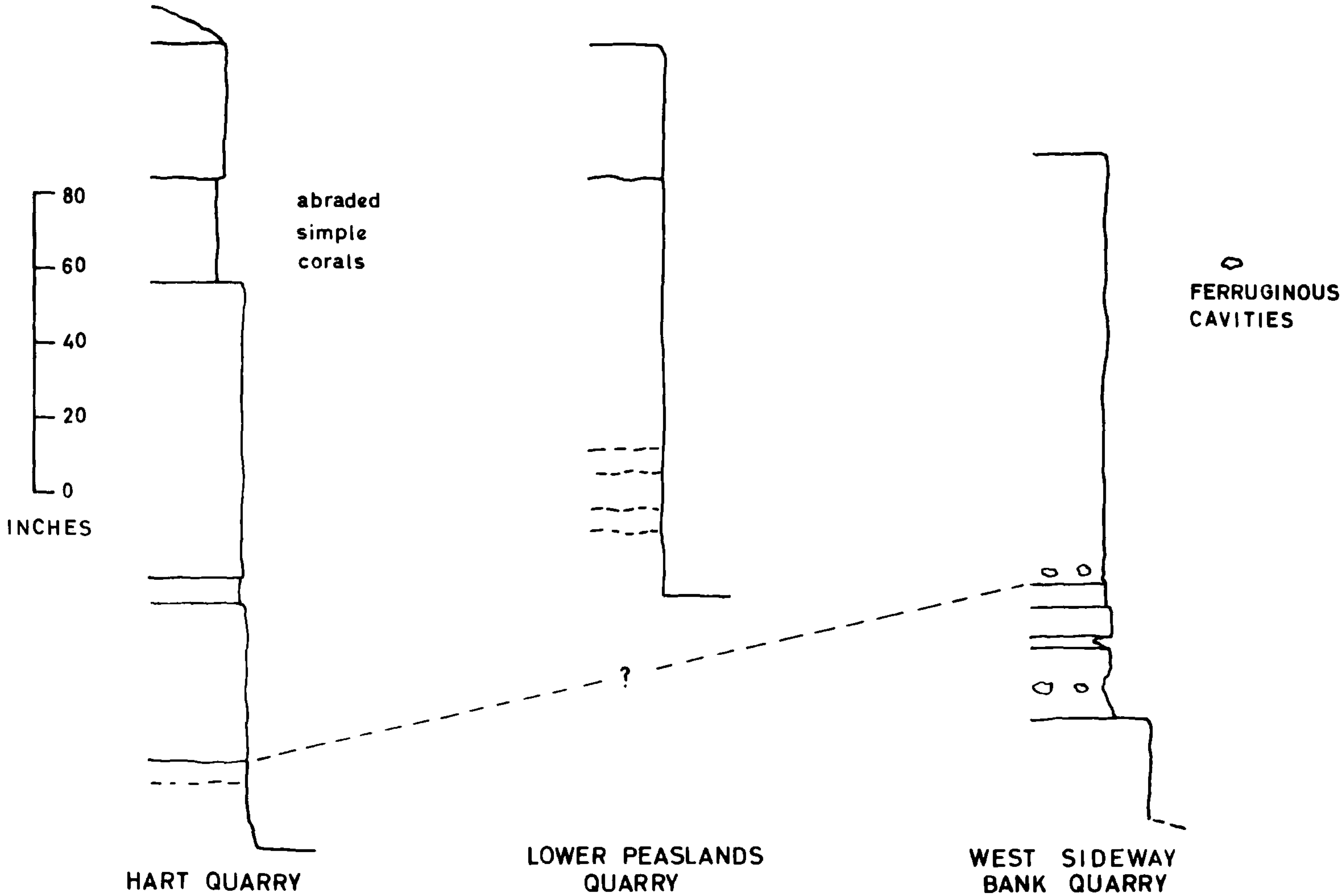
Appleby sub-area

The Limestone is obscured by drift south of Wickerfield Plantations and Fouson's Rigg but the lower part reappears north-west of Sloe Bank, where a series of quarries show typical pale and often fine-grained limestone which contrasts with that to the east in being only locally altered to a granular yellowish rock even though it is as close to the New Red Sandstone unconformity. A deep sink on the east side of Fouson's Rigg suggests that the outcrop passes northwards to the upper part of Hawkrigg Gill but no in situ rock occurs and just to the east it disappears under the New Red Sandstone.

The present topography and the relief of the pre-New Red Sandstone surface are such, however, that the Limestone reappears on the downthrow side of the Barwise Fault, being well exposed along the scarp at Rowley Wood (Fig. 5.1). A strongly reddened band of varying thickness is always present at the base and is locally extended upwards on either side of low-angle "joints". Just above the reddened zone, between 1' 6" and 2' 6"

Figure 2.20

MEASURED SECTIONS IN THE GREAT STRICKLAND LIMESTONE



above the base, strata rich in brachiopods and colonial corals, including Lonsdaleia and Diphyphyllum, can be found and some simple overturned corals occur at a slightly higher horizon. The only other distinctive horizon is a nodular bed of white and pink chert about 16 feet above the base of the Limestone in the most south-easterly large quarry. Sometimes, especially near the base, the limestone has its normal palish-grey colour but most is very altered to shades of yellow, orange and pink, frequently with dendritic pyrolusite and containing large crystal-lined cavities. Shell and crinoid fragments can often be recognised and the latter become particularly abundant in the highest limestone seen, which often occurs as knoll-like masses on the re-exposed pre-New Red Sandstone erosion surface north-east of the quarries.

c. THE GREAT STRICKLAND CLASTICS

Strickland sub-area

The biggest section which can, with most certainty, be attributed to this unit is visible in the River Leith by Melkinthorpe Wood. Although the shales immediately above the Limestone are not exposed, at the south end of Burnbank Dubs the overlying sandstone occurs to a height of 24 feet above the river; it is fairly thin-bedded at the base, but soon passes up into fine-grained, massive sandstone. Downstream, more sandstone is visible but, on account of its different appearance is thought to be from a slightly higher horizon; it is thinly-laminated, of lilac colour and fine-grained with abundant fine mica on the bedding-planes which are invariably of wavy type having poorly developed troughts in plan view. This sandstone is capped by a ganister, suggesting that a calcareous horizon might shortly follow and, although no exposures occur for 150 yards, the next rock seen, just before the sharp easterly bend, is a quite hard purplish poorly-bedded calcareous mudstone. It has casts and moulds of fossils, especially small brachiopods, and is rather like some of the siliceous beds at the top of the Newby Mill Limestone. It may represent the upper part of a limestone horizon above the ganister, which would in that case be fairly thick. Beyond, no further outcrops of Carboniferous strata occur.

To the east, much of Melkinthorpe Wood is probably underlain by this unit but there seems to be a thick cover of glacial material and it is not seen before Great Strickland village, where a little loose sandstone can be found above the road opposite St. Barnabas's Church. Further east, Woodhouse Gill shows medium-fine- or fine-grained sandstone, mostly quite thin- and relatively even-bedded with much mica and some interbedded shale and siltstone horizons, which undoubtedly overlie the Great Strickland Limestone. The stream cuts through only a small thickness of Carboniferous rocks and no calcareous beds appear before the New Red Sandstone is reached. The same absence of any calcareous horizons or other marker beds is found to the east, where a little loose shale and flaggy fine-grained sandstone overlying the Great Strickland Limestone is visible in the steep scarp running south-east from Jubilee Plantation and, in Greengill Sike, the existence of more than one sandstone in the unit is confirmed. Here the lower sandstone, which seems to be not far above the Great Strickland Limestone, is seen in the bed and banks of the stream north of Greengill Sike Farm and is medium-bedded and fine-grained with mica on wavy bedding-planes; at the top, it has a few purplish markings which may be altered <u>in situ</u> plant roots. Any possible overlying fossiliferous horizon must be thin because only 30 yards upstream pale bluish-purple soapy-feeling shaly mudstone with no trace of organisms (though with some deep maroon staining) occurs. At the head of the small northerly tributary which rises near Greengill Bank Farm, these shales, apparently about 20 feet thick, are seen to pass up into dull purple siltstone and then gently wavy-bedded pale micaceous sandstone which becomes thick-bedded at the top. Upstream, the argillaceous horizon is only poorly exposed as silty shale in the stream bed but coarser beds, thought to be from the higher sandstone member, are visible in the stream banks, where flaggy, pale, very micaceous sandstone with purple laminations is common.

The only other locality in the district where Carboniferous strata are seen is in a quarry 300 yards south-west of Hesley, which is more than ½ mile north of Greengill Sike. The medium-grained, dull purple and yellow-brown sandstone here exposed must, therefore, be from a horizon well above that of the highest strata seen in the Sike and, being above the

Great Strickland Cyclothem, is the youngest rock seen in the district.

Reagill-Morland sub-area

Although there is a long section of Morland Beck downstream from the Great Strickland Limestone before the first New Red Sandstone strata are visible, which must be underlain by members of this unit, no in situ rock occurs. Neither is it seen to the east, before the Lyvennet, and it is likely that the unconformity has here cut down to older horizons than it has further west, and that the thickness of the clastics has thereby been much reduced.

Meaburn sub-area

Purple and grey-green, silty and finely micaceous shales, with ironstone nodules and some thin deep-maroon-stained bands which were once horizons rich in ferrous carbonate, are visible above the Great Strickland Limestone in the River Lyvennet and are best seen by, and just north of, the old sheepwash. Here, 7' 6" are present and contain in the lower part quite rare fossil traces, mostly obscure but including thin-shelled lamellibranchs as well as some unusual black spheres, sometimes with a hollow centre, around which the shale has been reduced to a pale-green colour. Downstream, in the steep left bank of a deserted meander, these argillaceous beds are seen to be abruptly overlain by medium-fine-grained, slightly feldspathic, pale or purplish sandstone but having a coarse band, with very abundant mica, 2" above the base. The sandstone is bedded in strongly lens-shaped units with in which cross-laminations, sometimes planar or with a gentle trough-like shape, have been picked out by weathering. Its base, with planar cross-bedding in units averaging 5 inches thick, is well seen in the undercut bank where the river turns to the north-east, and has been affected by a small sharp anticline. This brings down the sandstone, which may be about 10 feet thick, into the river and, just before the lowest New Red Sandstone beds appear, it seems to be overlain in the right bank by dark-maroon micaceous siltstone and purple and grey-green shale.

To the south-east, glacial material almost completely obscures the outcrop of the clastics, though a little shale and gently cross-bedded sandstone not far above the Great Strickland Limestone is seen at several places low in the feature on which Sockenber stands and more sandstone, from a higher horizon, occurs in Coat Sike south-south-east of the farm, where it is worm-burrowed and has indistinct in situ root traces. Southwards, a series of old excavations near Hardpot, again not far above the top of the Limestone, show the same sandstone, here of massive appearance and medium-grained, and a feldspathic and micaceous sandstone, which is thought to be right at the top of the unit and has abundant molds of shell fragments, is visible near the road at the north end of Wickerfield Plantations. It can almost certainly be correlated with similar decalcified fossiliferous sandstone seen to the north-north-east in Swinegill Sike (Page 101) which underlies the next important limestone - the Swinegill Limestone.

Appleby sub-area

In Hoff Beck, the Great Strickland Limestone and the overlying shales are not seen, the former having been partially cut out by the Rainbow Plantation Fault, but the overlying sandstone is almost certainly that visible at the large quarry near Cuddling Hole and in the stream bed to the north. At least 25 feet of sandstone is here present so that, if the correlation is correct, it has increased considerably in thickness from the Lyvennet outcrop. It is a pale-purple, medium-grained sandstone with a little feldspar but much mica and has mostly gentle cross-laminations in units which are themselves bounded by surfaces of quite strong relief. It is well exposed downstream, where poorly developed irregular ripples and troughs are visible, at intervals as far as the wood where it is overlain by the Brockram. North of Bandley Bridge, more exposures of sandstone are present which are thought to be from similar horizons but their isolation from the main outcrop makes correlation difficult and they are described separately below (Page 100).

xii) The Highest Carboniferous Strata

Strata belonging to the Upper Limestone Group, mainly younger than the

Great Strickland clastics and sometimes of uncertain stratigraphical position, are exposed in several river sections and can best be described separately. Apart from the outcrop near Hesley mentioned above (Page 97) they are confined to the east and north-east of the region in the Meaburn and Appleby sub-areas. The low relief, often thick drift cover and the probability of faulting, all make the tracing of horizons away from the river sections hazardous.

a. THE HOFF BECK - COLBY BECK SUCCESSION

A series of outcrops of Carboniferous strata are visible along Hoff Beck (= Colby Beck) from 220 yards north of Bandley Bridge to its confluence with the Eden. The most complete part of the succession is that occuring in Bandley Wood, where all the dips suggest that the strata young in an upstream direction, so that the oldest beds are almost certainly those seen at the north end of the wood where the river turns to the west. Here, (Fig. 2.21) pale-purple, medium-fine-grained, micaceous sandstone is overlain by a thin bed (probably less than 3 feet) of impure and reddened limestone, above which is a thick sequence of purple and pale grey-green blocky mudstone passing up into thinly-laminated siltstone, thin- and wavy-bedded sandstone and thicker-bedded, medium-fine-grained sandstone, visible along the steep right bank in the wood. The mudstone has irregular better cemented parts recognisable by their deep vermillion alteration colour, as well as small nodules and a few fossil traces. The same horizons appear intermittently in the river to the south and are overlain by another impure red limestone, followed by pale-purple and yellow shale. Above this micaceous, thinly-laminated, fine sandstone appears and becomes thick-bedded and slightly coarser-grained upwards before being cut off by the basal conglomerate of the New Red Sandstone.

The exposures of silty purple mudstones and medium-coarse-grained, red and white-speckled, micaceous sandstone seen downstream near Nether Hoff Farm, and the silty shales and medium-grained, pale, feldspathic sandstone south-east of Colby Hall, cannot be related to the main part of the succession or to each other; they are probably from higher horizons and isolated by faulting. The part of the sequence with the limestones is, however, thought to be from the upper part of the Great Strickland clastics overlying the sandstone seen near Cuddling Hole, and separated from it by a fault below the Brockram near Bandley Bridge, which must downthrow to the north.

b. THE SWINEGILL SIKE SUCCESSION

The stream is very overgrown but many small rock outcrops occur in its upper part where, because of the relatively strong northerly dip, the oldest horizons are found.

The first rock seen, east of Burwain Hall, is a yellow sandstone which, at the top, has many moulds of shell fragments and is thought to be equivalent to the fossiliferous sandstone at the north end of Wickerfield Plantations. It passes up into the basal sandy bed of the Swinegill Limestone, which appears to total about 4 feet in thickness and is rather impure and reddened with some crinoid fragments. It becomes softer and argillaceous at the top and is overlain by about 5 feet of richly fossiliferous mudstone with many brachiopods and occasional phosphatic nodules, becoming shaly and unfossiliferous upwards and being capped by 1' 6" of brittle purple and greenish siliceous mudstone. Shales, perhaps totalling 15 feet in all, continue to be occasionally exposed and no sandstone seems to intervene before a very hard bed of calcareous siltstone with yellow fossil traces. Above this, a considerable but unknown thickness of purple and maroon shales and silty shales with small ironstone nodules occurs, apparently, from the excavations in the westerly valley side, once of some economic value. They pass up into medium- and wavy-bedded, medium-fine-grained, micaceous sandstone (the Bewley Castle Sandstone), which eventually appears in the stream at Bewley Wood where 8' 6" is present, though a small inlier of the underlying slabby siltstone and silty shale occurs near the confluence with Tees Sike.

c. THE TEES SIKE SUCCESSION

The succession seen in Swinegill Sike is continued upwards by that in Tees Sike, which shows strata from just below the Bewley Castle Sandstone to the base of the Bolton Quarry Sandstone, the highest member of the Upper Limestone Group exposed below the New Red Sandstone, and includes a distinctive thick fossiliferous and calcareous horizon, the Bewley Castle Limestone (Fig. 2.21).

The lowest rock, blocky mudstone passing up into parallel-bedded, finely micaceous silty shale with some delicately cross-laminated siltstone, occurs in an inlier at the confluence with Swinegill Sike. Otherwise, this part of the stream exposes several small sections of the Bewley Castle Sandstone, which is visible both upstream to beyond the castle and downstream where it dips quite strongly towards the New Red Sandstone unconformity, and shows some broad trough-bedding. It appears to be about 20 feet thick and is a pale or yellow and purple-stained slightly feldspathic and micaceous sandstone which ranges in grain-size from medium-fine to medium-coarse. It is capped by a very thin dull red, hard, silty limestone which has occasional small white fragments that may be pieces of shell, and is immediately overlain by yellow and purple blocky mudstone with a few irony nodules, thin impersistent ferruginous beds, and characterised by many unusual long tubes which are presumably plant stems, though probable shell traces also occur. This argillaceous horizon passes up, via thin-bedded siltstones, into another body of sandstone, unlike the lower in being apparently without feldspar, which is mainly medium-fine-grained, medium-bedded, purplish and micaceous, with a distinctive bed of softer fine silty sandstone near the top. The sandstone which overlies it has a locally erosive base and at the top is pale with *in situ* roots, the remains of the plants themselves occuring in the thin poorly-bedded soft siltstone above. This is capped by lilac-grey blocky mudstone with small irony nodules and possible plant remains, which becomes quite hard and shaly upwards, and is slightly calcareous. Fossils then appear, rapidly becoming very abundant and including crinoid fragments, lamellibranchs, brachiopods, bryozoa and trilobites; after a few feet, *Hyalostelia*, a fossil confined to these horizons and exceedingly common, enters. Upwards, the rock becomes harder with more calcareous mudstone and argillaceous limestone and is quite siliceous, though the highest rock seen is a purer red crinoidal limestone. All the beds are fossiliferous and

MEASURED SECTIONS IN HOFF BECK (a) AND TEES SIKE (b)

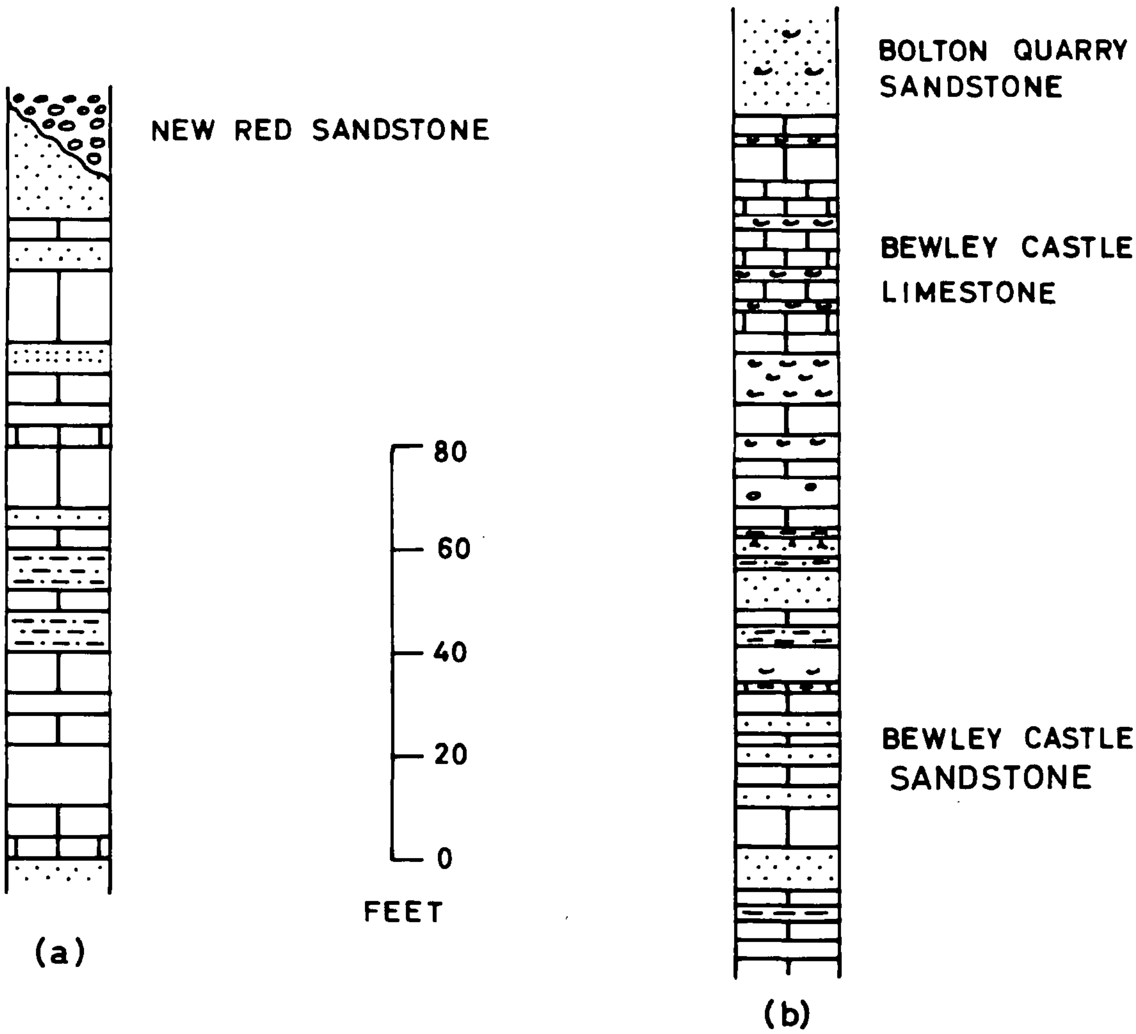


Figure 2.21

mostly altered to shades of pink and purple, although some very pale and often very crinoid-rich horizons also occur; the detrital nature of the strata is clearly indicated by the common occurrence of lenticular bedding, sometimes with sufficient relief to be termed washouts.

The whole of the fossiliferous succession, some 25 feet thick, has been called the Bewley Castle Limestone rather than just the more competent beds, since soft calcareous shales, though most common at the base, are present throughout and in fact, the harder beds themselves become soft and shale-like where weathered in the stream bed. These beds are best seen in the north side of the gorge but can also be found in the opposite side and in the stream itself where some fossiliferous shale with small irony nodules, probably above the purest limestone seen in the valley side, occurs and is overlain by a medium-fine-grained, buff, micaceous sandstone with bands containing moulds of shell fragments near the base. This, the fossiliferous lower part of the Bolton Quarry Sandstone, is the highest horizon occuring in Tees Sike, and is seen south of Bolton Quarry on the sharp easterly bend. Upstream, shales, some fossiliferous, from just below the sandstone are periodically visible, and the fossiliferous sandstone can be found loose in the banks.

Except for a possible sink-hole north of Bewley Castle Farm, there is no evidence for the position of the Bewley Castle Limestone outside the valley of Tees Sike, although it must underlie a considerable strip of country. The sandstone above it must be quite thick and appears to loose its fossil bands upwards where it has been extensively worked to the north at Bolton Quarry. This is now almost completely overgrown but shows a little medium-fine- to coarse-grained, massive, micaceous, feldspathic sandstone. What is almost certainly the same sandstone occurs in the small stream to the north-west and in old workings in an adjacent field; again feldspar is present and the medium-grained sandstone is locally cross-bedded. Upstream from where this stream joins Luz Beck, sandstone is again visible but here feldspar is not obvious and it is probable that this is a lower sandstone, separated from the other exposures by a fault. Horizons higher than the Bolton Quarry Sandstone must be present on Threat Rigg and as outliers to the south and west but are nowhere exposed.

d. THE RIVER EDEN SUCCESSION

Scattered exposures of Carboniferous rocks are visible in the River Eden from Dowpits Wood, west of Appleby, downstream as far as Crackenthorpe. They are of purple-stained shales, silts and sandstones but no calcareous beds or other marker bands have been found and, since also the outcrops seem to have been isolated by faulting, no detailed succession can be built up.

The biggest exposures occur below the Brockram at Whirly Lum where over 30 feet of purplish shales, siltstones and sandstones, the latter often gently cross-bedded and feldspathic, are visible. They probably dip under the mass of at least 20 feet of cross-bedded, medium-grained sandstone seen in the right bank on the bend to the north-east and in the river-bed where it is slightly calcareous, but this seems to be separated from the shales and sandstones to the north by faulting. These beds are at first well displayed and include shale and sandstone overlain by more shale and siltstone with a slumped sandstone mass at one point, and capped by more sandstone. Further north, only isolated exposures of pale-yellow and purple micaceous sandstone occur, and the same is true upstream at Dowpits Wood where the sandstone is possibly from below the shales of Whirly Lum. A distinctive rock, and probably the highest exposed in the Eden, is the sandstone of Millstone Grit facies seen underlying the New Red Sandstone west of Crackenthorpe Hall. At least 20 feet are present of mainly quite coarse sandstone with bands and lenticles of very coarse and conglomeratic rock, having pebbles up to 8 mm., much feldspar but little mica and a few small ferruginous nodules; it becomes on average slightly finer-grained upwards.

The position of these beds is unknown and they cannot be firmly correlated with any of the Upper Limestone Group Succession to the west, although parts may represent horizons between the Swinegill and Bewley Castle Limestones. They are, however, down-dip and probably on the downthrow sides of any faults which might occur so that parts at least are likely to be the youngest Carboniferous strata of the region, probably being of mid-Namurian age. The same can be said of the inlier of Carboniferous age which occurs still further to the north-east in Castrigg Cutting, where purple-stained shales and sandstone, some coarse to conglomeratic and cross-bedded, and not unlike the rock found in the River

Eden by Crackenthorpe Hall, again are visible.

xiii) <u>The New Red Sandstone-Carboniferous Junction</u>

The Carboniferous rocks are separated from the New Red Sandstone by a major unconformity during which time they were deeply dissected to produce a surface of some relief which became gradually buried under the younger strata. These have been preserved in the northern and eastern parts of the region, which co-incides with the lowest and most drift-covered ground, so that rocks adjacent to the boundary are infrequently seen and the junction itself can very rarely be examined. As a result, throughout much of its length, the position of the boundary has to be inferred, and even its nature, whether an unconformity or a fault, is locally in some doubt. However, it is certain that everywhere within the region mapped the New Red Sandstone rests on strata of Namurian age and usually is within 100 feet stratigraphically of the top of the Great Strickland Limestone, although east of the Lyvennet it rises considerably higher, only to cut down again, south from Bewley Castle, until it rests on the Limestone itself at Lookingflatt and may have just reached its base north of the farm.

Strickland sub-area

The junction is nowhere exposed and its position has had to be arbitrarily placed in the ground between the large exposures of cross-bedded red sandstone in the Leith west of Cliburn and in Trough Gill, and the Carboniferous of Woodhouse Gill and Hesley. In the River Leith, about 1 mile separates the highest Carboniferous rock at Melkinthorpe from the first New Red Sandstone but the junction has been placed near the former because of the probability that the extensive flat area east of the village is underlain by the more easily eroded Penrith Sandstone. It then passes south-eastwards and can be located fairly accurately in Woodhouse Gill in the vicinity of Woodside Farm, but further to the east its position is very uncertain except that it must lie south of the New Red Sandstone of Trough Gill.

Reagill-Morland sub-area

Again the junction is not exposed but, in Morland Beck, it must lie between Glenton Vale and the Penrith Sandstone 250 yards east of the ford downstream. To the south-east it probably skirts Morland Hall and must certainly pass south of Howe Gill, where Brockram is visible.

Meaburn sub-area

In the Lyvennet, Brockram on the right bank south-east of Woodhead Farm can be seen overlying Carboniferous sandstone in the river bed, with little difference in dip between the two formations. To the east, a thick cover of glacial drift obscures the solid rocks but the boundary probably passes eastwards to Luz Beck somewhere south of Bolton village and thence south-eastwards via Bolton Lodge to Bewley Wood, where Penrith Sandstone is seen in the right bank and bed of Tees Sike. Just a few yards upstream, in situ Carboniferous shales can be found, so that the boundary can be accurately placed though the exact nature of the junction is uncertain.

It is shown by the Geological Survey as a fault, and the absence of conglomerate from the New Red Sandstone and the strong dip (22 degrees) of the shales would seem to favour this possibility. However, conglomerate, as is shown below (Page 114), is by no means ubiquitous, especially to the north, at the base of the New Red Sandstone, so that its absence here is not necessarily due to its having been thrown down by a fault. Also, the strong dip in the shales, the culmination of gradually increasing dips in the beds upstream, whilst almost certainly suggesting that a fault in the Carboniferous is being closely approached, does not inevitably mean that this fault is of post-New Red Sandstone age. Hence, the junction has been mapped here and elsewhere in the region as a simple unconformity although it is recognised that locally it may have a faulted nature, movement having taken place a second time on pre-New Red Sandstone faults – for which there is, indeed, some evidence to the south.

Appleby sub-area

Some Brockram is visible in Hawkrigg Gill but the position of the boundary southwards from Tees Sike is largely unknown before Knock Bank, though at Little Clinch the stream goes underground down sinks in the Brockram (the calcareous conglomerate sometimes behaves as a limestone), probably shortly east of where it leaves the Carboniferous rocks. At Knock Bank there is a large steep face of Brockram, the base of which is well below the Carboniferous rocks seen at Barwise Hall and below the fieldhouse to the east, so that the evidence is strongly suggestive of a junction with very pronounced relief. The only other possibility is that the Brockram is faulted down into the Carboniferous by fractures both to the west and to the east, but this seems very unlikely; it is true that to the west the Carboniferous is affected by the important Barwise Fault but, although it may have moved again, this cannot have been of very great throw since it is Brockram and not Penrith Sandstone which remains in contact with the Carboniferous strata. Rather, it seems likely that the line of weakness created in the Carboniferous rocks by the faulting was utilised by agents of erosion to produce here a deep wadi-like channel (Fig. 2.22) which ultimately became filled with debris similar to that which had previously passed along it towards lower regions to the north-east. It is also likely that this faulting eventually resulted in the production of a northerly-trending and eastward-facing feature in this neighbourhood, the local strong relief of which will explain the apparently relatively linear nature of the boundary northwards to just beyond Tees Sike where it died out.

Clearly, similar channels to the one at Knock Bank will be present elsewhere at the base of the New Red Sandstone but can nowhere be so well demonstrated, although the apparently strongly indented nature of the boundary to the east is again suggestive of considerable relief. Steeply dipping Brockram can be seen overlying Carboniferous sandstone in the wood south of Bandley Bridge and here, as in the Lyvennet, there is a rough conformity between the two formations. This relationship seems to be as common as one of strong disconformity of dip and a satisfactory explanation is hard to find;

THE CHANNEL AT KNOCK BANK

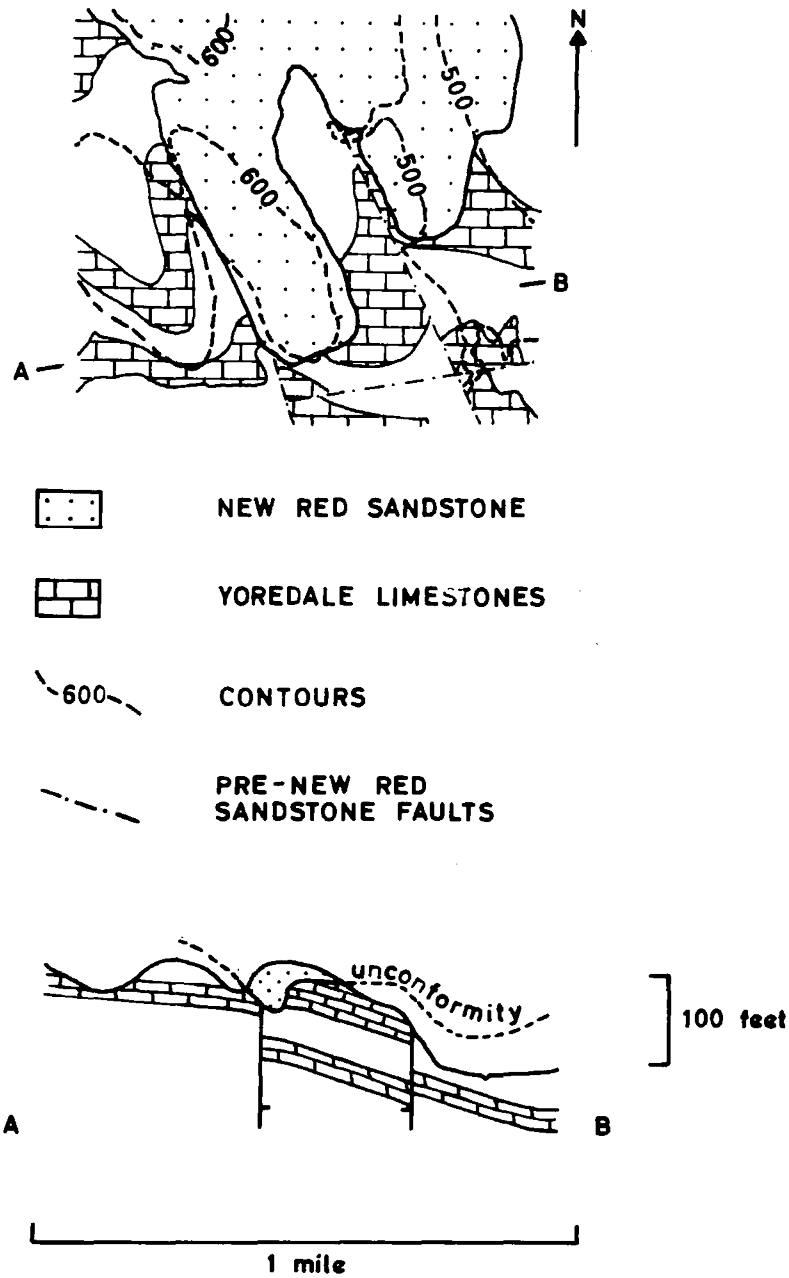


FIGURE 2.22

clearly, the Brockram must have been deposited on a land surface where erosion tended to produce large tracts where the dip of the ground co-incided with that of the rocks.

To the south, overlooking Hoff Beck, the Brockram feature stands up above a widening bench, which seems to be the re-exposed pre-New Red Sandstone surface (Plate 13) and is here relatively flat and even, being cut largely in the Great Strickland Limestone. As a result, the boundary can be traced accurately and is affected by a small fault south-east of the large Burrells Quarry, which throws back the escarpment for a short distance to the south and creates the gap taken by the main road. This is in line with the Rainbow Plantation Fault, which has a big effect on the Carboniferous rocks, so that two periods of movement, the second of only relatively minor amount, are clearly indicated.

At the south end of the strong Brockram feature, 200 yards north-west of Lookingflatt Farm, a small quarry shows one of the two exposures where the junction is visible and not under water. The base of the Brockram consists of large pieces of the underlying dolomitic limestone, which have been little moved but get smaller and more worn upwards with the result that this major unconformity is without a distinct line of separation. In a very overgrown quarry to the east, some loose sandstone is visible not far below the Brockram and it is possible that the Great Strickland Limestone has already been entirely eliminated and that the New Red Sandstone lies on the Visean; certainly, the difference in dip direction of the two formations seen in nearby quarries would alone be sufficient to cut out horizons of the Carboniferous rapidly in an easterly direction. At Lookingflatt the Brockram and Great Strickland Limestone features end abruptly and though the thinning of the Limestone probably partly accounts for this it seems possible that they are cut off by another fault, and to the south-east there is no evidence for the position of the boundary, there being thick boulder-clay in the neighbourhood of the Tilekiln Ponds.

Although this line separates the main mass of the Carboniferous from the New Red Sandstone, a quite large inlier of the former occurs just west of Appleby. The main part is centred on Colby and its southern margin is visible in Hoff Beck north of Bandley Bridge, where again the two formations dip in approximately the same direction. The opposite, however, is true in the Eden at Crackenthorpe Hall where Penrith Sandstone dipping to the north-west overlies Carboniferous sandstone with an easterly dip; unfortunately the junction lies under deep water but as far as can be seen it is a normal unconformity and there is no faulted relationship as is shown on the maps of the Geological Survey. This part of the inlier is probably connected, at and south of Whirly Lum, with the Carboniferous exposures along the Eden near Appleby. Here, in the large Whirly Lum Quarry, quite strongly dipping Brockram is visible overlying silts and silty sandstones of the Carboniferous with a very similar dip (Plate 14), and again there is a pseudo-conformable appearance due to the lowest part of the Brockram being made up of weathered Carboniferous material which has suffered virtually no transportation. Since Carboniferous rock is seen only 150 yards down-dip from the Brockram, there must be either a north-trending fault separating the two or else the Brockram must lie in a channel.

PLATE 13. Brockram feature above bench in Great Strickland Limestone near Burrells.

PLATE 14.
The Carboniferous/Permian unconformity at Whirly Lum. Base of hammer at junction.

Evidence from elsewhere (above, page 108) strongly suggests that the Brockram does, indeed, often occupy channels, and because Penrith Sandstone found in the right bank of the Eden east of Crackenthorpe Hall (where unfortunately <u>in situ</u> rock is under water too deep to allow its nature to be determined) indicates a position where such a channel could cut through the Carboniferous rocks to the north, the faulting hypothesis is not favoured. It may be true that elsewhere large faults do affect the New Red Sandstone, but this cannot be demonstrated in the area mapped and the boundaries of the inlier have been shown on the map as they might appear on the hypothesis that they delimit a region of strong relief which had been isolated from the main upland area to the south and west and which was dissected by deep gullies. This hypothesis, in view of the probable climatic and consequent physiographic conditions prevailing in immediately post-Carboniferous times (below, page 234) may appear not unreasonable.

Inevitably, because of the almost complete drift cover, the limits of the inlier as shown cannot in general, be more than intelligent guesses. The same applies with even greater force to the possibly smaller inlier which occurs to the north of the railway cutting east of Castrigg, where no New Red Sandstone whatsoever is visible to allow any boundary with the Carboniferous to be fixed. The inlier is, in fact, only known to exist due to the chance siting of the railway, so that the probability of similar inliers occuring over nearby unexposed ground, especially perhaps, south of Appleby, is very high. Indeed, the Carboniferous rocks in the Eden at Warcop (Trotter 1939) must form one such inlier.

xiv) The New Red Sandstone Rocks

a. THE BROCKRAM

The Brockram, often the basal bed of the New Red Sandstone, is a conglomerate of rather poorly size-sorted materials though usually made up almost entirely of limestone, except at the base where it consists of the rock on which it lies. A few sandstone pebbles, mostly of small size, can be found as well as pieces of hematite and vein quartz and the matrix is of finer often reddened sandy material. The bulk, however, is of limestone pebbles which may be up to 3 feet in diameter and all have clearly been derived locally from the Carboniferous rocks but with pronounced sorting according to degree of competence. The limestone pebbles can not only be an unaltered grey in colour and reddened as recognised by Trotter (1939) but also may be yellowish, having been dolomitised, the end effect of this process being to produce pebbles with central cavities (Plate 51). Bedding is of broadly lenticular type on well-spaced planes between which the rock is largely structureless (Plate 15), although pebble imbrication can locally be found.

b. THE PENRITH SANDSTONE

Everywhere in the region, the Penrith Sandstone is a medium-grained and distinctive rock of primary orange-red colour which contrasts with the purplish-reds of the altered Carboniferous sandstones. In

PLATE 15. Lenticular bedding in the Brockram at Burrells.

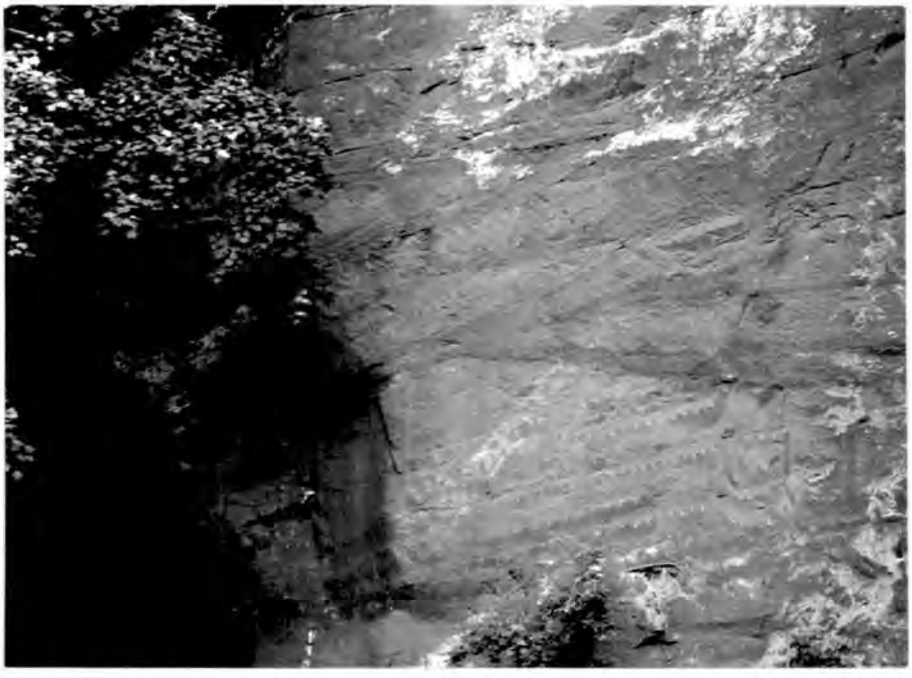


PLATE 16. Dune bedding in the Penrith Sandstone. Bongate Scar, Appleby.

constituents, too, it contrasts with most of the latter, mica being absent and whitish feldspar almost always easily visible. It is usually quite soft and has fairly even laminations, though some big exposures show very large-scale cross-bedding (Plate 16) which is of dune type (Shotton 1956).

The Brockram and the Penrith Sandstone are two extreme types and although most outcrops are of one or the other, many of the exposures show conglomerate with zones of sandstone, or thick sandstone with pebbly bands.

c. THE DISPOSITION OF THE LITHOLOGICAL TYPES (Fig. 2.23)

The true Brockram is largely confined to the southerly exposures and is especially well seen in the escarpment overlooking Hoff Beck, and in several steep south or south-westerly-facing features as at Knock Bank, west of Bandley Bridge, and at and south of Big Clinch. These are probably due largely to the action of ice which has come against the resistant Brockram, apparently in-filling deep channels. Most of this Brockram is little dolomitised but elsewhere, as in the dry valley south-east of Little Clinch, it has been quite affected, and that low down in Whirly Lum Quarry is very altered, having many pebbles with hollow centres. The most north-westerly exposure, that in the Lyvennet, also has very few pebbles that have not been altered though cavities are absent.

Northwards and north-westwards from Burrells, pebbles become less abundant and, in the Lyvennet, a thin bed of conglomerate overlying the Carboniferous grades up into pebbly sandstone and shortly becomes

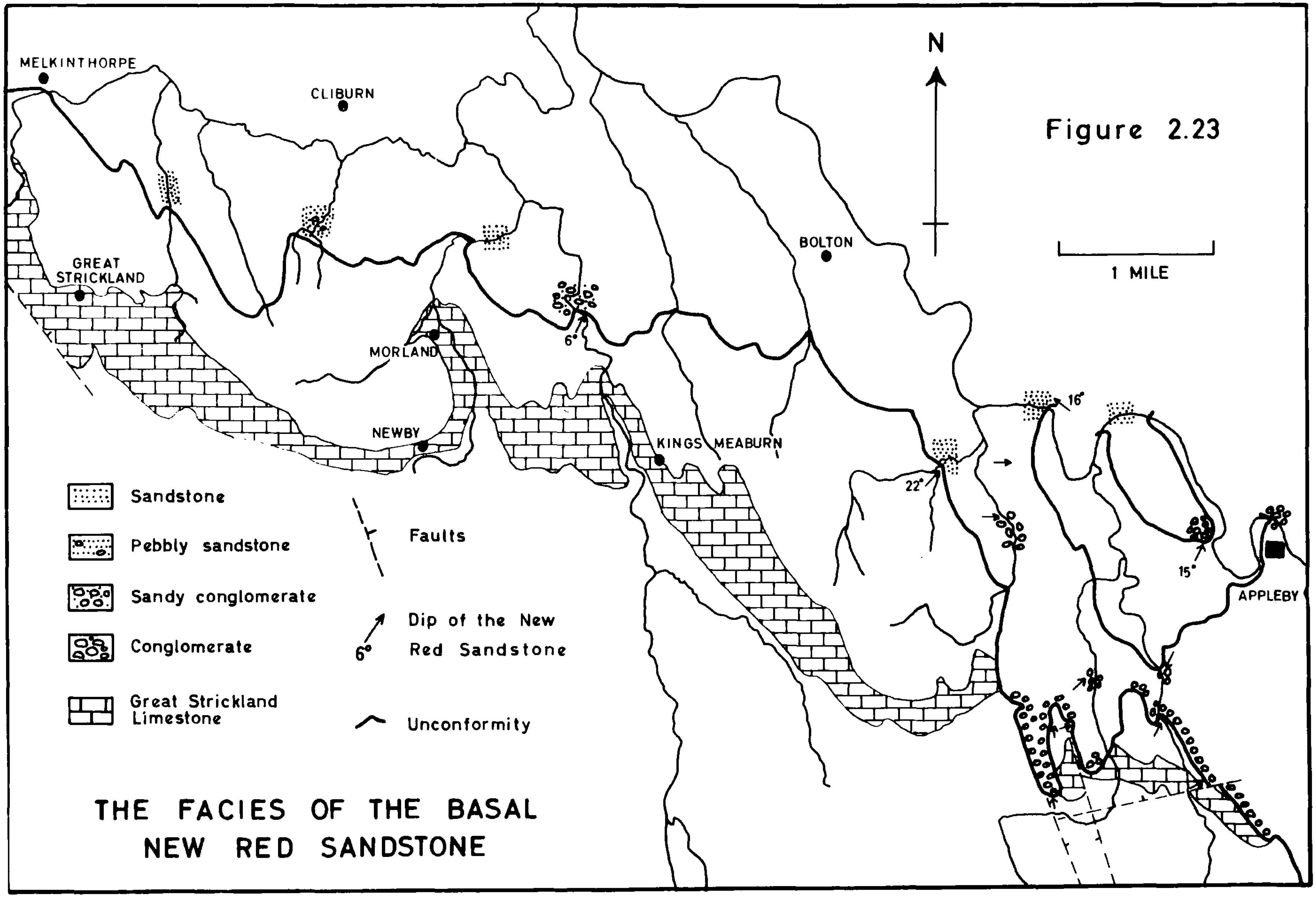


Figure 2.23
N
1 MILE
MELKINTHORPE
CLIBURN
BOLTON
GREAT STRICKLAND
MORLAND
NEWBY
KINGS MEABURN
APPLEBY
6°
22°
16°
15°
Sandstone
Pebbly sandstone
Sandy conglomerate
Conglomerate
Great Strickland Limestone
Faults
Dip of the New Red Sandstone
6°
Unconformity
THE FACIES OF THE BASAL NEW RED SANDSTONE

typical Penrith Sandstone. Further to the north-west, in Trough Gill, there is almost continuous sandstone with only occasional bands of conglomerate near the base. The north-easterly exposures, near Crackenthorpe Hall and Bewley Castle, are even finer with Penrith Sandstone probably lying directly on the Carboniferous.

The picture, therefore, is one of a northerly and easterly decrease in the amount of pebbles, which, considering the independent evidence of the channels for the main upland area being to the south and west, is what would be expected. It appears that the Brockram not only passes laterally into the Penrith Sandstone to the north and east but that there is also an element of overlapping consequent on the retreat of the higher ground so that Penrith sandstone can lie directly on the Carboniferous. Thus, in the south-west it is possible that most of the New Red Sandstone was of conglomeratic facies and the System may not have spread very far in this direction. To the north however, the Penrith Sandstone has lapped across the basal conglomerate onto the Carboniferous and the Brockram seems to be found only filling the deeper irregularities of the post-Carboniferous land surface. In Hawkrigg Gill, for example, Brockram (here quite dolomitised) is present, higher to the south and lower to the north than the Penrith Sandstone lying on Carboniferous rocks just to the west in Tees Sike. There is no reason to envisage a down-faulted strip of Penrith Sandstone to explain the absence of Brockram to the west; rather, it seems that it occupies a northward-plunging channel (perhaps the continuation of that recognised at Knock Bank) and was never deposited on the higher ground to the west, towards which the sandstone eventually overlapped, the present relief partially reproducing that of post-Carboniferous times and exposing the Brockram in the valley.

C. GENERAL STRATIGRAPHIC CONSIDERATIONS

i) The Shap-Appleby Region

a. CORRELATION

The accompanying geological map (folder at back of thesis) shows the disposition of the limestone horizons throughout the region studied, on the basis of the correlations favoured by the writer. The only other published map of the area, that of the Geological Survey (Sheet 102 S.W.; New Series, Sheet 30), shows a partially different interpretation except in the few places where exposure is very good. Some of the discrepancies have been discussed in previous sections (see for example page thirty six) but two further points may be mentioned here. In the Upper Limestone Group, the Bewley Castle Limestone must underly a considerably larger area than it does on the Geological Survey's map, the interpretation there favoured having resulted from a failure to recognise its presence on the south side of the Tees Sike gorge and its relationship to the Bolton Quarry Sandstone. More important, a mis-interpretation of the succession in the River Leith has led to errors of correlation within the Middle Limestone Group, where the Maulds Meaburn Limestone has been shown as the Little Strickland Limestone and, having failed to recognise the intervening Brackenslack horizon, what is in fact the Grayber Limestone is made the equivalent of the Reagill Limestone.

Detailed mapping has shown that, after allowing for the Little Strickland and Great Strickland faults, all eleven of the cycles that can be recognised in the east of the area, though showing many changes, can be correlated confidently with horizons seen in the Leith and consequently some of the correlations put forward by previous authors (Table 2) cannot be accepted. The Geological Survey, for example, consider that the Maulds Meaburn Edge and Brackenslack Limestones unite to form the horizon seen at Lowther Village Quarry which they have called the Lowther Limestone. However, both the Maulds Meaburn Edge and the Brackenslack Limestones are present as independent units in the Leith and there is no reason to suppose that they unite little more than 1 mile to the north-west. In fact, an examination of the Limestone at Lowther with its abundant Stenopora shows it to be undoubtedly the equivalent of the Grayber Limestone so that the alternative of Miller and Turner (1931) that the Lowther Limestone is equivalent to the Brackenslack Limestone alone, also cannot be supported.

Another horizon about which there has been much uncertainty is that of the Johnny Hall's Trees Limestone and its equivalents west of the Lyvennet. Miller and Turner claim that it unites with the Maulds Meaburn Edge Limestone west of the Lyvennet with the elimination of the intervening 55 feet of shale and sandstone which occur just to the east, whereas the Geological Survey tentatively correlate it with the limestone seen at Reagill. Though exposure is extremely bad, mapping has confirmed without much doubt this latter interpretation and it is clear that, further west still, far from showing any tendency to unite, the two limestone horizons both of which can be recognised with certainty in the Leith are now separated by almost 80 feet of strata. The correlation of Miller and Turner seems to be based upon the occurrence of the sponge Erythrospongia lithodes close to the top of the Johnny Hall's Trees Limestone and in the lower part of the Reagill Limestone, but since at present there are no satisfactory exposures of the Johnny Hall's Trees Limestone east of the Lyvennet and no exposures of <u>in situ</u> limestone whatsoever around Reagill, the writer is unable to comment further upon this. The only structures found which bear any resemblance to the description of this sponge (apart perhaps to the cavities seen everywhere in the Johnny Hall's Trees Limestone) are a series of ferruginous-weathering cavities which occur at a horizon about 6 feet above the base of the Maulds Meaburn Edge Limestone both in the quarries west of the Lyvennet near Blind Beck and east of that river on Maulds Meaburn Edge itself (Fig. 2.17); there is therefore no question of this Limestone uniting with any other, at least between these two localities.

b. THICKNESS AND FACIES VARIATION

The estimated thickness of Carboniferous strata in the area studied amounts to approximately 1100 feet of which an average of 20 feet belong to the Lower Limestone Group, just under 800 feet to the Middle Limestone Group, and a further 300 feet to the Upper Limestone Group although the latter figure may be considerably increased if the inliers near Appleby are taken into account.

As can be seen in the accompanying table (Table 3), in the Middle Limestone Group there is a definite, though slight, change in thickness between the west of the region (where the figures apply largely to the rocks seen in the River Leith) and that part of the area which lies east of the Lyvennet. Although most of the thicknesses are estimated, they seem sufficiently different to suggest that over the period of

TABLE 3

	LEITH		EAST OF LYVENNET	
	Limestone	Clastics	Limestone	Clastics
Newby Mill	32	23	24	41
Grayber	40	40	25	55
Brackenslack	11	63	30	30
Maulds Meaburn Edge	20	25	25	65
Bessygill	4	55	4	40
Johnny Hall's Trees	9	20	20	11
Little Strickland	40	100	37	111
Maulds Meaburn	37	30	46	40
Bank Moor	29	34	32	34
Halligill	-	-	4	46
Askham	40	90	40	65
	262	480	287	538
TOTALS	742		825	
	Limestone 35%		Limestone 35%	

Estimated thicknesses (feet) in the Middle Limestone Group of west Edenside.

deposition as a whole subsidence was slightly greater in the east of the region than to the west.

A consideration of this table and the succession shown in Fig. 2.2 shows that, whilst local facies variations are common, no overall major changes can be detected. Throughout the area, limestone makes up about 35% of the Middle Limestone Group succession; sandstone is of similar abundance though it shows much more variation and several sandstone members are better developed towards the east.

ii) Correlation with other Yoredale successions

Suggested correlations with neighbouring regions are shown in Fig. 2.24 and, in the case of the Westmorland Pennines at least, the succession is so similar that little room for doubt can exist. This is, perhaps, scarcely surprising since a distance of less than 5 miles separates the two areas. Between the Askham and Smiddy Limestone with their *Girvanella*-rich beds and the very thick Great Strickland and Great Limestones are, in both cases, seven well developed Limestones whose characters are in general so similar that they can be correlated with confidence. Of the others, the Halligill Limestone, which is of very local distribution in the Shap area appears to have no calcareous equivalent in the Pennines but the remaining horizons are all probably still recognisable. The Johnny Hall's Trees Limestone on lithological grounds must undoubtedly be the same horizon as the Single Post Limestone and the overlying Bessygill Limestone may be equated with the Cockleshell, and does indeed contain large Productids. The Iron Post Limestone of the Pennines may have died out to the west but, considering the appearance of thick shale within the Newby Mill Limestone in an easterly direction, it

THICKNESS AND CORRELATION OF STRATA OF YOREDALE FACIES IN NORTH WEST ENGLAND

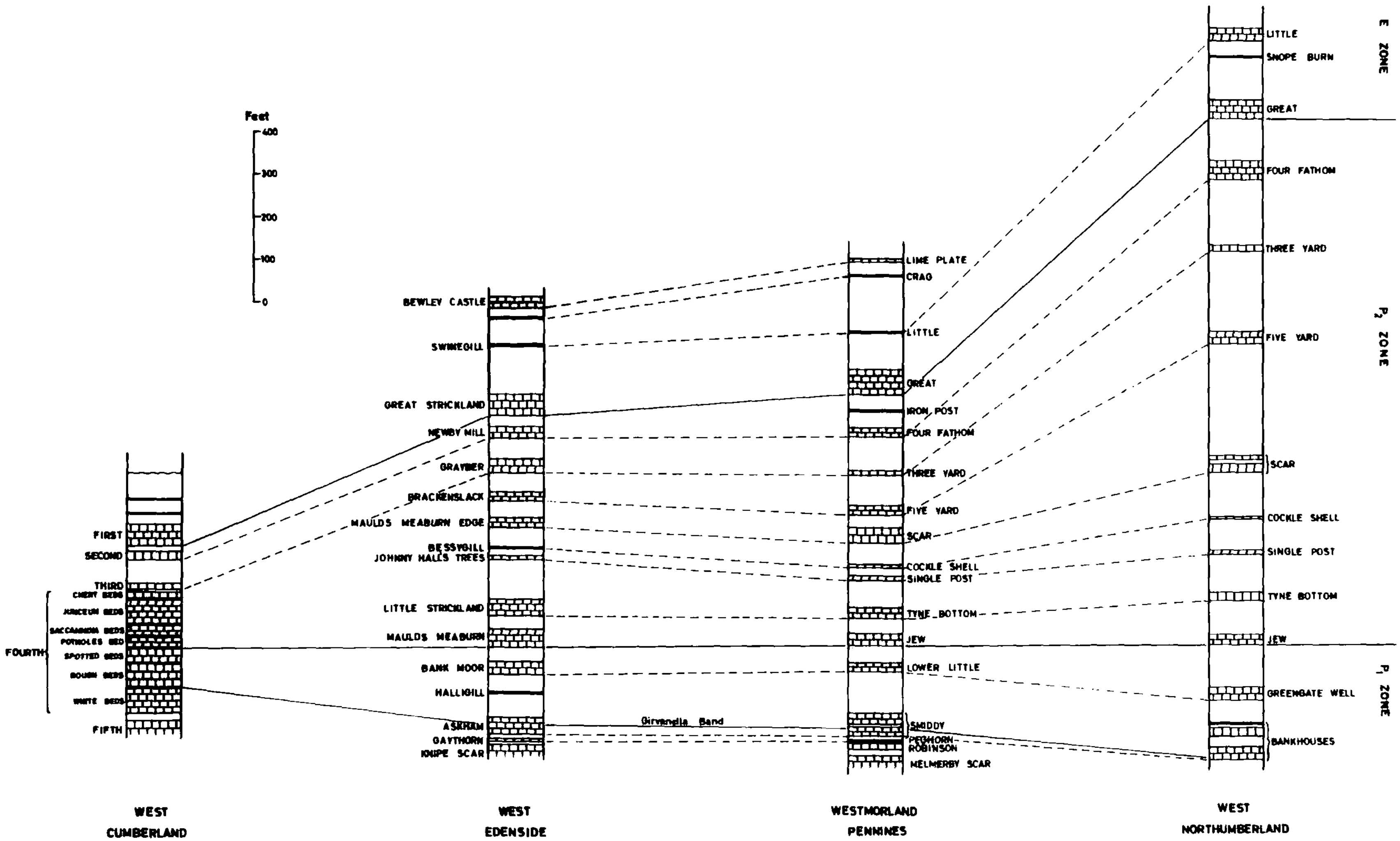


Figure 2.24

is more likely that the upper rather siliceous leaf of this Limestone is its equivalent.

Below the Askham Limestone the thin Gaythorn Limestone may correlate with the Peghorn Limestone of the Pennines, in which case the Robinson Limestone, there the first Yoredale Limestone above the Melmerby Scar Limestone, is in the Shap district represented by the top of the Knipe Scar Limestone. In the Upper Limestone Group, because a complete succession cannot be discerned, correlations are uncertain except that the Bewley Castle Limestone can confidently be said to be equivalent to a fossiliferous cherty limestone above the Crag Limestone of the Pennines termed the Lime Plate by Carruthers (1938, p. 240). Not only is the Bewley Castle Limestone similarly siliceous and apparently at about the correct distance above the base of the Upper Limestone Group (250-300 feet), but also it contains elongate anchoring spines of the sponge Hyalostelia parallela which characterises this horizon on the Alston Block. On thickness considerations, the thin calcareous band 23 feet below would seem to represent the Crag Limestone of the Pennines and this leaves the Swinegill Limestone as the most likely representative of the Upper Little Limestone. Like the latter Limestone in the Westmorland Pennines, it is less than 5 feet thick and it has siliceous beds above which suggests parallels with the Upper Little Limestone of the Askrigg Block to the south-east. It appears to be about the right height above the Great Strickland Limestone to support this correlation which would confirm the impression that the thin calcareous horizons of Hoff Beck represent marine members of the Coal Sills Group.

The Shap-Appleby succession can also be related to that of the Northumberland Trough via the Westmorland Pennines (Fig. 2.24) following the work of Johnson in both these areas (Johnson 1959 and Johnson &

Dunham 1962) and the same figure shows possible correlations with the largely calcareous succession in western Cumberland as described by Edmonds (1922) and Eastwood et al (1931). The First, Second and Third Limestones can be correlated confidently with the Great Strickland Newby Mill and Grayber Limestones respectively and below, terms such as Saccammina Beds and Junceum Beds suggest similarities with the Little Strickland and Maulds Meaburn Edge Limestones. There is in fact a continuity of outcrop between these two areas, north of the Lake District, and from the map of the Geological Survey (Sheet 23, Cockermouth) it appears that the passage of much of the Middle Limestone Group westwards into the thick Fourth Limestone can be followed. The distinctive Littlebeck Sandstone is even better developed in this region where it is known as the Orebank Sandstone Series.

iii) Facies and thickness variation in the Upper and Middle Limestone Groups of Northern England

A comparison of the thicknesses and the relative amounts of limestone in the Vale of Eden, areas to the west and east, and in the Northumberland Trough, is shown in Fig. 2.24. Perhaps the most noticeable feature is the remarkable similarity between the succession in the area studied and in the Westmorland Pennines. Not only are the thicknesses (Table 4) very similar but the detials of the stratigraphy (see, for example, Turner 1927 and Johnson & Dunham 1962) show a striking co-incidence. These considerations prove beyond doubt that there was not, during the sedimentation of the Middle and part of the Upper Limestone Groups at least, any fault or hinge-line separating the two areas and influencing the nature of the deposits. The Pennine Faults, therefore, unlike the other marginal faults of the Alston block, the Stublick and Lunedale-Swindale Beck Faults, can be said to have been initiated not before Upper Carboniferous times at the earliest. The trend of the Swindale Beck Fault, if continued, would take it east of the area studied so that though it appears to have separated regions having a different sedimentational history in pre-D2 times it had no significant influence on the Yoredale deposits.

The effect of the Stublick Fault is shown by comparing these successions with that for west Northumberland, where the Middle Limestone Group is almost doubled in thickness and limestone is proportionately less common. Since, where there is evidence that all the deposits are of shallow water type, the amount of sediment accumulated ultimately depends only upon the amount of subsidence of the basin, then the thickness of sediment (Table 4) clearly indicates the relative subsidence which the different areas have undergone. Whilst the Northumberland Trough was undergoing rapid subsidence in Middle Limestone Group times, the Alston Block was subsiding at only about half this rate and westwards the 'block' was even more stable and allowed the accumulation of little more than 300 feet of strata during this time. These differences are, however, much less in evidence after the deposition of the Great Strickland Limestone when clastic sedimentation predominated throughout the north of England.

The limestone percentage figures shown in the same table indicate how the predominantly open-sea deposits of west Cumberland contrasted with the sedimentation of mainly terrestrially derived material in the Northumberland Trough. The Pennine region has an intermediate limestone percentage and that for west Edenside is slightly but significantly larger showing the gradually increasing imprint of open-marine conditions

TABLE 4

	WEST CUMBERLAND*	WEST EDENSIDE	WESTMORLAND PENNINES**	WEST NORTHUMBERLAND**
Thickness	329	784	807	1527
Limestone thickness	242	274	234	269
Limestone percentage	74	35	29	18

Middle Limestone Group, North of England

* Data from Edmonds (1922)

** Data from Johnson and Dunham (1962)

in a westerly direction. A particularly interesting feature revealed by Table 4 is that the total thickness of limestone deposited in all four areas is remarkably constant. Since limestones deposited throughout northern England at this time are petrographically very similar, this identity of thickness may suggest that the whole area experienced open-sea conditions for broadly equal periods of time. However, if the more rapid subsidence in the Northumberland Trough was evenly spread through the cycle this would produce a greater rate of deposition of the limestone member as well as of the clastics and partially, at least, invalidate this conclusion.

iv) Palaeogeographical implications

The period of time which saw the accumulation of strata of Yoredale facies in the Shap-Appleby area was clearly characterised by frequent changes in environment resulting in a varied series of deposits. Land-derived material periodically advanced over the region but the area studied is too small to draw any firm conclusions as to the source direction of this material. However, considering the equivalent deposits to the east and west (Table 4 and Fig. 2.24) which were deposited in the same structural setting, i.e. on a rigid block, it is true to say that an open-sea marine influence is especially associated with the west of the area. An easterly terrestrial influence does, therefore, seem likely, although a comparison with the Middle Limestone Group succession to the south on the Askrigg Block where the limestones are less divided by clastic material indicates that a northerly component is also apparent. The very thick clastics in the Northumberland Trough are not valid pointers to a northerly source for the material because they are a function of the much greater subsidence of this area which does, in fact, show the same increasingly marine influence to the west as is seen on the rigid block.

The probability is, therefore, that uplift maintained a source area to the north-east of the northern Pennines, although the existence of positive areas in other directions but with less effect on sedimentation in the region is by no means excluded. A north-easterly source has been envisaged by many authors and appears to have been especially important during the succeeding Namurian Stage (see, for example, Gilligan 1919). The general strike of the rocks in the Shap-Appleby area is parallel to the deduced depositional strike thereby, perhaps, helping to explain the lack of significant facies variation in the region.

CHAPTER 3

PETROGRAPHY AND MINERALOGY

A. THE LIMESTONES

i) Constituents

a. ALLOCHEMS

Fossils.

Fragments of shells and crinoid ossicles (Plate 17) are by far the commonest allochemical members of the Yoredale Limestones studied. Crinoid ossicles, usually varying considerably in size up to about 2 cm. diameter are ubiquitous and pieces of brachiopod shell and foraminifera (and more rarely of lamellibranchs, gastropods and trilobites) are present in nearly all of the calcareous horizons. In addition, locally and often as biostromes, complete organisms constitute a significant part of the rock, the most important being corals, brachiopods, algae and bryozoa. The Grayber Limestone is unique amongst the major Limestones in being apparently without foraminifera, which can even be recognised in the almost completely recrystallised Johnny Hall's Trees Limestone though they have not been found above the Great Strickland Limestone. Infrequent and unusual constituents are the dark phosphatic fish teeth which were found in the Little Strickland, Bewley Castle, and Maulds Meaburn Limestones.

Pellets.

Pellets are rare in most of the Limestones but become quite common locally in the Knipe Scar and Maulds Meaburn Limestones (Plate 18). Typically they are of dusty fine-grained calcite with sometimes a secondary rim of clear calcite and are often oval-shaped, having diameters from 0.06 - 0.13 mm.

Intraclasts.

Large brown-grey sub-spherical bodies and elongated pieces of dusty calcite, both usually with recrystallised sparry interiors, occur in some of the limestones

PLATE 17. Shell and crinoid fragments in the Little Strickland Limestone. (x 28)

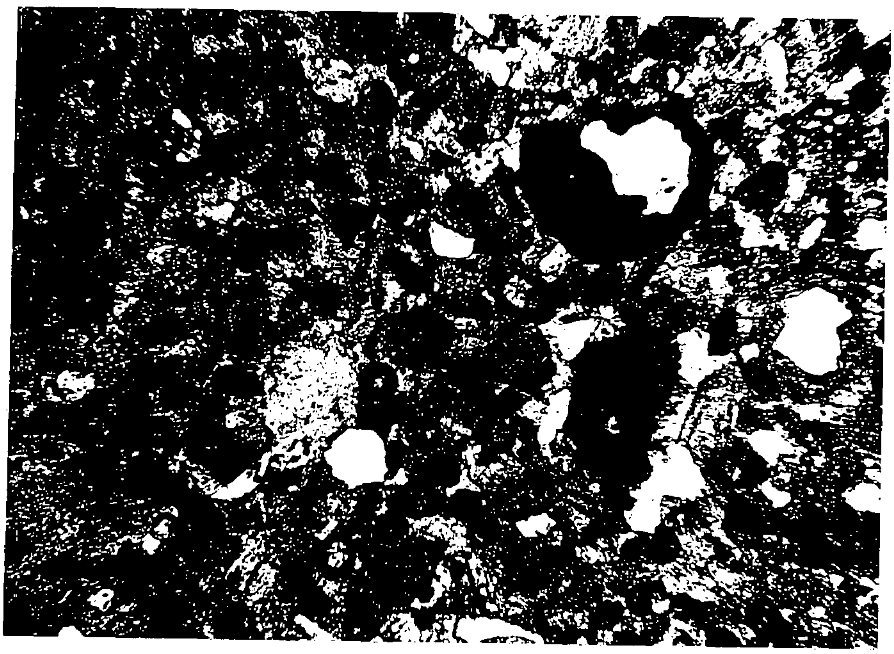


PLATE 18. Pellets in the Maulds Meaburn Limestone. (x 28)

and may be intraclasts. Definite intraclasts have only been found in a calcareous horizon above the Maulds Meaburn Limestone (Plate 19), where they have irregular form but with rounded edges, or are sausage-shaped; both types have recrystallised centres.

Oolites.

Rare spherical bodies having a diameter of about 0.5 mm. with clear calcite cores and laminated dusty exteriors may be pseudo-oolites but no true oolites have been found. The majority are, however, probably Calcisphaera.

b. ORTHOCHEMS

Microcrystalline calcite ooze.

Very fine grained (less than 0.004 mm.) calcite makes up the matrix of the bulk of the limestone deposits. It has a dusty grey or brown-grey appearance which is retained where it has been recrystallised to microspar (often about 0.015 mm.) and sometimes even when it has undergone coarser recrystallisation.

Sparry calcite cement.

A few rocks were found to have cement consisting of interlocking crystals of clear calcite (averaging 0.1 - 0.2 mm.). These rocks are invariably of pale colour and, apart from the band near the base of the Askham Limestone, are restricted to some minor calcareous horizons between the main Limestones.

Pyrite.

Finely-disseminated grains of pyrite can be found in all the darker limestones. It seems to be a primary constituent, with some aggregation after deposition occurring to form small cubes or sub-spherical patches as in the Gaythorn Limestone (Plate 20), and is frequently most abundant in close association with algal remains. The iron oxides which are nearly always present as hematite and limonite are probably not primary constituents but result from weathering effects

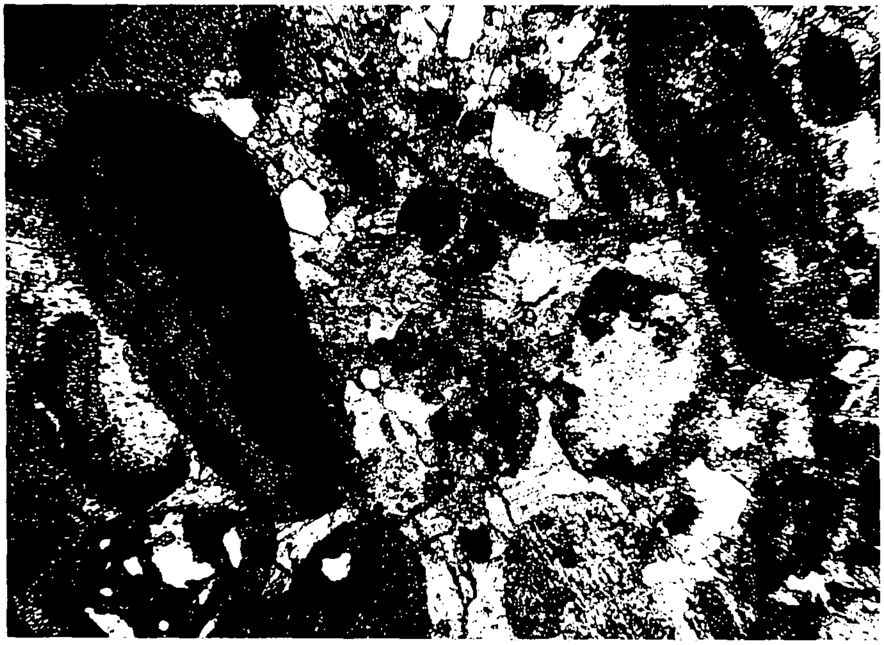


PLATE 19. Elongate micrite intraclasts in the 'calcareous grit'.
(x 28)

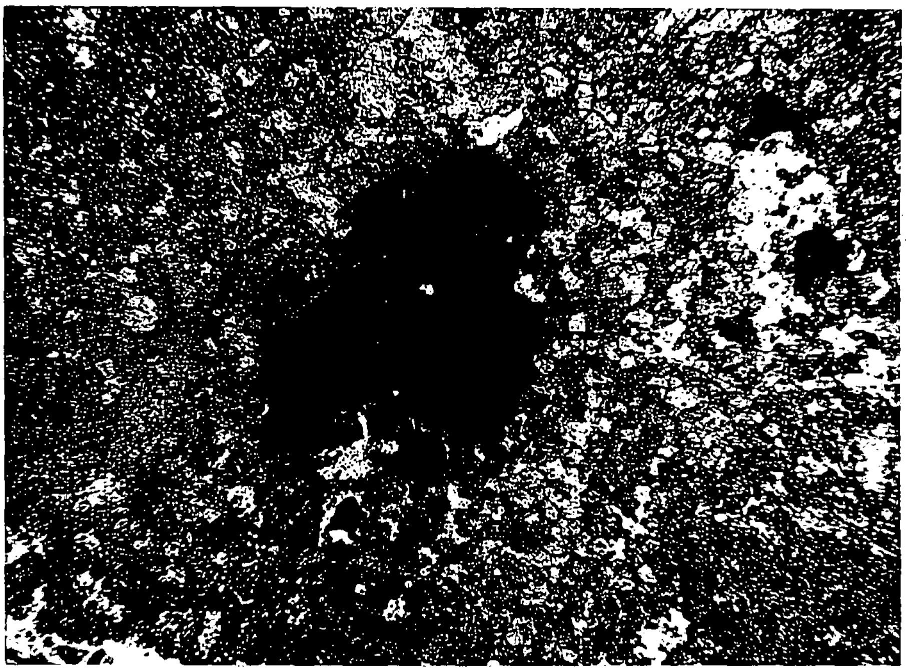


PLATE 20. Large subhedral pyrite patch in the Gaythorn Limestone.
(x 28)

in pre-New Red Sandstone and Recent times. They are usually derived from the pyrite which in many cases can be seen to alter first to dark-red vitreous hematite, which is often greyish and opaque in reflected light where well crystallised, and then to powdery orange-yellow limonite via a brown intermédiate product.

Silica.

The Grayber and higher Limestones all contain deposits of silica, usually in the form of chert nodules but sometimes more dispersed through the rock (page 86). In older Limestones silica is restricted to very small rounded patches which appear to be the result of small-scale accretion though some may be corroded sand grains.

Glauconite.

Small granules of a soft green mineral, of glauconite type, can be found at several horizons and seem to have formed on the sea floor or in the soft rock soon after deposition. It is found everywhere in the upper part of the Grayber Limestone, locally in the Little Strickland and Newby Mill Limestones and occasionally in the Bewley Castle Limestone and the calcareous 'grit' of Drybeck.

Ferro-dolomite.

Where the Limestones have suffered alteration close to the New Red Sandstone unconformity, iron-stained rhombs of a member of the dolomite-ankerite series may make up much of the rock. In this case it is clearly a late diagenetic mineral, but in the Johnny Hall's Trees Limestone which always contains many such rhombs it is thought to have a penecontemporaneous origin.

Other very minor constituents include finely divided organic material (now probably mainly carbon) derived from the decomposition of the soft parts of animals and plants, which gives the dusty grey appearance to the calcite in thin section and is partly responsible for the colour of the rock (page 165). Also a few horizons, usually those which have been subjected to strong pre-New Red Sandstone alteration, contain dendrites of pyrolusite.

c. TERRIGENOUS MATERIAL

Most of the major Limestones are pure chemical rocks (less than 10% terrigenous material) but impurities, including quartz grains, orthoclase and plagioclase feldspar, muscovite and argillaceous material can sometimes be recognised. However, impure chemical rocks grading into calcareous sandstones and shales are quite common at the base and top of the major Limestones and may form the whole of some of the thin calcareous horizons, when these detrital constituents can be recognized in abundance.

ii) Colour

The Yoredale Limestones have frequently been contrasted with the pale Great Scar Limestone and referred to as dark-coloured or blue-grey. Table 5 shows the colour of 154 specimens from the Askham Limestone to the Great Strickland Limestone inclusive. Although not a random sample, there is no doubt that they give a reasonable representation of the relative abundances of the different shades of grey in the rocks studied and, in fact, in so far as unusual types tend to be collected more often, the predominance of the medium and pale-medium grey rocks is not adequately reflected.

TABLE 5

Colour of some Yoredale Limestones

COLOUR	NUMBER
Pale	16
Pale-medium	37
Medium	56
Medium-dark	27
Dark	18

Limestones of dark aspect (medium-dark and dark limestone) constitute only 29% of the total and the bulk, 78%, are an intermediate grey in colour i.e. pale-medium, medium and medium-dark. It is true that they are normally of a darker shade than the underlying Great Scar Limestone although even this is not invariably pale, especially at the top; a limestone was never seen which would justify the term blue-grey.

Colour is not always a reliable guide to the place of a rock in the succession.

iii) Textures

a. DEPOSITIONAL

The bulk of the limestones are close-textured with fossil fragments scattered randomly through a micritic matrix. Occasionally shell fragments lie approximately parallel to the bedding-planes, as do many of the complete brachiopods, especially the Gigantoproductids. In a few of the more argillaceous horizons the crinoids, too, show a preferred orientation, apparently here having been influenced by stronger or more persistent currents.

Some of the foraminiferal limestones are of interest in that in thin sections the fine calcite ooze can be seen to have penetrated into the interior of some specimens, leaving above a space which is now filled with sparry calcite. Presumably the space is either due to contraction on lithification or it may have initially only filled up to the level of the entrance. Many samples are also notable for the abundance of algal material which they contain; filaments are not often recognisable but many dark nodules are present consisting of layers of dusty fine calcite, closely associated with small pyrite grains and often surrounding fossil fragments, expecially crinoids. Occasionally two masses can be seen to have grown together producing a composite nodule.

b. RECRYSTALLISATION

Nearly all sections show some evidence of recrystallisation, both the orthochems and the allochems being affected. Original aragonitic shell material has been converted to a mosaic of medium and coarse calcite crystals (Plate 21), and adjacent calcite mud within and around the fossil fragments frequently shows increasing crystal size towards the shells which have, therefore, acted as centres of recrystallisation. Often the micritic ground-mass has been at least partially recrystallised to equant interlocking crystals of microspar, still retaining however its impure greyish appearance. Sometimes the micrite has recrystallised locally to produce small spherulites with fine radiating fibres (Plate 22).

Most limestones examined show little evidence of diagenetic changes other than recrystallisation although the scattered quartz grains are frequently etched and, where sufficiently closely packed, may be sutured, so that some re-distribution of components has here occurred. Re-distribution of minor con-

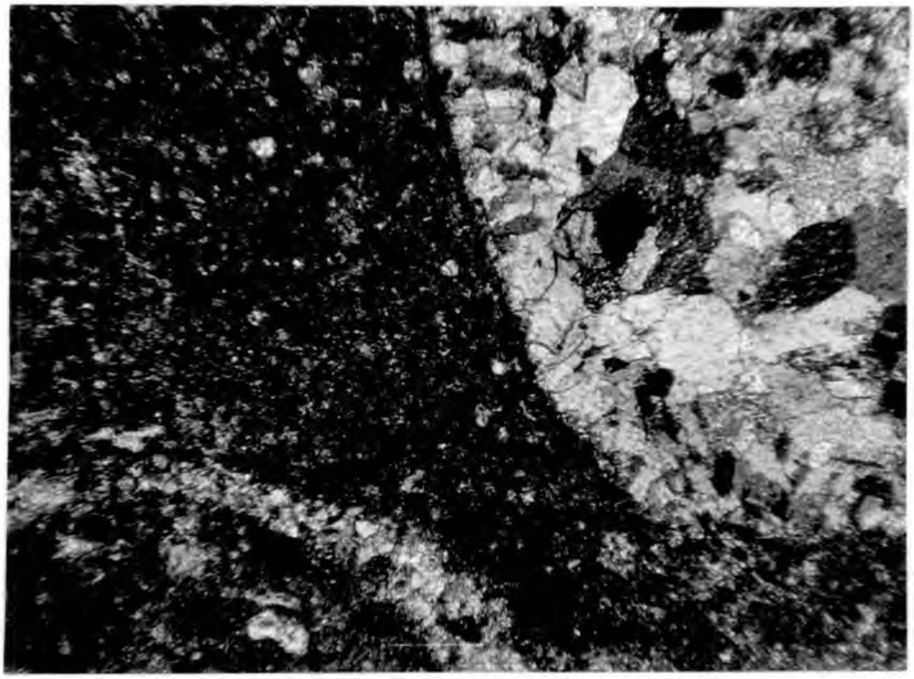


PLATE 21. Gastropod shell fragment now a mosaic of large calcite crystals. (x 28 nicols crossed)

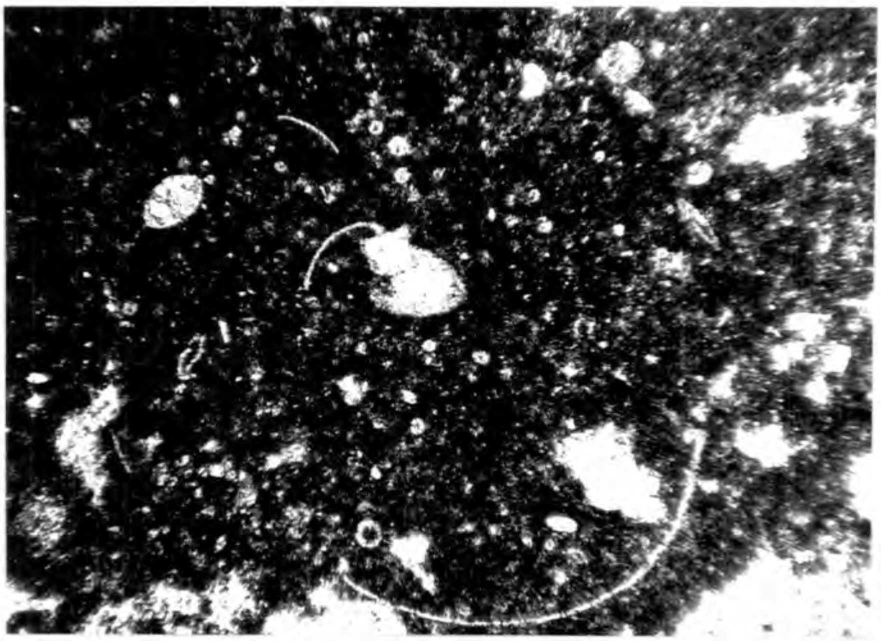


PLATE 22. Fossiliferous micrite showing recrystallisation spherulites. (x 28)

-stituents coupled with recrystallisation also seems responsible for the rare spotted beds and commoner pseudo-breccias (Garwood 1912, pp.475-478). The only truly spotted limestone is a bed low in the Maulds Meaburn Limestone which has a pale-grey matrix and medium grey spots, most of which are circular or oval with a distinct boundary and average 0.5 - 1.0 cm. in diameter. The darker areas appear to have the finest grain and often contain some transparent calcite; presumably they result from concretionary action affecting the dark colouring material of the limestone. The dark and pale-buff mottled, rubbly-weathering pseudo-breccias are common in this Limestone. Some look like genuine breccias but examination shows that the boundary between the pale and dark areas often intersects shell and crinoid fragments and is very irregular and interpenetrating. In hand specimen the pale material appears to have partially replaced the dark but this cannot be the case since in thin-section it is the darker limestone which has undergone most recrystallisation and contains an increased proportion of pyrite and fewer foraminifera.

iv) Diagenetic redistribution and alteration.

a. REDDENING

Small maroon flecks due to the oxidation of iron-bearing minerals to hematite are present at many horizons in all the Limestones and some of the thin limestones in the Upper Limestone Group have an overall red colour. The major Limestones may locally have a general pink tint but more usually reddening is restricted to a strongly altered zone at the base, as, for example, in the Great Strickland Limestone near Lookingflatt (Plate 10). This reddened limestone has a very granular appearance where weathered, much calcite having been removed, and upwards the red colour gradually lessens due to the incoming of pale areas, so giving a finely mottled effect. There is then sometimes a thin, distinct but very irregular band of deep purple alteration (Plate 23), beyond which there is only a very minor amount of reddening. The impression is given that this band marks the uppermost limit of oxidising solutions which have penetrated the limestone from the sandstone below, causing local strong oxidation of iron at their inward limit where the process has been arrested before migration to produce an even distribution of the red pigment could occur. The resulting pattern is so much like that produced by, say, tea-staining of a tablecloth, that a similar staining process is strongly suggested.

The reddened limestones are usually a pinkish-purple when fresh but weathering produces a brown-pink, probably as a result of partial hydration of the hematite.

b. SILICIFICATION

The Grayber, Newby Mill and Great Strickland Limestones have nodules in which silica is strongly concentrated and the upper part of the Newby Mill Limestone and the Bewley Castle Limestone are also often highly siliceous. The silica content is not related to faulting or jointing but occurs in layers parallel to the bedding so that there is no reason to believe that it was not chemically deposited with the rest of the limestone, though it has usually undergone later segregation into layers and nodules. The nodules are pale grey or pinkish and often contain crinoid fragments which, in thin-section, can be seen to have been corroded by the silica but are rarely entirely replaced (Plate 24). The margins of the silica are fairly clearly defined but in detail are very irregular, and patches of carbonate may still occur within the chert. There can be no question of its having been a primary sedimentary mass of gel on the seabed. The silica

PLATE 23. Reddened zone at the base of the Great Strickland Limestone and showing a thin deeply stained band at its upper margin.

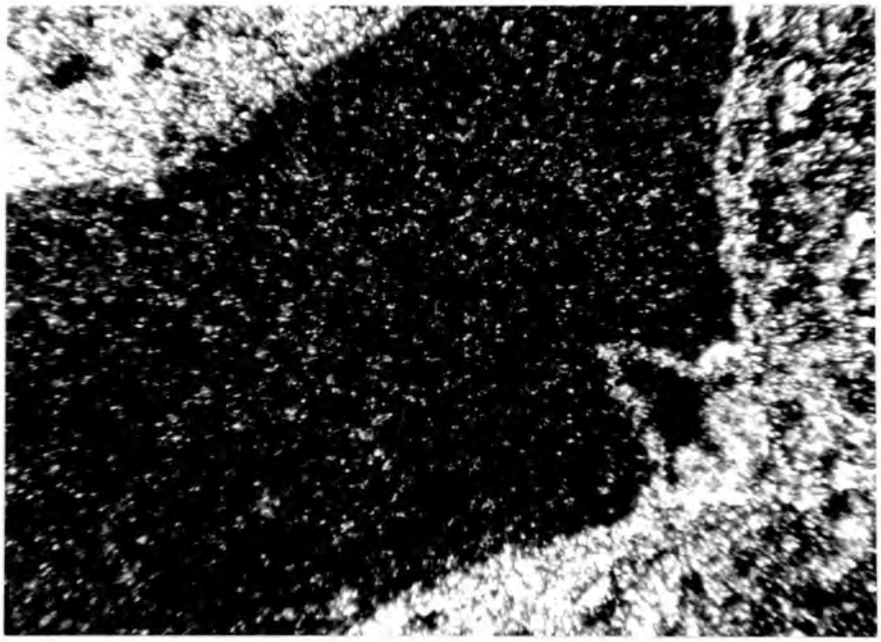


PLATE 24. Part of a crinoid ossicle (dark) which has been irregularly replaced by chert. This has since devitrified to produce small quartz crystals.
(x 28 crossed nicols)

is of pale yellow colour, partly cryptocrystalline, but usually has crystallised to a very fine mass of quartz crystals with a few spherulites having radiating fibres. The quartz crystals are often largest near the included crionoid fragments and sometimes quartz crystals can be found in the centres of crinoid fragments and other fossils in the parts of the rock which remain carbonate (Plate 25).

c. DOLOMITISATION

A small amount of dolomite-ankerite, derived probably from fossil skeletons initially rich in magnesium is present in all of the limestones and is sometimes segregated into small brown-weathering pockets as, for example, locally in the Maulds Meaburn and Askham Limestones. In contrast, the Johnny Hall's Trees Limestone invariably contains much dolomite-ankerite throughout, which seems, therefore, unlikely to have the same origin. There is no evidence that it is made up of organisms which could be responsible for sufficient magnesium to avoid the necessity of invoking an external source and the numerous cavities suggest that this element has indeed been brought in from outside and replaced calcium on a molecular basis. However, the Johnny Hall's Trees Limestone and its correlatives throughout the north of England display these characters which are not found in adjacent Limestones, so that addition of magnesium soon after or even during deposition is strongly suggested.

The Limestone has been almost entirely recrystallised to a mass of interlocking crystals which are often ferruginous-weathering. Although fossil-ghosts can sometimes be found, the exact nature of the rock as deposited is unknown but its pale colour may suggest that it was without much fine-grained matrix. Scattered through and post-dating the recrystallised calcite are numerous euhedral rhombic crystals with zones of iron oxide parallel to the crystal edges. They are weathered, zoned crystals probably of calcite and dolomite-ankerite but possibly of iron-poor and iron-rich dolomite. Dendritic limonite patches, also produced by weathering, are common and the rock has an overall brownish appearance on weathered surfaces.

The Newby Mill and Great Strickland Limestones, too, are locally rich in dolomite but this only occurs where they are in close proximity to the New Red Sandstone unconformity and is clearly a late diagenetic effect. Unlike the Johnny Hall's Trees Limestone, where it is most altered, very little calcite remains except near the base. The rock is a uniformly yellow or orange color with black pyrolusite dendrites and consists of a mosaic of equant dolomite crystals.

Near the base, adjacent to curving diagonal joint-planes, reddening and dolomitisation both affect the Great Strickland Limestone of Lookingflatt and the evidence provided of their relative dates is hard to reconcile with other mainly stratigraphical evidence. The red and yellow limestone is intimately mixed in such a way that the reddening looks to be post-dolomitisation, the yellow areas being seemingly relics of a dolomitised limestone which has been eaten into and veined by the reddening agents. In thin section (Plates 26 and 27), the yellow areas are seen to consist of an irregular mosaic of subhedral crystals, most of which are dolomite but with some calcite and fossil ghosts; cavities produced by dolomitisation have been filled with single quartz crystals. These fragments are surrounded by channel- and vein-like areas, having the appearance of reaction rims, very rich in translucent red-brown hematite and some opaque dense silvery-grey hematite patches also occur. The translucent hematite is usually in the form of zig-zag bands separated by clear carbonate, giving the areas a toothed appearance, and apparently due to alternate hematite and carbonate precipitation. There is independent evidence that dolomitisation (or at

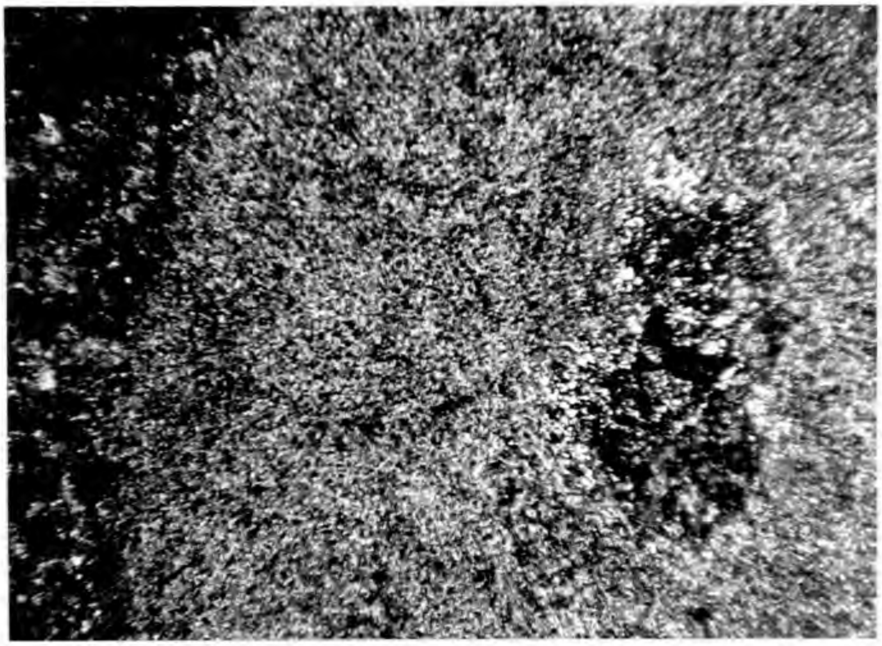


PLATE 25. Relatively large quartz crystals developed in the centre of a crinoid fragment. In chert from the Grayber Limestone. (x 28 nicols crossed)

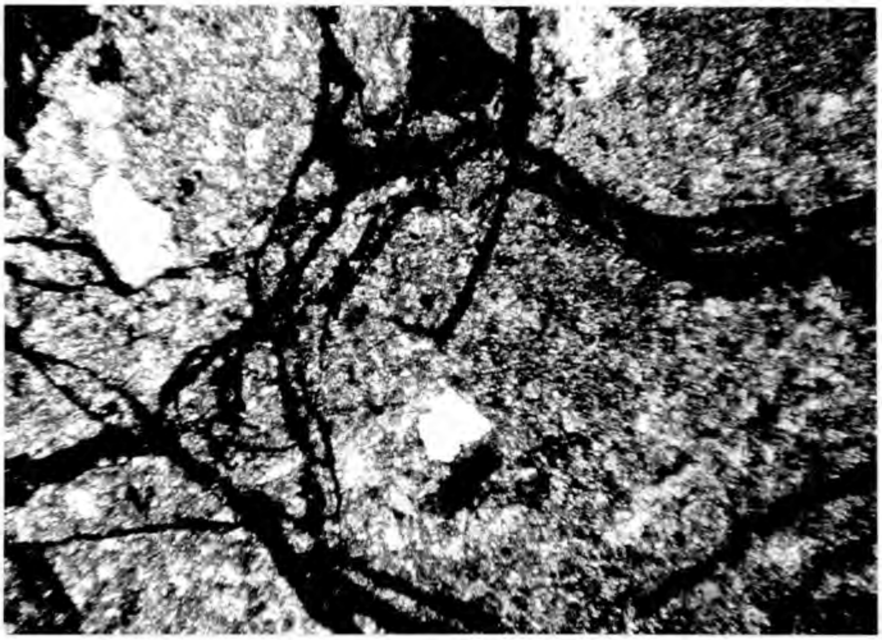


PLATE 26. Dolomitised limestone in which cavities have been filled by single quartz crystals (white). Limestone fragments isolated by hematite veins. (x 28 nicols crossed)

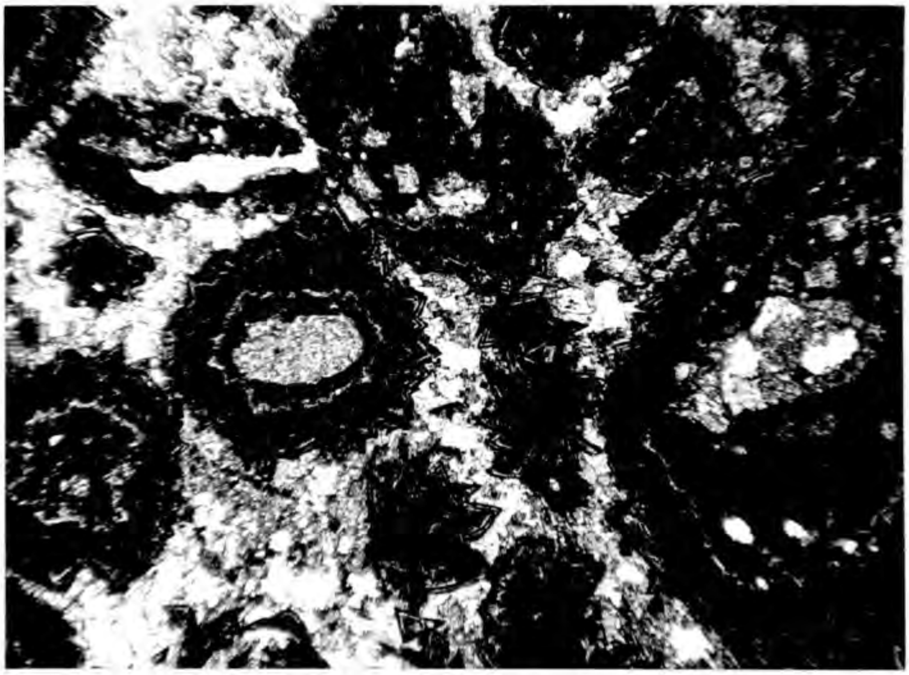


PLATE 27. Zig-zag bands of translucent hematite in dolomitised limestone. (x 28)

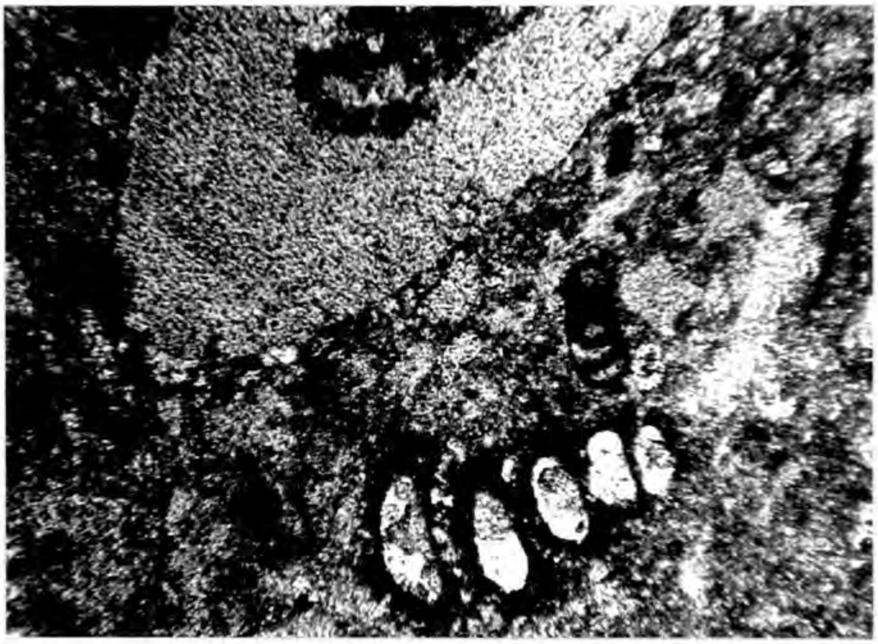


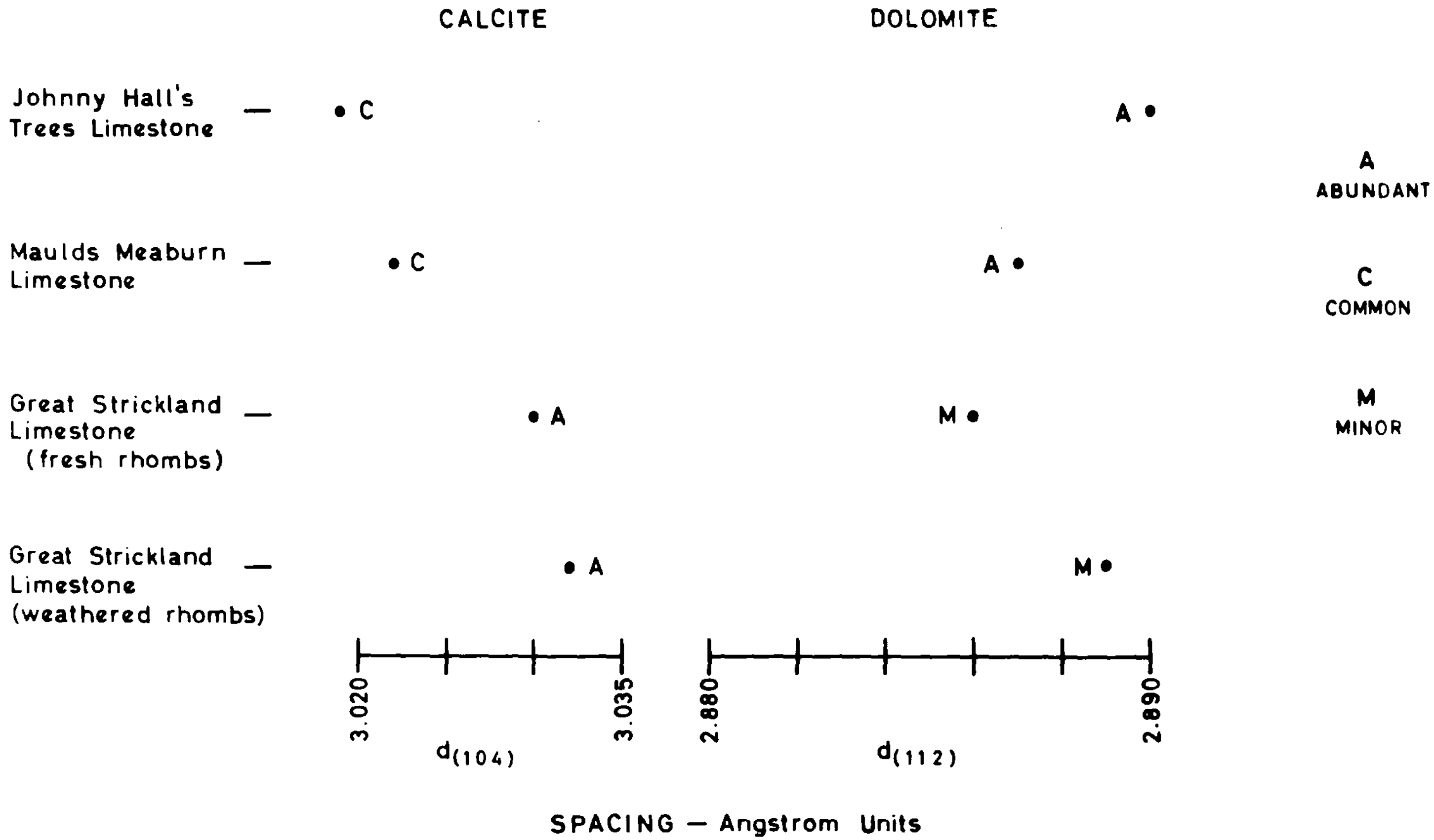
PLATE 28. Typical Biomicrite from the Little Strickland Limestone. (x 28)

least some dolomitisation) post-dates the reddening (page 244) and a possible interpretation of this rock is that the unaltered limestone was attacked by oxidising solutions which caused recrystallisation accompanied by the rhythmic precipitation of hematite; the dolomitisation would follow later and was only able to attack non-reddened fragments of the rock. However it is, perhaps, difficult to imagine a process of rhythmic precipitation of hematite in these circumstances, and the serrated bands look so much like what would be expected to be produced by the oxidation of iron-rich and iron-poor carbonate, zoned parallel to rhombic faces, that the possibility of this reddening being post-dolomitisation cannot be discarded. In this case, either two periods of reddening separating one of dolomitisation or vice-versa are necessary to explain all the facts of the geology of the area; the former alternative seems preferable.

Both the Johnny Hall's Trees Limestone and the Great Strickland Limestone contain vugs which are consequent upon dolomitisation and have subsequently received encrustations of rhombic carbonate crystals. A few were removed and examined by X-ray diffraction to determine their nature (Figure 3.1). Two fresh, approximately equal-sized rhombs from the Great Strickland Limestone give a trace showing predominant calcite but with minor dolomite. The relative heights of the two main peaks are such that all of the calcite could not have been contributed by only one crystal so that at least one of the crystals must contain both types of carbonate, probably with zoned distribution parallel to the rhomb faces. This calcite has more-closely spaced 104 planes than has pure calcite so that some substitution of smaller ions, probably Fe, Mn, or Mg, for calcium must have occurred. The dolomite, too, is not pure magnesium-calcium carbonate, iron probably having replaced some magnesium to give a member of the dolomite-ankerite series. Weathered crystals from nearby show a similar combination of the two carbonates but with slightly

Figure 3.1

THE COMPOSITION OF SOME RHOMBIC CRYSTALS FROM VUGS IN THE LIMESTONES



purer calcite and correspondingly less-pure dolomite, suggesting perhaps that some transfer from the calcite to the dolomite of iron or possibly manganese ions has occurred. Crystals from a vug in the Johnny Hall's Trees Limestone were examined in the same way and also found to contain two phases, impure calcite and impure dolomite, though in this case the latter is slightly more abundant than the calcite; again the two carbonates are probably together in individual rhombs. Their compositions differ from those of crystals in the Great Strickland Limestone in that both are still less near the ideal end-member value. Examination of a brown dolomitic patch from the Maulds Meaburn Limestone, with dolomite now predominating over calcite, shows that both phases have d-spacings lying between their values for fresh crystals from the other two Limestones. Consequently, there is here some indication of a rational distribution of minor ions between the two carbonates and probably, therefore, some constancy in the supply of these ions throughout the period of crystallisation of the different carbonates.

v) Classification

The most satisfactory and useful classification of the limestones has been found to be that due to Folk (1959) which is shown in Figure 3.2. Locally, diagenetic changes have resulted in the masking of the original nature of a few of the rocks but most remain sufficiently unaltered to assign to a definite group. Biomicrites, that is limestones made up of fossil debris with a matrix of calcite ooze (Plate 28), are overwhelmingly predominant, with associated but very subordinate biopelmicrites and fossiliferous micrites (less than 10% fossils) (Plate 22), and rare pure micrite horizons. All are suggestive of environments of not very high energy. Biosparites (Plate 29) do occasionally occur as thin beds but primary spar is

(after Folk 1959)

TABLE I. CLASSIFICATION OF CARBONATE ROCKS

Volumetric Allochem Composition	Limestones, Partly Dolomitized Limestones, and Primary Dolomites (see Notes 1 to 6)					Replacement Dolomites[7] (V)	
	>10% Allochems Allochemical Rocks (I and II)		<10% Allochems Microcrystalline Rocks (III)				
	Sparry Calcite Cement > Microcrystalline Ooze Matrix	Microcrystalline Ooze Matrix > Sparry Calcite Cement	1–10% Allochems	<1% Allochems	Undisturbed Bioherm Rocks (IV)	Allochem Ghosts	No Allochem Ghosts
	Sparry Allochemical Rocks (I)	Microcrystalline Alochemical Rocks (II)					
			Most Abundant Allochem			Evident Allochem	
>25% Intraclasts (i)	Intrasparrudite (Ii:Lr) Intrasparite (Ii:La)	Intramicrudite* (IIi:Lr) Intramicrite* (IIi:La)	Intraclasts: Intraclast-bearing Micrite* (IIIi:Lr or La)	Micrite (IIIm:L); if disturbed, Dismicrite (IIImX:L); if primary dolomite, Dolomicrite (IIIm:D)	Biolithite (IV:L)	Finely Crystalline Intraclastic Dolomite (Vi:D3) etc.	Medium Crystalline Dolomite (V:D4)
<25% Intraclasts; >25% Oölites (o)	Oösparrudite (Io:Lr) Oösparite (Io:La)	Oömicrudite* (IIo:Lr) Oömicrite* (IIo:La)	Oölites: Oölite-bearing Micrite* (IIIo:Lr or La)			Coarsely Crystalline Oölitic Dolomite (Vo:D5) etc.	Finely Crystalline Dolomite (V:D3)
<25% Intraclasts; <25% Oölites; Volume Ratio of Fossils to Pellets >3:1 (b)	Biosparrudite (Ib:Lr) Biosparite (Ib:La)	Biomicrudite (IIb:Lr) Biomicrite (IIb:La)	Fossils: Fossiliferous Micrite (IIIb: Lr, La, or Ll)			Aphanocrystalline Biogenic Dolomite (Vb:Dl) etc.	
<25% Intraclasts; <25% Oölites; Volume Ratio of Fossils to Pellets 3:1–1:3 (bp)	Biopelsparite (Ibp:La)	Biopelmicrite (IIbp:La)	Pellets: Pelletiferous Micrite (IIIp:La)			Very Finely Crystalline Pellet Dolomite (Vp:D2) etc.	etc.
<25% Intraclasts; <25% Oölites; Volume Ratio of Fossils to Pellets <1:3 (p)	Pelsparite (Ip:La)	Pelmicrite (IIp:La)					

Figure 3.2

very restricted in distribution and is most frequently found in the thin sandy calcareous beds between the major limestones (Plate 30). These tend to be intraclast-bearing sandy biosparites grading, as at the base of major limestones, into calcareous fossiliferous sandstones. Biolithite, too, forms only a minor part of any given limestone.

Of the dolomite-bearing horizons, the Johnny Hall's Trees Limestone is, at least in part, a dolomitised biomicrite (Plate 31), whilst the Newby Mill and Great Strickland Limestones are, locally, dolomitised biomicrites becoming medium and coarsely crystalline dolomite with the loss of all fossil traces (Plate 32).

vi) The glauconite of the Yoredale Limestones

Although this soft greenish mineral is only easily recognised in the Grayber Limestone and is never very abundant, making up probably less than 5% of the rock at the maximum, it is interesting in that it has rarely been previously reported from the Middle Limestone Group, and because it has often been considered to give an indication of the conditions prevailing at the time of deposition (see, for example, Pettijohn 1957, pp.468 and 469, and Cloud 1955).

As far as its occurrence in the rocks studied is concerned, it has a fairly wide but, except in the Grayber Limestone, restricted distribution. Appearing as it does in the Bewley Castle, Newby Mill and Grayber Limestones, which are the horizons where silica is most abundant, it may be said to occur when conditions were somewhat different from those under which the majority of the major limestones were deposited. The same is true of its presence in the calcareous 'grit' above the Maulds Meaburn Limestone which, though not siliceous, is atypical amongst even the minor calcareous horizons, whilst

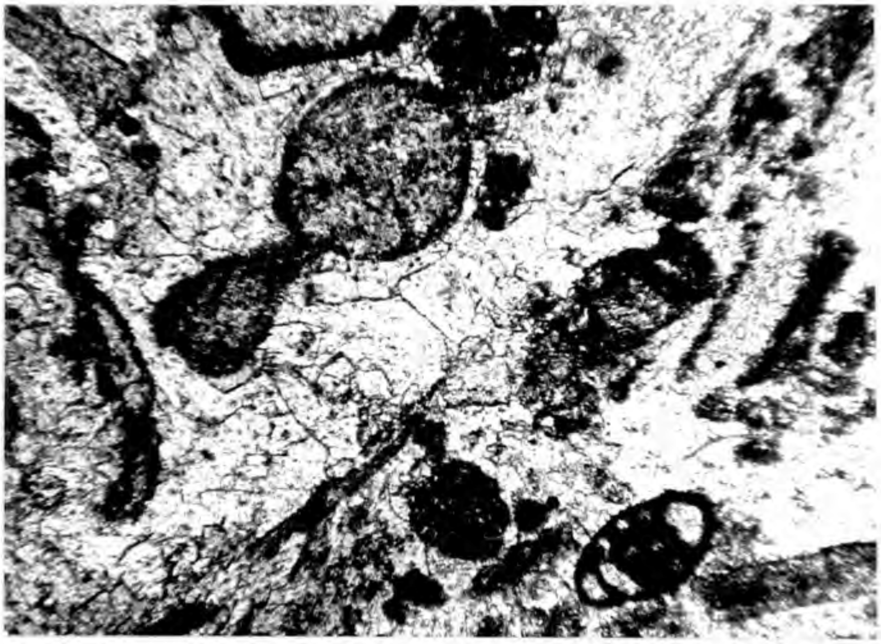


PLATE 29. Biosparite from the Askham Limestone. (x 28)

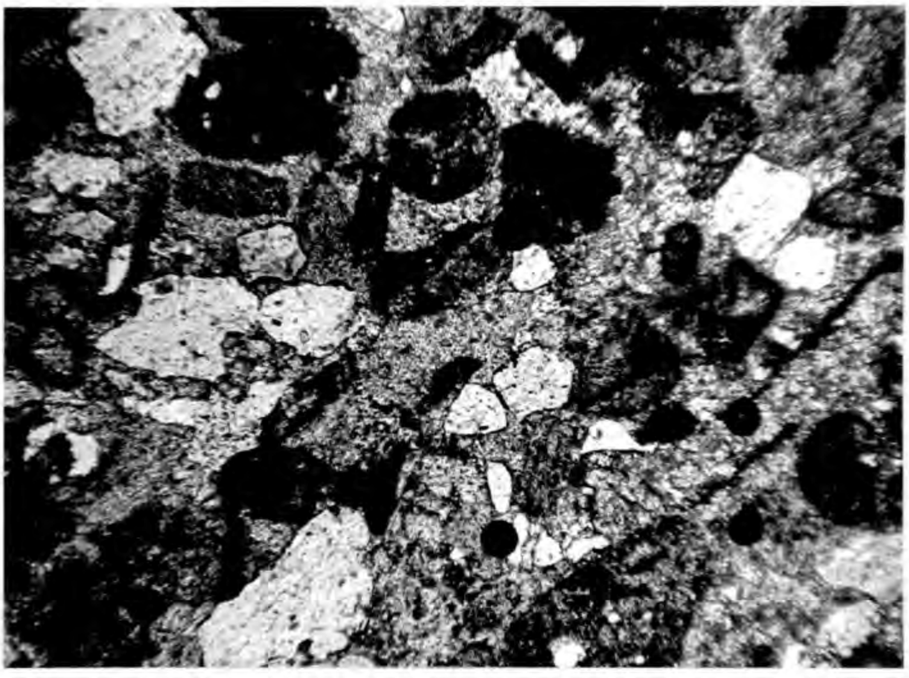


PLATE 30. Sandy Biosparite; quartz grains, fossil fragments and intraclasts set in sparry calcite. (x 28)

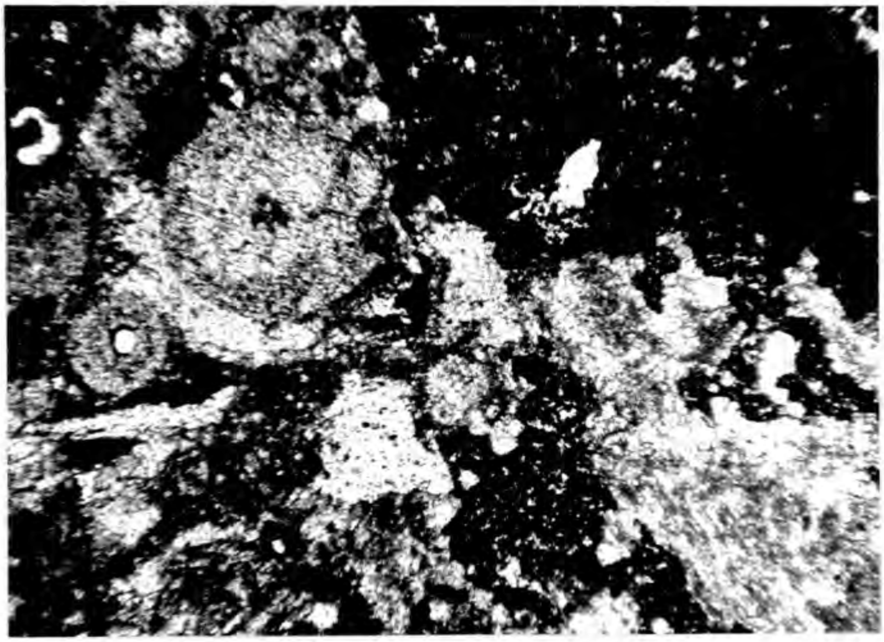


PLATE 31. Dolomitised Biomicrite from the Johnny Hall's Trees Limestone. Ghosts of crinoid fragments can be recognised. (x 28)

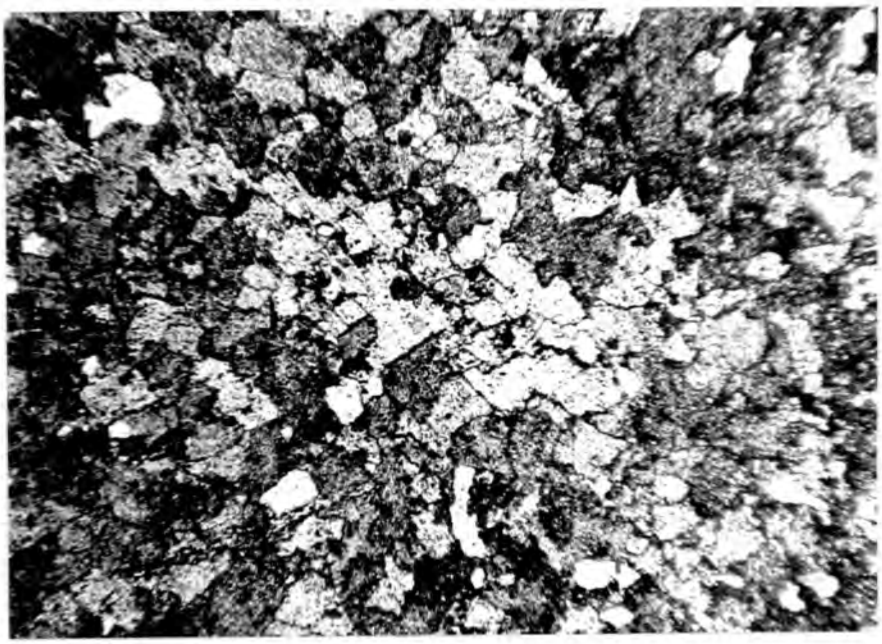


PLATE 32. Medium- and coarsely-crystalline dolomite from the Great Strickland Limestone at Lookingflatt. (x 28)

its rare appearance in the Little Strickland Limestone is almost at the base, when the normal conditions of limestone deposition had, perhaps, not become fully established.

The glauconite occurs as scattered granules of rather irregular shape or occasionally with smoothly curved lobate outlines which are probably casts of foraminiferal chambers in which it formed. Also it frequently can be found apparently impregnating and partially replacing calcite, especially crinoid ossicles, when it has a porous aspect due to the original organic structure. Almost always the glauconite is closely associated with pyrite.

When fresh, it is a deep bright green but weathering makes it duller and paler and it eventually becomes a yellow colour with the conversion of much of the contained iron to hydrated ferric oxide. In thin section, a sample from the Grayber Limestone is pale green and non-pleochroic and occurs as a well defined mass with good relief. Under crossed-nicols it can be seen to consist of many small grains with low polarisation colours.

The mineral is, however, being soft and friable, difficult to study in thin section and X-ray techniques are required to further explore the mineralogy. It is most satisfactorily studied using a powder camera technique and Table 6 shows data obtained from five different samples. The spacings given by glauconites from the Grayber Limestone (columns 2 and 3) are the most complete and are sufficiently similar to those from the Venezuelan glauconite shown in column 1 for the mineral to be reasonably termed a true glauconite.

The 3.09Å reflection is very weak or absent and a few of the weakest lines of the standard glauconite pattern are not visible but, on the other hand, additional lines are present at 3.71Å, 2.94 - 2.92Å, 2.79Å, 2.70Å, and 2.028 - 2.025Å, the latter occurring in all of the glauconites studied whilst that at 2.70Å is absent only from the Little Strickland Limestone.

TABLE 6

1		2		3		4		5		6		7	
dÅ	1/1	dÅ	1/1	dÅ	1/1	dÅ	1/1	dÅ	1/1	dÅ	1/1	dÅ	1/1
10.1	10	10.6	8 B	10.3	10 B	11.2	8 B	10.9	10 B	10.8	10 B	10.0	10
4.98		5.00	2	5.03	1	4.98	1	5.03	2	5.02	3	4.95	2
4.53	8	4.53	10	4.52	8					4.51	9		
						4.50	10	4.50	9			4.48	9
4.35	2	4.36	2	D									
4.12	1	4.12	1	D									
		3.71	4	3.71	3 B	3.70	2 B	3.67	4	3.68	3	3.69	2 B
3.63	4												
3.33	6	3.35	6	3.34	6	3.35	6	M		M		3.33	9
												3.17	1
3.09	4	D								3.05	2 B		
		2.92	8	2.91	10	2.94	1						
2.89	1									2.86	1	2.87	1
		2.79	3										
		2.70	3	2.70	1			2.70	3	2.70	3		
2.67	1					2.67	1						
2.587	10	2.594	8 B	2.585	5 B	2.583	10 B	2.580	8 B	2.584	8 B	2.61	6
												2.51	1
2.396	6	2.415	4	2.418	2	2.401	1	2.405	2	2.399	2	2.42	4
2.263	2	D											
2.213	1	2.207	3	2.201	3			2.197	1	2.201	1		
2.154	2											2.16	2
		2.028	2	2.025	3	2.026	1	D		D			
1.994	2 B	1.979	1 B	D		1.980	1			D		1.986	1
1.817	1	1.805	1	1.810	3 B								
1.715	1	1.706	1					1.699	2	1.701	1		
1.660	3 B	D		D								1.530	6
1.511	6	1.518	5 B	1.517	4 B	1.504	6	1.511	6 B	1.504	4 B		
1.495	1												
												1.449	1
												1.323	1
1.307	3	1.301	2							D			
1.258	1												

Powder photograph data for glauconites from the Yoredale Limestones

1. Cretaceous glauconite, Venezuela (X.P.D.F. card 9-439).
2. Glauconite from the Grayber Limestone.
3. Glauconite from the Grayber Limestone.
4. Glauconite from the Little Strickland Limestone.
5. Glauconite from the Newby Mill Limestone.
6. Glauconite from the Bewley Castle Limestone.
7. Illite (X.P.D.F. card 9-343).

B Broad D Diffuse M Masked

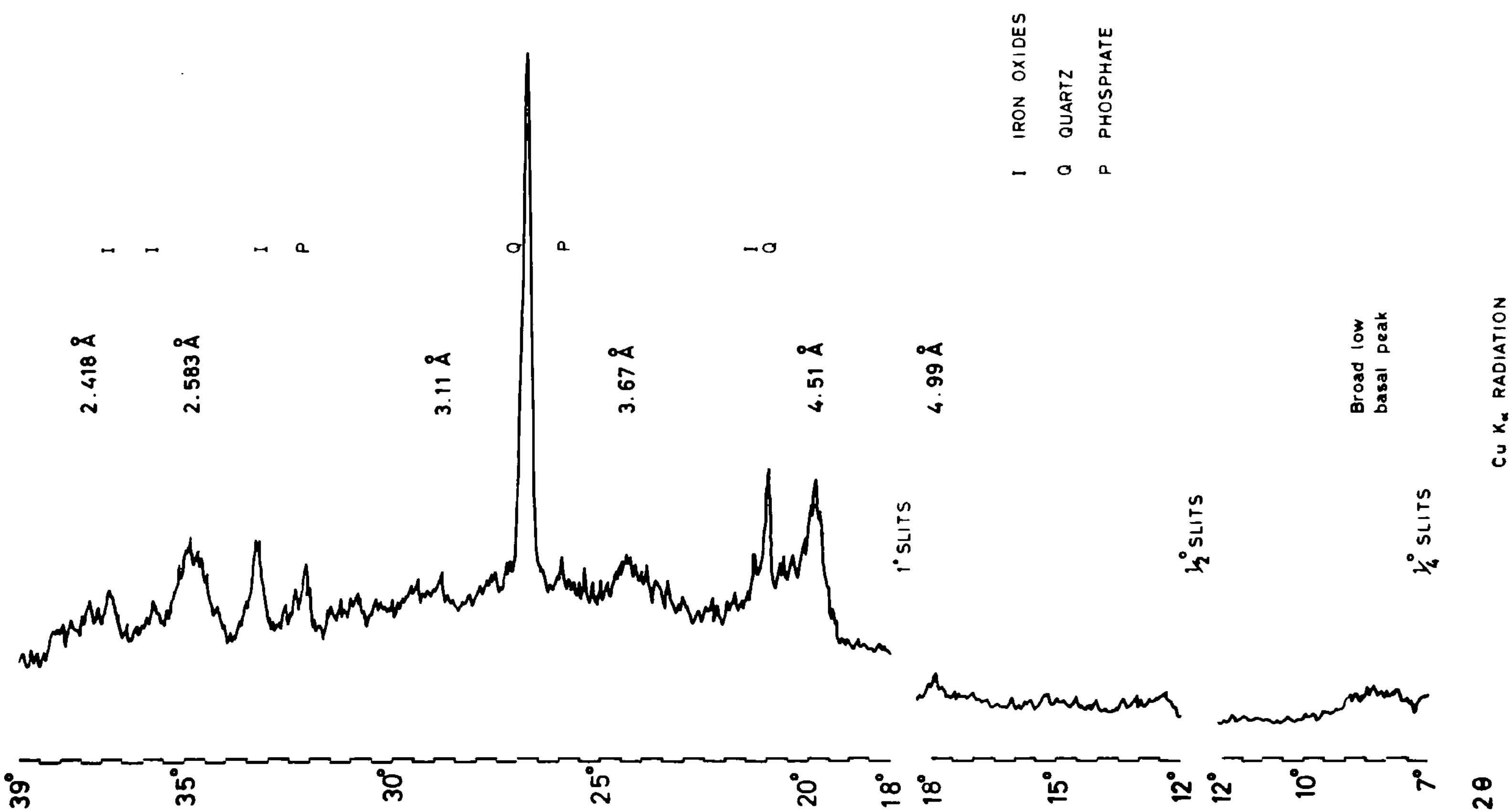
(Relative line intensities visually estimated)

The first-order basal reflection is invariably broad and rather diffuse and ranges upwards from 10Å suggesting that some mixed-layering is always present. Two particularly interesting and persistent lines occur at 3.71 - 3.67Å and at 2.94 - 2.91Å, the former being found on all of the photographs. It is of the same intensity as, and apparently occurs in place of, the standard 3.63Å line which is nowhere seen, and its value is closer to that of illite (column 7) than of glauconite. The other somewhat anomalous line occurs strongly only in the Grayber glauconites; it is closely similar, though not in intensity, to a spacing for the trioctahedral biotites but the 2.79Å spacing is almost identical to a value for dioctahedral micas and the occurrence of the 060 reflection at about 1.518Å leaves no doubt as to its essentially dioctahedral character. Some of the patterns, especially those of glauconites not from the Grayber Limestone, show occasional reflections whose values fit better with those for illite than for glauconite, indicating, perhaps, that some illitic layers are also present but the strong reflections around 2.587Å and 1.511Å show that the iron-rich end-member is predominant.

Even where most abundant, there is scarcely enough of the glauconite for it to be satisfactorily separated in bulk. A small quantity of reasonably pure glauconite was obtained by crushing a piece of the Grayber Limestone, electromagnetically separating the 60 - 90 mesh fraction (which removed much calcite but not the iron-bearing impurities), and dissolving remaining carbonate in dilute acetic acid. The method produced sufficient material to allow the mineral to be examined by X-ray diffraction using a smear mount. The trace (Figure 3.3) shows the main glauconite peaks but also has peaks due to quartz, iron-bearing minerals and, probably, some phosphate. The first-order basal peak is very low and broad probably partly because of the extremely finely divided state of the mineral but also because it is

Figure 3.3

X-RAY DIFFRACTOMETER TRACE OF A 10 Å GLAUCONITE-TYPE MINERAL



disordered (Burst 1958). Even the well formed peaks are relatively low and broad, again due to its disordered nature and probable variations in layer composition. Values compare closely with those for the standard glauconite except for the lines at 3.67Å and 2.418Å which, as in the powder photographs, are closer to illite, although the former in particular is very broad and encompasses the whole region between the glauconite and illite values. The strong line present on the powder photographs at about 2.92Å is here only poorly represented whereas the 3.09Å line of the standard glauconite pattern is now recognisable.

The X-ray examination shows that the green mineral of the Yoredale Limestones is basically of dioctahedral glauconite type and is the disordered 1Md polymorph but includes some illite-like and probably larger-spacing layers. Much was probably produced by the action of sea-water on detrital mixed-layered but essentially illitic clay grade material in a suitable environment (page 223).

vii) <u>Depositional structures</u>

The Yoredale Limestones show a variety of approximately horizontal joints which are considered to be primary bedding structures. Usually these joints are open, shale and marl partings being not very common, and have a gently undulating form which has been referred to as wavy-bedding (Plate 33). Sometimes, these undulations are very pronounced and, where they bound a thin limestone bed, can locally break this up into isolated lenticles (Plate 34). In contrast, certain horizons, especially in the Maulds Meaburn Limestone, are characterised by relatively even bedding with only very minor undulations on bedding surfaces (Plate 35). These even-bedded limestones tend to be rather darker in colour than the wavy-bedded ones (c.f. Johnson, 1959).

PLATE 33. Wavy-bedded limestone; the Little Strickland Limestone at Towcett Cottages.

PLATE 34. The distinctive bedding-plane with pronounced undulations in the Little Strickland Limestone.

PLATE 35. Even-bedded limestone: the Maulds Meaburn Limestone at Raise Howe Quarry.

PLATE 36. Lenticular horizontal joints in the Maulds Meaburn Edge Limestone.

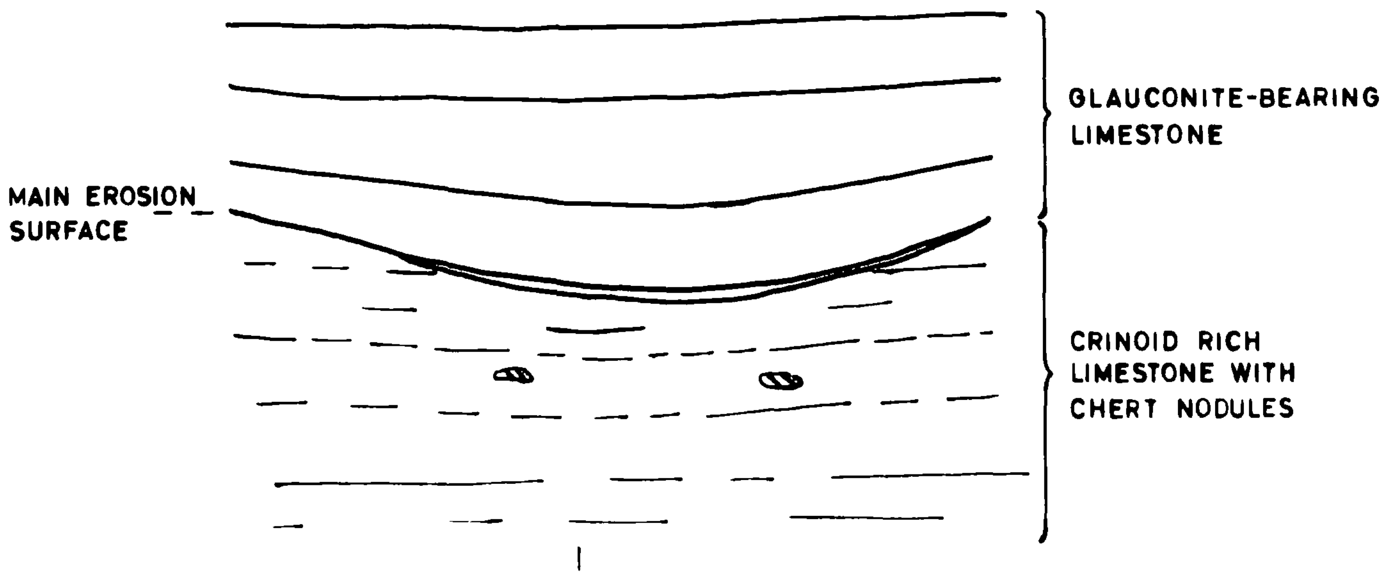
These planes probably represent periods when increased current action prevented deposition or caused erosion and the lime mud of the sea floor became consolidated before the next deposits were laid down. The degree of irregularity of the surface presumably depends largely upon the strength and other hydrodynamic properties of the current. Sometimes a definite increase in the number of fossils near a major bedding-plane has been recognised as, for example, of crinoid fragments in the Maulds Meaburn Edge and Grayber Limestones, and lend support to the idea that these planes are due to increasing currents whose first effect would be to winnow away the ooze.

Very often the major bedding-planes are widely spaced and the limestone must then have accumulated under scarcely changing conditions during long periods of time. Minor fluctuations of the environment appear to have slightly influenced the accumulating calcareous material and are manifested, upon weathering, by the occurrence of discontinuous irregular sub-horizontal cracks, which have been termed lenticular horizontal joints (Plate 36).

Cross-bedding of the allochems has nowhere been recognised but slight channel-shaped bedding, having an amplitude of at least 2 feet, can be seen in the Grayber Limestone at Low Moor where a gently curved main erosion plane separates glauconitic limestone above from very crinoid-rich limestone without glauconite below (Plate 37 and Fig. 3.4). Although laminations in the limestone below the erosive plane are hard to trace, there is no doubt that positive erosion has occurred and that several are intersected. The number that are cut out is, however, considerably lessened because these laminations, except for the lowest, themselves undergo a thinning which reaches a maximum two yards to the west of where the erosion plane is at its lowest. Clearly, the special environment which ultimately led to the erosion of a channel was operating for some time previously and reducing the

PLATE 37. Strong erosion surface in the Grayber Limestone at Low Moor.

Figure 3.4



A CHANNEL IN THE GRAYBER LIMESTONE

thickness of material deposited approximately in line with the subsequent channel. The beds above the disconformity are initially gently curved but the hollow was then filled in and at the top the beds are horizontal.

B. THE ARGILLITES

i) Constituents

a. DETRITAL COMPONENTS

Quartz.

Silt-sized and probably smaller detrital grains of quartz can be recognised in many of the argillaceous rocks. X-ray diffraction traces invariably have large quartz peaks and this mineral is probably often a major component of such rocks in spite of their fine grain.

Feldspar.

A little feldspar is present in some of the shales studied by X-ray diffraction; although some may be authigenic it is logical that, as with quartz, detrital feldspar of finer than sandstone grade will occur but only in small quantities.

Mica.

Muscovite is visible on the bedding-planes of most of the shales, especially towards the top of the member where silty material becomes increasingly abundant. Even in the shales directly overlying the limestone, however, very fine mica can usually be distinguished, either by eye or under the binocular microscope.

Clay minerals.

The clay fraction in general is too fine-grained to be analysed using a microscope but X-ray diffraction reveals that a variety of clay minerals are present. Illite, frequently degraded, is the most important primary component but mixed-layer minerals and chlorite can usually be recognised in small quantities. Almost invariably present, even in shales which show no sign of alteration, is much kaolinite. It is not restricted to the upper 'non-marine' part of the cycle but occurs throughout and has even been recorded in the limestones themselves. Although it is possible that its presence results from the erosion of kaolinite produced by weathering of source rocks under conditions of strong leaching, a secondary origin is more likely. The equivalent shales of the Alston Block, only a few miles to the east, show no similar predominance of kaolinite (Johnson and Dunham, 1962) and it is difficult to imagine that the detrital components could have had a different source. The fact that the Alston Block was relatively depressed in late Carboniferous or early Permian times (Turner, 1927), whereas the area studied was on the upthrow side of the Inner Pennine Fault, suggest that the appearance of kaolinite in the Yoredale Series of the latter district is a consequence of changes occurring under the influence of the early-Permian climate. This conclusion is strongly supported by the fact that in the most clearly altered green and purple 'soapy'- textured mudstones, which were very near the surface in early-Permian times, kaolinite is greatly enhanced and, together with quartz, makes up the bulk of the rock. At greater depth alteration becomes less apparent to the eye, but that circulating fluids did bring about changes in the clay mineralogy seems certain.

Organic material.

Shell fragments, especially brachiopods, bryozoa and crinoids often form a substantial part of the shale immediately above and within limestones but soon die out upwards with the coarsening grade of the terrigenous components. Characteristic of horizons in the shales where abundant calcareous fossils decrease rapidly in numbers upwards are dull olive-green branching frond-like streaks whose origin is unknown, although they are almost certainly organic traces of some kind. In shales closely associated with coarser material, plant-debris is often conspicuous on the laminations.

b. CHEMICAL PRECIPITATES

Calcite occurs in the argillaceous rocks deposited in close proximity to the limestones but, except as the shells of animals, is rarely very common. As its abundance decreases upwards it tends to be segregated into concretions, being joined by a member of the dolomite-ankerite series, and ultimately giving way to siderite, which also occurs frequently as concretions although it may form the cement of the silty shales and siltstones. Occasionally, at horizons immediately above the limestone member, silica has been precipitated and has produced a compact hard rock.

Pyrite is present at most horizons, though rarely in sufficient quantities to be visible to the naked eye; it also probably helps to give the shales their prevalent dark grey colour. In general the colour of the shale tends to be related to its position in the cyclothem, due to some extent to the varying dilution with quartz. Those just above the limestone member are very dark whilst some of the shales at the top of the cycle, especially those occurring as thin layers in sandstone bodies, may be pale, as is some of the shale which occurs as part of minor rhythms. Where weathered, the argillaceous rocks almost invariably show a yellow or orange-brown limonitic stain due to the oxidation of ferrous compounds, particularly of the finely-divided pyrite.

More details of the mineralogy of the argillaceous rocks can be found in the study of the shales above the Askham Limestone presented in Chapter 4.

ii) Depositional structures

The argillaceous rocks, where they contain a minimum of silt- and sand-sized particles, show little in the way of lamination or other signs of bedding. The dark fossiliferous shales are poorly fissile, breaking in an irregular crumbly fashion; any primary lamination or differences in colour has probably been destroyed by the abundant organisms which lived in the mud. Upwards, where the conditions became less suitable for life, some indication of bedding is often discernable and the rock weathers in a 'blocky' fashion, breaking into large slabs bounded by curving joints and by apparently depositional surfaces which have a gently curved relief and often lobate margins giving the impression that the rock was deposited rapidly.

With the incoming of less-fine mica and quartz, fissility greatly increases and some of the upper part of the main shale member of the cyclothems is quite thinly laminated and splits easily on smooth parallel planes. Some of these rocks are true siltstones and in these as well as in the silty bands within the shales very gentle small scale wavy- or cross-lamination can often be found. These strata, though in bulk a mixture of clay and coarser grade material, have the different components well-sorted into separate laminae so that true muddy sandstones of greywacke composition do not occur. The only occasions when mud appears to form a matrix to the coarser materials is in rocks where there is evidence that the initial size-sorted laminations have been destroyed by burrowing animals. Animal trails and burrows are indeed quite common in this facies, transitional between the main argillaceous and arenaceous members of the cyclothem, another often noticeable feature of which is the occurrence of shale siltstone and sandstone in frequently repeated rhythms of small thickness.

Argillaceous pellets, resulting from penecontemporaneous erosion of muddy material, are present in a number of sandstone bodies. They occur usually as thin flakes lying parallel to the bedding and are often unusual in having a khakhi colour which contrasts with the grey of nearby normally bedded argillite. The colour is probably due to the state of oxidation of the contained iron and carbonaceous matter which must be different from that in the main mass of the shales because of the different diagenetic environment resulting from complete enclosure within sandstone.

iii) Major diagenetic changes

a. CONCRETIONS

Hard concretionary bodies produced by the segregation of the dispersed minor components of the shales into discrete areas, allowing a decrease in the free energy of the component (Ramberg, 1952, p.222) are a common feature of the argillaceous horizons of the Yoredale Series. The vast majority are predominantly of siderite though some calcareous concretions, including ankerite, and rarer phosphatic ones, are also present. Many have a septarian structure with cracks containing calcite, kaolinite and sometimes pyrite; often however pyrite is absent from, or very subordinate in, the concretions in contrast to the adjacent shales.

The concretions occur from just above the limestone member to high up in the shales and generally decrease in size upwards. The lowest may be mostly of calcite but the majority are of siderite; no true pyrite concretions were found in the shales. Their shape varies from almost spherical, through bun-shaped, to very pancake-like where lateral segregation has played the major role and vertical migration of material has been at a minimum.

Laminations have never been seen to pass through the concretions and this, together with the fact that the shells which they contain are always in an uncrushed state and contrast with the fossils of the adjacent shales, shows that they formed at an early stage in the history of the rock. The carbonate probably accumulated before there had been much compaction of the

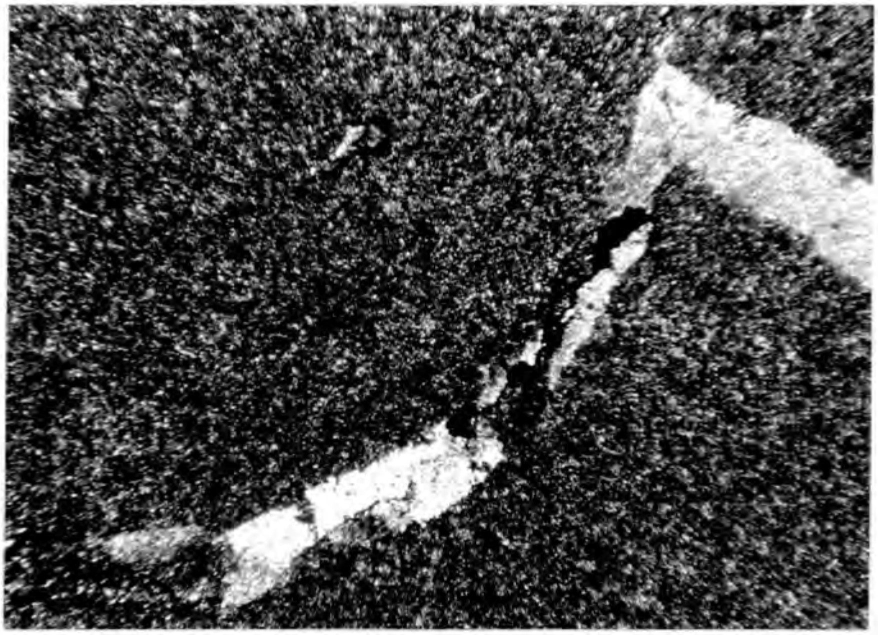


PLATE 38. Fine-grained siderite of a concretion with a vein containing large calcite crystals.
(x 28 nicols crossed)

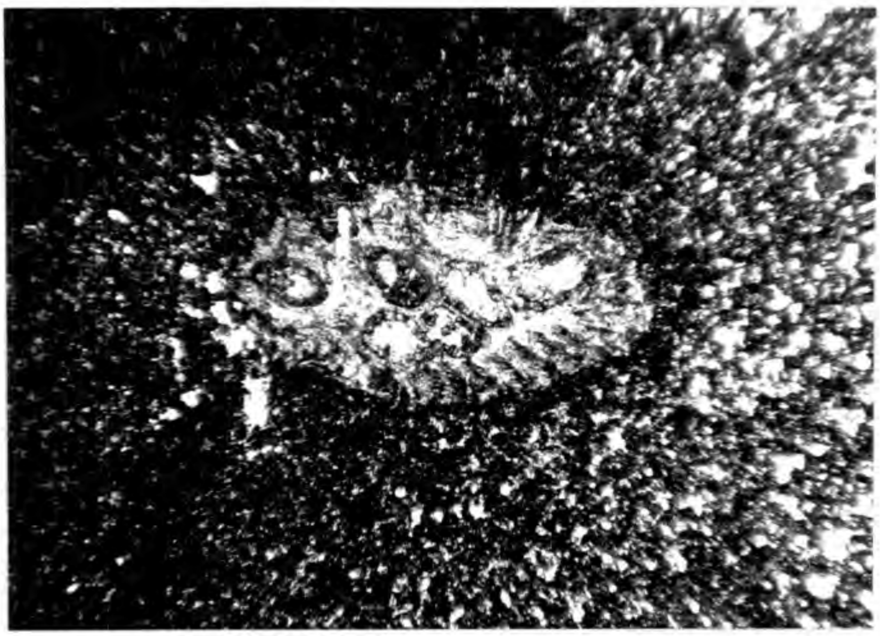


PLATE 39. Bryozoan in siderite concretion. Pores are rimmed by small siderite crystals and filled with a large calcite crystal. (x 120)

rock and filled the then considerable pore space; carbonate does, however, seem to predominate so greatly over the quartz and clay fraction that a concurrent partial removal of these materials must have taken place. In the septarian nodules some of the clay appears to have been converted to a member of the kandite group and is often concentrated, along with calcite, in the radiating cracks. The powder-pattern of the mineral has similarities with both kaolinite and nacrite and is compared with that of those minerals in Table 7. A similar pattern was given by particles of a pale-blue soft material occurring quite commonly in small carbonate concretions from the pale shale underlying the calcareous 'grit' of the Maulds Meaburn cycle, where it is also associated with much quartz and a 10Å mineral.

The relative scarcity of pyrite in the concretions suggests that, if anything, they developed in a less reducing micro-environment than was prevailing in the adjacent argillite. The same may be true of a dark-grey elongate body from the shales immediately above the Swinegill Limestone which is surrounded by an area of bleached shale as if the colouring matter had been locally oxidised. It contains quartz and kaolinite but appears to be largely of a phosphatic mineral whose d-spacings are compared with those of carbonate-apatite and fluorapatite in Table 8.

In thin-section the siderite concretions (Plate 38) consist of equant interlocking crystals of brown-yellow carbonate averaging about 0.02mm. diameter. This material is often cut by a series of irregular cracks which may be filled with calcite showing the same orientation over large areas. The same pattern of calcite crystallisation following that of siderite can also sometimes be recognised where bryozoa occur in the concretions and have pores lined with a series of crystals of siderite and filled later with calcite usually as one large crystal (Plate 39).

Rare concretions occur which exhibit an unusual internal structure.

TABLE 7

1		2		3	
dÅ	1/1	dÅ	1/1	dÅ	1/1
7.26	9			7.23	10
7.08	10	7.15	10		
4.43	7	4.45	5	4.38	7
4.33	8	4.35	6		
4.16	7	4.17	6		
		4.12	3	4.12	6
3.83	6	3.84	4	3.96	1
3.71	3	3.73	2		
3.61	7			3.59	8
3.56	10	3.57	10		
3.37	4	3.37	4	3.44	2 B
3.13	1	3.14	2		
3.05	4	3.09	2	3.07	4
3.01	4			2.93	1
2.74	1	2.75	2		
2.56	6	2.55	7	2.59	2
2.52	3	2.52	4	2.52	4
2.486	7	2.486	8	2.43	6
2.380	2	2.374	7		
2.334	8	2.331	9	2.34	1
2.288	7	2.284	8	2.29	1
2.246	1	2.243	1	2.26	1
2.189	2	2.182	3		
2.086	2	2.127	2	2.09	2 B
1.990	5	1.985	7		
1.937	1	1.935	4	1.95	2
1.896	1	1.892	2	1.897	1
1.868	2	1.865	1		
1.838	2	1.835	4		
		1.805	1	1.800	1
1.789	3	1.778	6	1.772	1
1.707	1	1.704	1	1.735	1
1.686	2	1.682	1	1.685	2
1.663	5	1.659	8	1.660	1
1.621	4	1.616	7	1.619	2 B
1.586	1	1.581	4	1.584	1 B
1.542	3	1.539	6 B		
1.490	7	1.486	9	1.489	8
1.470	1	1.464	1	1.463	5

D-spacings of some Kandites

1. 7 Å clay mineral from septarian nodule in the Askham Clastics.
2. Kaolinite (X.P.D.F. cards 5-0143, 5-0144).
3. Nacrite (X.P.D.F. card 7-320).

B Broad

(Relative line intensities visually estimated)

TABLE 8

1		2		3	
dÅ	I/I	dÅ	I/I	dÅ	I/I
4.06	2	4.08	2		
3.87	2	3.90	2		
3.45	7	3.44	8	3.44	2
3.17	3	3.18	1		
3.07	3	3.08	2	3.07	3
2.80	10	2.82	10	2.81	10
2.78	9			2.78	4
2.70	9	2.71	9	2.71	6
2.62	5	2.62	5	2.63	3
2.52	1	2.52	1	2.53	1
2.25	4	2.25	6	2.26	2
M		2.14	1	2.14	1
2.06	1	2.06	1	2.06	1
2.00	1	2.00	1	2.00	1
1.93	4	1.92	7	1.94	4
1.88	3	1.89	3	1.89	1
1.84	5	1.83	7	1.84	6
1.79	3	1.80	4	1.80	3
1.77	3	1.77	4	1.77	3
1.75	3	1.75	4	1.75	3
1.72	3			1.72	3
1.64	1	1.64	2	1.64	1

D-spacings of some phosphates

1. Phosphate from nodule in shales above the Swinegill Limestone.
2. Carbonate-Apatite (X.P.D.F. card 4-0697).
3. Fluorapatite (X.P.D.F. card 3-0736).

M masked

(Relative line intensities visually estimated)

They consist of a normal medium-grey matrix together with paler buff areas which often have the form of irregular branching tubes and end on the surface of the nodule as slight bumps. In thin section both types of material can be seen mainly to be siderite but it is slightly coarser-grained in the buff areas which may also contain a little calcite. X-ray powder photographs suggest that clays are absent from the tube-like parts and, in view of their paler colour, this may also be true of organic material. The cause of this minor differentiation remains a problem but it seems possible that the early segregation of carbonates may have led to the preservation of traces of worm activity which have been destroyed in the adjacent softer rock.

b. REDDENING

The normal grey shades of the argillaceous rocks are replaced by purple, red-brown and grey-green where they are in close proximity to the early New Red Sandstone land surface. The reddish shades are the result of oxidation of iron-bearing minerals in the shales to hematite, which is finely disseminated but not universally present, a red and greenish mottle often characterising these strata. The green tint may be due occasionally to an absence of all iron compounds but is more likely suggestive of the presence of hydrous ferro-ferric minerals together with hydrated ferric oxides (MacCarthy, 1926). Oxidation was, therefore, strong but incomplete.

The oxidation has also affected the siderite concretions and the rarer sideritic bands, altering them almost entirely to a mass of brown-maroon rather porous hematite. An unusual feature of some of the altered shale is that particles of carbon have undergone concretionary action during weathering and have been segregated into brittle small black spheres, sometimes with a surface of interfering lobes, and except when very small, with hollow centres. They are surrounded by green reduction spots contrasting sharply with the adjacent dull-purple shale.

C. THE SANDSTONES

i) Constituents

a. FRAMEWORK

Quartz.

Quartz is by far the most abundant constituent of nearly all of the Yoredale sandstones studied, occurring as non-undulatory, undulatory and polycrystalline grains. The latter are rare and normal unstrained grains are the commonest so that, on this basis, the sandstones are fairly mature (Blatt and Christie, 1963).

Feldspar.

A small quantity of feldspar can be found in most of the sandstones and it occasionally becomes a quite important constituent in some of the coarser-grained rocks in the upper part of the succession where large pink or white grains can be clearly seen. Plagioclase tends to be less altered than the alkali feldspar which frequently contains patches of grey-brown very finely micaceous material, although fresh microcline and perthite can sometimes be recognised.

Rock Fragments.

Occasional fine-grained polygranular fragments due to the incomplete destruction of earlier mudrock are present but they never form more than a very minor fraction of the framework constituents.

b. CEMENT

Silica.

The majority of the sandstones are entirely or in part cemented by silica. The quartz grains are pressure-welded or have sutured contacts and the silica derived from these points has been precipitated in adjacent areas of reduced pressure as overgrowths in optical continuity with the rest of the grain and occasionally has produced complete crystal faces. A few examples with chalcedony filling some of the pores can also be found.

Calcite.

Some cementing calcite is present in many of the sandstones and occasionally it forms up to 50% of the rock, when it must have been introduced at an early stage. Sometimes in fact, when the rock can be seen to grade into a sandy limestone, it was precipitated with the grains of quartz and often then appears as quite large ill-defined patches which tend to be elongated in the plane of the bedding. Other rocks now having much calcite were apparently deposited without it because their texture and bedding features are identical to laterally adjacent calcite-free strata (Plates 40 and 41). It occurs as very large crystals which formed soon after deposition since suturing and overgrowths of quartz are absent and rare biotite has remained in a fresh state. More frequently, the carbonate occurs in isolated patches of small crystals which sometimes have weathered to an ochreous stain, suggesting that the calcite contained some iron, or even perhaps that a ferruginous dolomite was precipitated.

Others.

Strongly brown-weathering siderite is present in some of the finer-grained sandstones and was probably penecontemporaneously deposited. Other minor cementing materials include pyrite which tends to be patchily

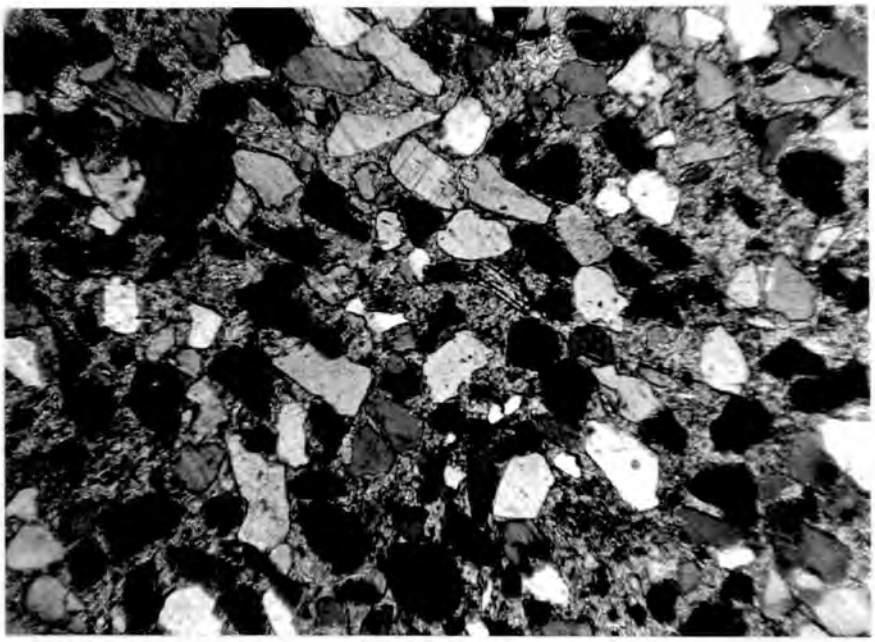


PLATE 40. Sandstone with carbonate cement which developed at an early stage of diagenesis. (x 28 nicols crossed)

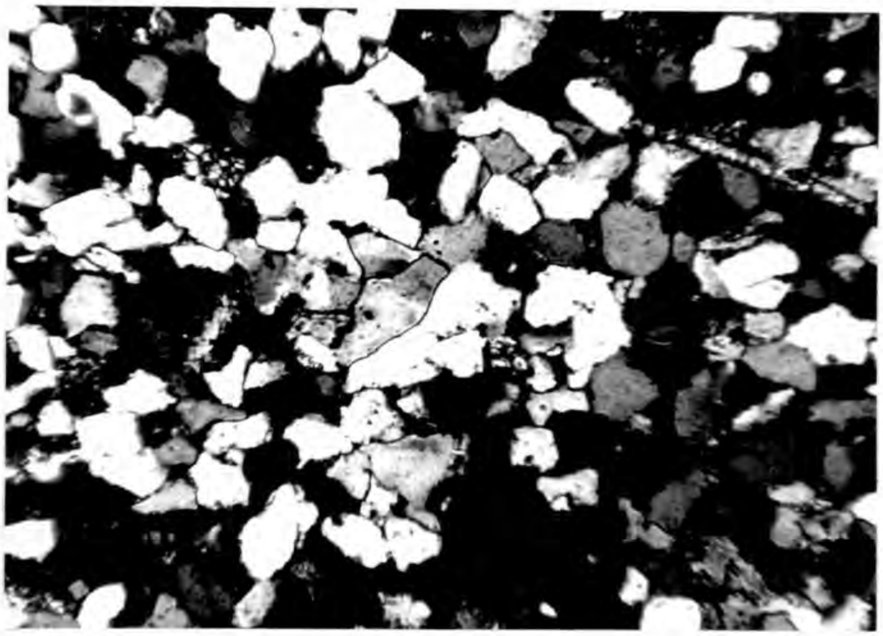


PLATE 41. Same sandstone without cement. The quartz grains are sutured and have silica overgrowths.
(x 28 nicols crossed)

distributed, and argillaceous matter though this is not common and never forms the sole cementing material of the rock. Illite has been found in X-ray diffractometer traces but kaolinite is more common and probably results from the decomposition of feldspars, whilst in one specimen from immediately below the Maulds Meaburn Limestone montmorillonite was discovered. Yellow or brown-orange limonite is invariably present in the sandstones as a product of weathering. It generally coats many of the quartz grains giving the sandstones their overall yellowish colour but, being a fine soft powder cannot be described as a true cement. It is frequently gathered together in small patches when it seems to be the result of the decomposition of areas of pyrite or iron-bearing carbonate.

c. ACCESSORIES

Mica.

Muscovite is present almost throughout the Yoredale sandstones and is especially concentrated on the bedding-planes of the thinly-laminated rocks. In diameter it averages about four times that of the accompanying quartz but occasional flakes up to ten times as large can be found. The muscovite is often stained purple-brown due to fine hematite, especially around mud-flakes which seem to be the main repositories of iron minerals in the sandstones. A few brown-green slightly pleochroic micas occur which seem to be altered biotite, whilst some pale-green micaceous material, often associated with thin clay-rich bands in the sandstone below the Great Strickland Limestone, appears to be authigenic and has, perhaps, some chlorite layers.

Fossils.

Shelly sandstones occur at many horizons but only as thin bands.

Complete fossils are uncommon but fragments of crinoids, brachiopods and lamellibranchs can often be recognised though usually only a mould now occurs, the carbonate having been dissolved by percolating solutions.

Many of the thinly laminated sandstones contain abundant plant debris amongst which leaves and stems can sometimes be recognised. In thicker-bedded sandstones the carbonaceous material is more broken and small grains are then quite common, though a few larger coal lenticles may be present. In additon, the upper parts of many of the sandstone bodies contain <u>in situ</u> roots but, because of the strong oxidation which has often occurred, usually only as faint traces.

Heavy minerals.

A few grains of zircon and rutile can be seen in most thin sections; garnet, tourmaline and hornblende are rarer. Very fine hematite of diagenetic origin gives the maroon colour to the reddened sandstones and occasionally occurs as tiny deep-purple crystals on quartz grains producing a local dark mottle which could be mistaken for carbon.

ii) <u>Textures</u>

The majority of the sandstones studied are very fine- to medium-grained on the Wentworth grade scale (1/16 to 1/2 mm.) of which the greater part are fine sandstones averaging 0.15 - 0.20 mm.diameter. Apart from the calcareous 'grit' horizon of the Maulds Meaburn Clastics, coarse sandstones are absent below the Grayber cycle. Above, except in the Newby Mill Clastics, some part of the strata between all of the limestones is coarse sandstone and often includes pebble-sized grains.

Quartz grains are generally sub-rounded with sub-angular particles predominating occasionally, although the degree of angularity may be accentuated by the corrosive effect of any carbonate cement. Sorting varies from good to poor but most rocks are quite well-sorted and it is only the coarser sandstones which show a really wide variation in particle size.

The framework grains have an approximately equant shape with the consequence that, except where there is an abundant carbonate or pyrite cement, porosity is generally high. Also, orientated textures are uncommon; mica flakes usually indicate the bedding-planes but in some of the more-massive sandstones it is scattered through the rock in many orientations probably as the result of the action of burrowing organisms. Plant debris sometimes has a discernable alignment on bedding-planes having its elongation parallel to the current direction, indicated in one case by the occurrence of ripples transverse to this direction on an adjacent bedding surface.

iii) Structures

a. MAJOR DEPOSITIONAL STRUCTURES

Slight compositional or textural differences which allow the form of depositional surfaces to be discerned are present throughout most of the sandstone bodies, although they often appear only when the rock has been strongly weathered. Essentially parallel-bedded units are restricted to some siltstones and very fine sandstones, except for a few of the thick sandstones which have approximately parallel widely-spaced major bedding-planes, apparently produced by pronounced periods of erosion.

Cross-laminations are characteristic of most horizons and their scale varies with the grain size of the rock. The very fine and some of the fine sandstones have small scale cross-lamination (Plate 42), or occasionally, very gentle wavy bedding resulting from rippling. Sometimes trough cross-laminations occur but usually a clear pattern is absent and in plan-view the bedding-surface has a series of irregular basins and swells as might be produced by rather variable gentle currents.

The thinly-laminated flaggy sandstones occur most commonly above the main shale member of the cyclothems and are followed by thick sandstones which often appear massive but when weathered can be seen to be bedded in medium- and large-sclae interfering lenticular units i.e. festoon cross-bedding (Plate 43). There are also a few units with fairly constantly dipping planar cross-laminations and some with small-scale cross-laminations, but the sandstone is characterised by having a very great variation in the direction of cross-bedded dips. These rocks are fine or medium-fine in grain size and it is only in the coarser sandstones that well-developed planar cross-bedding and large-scale troughs are common, although even in these irregular wavy and lenticular beds can be found. The coarser sand-stones have usually erosive contacts with neighbouring rocks and at any one locality the direction of dip of the cross-laminations is fairly con-stant. The Littlebeck Sandstone is the only one of the Middle Limestone Group sandstones in which these features can be clearly see but here, too, insufficient exposures occur to make a statistical study of the cross-bedding dip directions. There is however considerable evidence that it was largely deposited from currents flowing in a general easterly and south-easterly direction. A feature of several exposures of this sandstone are swarms of steeply dipping troughs together with sandstone lobes with divergent dips and having the same axial direction as the troughs.

PLATE 42. Small-scale cross-laminated sandstone at Scattergate Quarry.

PLATE 43. Large-scale irregular cross-bedding; the Littlebeck Sandstone in Newby Beck.

b. MINOR STRUCTURES

A few small-scale washouts with gently sloping sides and a large variety of smaller structures, most of which had a penecontemporaneous origin, are present in the sandstones. Those arenites which lie on soft argillaceous deposits always show an abundance of bottom-marks usually of irregular meandering form, which are largely loaded casts of markings made by worms and other small animals, and tubes due to the former can sometimes be found within the sandstones. Occasionally more regular sole-markings such as straight ridges, like groove casts, and lunate rill-marks are visibe on the underside of sandstones. Associated with the abundant trails and ripple-marks of the interbedded flaggy sandstones and shales are sometimes found small circular pits which have the appearance of having been punched through several laminations. They are unlike worm burrows and the material was probably too incompetent to preserve rain prints; rather, it is thought that they were produced by gas escaping, some time after deposition, from decomposing organic matter trapped in underlying mud.

A few examples of over-steepened bedding-planes are usually the result of slight slumping of sandstone where it rests on incompetent clay, sometimes producing nodule-like structures (Plate 44). Over-steepening can, however, also affect the thicker sandstones and produces very contorted bedding but only very rarely has slumping caused the detachment of lobes of sandstone.

PLATE 44. Nodule-like structures in fine-grained sandstone at Scattergate Quarry.

c. CHEMICAL REDISTRIBUTION

The cementing materials of the sandstones have sometimes undergone redistribution but, in general, changes have been at a minimum and accretionary structures are relatively uncommon. A few large carbonate concretions are present at some horizons but normally patches of carbonate cement remain small and poorly-defined. Layers of small brown-maroon nodules consisting of hematite in the process of hydration are frequently seen in the coarser sandstones and in a few ganisters. They often are hollow and it is likely that they have been derived from pyrite which, in some, remains in their cores, although some of the nodules in the ganister horizons are undoubtedly altered sphaerosiderite. Fresh pyrite, in places having cross-jointed columns with polygonal cross-sections, has been found in sandstone closely associated with thin coals and seems to have resulted from the molecular replacement of plant structures.

The most striking redistribution of materials is that which has occurred in some of the sandstones just below the New Red Sandstone unconformity. Here, iron has been oxidised to hematite and now occurs in patches, or locally as a remarkably regular series of maroon bands separated by white sandstone (Plate 9). The boundaries of the red layers, in which nearly all the quartz grains have received a thin coating of hematite, are not completely regular but are quite sharp and pronounced rhythmic deposition must have occurred.

iv) Classification

A useful classification which can be applied to the Yoredale sandstones

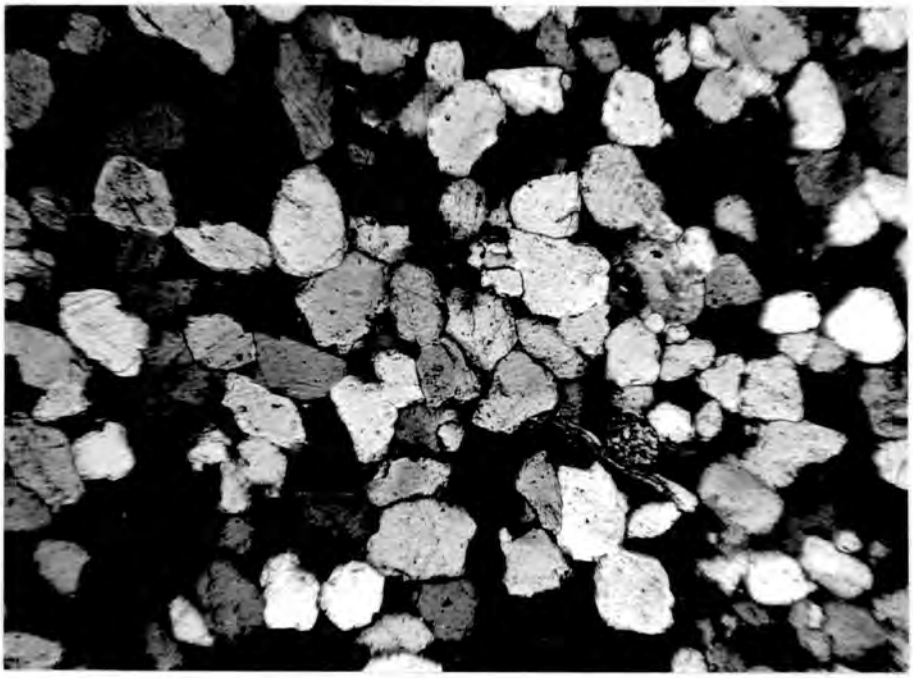


PLATE 45. Fine quartzarenite; Maulds Meaburn Edge sandstone member, Maulds Meaburn Moor. (x 28 nicols crossed)

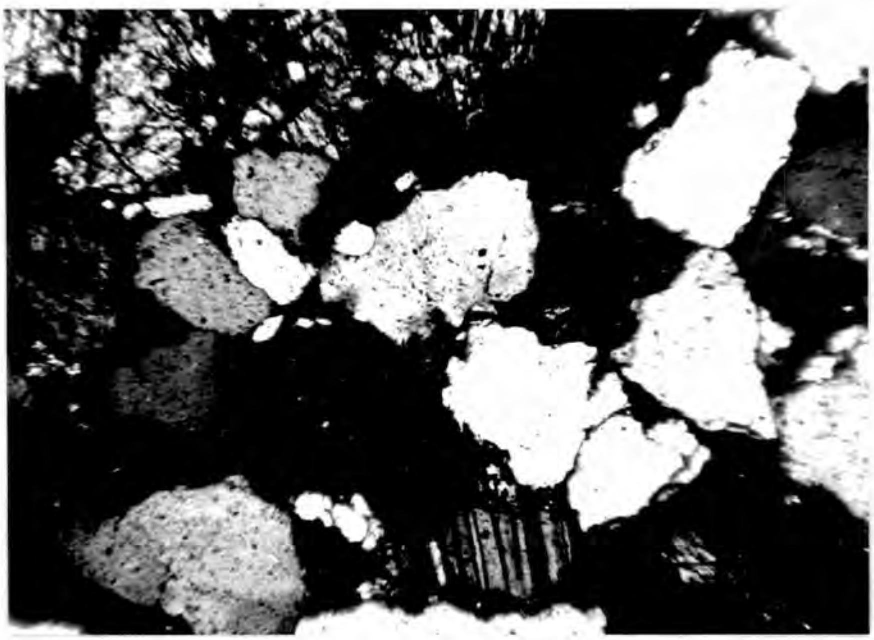


PLATE 46. Coarse subarkose; Grayber sandstone member, Lookingflatt. (x 28 nicols crossed)

is that of McBride (1963) (Fig. 3.5). The bulk of the sandstones examined consist largely of the most stable particles, having more than 95% quartz and so belong to the Quartzarenite group, of which fine quartzarenite (Plate 45) is the commonest. Although most of the rocks contain a little feldspar, it only occasionally exceeds 5% when the rock becomes a subarkose (Plate 46), and true arkoses are confined to a few coarse horizons in sandstones of the Upper Limestone Group. The other types of McBride's classification are not represented in the sandstones studied, except perhaps that some of the mud-flake-bearing rocks may be classed as sublitharenite, although strictly the mud-flakes were never true rock fragments.

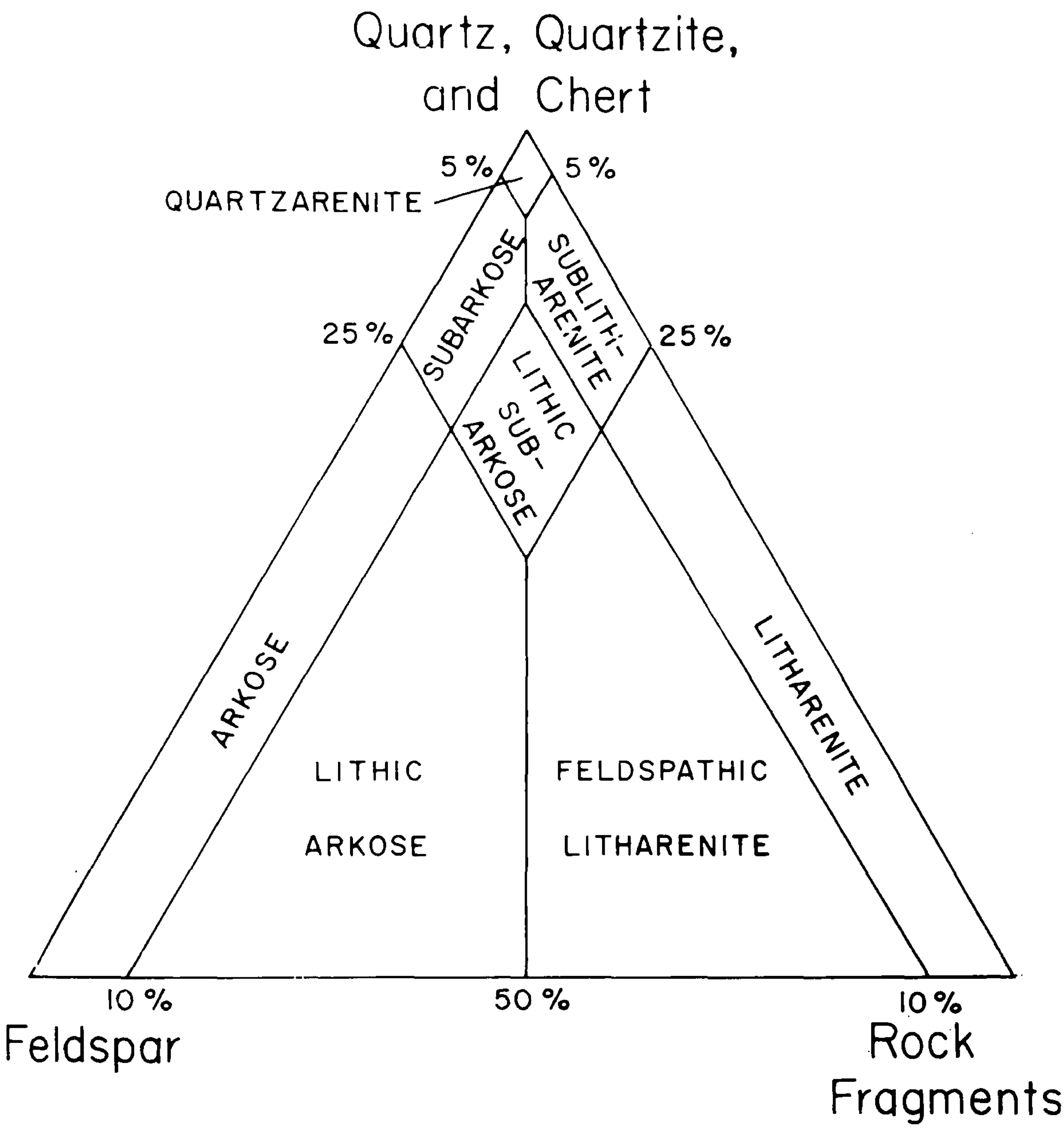


Figure 3.5

(after McBride 1963)

CHAPTER 4

ASPECTS OF THE MINERALOGY AND CHEMISTRY OF SOME TYPICAL STRATA OF YOREDALE FACIES

A. THE LITTLE STRICKLAND LIMESTONE

(A dark Yoredale Limestone)

i) Mineralogical variation through the Limestone

Diffractometer traces of a series of medium- to dark-grey limestone samples were prepared in order to study vertical changes in mineralogy. The central part of the Limestone was sampled at two localities (Fig.4.1) 3/4 mile apart and two additional rocks, representative of the basal and top part of the Limestone (C30LS and C31LS) were also examined. In thin section the rocks are similar in all important respects except for C31LS which is very impure, having 16% of detrital material and with bedding distinctly visible. The other rocks consist largely of varying proportions of shell and crinoid fragments and foraminifera set in a fine-grained matrix which is usually recrystallised to microspar but retains its 'dusty' appearance; dark fine pyrite dust, sometimes altering to brown oxides of iron, and a little quartz, can also be recognised in most specimens.

The results of the X-ray analyses are shown in Fig. 4.2 where, although the diffractometer was not calibrated for quantitative work, some indication of changes in abundance of the minerals is given, having been obtained by measuring the prinicpal peak heights; these were classed into one of seven arbitrary divisions ranging from absent to abundant.

As might be expected, relatively little variation in mineralogy occurs, especially if the samples from near the base and top of the Limestone are neglected. These have more quartz and pyrite than the central part of the Limestone but are otherwise similar. Carbonates, other than calcite, are subordinate; there is a very minor quantity of dolomite-ankerite which is evenly distributed through the Threaplands section but at Greenrigg is

Figure 4.1

LOCATION OF SAMPLES FROM THE LITTLE STRICKLAND LIMESTONE

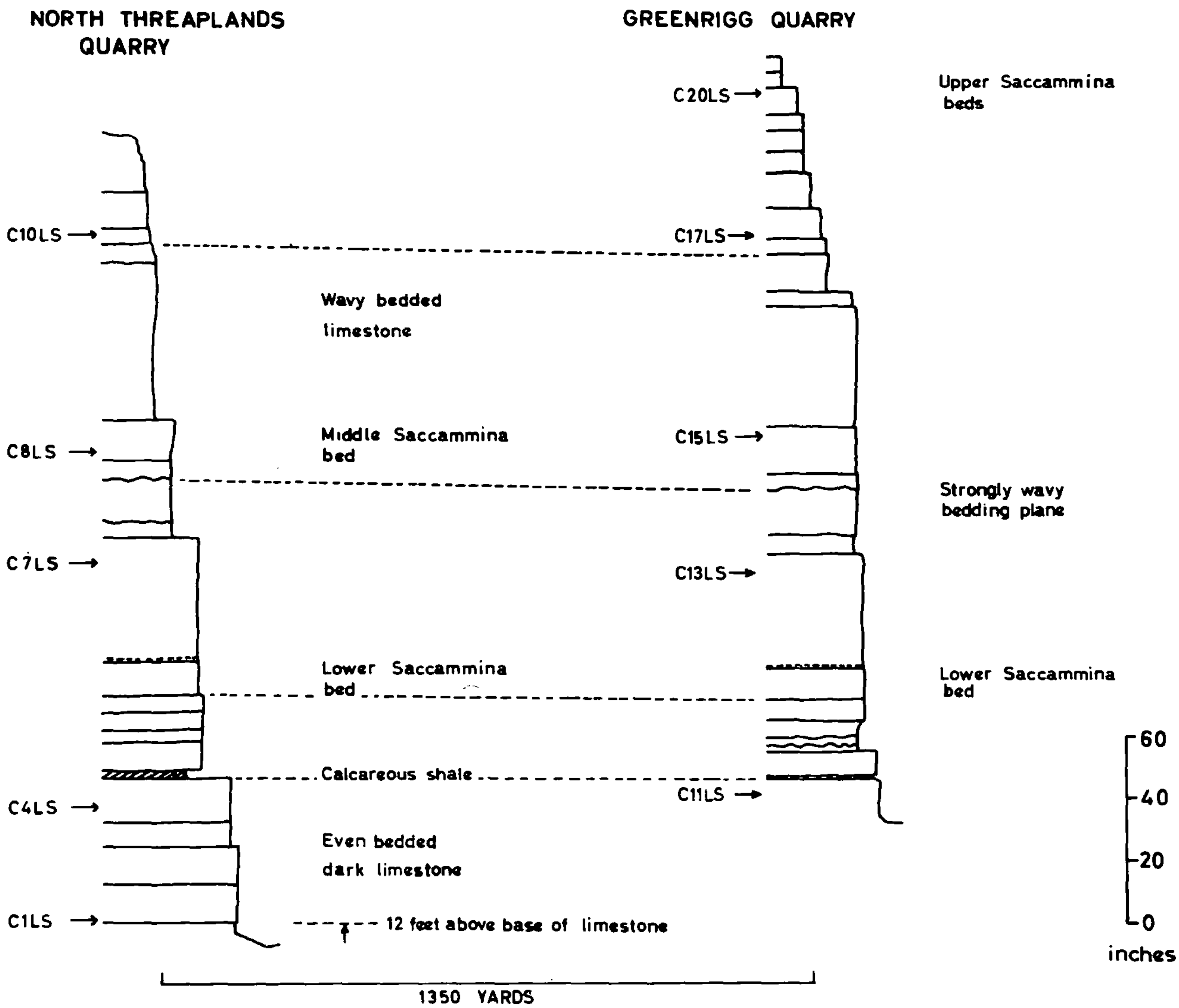
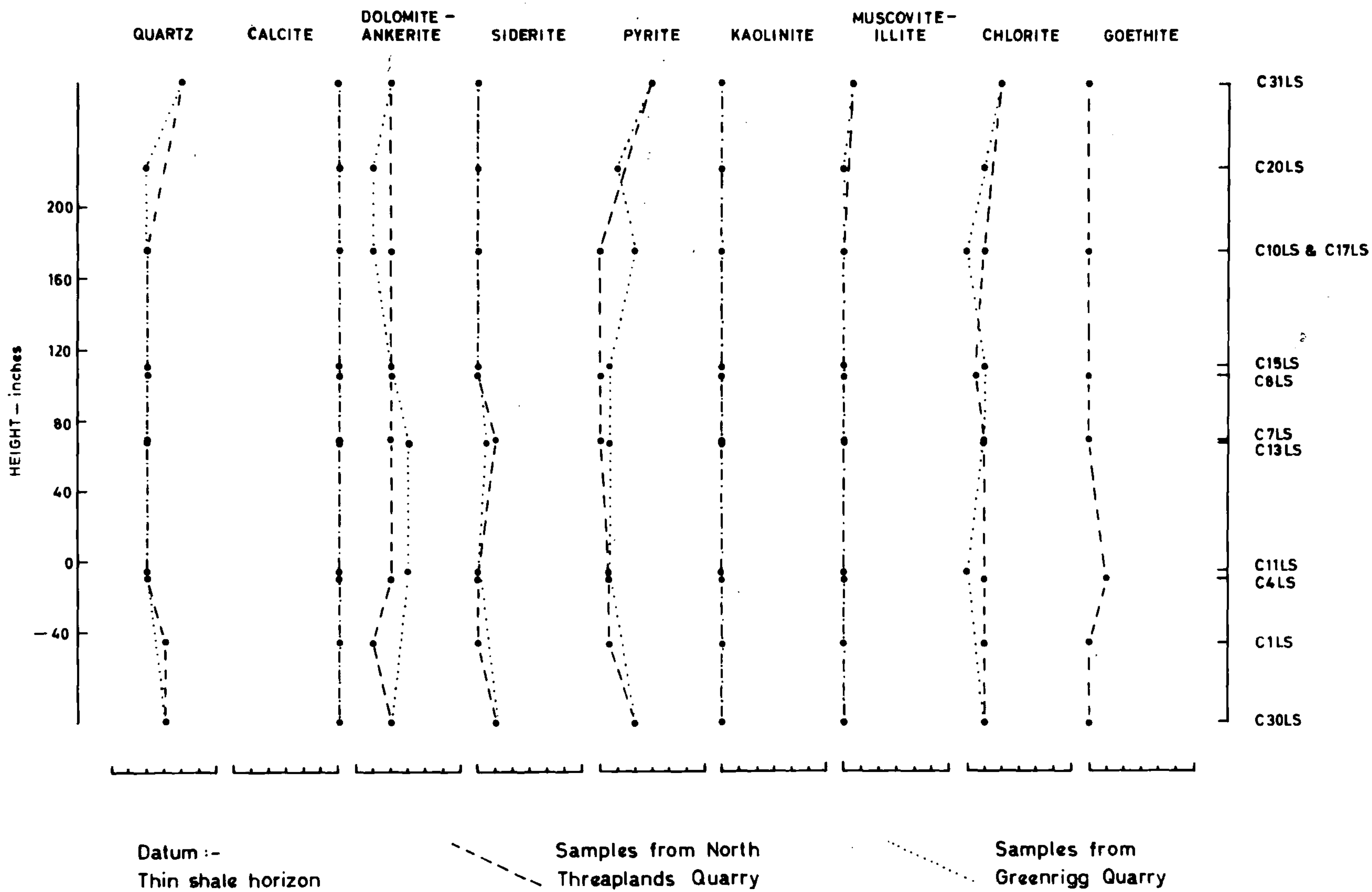


Figure 4.2

MINERAL VARIATION THROUGH THE LITTLE STRICKLAND LIMESTONE



concentrated in the lower part, possibly due to some redistribution; siderite is only found at the base and in one horizon near the middle.

Pyrite is present throughout, though only in very small quantities, but a good indication of its distribution has been obtained by dissolving the carbonates in dilute acetic acid and re-examining the detrital fraction (Table 9). A gradual upwards increase is detectable except for the C4LS-C11LS horizon, just below the thin calcareous shale, which is especially rich in pyrite (indeed, this can be seen in hand-specimens and is closely associated with algal traces as it is also in samples C8LS and C10LS). The Greenrigg samples contain consistently slightly less pyrite than those from Threaplands and rocks from closely comparable horizons, in two of the four cases, contain very similar quantities, so that on the whole the evidence supports the conclusion that the pyrite has not been redistributed and therefore that the detected variation represents primary differences in the composition of the calcareous mud. The rather large difference between samples C8LS and C15LS may be at least in part due to the fact that they differ in position with respect to bedding-planes; C15LS with least pyrite is immediately below one such plane in a position where independent evidence suggests that current action is often more pronounced (p. 141).

The clay minerals occur in too minor quantities to be properly studied and, apart from some illite in the argillaceous limestone C31LS, only chlorite has been recognised. When, however, the proportion of clays is greatly augmented by acid digestion of the carbonates, a little more information can be gained. In order that the clay minerals should remain unaltered, it is important that only very dilute acid is used to attack the carbonates (Ray, Gault and Dodd, 1957). In the present study, one volume of acetic acid was diluted with three volumes of water, producing

TABLE 9

Sample number	Pyrite 200 reflec--tion	Phosphate 211 reflec--tion	Sample number	Pyrite 200 reflec--tion	Phosphate 211 reflec--tion
C31LS	147	8			
			C20LS	186	43
C10LS	159	63	C17LS	145	62
C8LS	125	41	C15LS	73	58
C7LS	66	36	C13LS	58	35
C4LS	125	25	C11LS	88	13
C1LS	28	12			
C30LS	172	12			

Peak-height variation of Pyrite and Calcium Phosphate in the acid-insoluble fraction of the Little Strickland Limestone.

Samples 1 to 10 from Threaplands Quarry.

Samples 11 to 20 from Greenrigg Quarry.

Samples 30 & 31 from Threaplands Gill.

Heights of peaks in millimeters.

an acid which dissolves a high proportion of the carbonates and has a minimal effect on the clays, although the loss of most 14Å peaks suggests that the chlorites have been attacked.

Illite is the most abundant of the clay minerals in the Limestone but basal reflections, especially of the first order, are invariably very poor, several small peaks usually occurring in the range 10Å to 12Å. The illite, therefore, is both poorly crystallised and has a high proportion of longer spacing units in with the mica layers. A small amount of chlorite, also with some layers of different composition, is present throughout and a trace of kaolinite occurs locally towards the top.

X-ray examination of the detritial fraction also reveals minerals which are present in too small quantities to appear on the traces of the whole rock. A calcium phosphate is present in all of the samples and, with its main peak at 2.80Å, is of similar composition to the phosphate from the nodule shown in Table 8 and probably contains both fluoride and hydroxyl ions (i.e. of the type $Ca_5(PO_4)_3(OH,F)$). Like pyrite it gradually increases in abundance upwards through the central part of the limestone (Table 9), although it falls again in the Upper Saccammina Beds and contrasts with pyrite in being very low in the samples from the base and top of the Limestone. Some of the samples from approximately equivalent horizons have very similar abundances and there is no reason to believe that the phosphate had a primary distribution any different from that now found.

Also present in the detrital fraction is fluorite which, in the samples from Threaplands Quarry, increases in abundance upwards but falls in C10LS; the lowest two of the Greenrigg samples contain a small amount of this mineral but it is absent at higher levels. If the mineral is a primary precipitate, rapid changes in only a small lateral distance must have occurred; more likely is the alternative that it has been produced locally at a later stage. Graf (1962) suggests that some fluorite in limestones is due to the re-organisation of existing compounds. Sedimentary apatite group minerals take up fluorine from ground water after burial and release it later under different conditions to give calcium fluoride. Certainly the necessary phosphates do occur but the distribution of the two minerals is different so that extensive redistribution, probably of the fluorite, would be involved.

The small amount of feldspar, usually of alkali type, detected in most samples is also probably largely of secondary origin.

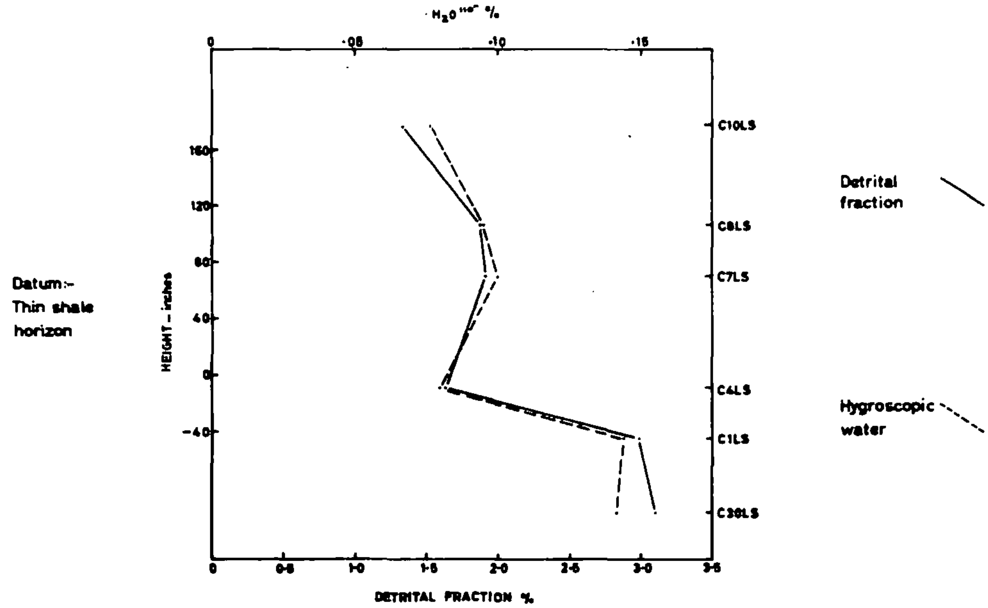
ii) Other compositional characteristics

a. ACID-INSOLUBLE FRACTION

The variation in the proportion of acid-insoluble material through the Limestone was determined by digestion of the rock in dilute acetic acid; the results are shown in Figs. 4.3 and 4.4. They do not give a completely accurate picture of the distribution of the detrital components both because they include sulphide and, more important, because the acid used was not always sufficiently strong to dissolve all of the magnesium- and iron-bearing carbonates so that varying amounts of these, especially of dolomite, remained in the residue. Through by far the greater part of the Limestone the variation is only between 3% and 1%, with an overall upwards decrease but with a rapid increase to 16% in the argillaceous top of the member (C31LS). Values for corresponding horizons at the two localities show only a moderate correlation although in both cases the upwards fall is broken by the especially pyrite-rich C4LS-C11LS

Figure 4.3

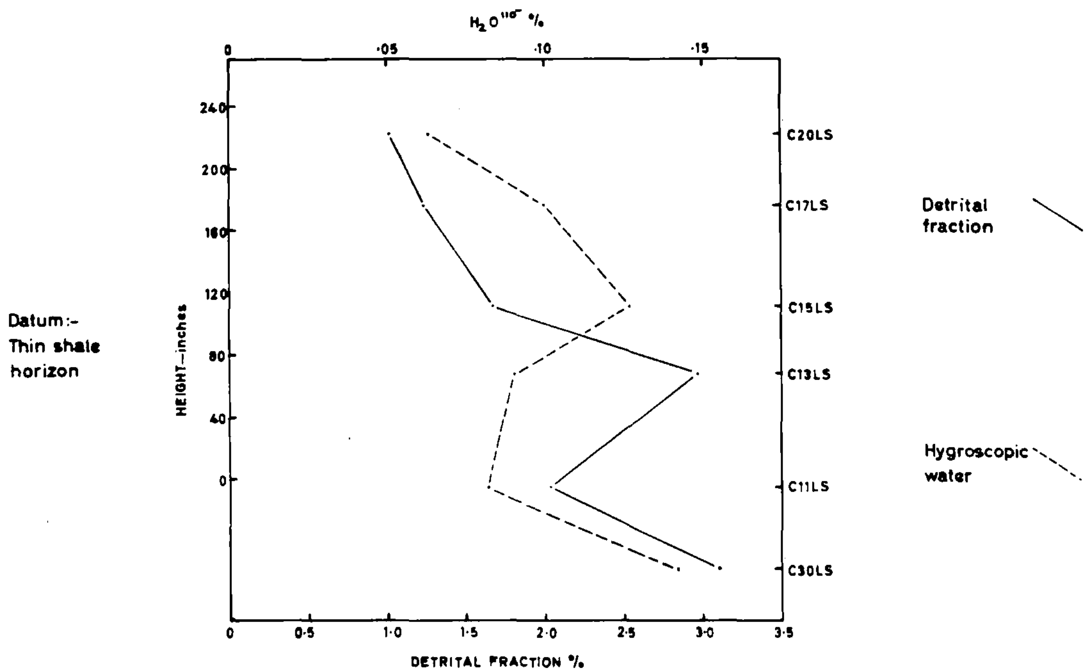
DETRITAL FRACTION AND HYGROSCOPIC WATER



LITTLE STRICKLAND LIMESTONE
AT
NORTH THREAPLANDS QUARRY

Figure 4.4

DETRITAL FRACTION AND HYGROSCOPIC WATER



LITTLE STRICKLAND LIMESTONE
AT
GREENRIGG QUARRY

horizon which has an unusually small amount of acid-insoluble material.

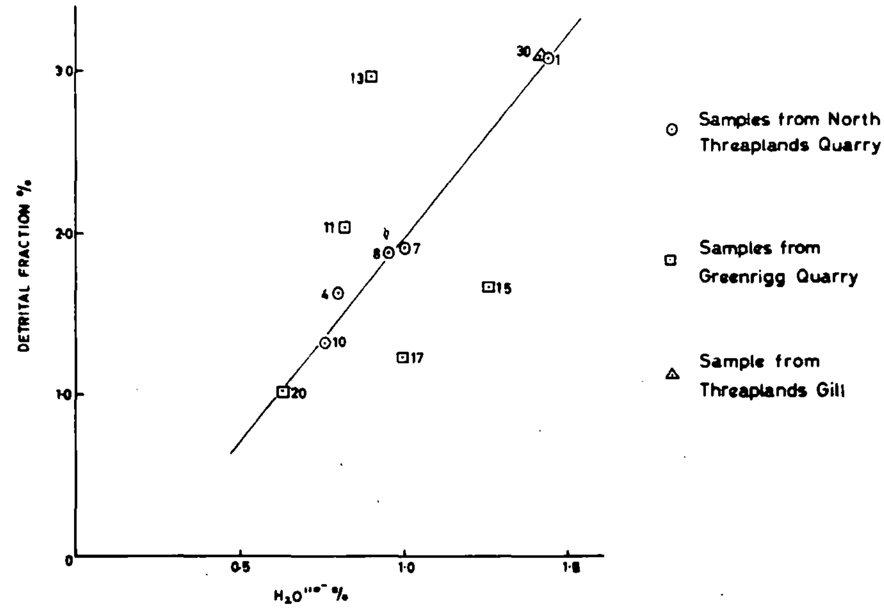
As an incidental result of the drying of the rock powders at 110°C the amount of hygroscopic water was determined (Figs. 4.3 and 4.4). In the Threaplands samples its distribution follows remarkably closely that of the detrital fraction but the correlation is much less strong in the Greenrigg samples (Fig. 4.5). Clearly the amount of hygroscopic water depends on the non-carbonate constituents, but it will vary according to the exact nature of these, probably being most abundant when organic material and some types of clay minerals are common.

b. ORGANIC CARBON CONTENT

The results of organic carbon analyses using the standard oxidation method involving the determination of total CO_2 and carbonate-derived CO_2 (Groves pp. 109-117) are shown in Fig. 4.6. Difficulty was experienced in obtaining reproducable results and the values given probably show no more than a general order of magnitude of the carbon content; for this reason the study was not further extended. Although the limestone often has a fairly dark colour the maximum carbon found is only 1.04% and the mean value is 0.36%. Both sections show an overall upwards decline in carbon content but correlation between comparable horizons is apparently poor. This is, perhaps, not surprising because slight variations in both pH conditions in the water and in the availability of organic matter with place and time are probable.

The colour of the samples varies between pale-medium- and dark-grey and it would, perhaps, be expected that this depended largely upon the organic carbon content. However, apart from C1LS which is the darkest rock and also the richest in carbon, there is no positive correlation

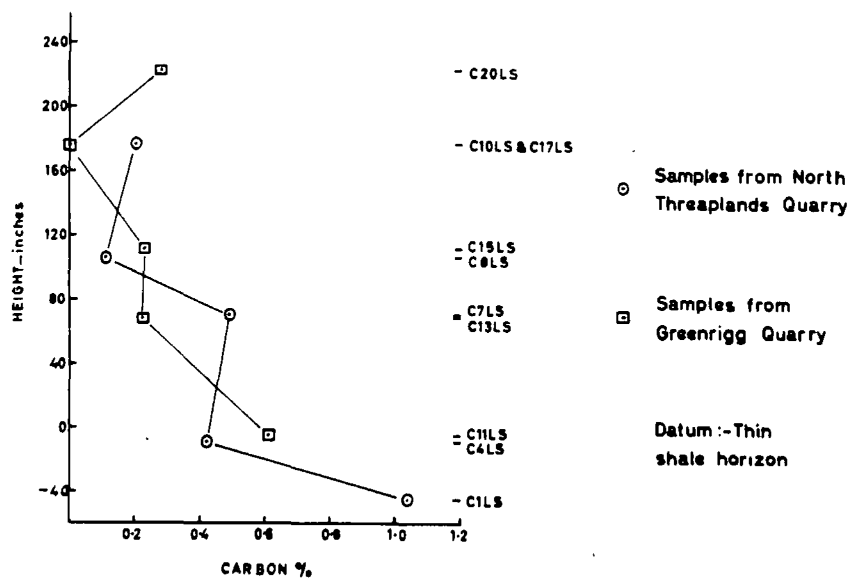
Figure 4.5



RELATIONSHIP BETWEEN CONTENTS OF
ACID-INSOLUBLE MATERIAL AND HYGROSCOPIC WATER
IN THE LITTLE STRICKLAND LIMESTONE

Figure 4.6

ORGANIC CARBON CONTENT



LITTLE STRICKLAND LIMESTONE

between the two; they do in fact sometimes vary inversely. Correlation with the pyrite content (Table 9) is much closer but this, too, fails in some samples. It is noticeable that the pyrite content frequently varies inversely with the organic carbon content. This is unusual in so far as pyrite is generally indicative of bottom conditions suitable for the anaerobic decomposition of organic matter and therefore for its preservation as carbon or carbon-bearing organic molecules in the rocks. The explanation is, perhaps, that the anaerobic conditions prevailing where pyrite is most abundant inhibited animal life and so greatly reduced the availability of suitable material such as the soft parts of corals, crinoids and brachiopods. The algal-bearing rocks (for example C10LS) and the Upper Saccammina Beds (C20LS) are exceptions and have appreciable quantities of both pyrite and carbon.

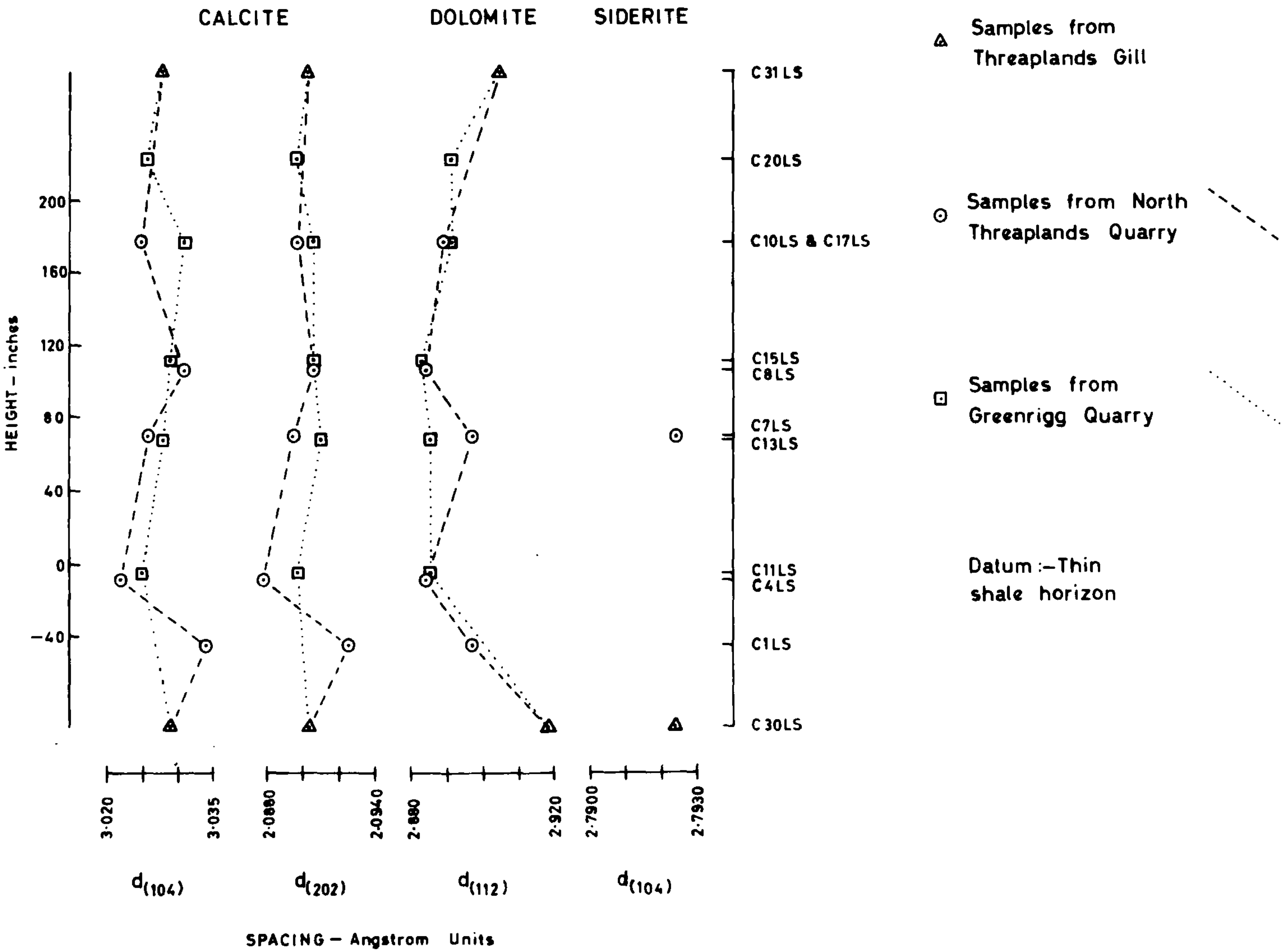
It may be concluded that the colour of the limestone does not depend exclusively upon any one component and that although it is related to the pyrite and carbon contents, much depends on their exact nature. Carbon is most likely to influence the rock colour if it is not combined in complex organic molecules or hydro-carbons and only very finely-divided pyrite is of dark colour.

c. CARBONATE MINERALOGY

Measurements of the position of the strongest X-ray powder diffraction lines for calcite, dolomite and siderite show that pure phases are not present (Fig. 4.7). Because of the substitution of ions of small radius (Fe, Mn, Mg) for calcium, clacite invariably has a smaller d_{104} value than the 3.035Å for the pure mineral and it can be as low as 3.022Å. No regular

Figure 4.7

VARIATION IN CARBONATE COMPOSITION THROUGH THE LITTLE STRICKLAND LIMESTONE



variation through the Limestone occurs but that the changes are genuine is shown by the similar variation of other lines, as for example d_{202} illustrated in the Figure. Correlation between similar horizons at the two localities is poor and undoubtedly considerable changes in composition must occur over short vertical, and probably horizontal, distances.

Neither is there any steady variation in the dolomite compositions, all of which must contain some iron substituting for magnesium, especially in the samples from near the base and top of the member which have ankerite rather than dolomite. Substitution of manganese for magnesium will also increase the d_{112} value, and to a greater extent since the Mn^{++} ion (0.91kX) is slightly larger than the Fe^{++} ion (0.83kX). In contrast to the calcite results, the spacings of the dolomites from comparable horizons are closely similar except for the samples C7LS and C13LS. Here, at Threaplands an excess of iron appears to have been available, for not only is d_{112} of the dolomite greatly increased but also siderite occurs as a separate phase. This mineral has only been detected elsewhere at the base of the Limestone, again in association with an unusually large d_{112} spacing of the dolomite. In both cases, the siderite has a d_{104} spacing much greater than that for the pure mineral and some substitution of manganese and/or calcium is indicated.

iii) Trace element distribution

Using an X-ray spectrograph, the content of nine trace elements has been investigated, although of these zirconium, rubidium, zinc and cobalt lie below the detection limit in most samples, whilst lead is always close to this limit and its apparent variation will not be discussed. Table 10 shows the abundances of the elements and Figs. 4.8 and 4.9 illustrate the variation graphically.

TABLE 10

	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
	Trace element content in parts per million*							
C31LS	3279	20	37	-	30	52	(7)	1241
C20LS	2296	-	28	-	22	21	-	281
C17LS	3134	-	(22)	-	23	22	-	201
C10LS	3128	-	31	(7)	23	23	-	249
C15LS	2509	-	-	-	25	24	-	233
C8LS	2779	-	(25)	-	26	22	-	168
C7LS	1944	-	28	-	21	23	-	197
C13LS	1933	-	28	-	26	26	-	249
C11LS	3595	-	-	-	25	26	-	216
C4LS	3144	-	-	-	25	30	-	197
C1LS	3573	-	31	-	26	22	-	195
C30LS	2431	-	-	-	25	25	-	354
MEAN**	2770	-	(23)	-	24	24	-	231

The trace element content of samples from the Little Strickland Limestone.

( ) values close to the detection limit.

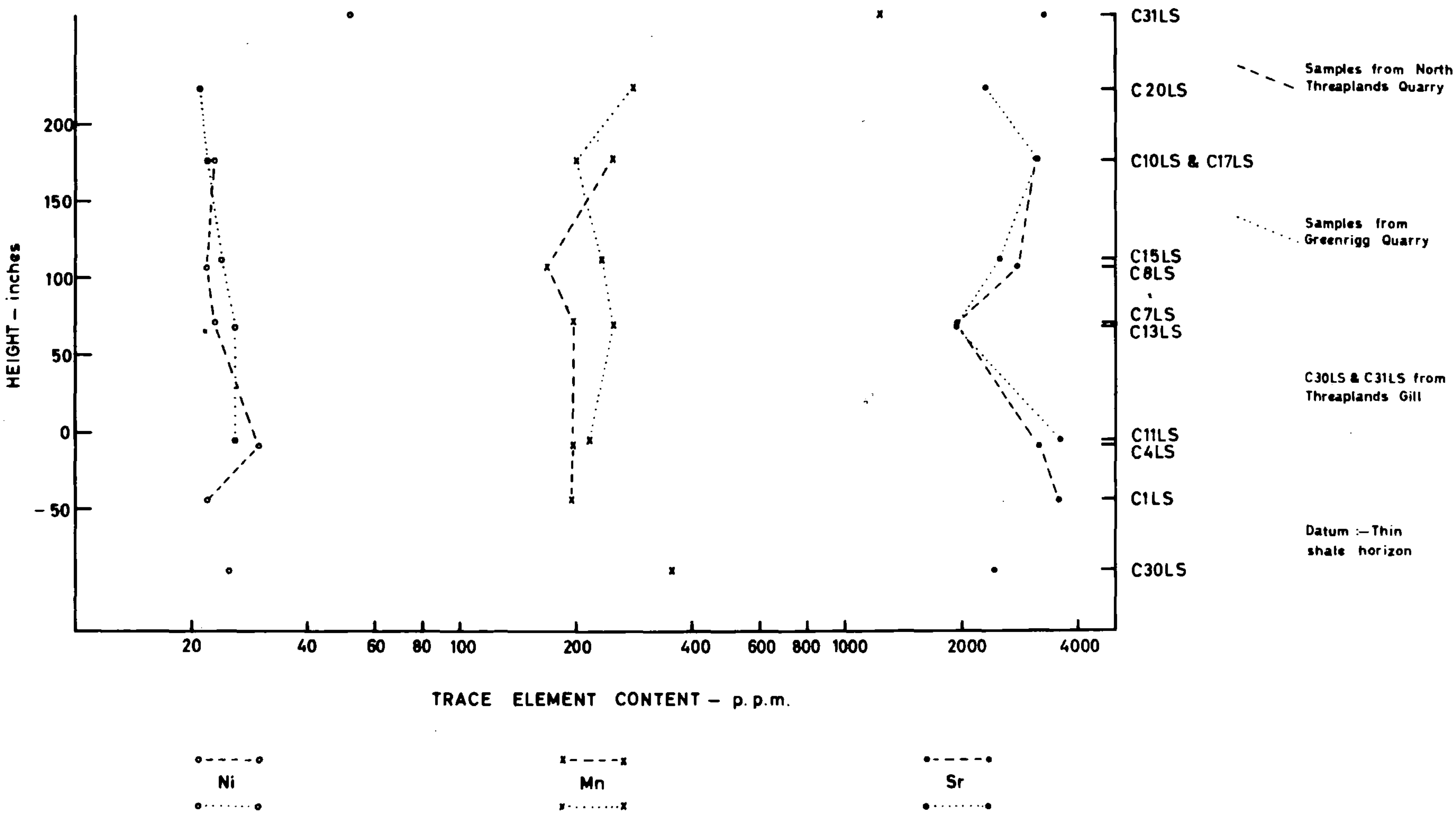
\- values below the detection limit.

* Because of the presence of Cu and Ni impurities in the X-ray tube, the values for these elements are too high (perhaps by up to 50%); the variation is unaffected. This applies to all of the Cu and Ni values reported.

** The mean value excludes the argillaceous limestone, C31LS.

Figure 4.8

VARIATION IN MANGANESE, NICKEL AND STRONTIUM THROUGH THE LITTLE STRICKLAND LIMESTONE



a. STRONTIUM

Strontium, with a mean abundance of 2770 ppm. in this Limestone, is by far the most common of the trace elements investigated and shows a marked though irregular variation from 1933 ppm. to 3595 ppm. A particularly interesting feature is the close similarity in shape between the curves for the two localities and especially the essentially identical contents of two of the horizons which were sampled at both quarries. These facts strongly suggest that the strontium contents remain practically as they were at deposition. If ground water had caused any changes a more regular variation would be expected and it is extremely doubtful if such closely similar distribution patterns would then be found at both localities. Any mechanism of pene-contemporaneous redistribution in the soft sediment on the sea floor which would produce the present pattern is also difficult to imagine.

The significance of this variation is difficult to assess owing in part to lack of knowledge as to the location of the strontium. Its distribution does not fit closely with that of any of the detected minerals and it is almost certain that it is related closely to the primary nature of the calcium carbonate. This is now entirely calcite but initially there must have been a large proportion of aragonite which would invert to calcite early in the history of the sediment. Strontium, because of its large ionic radius (Sr^{++} 1.27kX; Ca^{++} 1.06kX), can more easily be taken into the orthorhombic rather than the trigonal lattice, and in calcite rarely exceeds 610 ppm. (Turekian and Kulp, 1956).

The very high mean abundance of strontium in the Little Strickland Limestone, which compares with a figure of 475 ± 50 ppm. for the average carbonate (Ingerson, 1962), can therefore be most satisfactorily explained by postulating that much of the initial calcium carbonate was in the form of aragonite, occurring both as a fine precipitate and in the shells of organisms. By far the greater part of the fossils, namely, the crinoid ossicles, the foraminifera and the brachiopod shell fragments, are formed of calcite (Chave 1954); only some corals, bryozoa and mollusc shells would contribute any aragonite and they are all quantitatively of minor importance at most horizons. Consequently primary precipitated aragonite mud is thought to be the main source of the strontium. Analyses of aragonite shown in Deer, Howie and Zussman (1962, Vol.5, p.307) indicate that strontium contents of the order of 0.3% to 0.4% are not uncommon in this mineral. Upon inversion to calcite, much of the strontium must be released and its fate is unknown but there is no doubt that in this case most, at least, has undergone very little redistribution. Presumably it occurs as scattered crystals of strontianite or celestite although they are not sufficiently abundant to appear on the X-ray diffractometer traces.

The strontium variation can, then, be largely attributed to differences either in the initial proportion of aragonite mud in the samples or in the amount of strontium present in a reasonably constant amount of this material. In so far as the latter possibility is concerned, as stated by Turekian (1955), this will to a large extent depend on such factors as temperature, salinity and the Sr/Ca ratio in the liquid phase from which the solids have been derived. Odum (1951) has shown that the latter are directly related, so that variations in the strontium content of the sea would produce the desired effect. This would account for the close similarity between the strontium distributions at the two localities but it is very doubtful whether these factors could change sufficiently in the open-sea conditions which prevailed to cause, in this way, the very marked variation detected. Rather, it seems that differences in the amount of aragonite mud must be responsible, and this could be produced in two ways:-

1. Dilution of a precipitate of aragonite mud with varying quantities of organic debris (due to changes in the rate of supply, by currents, of either).
2. Different amounts of both calcite and aragonite mud deposited at different times (and again diluted with varying quantities of organic debris).

No quantitative measurements have been made but inspection of thin-sections is sufficient to show that the strontium distribution cannot be explained by variations in the amount of aragonite mud and organic debris alone. Although, for example, most samples appear to have rather similar amounts of mud, at the C10LS-C17LS horizon there is a particular concentration of fossils and, consequently, much less mud. It would be expected, therefore, that the strontium content would here be at a minimum (the fossils are not principally those with primary aragonitic shells), whereas in fact it is much higher than average. The close similarity in strontium content of comparable horizons at the two localities also does not support this first alternative, since the chances of approximately equal amounts of debris being incorporated into the calcareous ooze in different places must be small.

It appears, therefore, that the strontium distribution can best be explained by postulating that, with time, differing amounts of strontium-rich aragonite mud and strontium-poor calcite mud were deposited together. At any one time the proportion remained constant over a considerable area (and also, in view of the fact that exactly time-equivalent horizons were not sampled, it probably varied only relatively slowly with time), with differences in the strontium content then due to differing admixtures of organic material.

According to Cloud (1962) aragonite, although the unstable polymorph at atmospheric temperatures and pressures, is precipitated in the sea in preference to calcite when there is high apparent supersaturation of calcium carbonate. This appearance of the more soluble higher energy form is consistent with Ostwald's rule of successive reactions:-

> The release of solid polymorphs from an unstable solution takes place stepwise, from the least to the most stable solid form that can precipitate from a given initial concentration.

Only calcite, therefore, should form when the concentration has dropped to levels between the saturation points for the two minerals, but it is probable that the reaction can be retarded at metastable levels due to the existence of entropy barriers (Cloud, op.cit.), with the result that aragonite precipitates indefinitely. Factors which promote supersaturation such as increasing temperature and pH, as well as a high salinity, will therefore favour the precipitation of a maximum amount of aragonite and the variation in the strontium content may well be a record of the fluctuation in these factors with time. It is not at this stage possible to evaluate their relative importance but it is felt that the open-sea conditions suggest the probability of only minor salinity and pH variations so that temperature changes may have had the main influence. Of course, overall changes in air temperature are not necessarily implied; it is the temperature of the water which is significant and, given restricted circulation at some places, this could vary considerably in the same body of water.

An interesting feature of the strontium distribution is that, with the exception of C30LS at the base, the parallel-bedded limestones (C1, 4, 10, 11, 17 and 31LS) all contain much more strontium than do the wavy-bedded limestones (C7, 8, 13, 15 and 20LS). Perhaps, then, aragonite precipitation tended to predominate over that of calcite in the less disturbed (and possibly shallower, more cut-off) lower energy environments (page 218), conditions where, indeed, supersaturation is most likely to be achieved and to persist. It is also noticeable that these even-bedded, strontium-rich limestones invariably have a more recrystallised matrix than the wavy-bedded rocks, which is precisely what would be expected if, as is thought, they had a greater proportion of aragonite on deposition since the inversion will involve the production of relatively large crystals of calcite; the primary calcite mud, on the other hand, is able to remain in the same fine form in which it was precipitated.

b. MANGANESE

Manganese is the next most abundant trace element but shows relatively little variation through the major part of the Limestone; it reaches a maximum value of 281 ppm. in the Upper Saccammina Beds. It is considerably more abundant in the samples from near the base and top of the Limestone, especially in the latter which has 1241 ppm. Comparable horizons at the two localities have rather different quantities, the samples from Greenrigg generally containing more of this element than those from Threaplands. In the case of the former, there is a distinct inverse relationship between manganese and strontium.

Although the distribution of manganese cannot be related to that of any of the minerals present, it must, like strontium, be largely associated with the carbonate fraction. It will be located partly in the dolomite-ankerite, probably occupying the Mg-Fe sites in the lattice, and partly in any siderite present, the latter mineral probably accounting for the high content in C30LS. Because, however, it is not closely related in abundance to that of these two minerals, it must also occur in the calcite and probably accounts to a large extent for the relatively short spacing of d_{104} for this mineral; being of larger size than Fe^{++} and Mg^{++}, it will substitute in the calcite lattice more easily than either of these two ions. The cause of the very high content in the argillaceous limestone, C31LS, is unknown though it is possible that small quantities of a manganese sulphide are present.

c. NICKEL

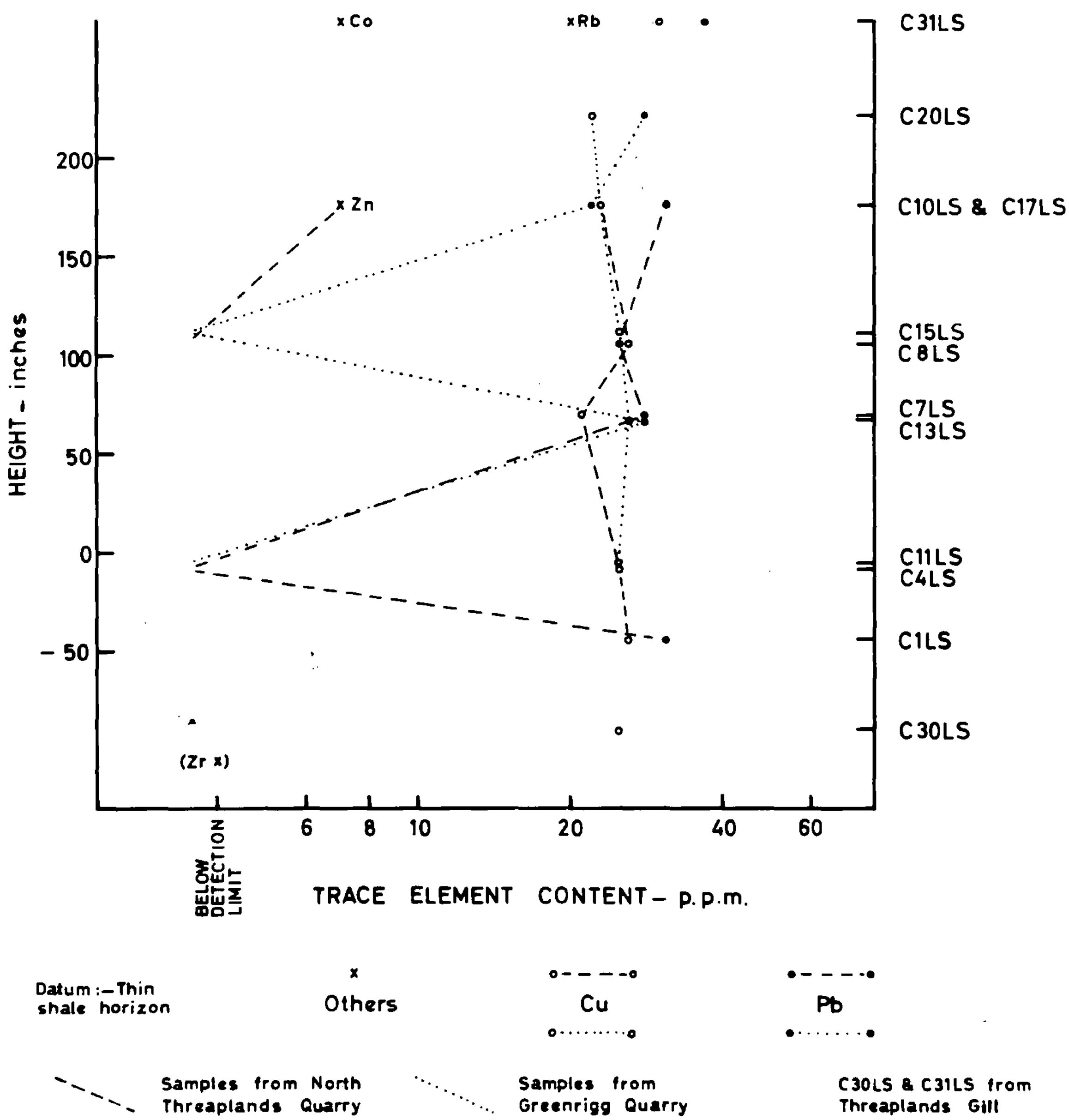
Only very small quantities of nickel are present and there is little variation; the mean value of 24 ppm. is high due to X-ray tube impurity (see footnote to Table 10) and the true value is probably close to the 9 ppm. given by Ingerson (1962) as the mean abundance of limestones. The location of the nickel is unknown; it may substitute for Ca, Mg and Fe in the carbonates but also probably occurs in the clay fraction which would partially account for its considerably greater abundance in the argillaceous limestone. This rock contains unusually large amounts of manganese and strontium as well as of nickel and it appears that it must have been deposited in a situation where larger than normal quantities of trace elements were liable to be removed from solution.

d. COPPER

Copper remains essentially constant throughout the Limestone and has a mean value which is again too high (see above, under nickel) though it is close to the figure of 20.2 ppm. given by Rankama and Sahama (1950) for limestones. The ionic radius of Cu^{++} is 0.83kX which is the same as

Figure 4.9

VARIATION IN COPPER AND LEAD THROUGH THE LITTLE STRICKLAND LIMESTONE



that of Fe^{++} so that it may be associated with iron in the carbonates but also occurs in the clays with the result that there is a slightly higher content in the argillaceous limestone. The constancy of the copper content throughout the Limestone may be due either to there having been a limited supply of this element or to the inability of the minerals to take up greater quantities.

Rubidium and cobalt have only been detected in the argillaceous limestone and zinc only occurs in measurable amounts in C10LS.

B. THE GREAT STRICKLAND LIMESTONE

(A pale Yoredale Limestone)

Samples of the Great Strickland Limestone were studied primarily in connection with the alteration under the New Red Sandstone unconformity, but a comparison of a relatively fresh series of samples from this Limestone with the Little Strickland Limestone is useful. It differs from the latter essentially in being much paler in colour (pale to pale-medium grey) and wavy-bedded through the greater part of its thickness. However, because it is always quite close to the unconformity, it has undergone much more alteration than has the Little Strickland Limestone and this fact must be continually borne in mind. The alteration is only strong at the base where a reddened and dolomitised zone, of which C1G is an example, occurs. Upwards there has been, at least in appearance, little change; a few maroon flecks are present and occasional calcite veins can be found. Dolomitisation is largely restricted to limestone adjacent to bedding-planes, when scattered rhombs may be seen in thin section, but basically this Limestone has the same constituents as the Little Strickland Limestone, namely, foraminifera, crinoid ossicles and shell fragments set in a matrix of partially recrystallised ooze. The location of the samples of the minimally-altered rock, collected at Jackdaws' Scar, is shown in Fig. 5.1.

i) Mineralogy

The mineral content (Fig. 5.2) is very similar to that of the Little Strickland Limestone when the effects of alteration, such as the relatively high dolomite-ankerite contents of the C1G and C7G horizons, are discounted.

Small quantities of chlorite occur throughout, kaolinite is only very doubtfully present and the most abundant clay mineral seems again to be a poorly-crystallised illite with much mixed-layering. A trace of feldspar has been locally recognised and, again, phosphate occurs throughout but here has an irregular distribution. The most important difference between the two Limestones is in the almost complete absence of pyrite from the Great Strickland Limestone. It is unlikely that its absence is due to oxidation since, except at the base, neither goethite nor hematite are any more abundant than in the Little Strickland Limestone. Rather, it is thought that pyrite was rarely deposited with this Limestone and that its absence accounts for its having a predominantly paler colour than the Little Strickland Limestone, although less organic carbon may be a contributory factor.

The mean value for the acid-insoluble fraction of the Great Strickland Limestone is 2.21% which compares with 1.97% for the older Limestone. However, because of the much larger quantity of undissolved dolomite-ankerite in the detrital fraction from the former, no significance can be attributed to these figures. If all of the carbonates were dissolved it is probable that the residue would be less than 1% in the Great Strickland Limestone and, perhaps, nearer $1\frac{1}{2}\%$ in the Little Strickland Limestone; because a stronger acid would attack the clays it is impossible to determine these quantities accurately.

The variations in the d_{104} and d_{202} spacings of calcite (Fig. 5.3) is less than that found in the Little Strickland Limestone and the mineral is generally less pure. Both differences may be due to reorganisation caused by solutions associated with the New Red Sandstone land surface; manganese and iron have probably been added and there may have been a tendency to even out compositional differences. The dolomite, which seems to have few foreign ions, also varies less in composition than does that in the Little Strickland Limestone and probably for the same reason. The parallelism between the calcite and dolomite curves is such that as the calcite becomes more pure the dolomite becomes less so and vice-versa; transfer of iron and manganese ions between the two minerals seems to be indicated.

ii) Trace elements

Zirconium, rubidium, zinc and cobalt occur in amounts which do not exceed their respective limits of detection. The mean abundances of the other elements in the two Limestones are compared in Table 11 (below) from which C1G is excluded because of its greater alteration. Their variation in the Great Strickland Limestone is shown in Figs. 5.4, 5.5 and 5.6 as well as in Table 18.

TABLE 11

Trace element content in parts per million

	Sr	Pb	Cu	Ni	Mn
Little Strickland Limestone	2770	(23)	24	24	231
Great Strickland Limestone	1034	(20)	27	22	467
Maulds Meaburn Limestone	1632	31	30	23	355

Mean abundances of trace elements in some Yoredale Limestones

a. STRONTIUM

The mean strontium content (Table 11) is only 38% of that in the Little Strickland Limestone and the amount of variation is much less. The very low content in the reddened sample from near the base (360 ppm., Table 18) shows that the alteration was effective in removing much of the original strontium and, to a lesser extent, the values for the fresher higher part of the Limestone will also be lower than they were at the time of deposition. It is very unlikely, however, that the original abundance was ever as great as that in the Little Strickland Limestone because the variation does not fit with the distribution of dolomite-ankerite (Fig. 5.2) which can reasonalby be taken as a measure of the effectiveness of the percolating solutions in causing compositional changes. In particular C2G, in spite of containing considerable dolomite, has the highest strontium content and this decreases upwards through C6G to C7G even although the dolomite content first decreases and then increases. Thus, although no great significance can be placed on the present strontium variation because of subsequent changes, probably leading to an equalisation in the strontium contents, it is almost certain that the Great Strickland Limestone contained initially less than did the Little Strickland Limestone. If the reasoning in the previous section (pages 167 to 171) is correct, then the difference is probably due to the deposition of more equal amounts of calcite and aragonite mud in this Limestone, rather than the strong predominance of aragonite which characterised the Little Strickland Limestone.

b. MANGANESE

The mean abundance of manganese (Table 11) in the Great Strickland Limestone is double that in the Little Strickland Limestone and its variation is much greater. There can be no doubt that this results from the fact that the Great Strickland Limestone contains much more dolomite-ankerite, since there is a close similarity between the two curves and, in particular, the reddened lower part (C1G) is very rich in both dolomite and manganese. The only horizon which does not fit this pattern is C2G which would be expected to have about 50 ppm. more manganese from its dolomite content; this may be partly due to the fact that it is on the margin of the upper limit of reddening where chemical imbalance is probably most likely to occur. Manganese, perhaps of the order of 200 ppm., has therefore been added to the rock along with the magnesium and iron during the changes which brought about minor dolomitisation.

It is interesting that the inverse relationship with strontium, recognised in the Greenrigg samples, still occurs (Fig. 5.4). This is in spite of the fact that the variation of both elements in this Limestone is now the result, in part, of processes of redistribution, and the reason for this behaviour is unknown. It cannot be solely the result of the close association of strontium with calcium carbonate and of manganese with the iron- and magnesium-bearing carbonates, because neither the positive correlation of manganese, nor the negative correlation of strontium, with dolomite-ankerite is, in detail, sufficiently strong. It is, therefore, tentatively suggested that the inverse relationship is partially due to the fact that both elements can occupy sites in one mineral, in this case presumably in calcite, and that the inclusion of one tends to cause the exclusion of the other. This seems very likely because the ionic radii of Sr^{++} and Mn^{++} (1.27 kX and 0.91 kX respectively) lie on either side of that of Ca^{++} (1.06 kX). The initial inclusion of, say, strontium ions in the calcite would so expand the lattice that it would be less able to accommodate the small manganese ions. Thus, where the fine calcite results largely from inversion of aragonite and probably contains much strontium, there will be less chance of manganese inclusion, but where greater quantities of strontium-poor calcite mud were precipitated the possibilities for the taking up of manganese (both contemporaneously and subsequently) will be multiplied.

c. OTHER TRACE ELEMENTS

Nickel and Copper

These elements are essentially constant throughout the Limestone and their mean abundances do not differ significantly from those in the Little Strickland Limestone.

Of the remaining elements, lead (Fig. 5.5) appears to decrease slightly in abundance upwards, but it has essentially the same mean value as in the Little Strickland Limestone (Table 11). The rubidium and cobalt contents (Fig. 5.6) lie below their respective detection limits except in the reddened horizon C1G, but even this has only very minor quantities (Table 18).

C. THE MAULDS MEABURN LIMESTONE

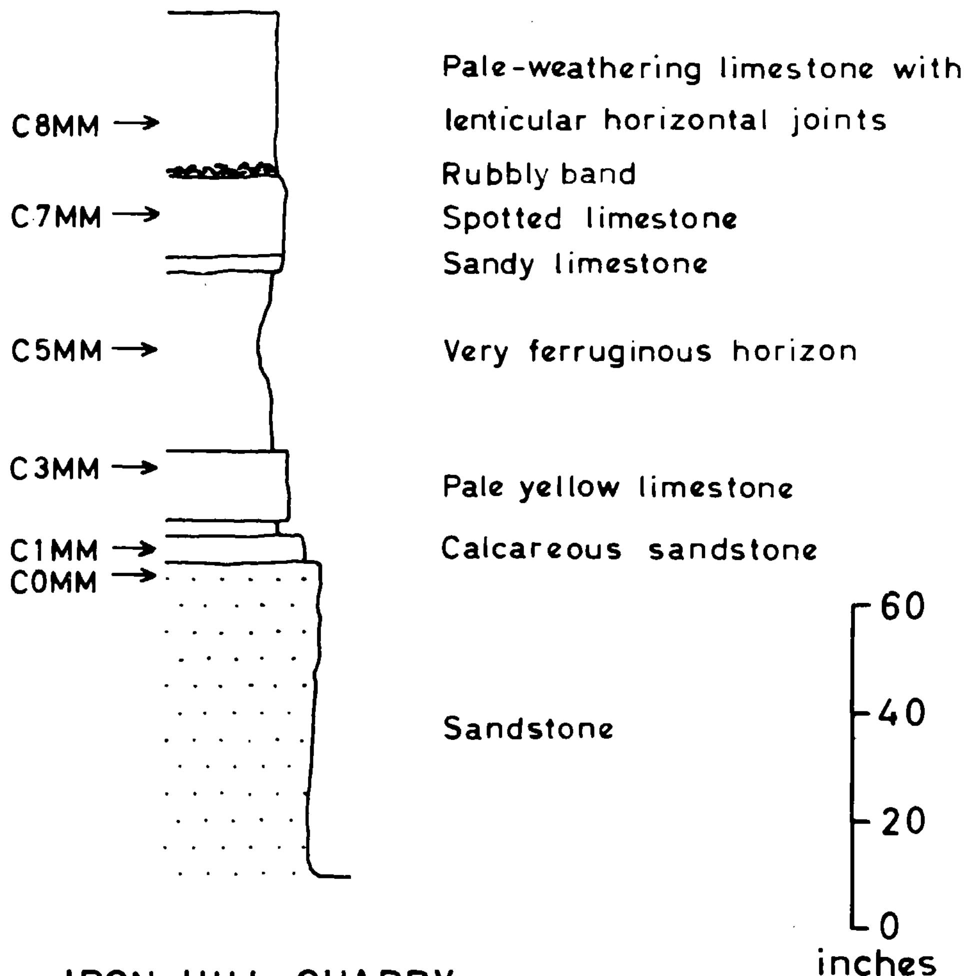
The succession from the top of the Bank Moor Cyclothem sandstone member through to the pale-weathering lower part of the Maulds Meaburn Limestone has been studied with a view to elucidating the changes which occur during this major facies transition (Fig. 4.10 and Plate 47). The lowest horizon, COMM, is a fine-grained slighly micaceous sandstone and is overlain by a calcareous sandstone with a few fossils, C1MM, which has 33% of acid-soluble material. The four higher samples are representative of the basal part of the Maulds Meaburn Limestone which always contains a strongly ferruginous-weathering zone, here about 2'6" above the base (C5MM) though more frequently immediately following the calcareous sandstone. C5MM consists of shells and crinoid fragments together with small angular quartz grains, set in a mosaic of largely irregular but sometimes rhomb-shaped iron-bearing carbonate crystals which have been partially oxidised to goethite. Of the remaining samples, only C7MM is a normal very fossiliferous micrite; C3MM is unusual in containing some sparry calcite which seems primary, whilst C8MM has been affected by intense recrystallisation which has caused a strong irregular pale- and medium-grey and ferruginous mottle.

i) Mineralogical variation

Inevitably, because of the major facies transition, mineral variation is considerable, but even without the quartz-rich beds at the base important changes are present (Fig. 4.11). The most striking variation is in the carbonates; calcite, absent in the sandstone which only contains carbonates rich in magnesium and iron, appears in abundance immediately above the bedding-plane at its top, and dolomite-ankerite although present in very

Figure 4.10

LOCATION OF SAMPLES FROM THE MAULDS MEABURN LIMESTONE



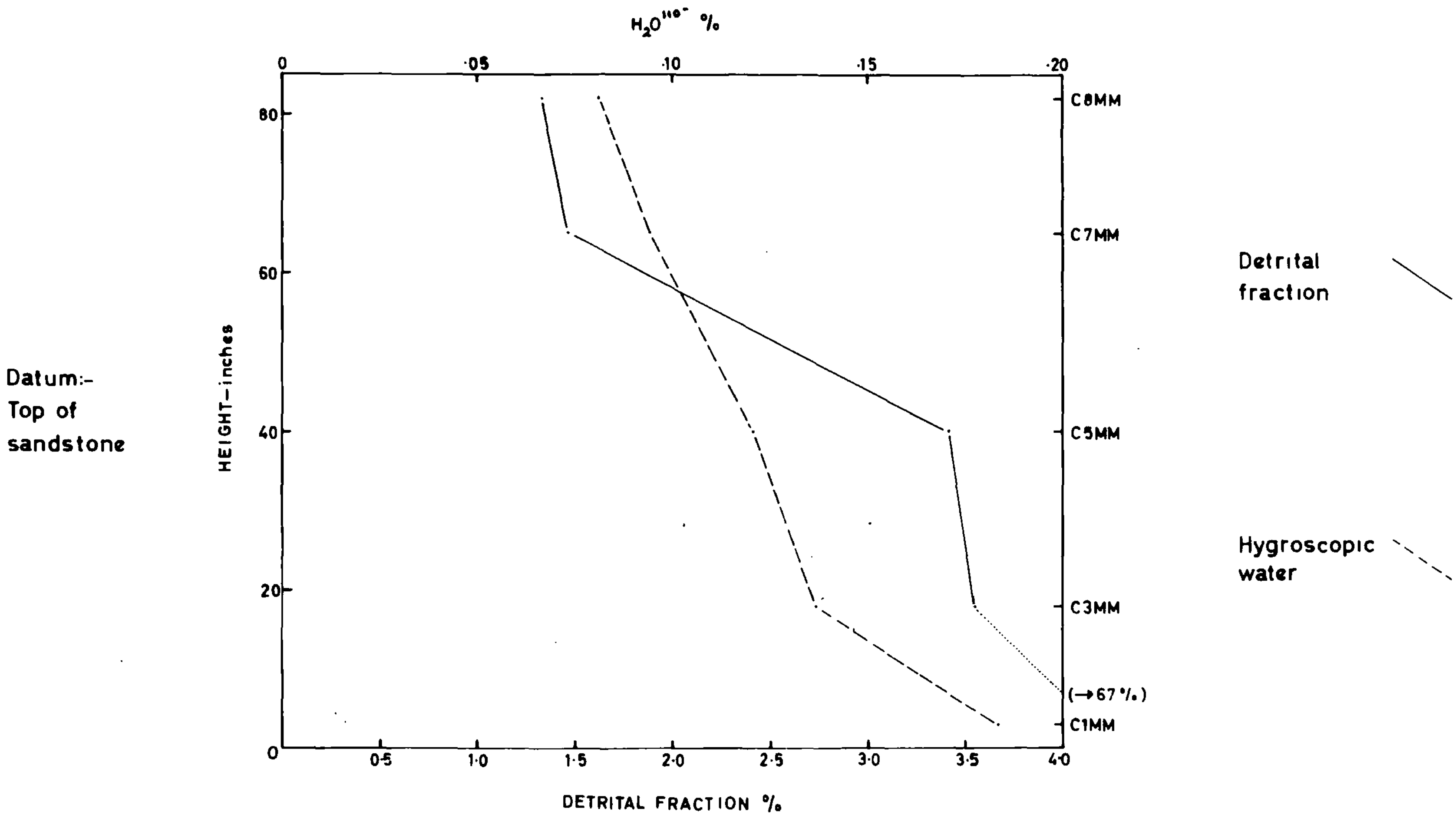
IRON HILL QUARRY

minor quantities throughout becomes abundant in the narrow ferruginous-weathering zone. Siderite is only present in the lower part of the succession but is very subordinate. Its absence from C1MM may be because it has been oxidised to goethite, which increases at this level, but non-precipitation is more likely since it has remained quite fresh in the more porous sandstone below. The goethite, which partly occurs within carbonate cement but also as grains around the quartz, may in fact be partially the result of primary hydroxide precipitation. The reduction upwards in the amount of quartz is noticeably less sudden than the corresponding increase in calcite and the steady fall is distinctly broken at the level of the ankerite band (C5MM).

Pyrite is doubtfully present except in the ankerite bed, which contains only a trace, and the clay minerals also occur in only very minor quantities. Examination of the detritial fraction shows that chlorite is present at all horizons above the sandstone and mixed-layer illites occur throughout. Kaolinite is of uncertain distribution and is well-developed only in the sandstone where it shows sharp basal peaks, reflecting its well-crystallised nature and suggesting that it may be the product of the alteration of feldspar. Also present in the sandstone and the calcareous sandstone above is a clay belonging to the montmorillonite group, a type which has not been found in unaltered rocks from any other horizon. Phosphate was only detected in the ankerite bed and in C8MM and it appears that the downwards decrease in phosphate noted from the Little Strickland Limestone is probably also a feature of this Limestone.

Figure 4.12

DETRITAL FRACTION AND HYGROSCOPIC WATER



MAULDS MEABURN LIMESTONE
AT
IRON HILL QUARRY

ii) Other compositional characteristics

a. ACID-INSOLUBLE FRACTION

Little contamination by dolomite-ankerite occurs and pyrite is present only in C5MM so that Fig. 4.12 gives a fairly accurate picture of the distribution of the detrital fraction. Above the calcareous sandstone with 67% of non-carbonates is a rapid decrease to only 3½% ultimately levelling off at between 1½% and 1%, this order of magnitude being probably typical of the rest of the Limestone and therefore comparable to that of the Little Strickland Limestone once allowance is made for dolomite-ankerite. The slight fall in detrital content from C3MM to C5MM, in spite of the rise in quartz, must mean that C3MM is much richer in clays than is the ankerite bed.

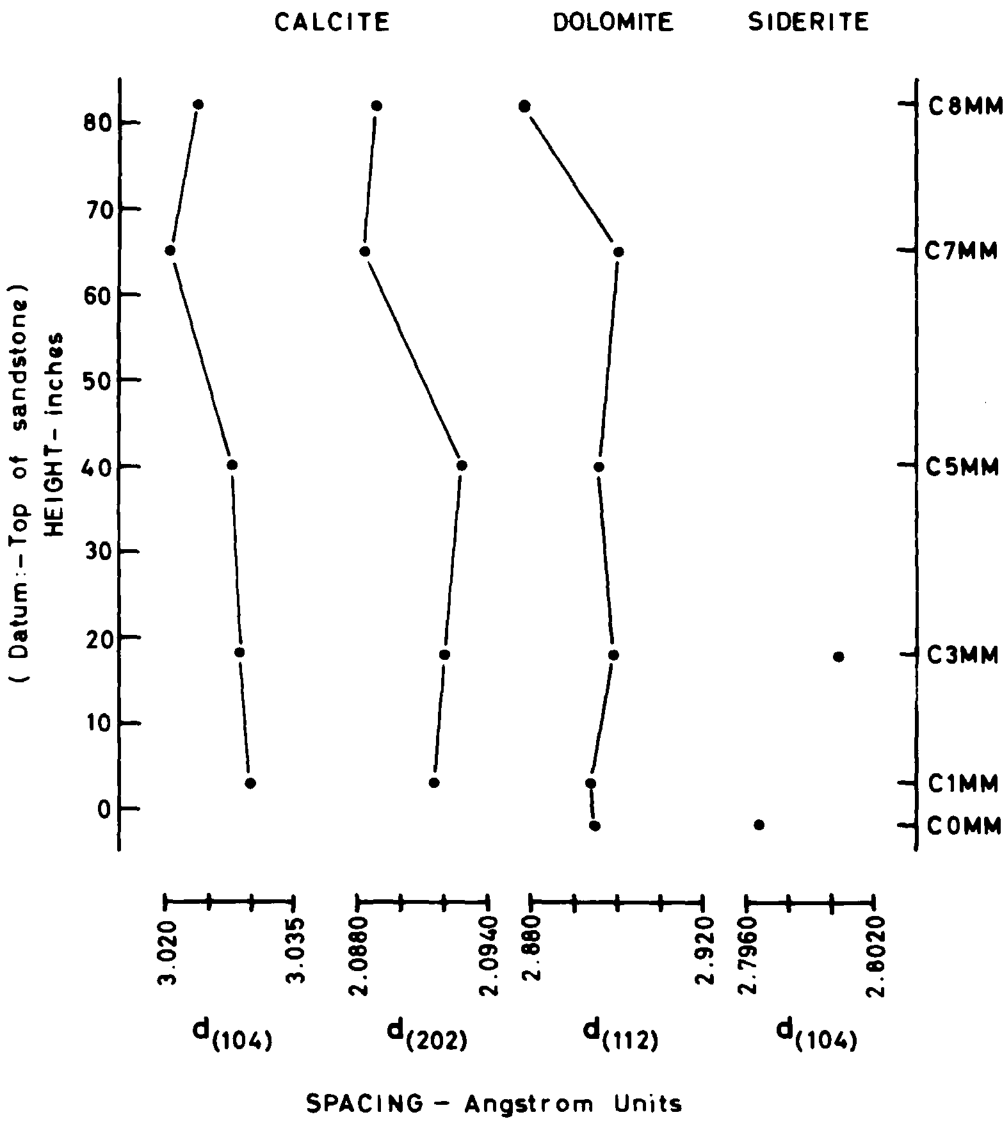
As might be expected, the amount of hygroscopic water (Fig. 4.12) falls gradually upwards to a similar value to that found in the Little Strickland Limestone where it has a comparable amount of detrital material.

b. CARBONATE MINERALOGY

Fig. 4.13 shows the variations in the spacing of the main X-ray diffraction lines of the carbonate minerals. At the base of the Limestone the calcite composition stays constant but above the ankerite bed there is an appreciable fall in the value of d_{104} which is only partially restored in C8MM. Probably in the lower part of the succession iron and manganese ions were incorporated in carbonates other than calcite, whereas above the ankerite bed, where siderite and dolomite-ankerite are poorly represented, greater quantities of these ions were available for inclusion in the calcite.

Figure 4.13

VARIATION IN CARBONATE COMPOSITION THROUGH THE MAULDS MEABURN LIMESTONE



The dolomite-ankerite apparently varies little in composition and is quite iron-rich with a d_{112} value close to the 2.899 Å of ankerite (Howie and Broadhurst, 1958). At the top, however, it appears to be almost pure dolomite and it is possible that at this level iron was precipitated directly as the hydroxide and that the high goethite content (Fig. 4.11) of this horizon is not entirely the result of weathering. The two siderite values suggest that it contains ions of larger size but the peaks are too small to be measured accurately.

iii) <u>The ankerite horizon</u>

Most of the descriptions of this mineral in the literature have been from ankerite occurring along cleats in coal and in veins, as for example Hawkes and Smythe (1935) and Smythe and Dunham (1947) where it has clearly formed at a later stage than the surrounding minerals. Deer, Howie and Zussman (1962, vol.5, p.299) state that ankerite in sedimentary rocks is a hydrothermal or low temperature metasomatic mineral and it appears that only in some works by Soviet authors is a sedimentary origin for some ankerite clearly stated or implied. Teodorovitch (1961) for example refers to beds and seams of sedimentary ankeritic ore.

The occurrence of ankerite in the Maulds Meaburn Limestone provides every reason for believing that it was a primary deposit or, at least, of penecontemporaneous origin. It is present as a conformable bed which is often at the base of the Limestone but not invariably so (Plate 47); the bed occurs over a very large area and its distribution is not related to faults or joints along which solutions could have migrated at a late stage in diagenesis. Secondary alteration is therefore ruled out, especially as the cavities which characterise dolomitisation, as in the Great Strickland

PLATE 47. The base of the Maulds Meaburn Limestone at Iron Hill. The hammer rests on the top of the sandstone and the notebook marks the position of a thin sandy horizon above the orange coloured ankerite bed.

PLATE 48. Pale silty shales with impersistent calcareous horizons; strata low in the Maulds Meaburn clastic succession.

Limestone, are absent.

At the Iron Hill locality, the intensity of the ferruginous staining produced by weathering shows that ankerite gradually increases upwards, reaches a maximum and then steadily dies out; fossils are not noticeably reduced in abundance but neither has the shell material been replaced by iron-bearing carbonates. Neither of these lines of evidence suggests that migrating fluids attacked an originally normal limestone. Rather, it appears that conditions in the sea changed slowly to favour the deposition of ankerite and then reverted to normal. This conclusion is also supported by the independent evidence of the variation of quartz and of pyrite both of which increase at this horizon. It is true, of course, that the primary precipitation of dolomite has never been proved (see for example Ingerson, 1962) and the same may be said of ankerite, so that the possibility of a penecontemporaneous origin, i.e. alteration of say high-magnesium calcite a short distance below the sea-floor, cannot be discarded. However there is no reason to believe, from the rocks themselves, that the ankerite was not a precipitate and, irrespective of this, the case for there having been changes in the chemical environment is in no way destroyed, but merely slightly postponed in time, by the adoption of a penecontemporaneous hypothesis.

iv) Trace element distribution

Table 12 and Fig. 4.14 show the variation in trace element content from the sandstone up into the Limestone. Zinc is below the detection limit throughout and rubidium and cobalt can only be measured in the sandstone. The mean abundance values for the other elements are shown along with those for the Little Strickland and Great Strickland Limestones in Table 11; these abundances are the average of the three purer limestone

TABLE 12

Trace element content in parts per million

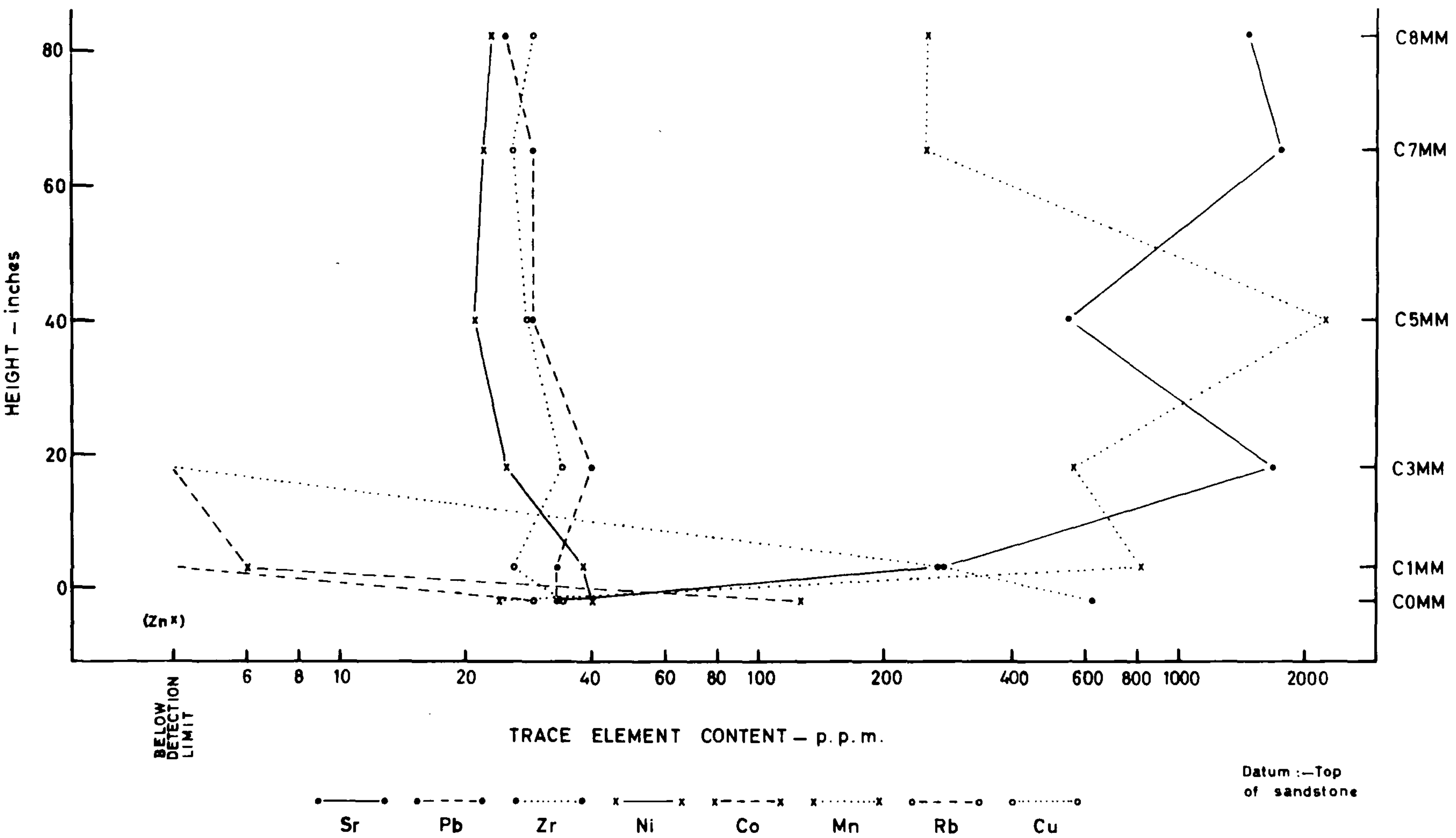
	Zr	Sr	Rb	Pb	Cu	Ni	Co	Mn
C8MM	-	1466	-	(25)	29	23	-	252
C7MM	-	1748	-	29	26	22	-	251
C5MM	-	545	-	29	28	21	-	2192
C3MM	-	1682	-	40	34	25	-	562
C1MM	267	276	-	33	26	38	(6)	812
COMM	622	33	29	33	34	40	126	24
MEAN*	-	1632	-	31	30	23	-	355

The trace element content of samples from the Maulds Meaburn Limestone.

* The mean value includes only the three purest rocks (C8MM, C7MM, C3MM).

Figure 4.14

TRACE ELEMENT VARIATION IN THE MAULDS MEABURN LIMESTONE



samples, the ankerite bed being omitted.

a. STRONTIUM

Strontium, with a mean value of 1632 ppm., has an abundance which lies between that in the other two Limestones investigated (Table 11). Since there is no reason to believe that it has been redistributed to any great extent, it is probable that the lower part of this Limestone, at least, was deposited with less strontium than was the Little Strickland Limestone. Again, a greater amount of precipitation of calcite mud is thought to have been responsible; certainly it does not seem likely that there could be a sufficiently great change in the strontium content of the sea in the period intervening between the deposition of these two adjacent Limestones.

Variation amongst the three purer Limestone samples is less marked than in the Little Strickland Limestone, suggesting perhaps more uniformity in depositional conditions over much of the time. Strontium clearly follows calcium and so is very low (33 ppm.) in the sandstone where it is probably associated with the clay minerals, especially montmorillonite. Its quite low value in the ankerite bed is also because of a relative shortage of calcium carbonate for, although calcite remains abundant, it is slightly subordinate to ankerite.

b. MANGANESE

The manganese content of the two purest samples at the top is similar to that in the Little Strickland Limestone, but below it is much more common and variations are pronounced. The very high value in the ankerite bed is undoubtedly owing to its presence in this mineral, but between C1MM and C3MM the amount of dolomite-ankerite increases whereas that of manganese falls and it is possible that some of the excess manganese of the calcareous sandstone was precipitated directly as oxide at this horizon. $Mn(OH)_4$ hydrosols are negatively charged and those of $Fe(OH)_3$ have a positive charge (Rankama and Sahama, 1949, p.649) so that if the two are brought into contact they will flocculate together; however, although it is true that goethite, which may be primary (see above, page 181) is relatively common at this horizon, no oxide of manganese has been detected. The probability that some of the manganese is associated with the calcium carbonate, as deduced above (page 178), is indicated by its very low value in the sandstone, where calcite is absent. This is in spite of there being both dolomite-ankerite and siderite present and suggests that these minerals, probably introduced at a late stage, were deposited from water containing very much less manganese than did that from which the same minerals in the limestone above were precipitated.

c. NICKEL, COPPER, LEAD

These elements form a group which shows little variation in spite of the facies changes, though nickel does decrease slightly in abundance upwards. Their mean values are all very close to those in the other two Limestones studied (Table 11). The slightly greater abundances of lead and copper are a consequence of their higher value at the base of the Limestone (C3MM) where there is an increased quantity of clay minerals (above, page 182). These elements are less abundant in the calcareous sandstone and the sandstone, in contrast to nickel which is much higher than in the Limestone, possibly because of its association with montmorillonite. The absence of significant changes in these trace elements at the ankerite horizon also argues in favour of its not having been subjected to major diagenetic changes.

d. ZIRCONIUM, RUBIDIUM, COBALT

The distribution of zirconium (Table 12) is closely associated with that of quartz and it is therefore largely related to the content of detrital zircon. A very minor amount of cobalt has been detected in the calcareous sandstone and although it is extremely abundant in the underlying sandstone (126 ppm.) its location is unknown; montmorillonite seems the most likely source. To a lesser extent rubidium has been concentrated in the sandstone, again presumably because of the clay minerals present.

D. THE ASKHAM CLASTICS

Mineral and trace element variations in an upwards-coarsening cycle has been investigated in the lower part of the Askham clastic succession, between the Askham and Halligill Limestones (Fig. 4.15). The samples were selected in order to take in a wide range of lithological types and include two examples of concretions (C3H and C7H). They are widely spaced except for C1H and C2H which are on either side of the horizon where fossils almost completely die out. The cycle is atypical in that no major sandstone body occurs below the minor Halligill Limestone, but the highest sample (C6H) is a gently wavy-bedded very fine sandy and silty rock with an admixture of argillaceous material which is partially concentrated into thin layers.

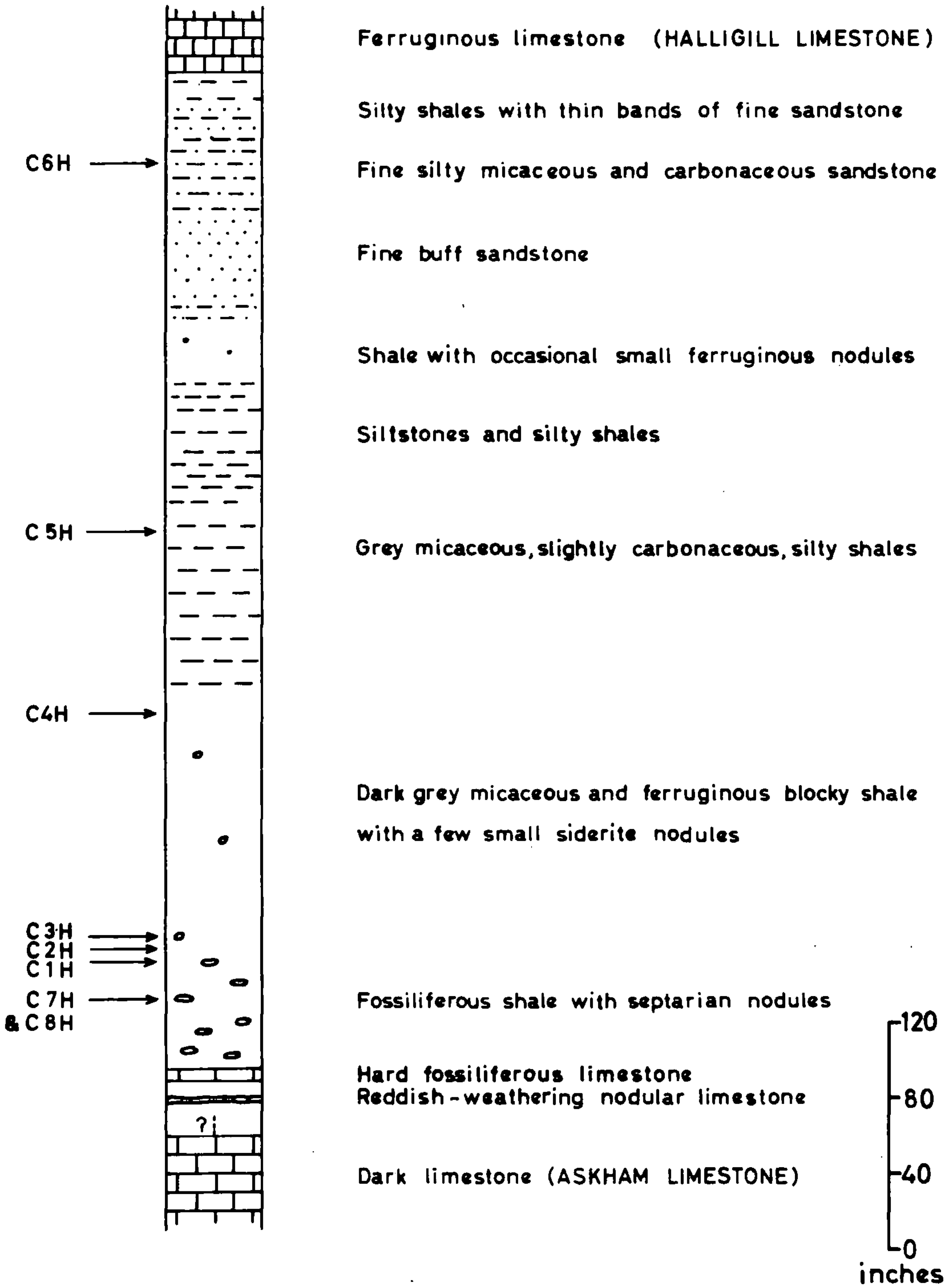
i) Mineralogical variation

Considerable changes in mineralogy (Fig. 4.16) are evident through the shale sequence. Quartz is a major constituent at all horizons but increases slightly in abundance upwards. In the concretions only minor quantities occur and it is probable that this can be only partially explained by the early migration of carbonates when the rock was uncompacted; almost certainly some solution or bodily removal of the quartz must have accompanied the concentration of the carbonates.

Of the carbonates, calcite is essentially confined to the lower part of the succession where the majority is thought to have been contributed by the calcareous fossils; the smaller quantity found in the lower of the two calcareous shales may be attributed to its location next to a concretion, into which some has been concentrated. Where the fossils largely die out, calcite falls to zero and, apart from the very rare fossils, does not reappear

Figure 4.15

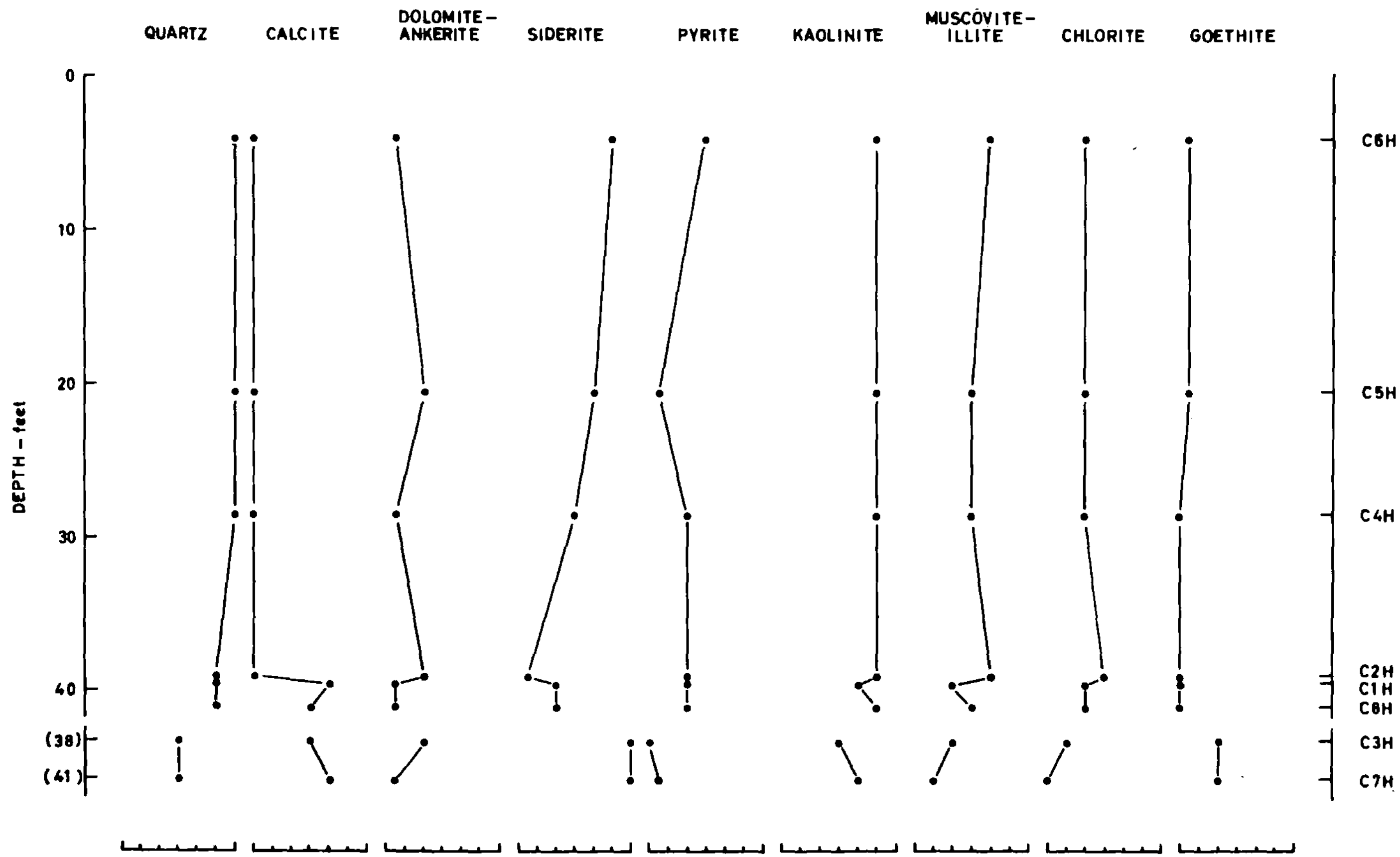
LOCATION OF SAMPLES FROM THE ASKHAM CLASTICS



HALLIGILL GORGE SECTION

Figure 4.16

MINERAL VARIATION THROUGH THE ASKHAM CLASTICS



Datum :- Base of Halligill Limestone

in the main mass of shale. Instead, the minor quantities which do occur are now segregated into the small concretions (Fig. 4.16, C3H), usually occurring in the irregular central cracks. The opposite relationship is shown by siderite, which occurs only in very minor quantities in the fossiliferous shales and is doubtfully present in the beds just above (C2H), being, at these horizons, almost completely concentrated into concretions. At higher levels, this segregation still occurs to some extent but the concretions are smaller and more scattered, and there is a gradually increasing amount of siderite remaining in the shales, especially in the sandy shales at the top. Dolomite-ankerite never occurs in more than very minor quantities and usually is only doubtfully present. It increases in abundance immediately above the fossiliferous shales where it is temporarily the main carbonate; this change is also reflected in its appearance in the concretion from this horizon (C3H) whereas it is probably absent from that (C7H) from the calcareous shales.

Pyrite shows no significant change at the top of the fossiliferous shales. It is most abundant in the argillaceous sandstone (C6H) and is noticeably lacking in the concretions where it occurs only as occasional grains lining the calcite- and kaolinite-filled cracks. The concretions also differ from the rest of the succession in containing small amounts of a ferric oxide which gives some X-ray diffraction peaks of both hematite and goethite and presumably lies between these two minerals in composition, being partially hydrated. The impression that the concretions formed in a less reducing micro-environment (page 148) therefore is supported by this evidence.

Throughout the succession, 7 Å, 10 Å and 14 Å clay and micaceous minerals can be recognised together with much mixed-layered illite. Their apparent variation is probably not significant because it is based upon peak heights which will depend partially on the degree of crystallinity of the minerals. For the same reason, their relative abundances are unknown; the apparent predominance of kaolinite being, perhaps, because it is a secondary mineral (page 144) which is well-crystallised. The chlorite gives broad peaks and contains layers of differing composition, as do the micaceous clay minerals, which probably form the main part of the clay fraction. A sharp peak occurs superimposed on the broad 10 Å reflections in the higher samples and indicates the larger size and greater abundance of muscovite at the top of the succession. The apparent sudden increase in clay content at the top of the fossiliferous shales is due largely to the loss of the carbonate fraction and, in contrast, the great concentration of the latter in the concretions reduces the clays, like quartz, to minor constituents.

ii) Trace element distribution

a. SHALES

All nine of the trace elements studied occur in detectable amounts in the shales; their abundance and variation are shown in Table 13 and Fig. 4.17. In the absence of a quantitative knowledge of the variation in the clay mineralogy and the total clay content, it is impossible to discuss adequately the trace element variation but it is likely that those elements (strontium, rubidium, zinc and nickel) which fall steadily in abundance upwards, above the fossiliferous shales, do so because they are found in the clay minerals which also decrease as more quartz appears.

Strontium

The strontium distribution follows closely that of calcite (Fig. 4.16) being highest (353 ppm) in C1H; above this level, it is almost entirely contributed by the clay fraction.

TABLE 13

Trace element content in parts per million

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
C6H	274	90	77	36	24	40	51	-	1352
C5H	381	123	151	(20)	32	42	77	(8)	610
C4H	283	131	167	31	34	51	86	(7)	406
C2H	237	133	181	-	40	44	96	10	322
C1H	182	353	172	(23)	41	45	87	(7)	281
C8H	155	186	197	-	37	46	97	-	305

The trace element content of shales above the Askham Limestone

TABLE 14

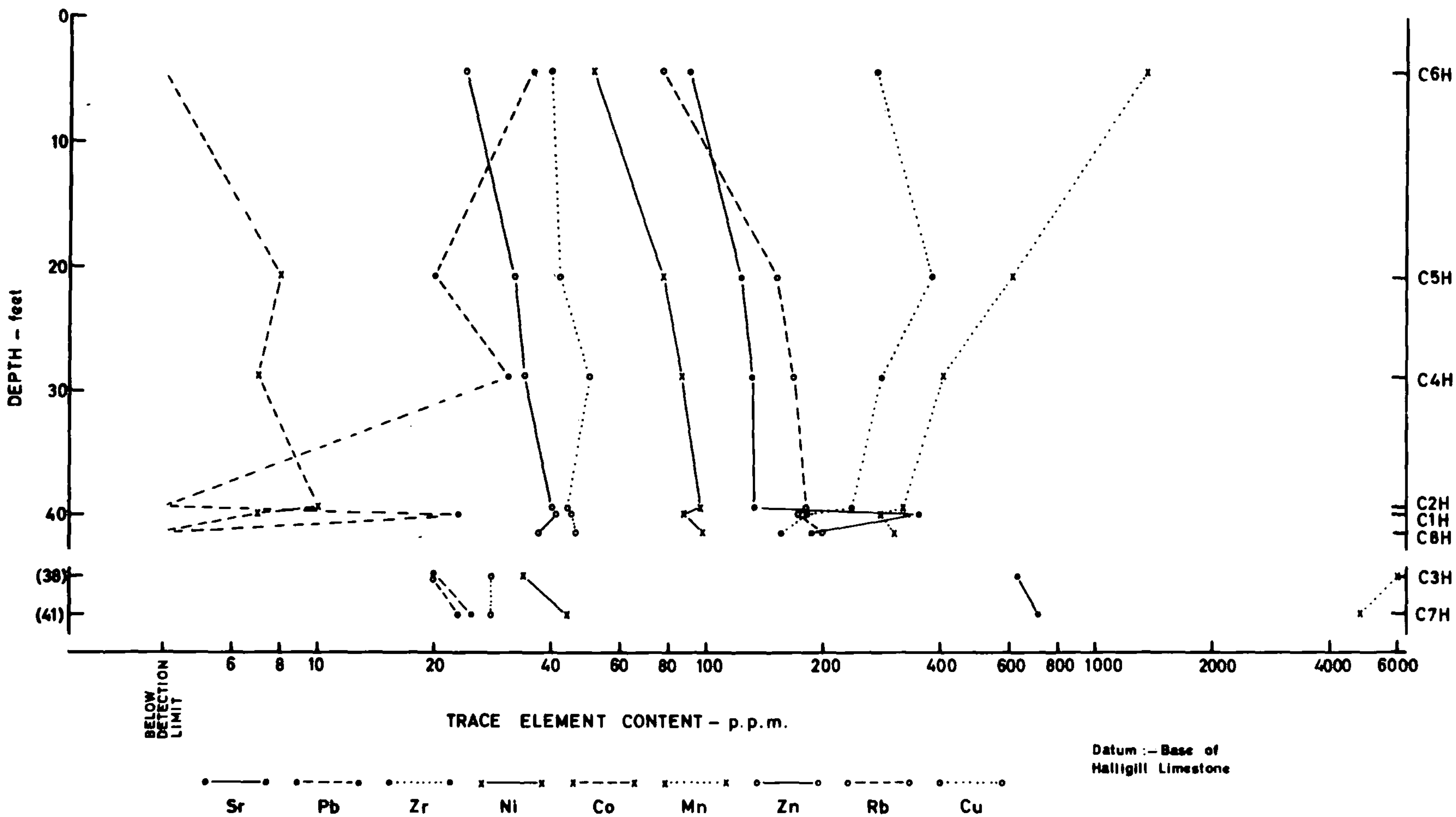
Trace element content in parts per million

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
C3H	-	630	20	(20)	-	28	34	-	6013
C7H	-	710	23	(25)	-	28	44	-	4796
C8H	155	186	197	-	37	46	97	-	305

The trace element content of siderite concretions and associated shale.

Figure 4.17

TRACE ELEMENT VARIATION THROUGH THE ASKHAM CLASTICS



Manganese

The steady upwards rise in manganese above the fossiliferous shales exactly parallels that of siderite and there is no doubt that the bulk of the manganese is substituted for iron in this mineral. However, there is more siderite but less manganese in the fossiliferous shales than in C2H and it would seem either that the element has undergone exceptional redistribution (below, page 194) or that less was available at this stage of deposition.

Nickel

The nickel distribution closely follows the apparent distribution of illite, once the upwards appearance of much coarse mica is allowed for. It is, therefore, probably incorporated into the lattice of this clay and also of the chlorite and largely entered the basin of deposition together with these minerals. Of course, it is possible that the decreasing content of this element, as well as that of Sr, Rb and Zn, could be partly the result of an increased rate of deposition of material upwards, thereby giving less time for any fraction of these elements which was in solution to be incorporated into the minerals; it would be necessary to determine the relative amounts of the detrital and non-detrital fractions (Nicholls 1958) of these elements before the significance of this factor could be assessed.

Copper

As in the Limestones, copper does not vary significantly. Its distribution is not related to that of any of the minerals detected and its content scarcely falls in spite of the decreased amount of clay at the top of the succession. It must be largely present in the clays but if it came into the basin of deposition combined with these minerals, then proportionately more must have been incorporated in the lesser amount of clay that was deposited high in the sequence. More acceptable is the possibility that most of the copper entered the clay minerals (and perhaps also the ferrous sulphide) from solution at the time of deposition, that constant quantities were present in the water at all levels and that this quantity was much less than was necessary to saturate these minerals.

Lead

The lead content is close to the detection limit and little importance can be placed upon the variation shown. In the lower part of the succession, it only appears in the rock, C1H, with most calcite, whereas at high levels it may be associated with the sulphide phase, being low in C5H which is also poor in pyrite.

Zirconium

Some zirconium occurs in the clays but much must be due to detrital zircon and, as would be expected, it increases upwards with the quartz content. The comparatively low value of C6H may be attributed to a decreased clay contribution together with a sudden decrease in the amount of zircon grains entering the basin of deposition along with the quartz.

Rubidium

Rubidium closely follows nickel and, like this element, probably entered the basin of deposition occupying structural sites in the illitic and chloritic clay minerals.

Zinc

The zinc content falls steadily upwards and its distribution can be largely explained in the same way as those of rubidium and nickel. Unlike these, however, it follows strontium in being richest in the horizon, C1H, with most calcite; it may be partially associated with this mineral but in this case it is unusual that it is absent from the limestones and from the calcite-bearing concretions in the shales (below). Instead, it may be postulated that there were differences in availability of zinc at the site of weathering with time.

Cobalt

Cobalt probably occurs incorporated in the clay minerals but its content does not exceed 10 ppm, and no importance can be attributed to the variations shown.

b. CONCRETIONS

Fig. 4.17 shows the relative abundance of the trace elements in the two concretions examined, whilst Fig. 5.9 compares their contents in one of the concretions and in the shale immediately surrounding it. The same values are given in Table 14.

A majority of the trace elements decrease in abundance, or scarcely change, upwards through the shales and their behaviour is the same in the concretions, that from the calcareous shales being richer in these elements than that from just above them. Of those elements which increase upwards, three, zirconium, zinc and cobalt, are below the detection limit in the concretions and the other, manganese, also shows an increase. The difference in trace element content of the two concretions tends to be of a greater order than that of the nearby shales.

Fig. 5.9 shows that very great differences occur between the trace element content of the siderite concretion from the fossiliferous shales and the shale immediately surrounding it. Two elements, strontium and manganese, are strongly enriched, being always especially associated with the carbonate fraction of the sediment. Lead is, perhaps, slightly enriched but is only just detectable in the concretion. Cobalt is below the detection limit and the remaining five elements all show a decrease in abundance, zirconium largely because of the great decrease in the coarse detrital fraction and rubidium, zinc, copper and nickel because of the decreased proportion of clay, although the lesser fall in the abundance of the latter two elements implies their presence in the carbonate, or possibly the sulphide, phase. Clearly, the concretion represents a striking concentration of manganese-rich siderite and, to a much lesser extent, of strontium-bearing calcite. The manganese constitutes nearly a half percent of the rock but whether it is more concentrated in this redistributed siderite than in the primary siderite at higher levels in the succession cannot be determined in the absence of quantitative knowledge concerning the siderite at the different horizons. If it is more concentrated in the concretions, then this would probably indicate that relatively widespread redistribution of the manganese had taken place in the fossiliferous shales and would account for the low manganese content of these beds in spite of the presence of disseminated siderite.

E. THE MAULDS MEABURN CLASTICS

Mineral and trace element analyses were made of two horizons in the Maulds Meaburn clastic succession because of their atypical lithologies reflecting, possibly, a 'non-marine' origin (Plate 48). C1D is from a thin nodular impersistent calcareous band within pale-grey unfossiliferous silty shale of which C2D is a representative.

i) Mineralogy

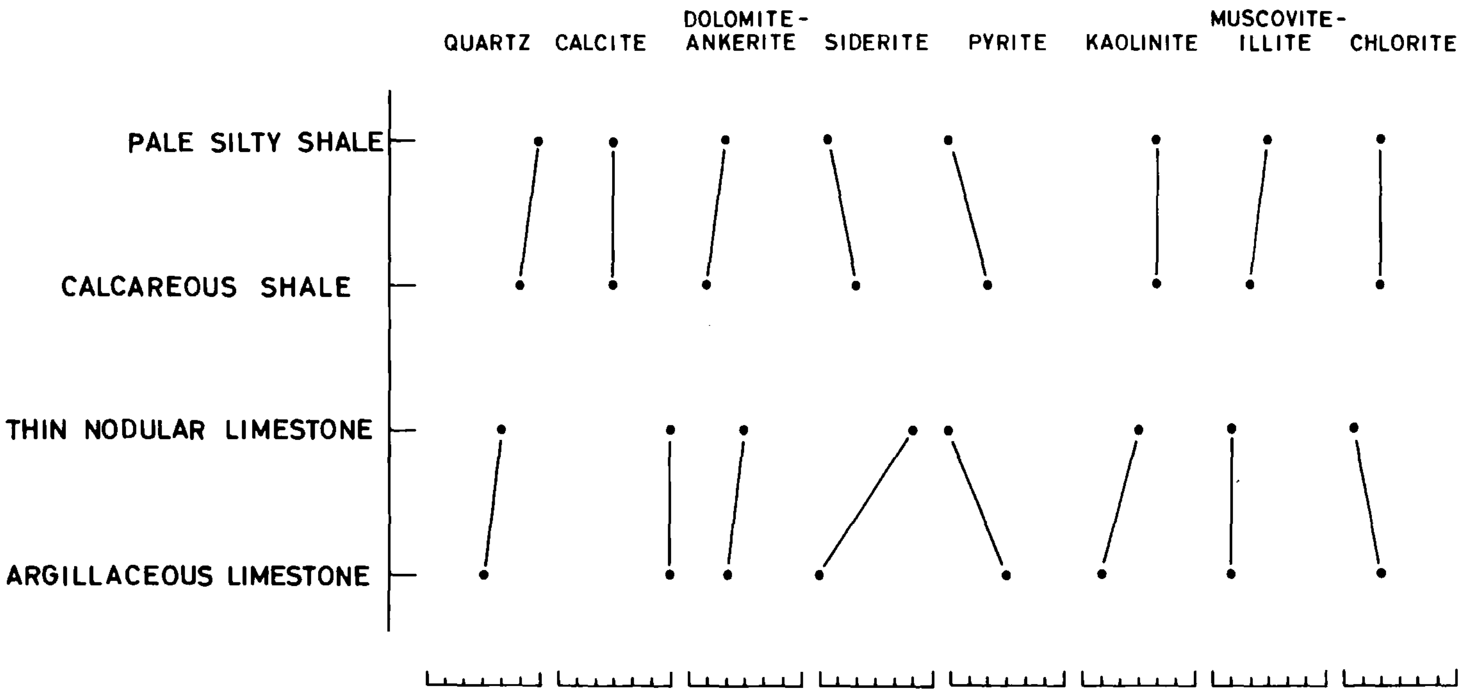
The impure limestone, though mainly of calcite, also contains much siderite and some dolomite-ankerite; all of the carbonates have d-spacings which indicate a greater substitution of foreign ions than in other calcareous horizons examined, the siderite, in particular, being impure. A moderate amount of quartz and some feldspar are present and, of the clays, kaolinite and illite both occur and there is probably also a little chlorite. No environmental significance can be attached to the presence of kaolinite since it could be largely of secondary origin as in other horizons studied. A trace of phosphate is probably present.

Quartz, illite kaolinite and muscovite make up the bulk of the pale shale but chlorite is definitely present as is quite a large quantity of calcite, here rather purer than in the limestone. Ankerite completes the carbonate fraction and there is a little feldspar.

A comparison of the mineralogy of these rocks with horizons of generally similar nature but with marine fossils is shown in Fig. 4.18. The argillaceous limestone (C31LS) was chosen because it contains exactly the same amount of detrital material (16%) and, because of the carbonates in C2D, the average of the two calcareous shales (C1H and C8H) was preferred to a siltier

Figure 4.18

COMPARISON OF MINERALOGY OF MARINE AND POSSIBLE NON-MARINE IMPURE LIMESTONES AND CALCAREOUS SHALES



but non-calcareous horizon.

Between the two calcareous horizons the most important differences are in the absence of siderite from the argillaceous fossiliferous limestone and the absence of pyrite from the nodular limestone. In addition, ankerite is more abundant in the latter and chlorite in the former.

The absence of pyrite also distinguishes the pale silty shale from the other calcareous shales as does the occurrence of a greater quantity of ankerite, for, in the fossiliferous shales, siderite is the main carbonate apart from calcite. It is however possible that there was, when deposited, much more siderite in the pale silty shale but that this has since separated into the nodular bands along with the calcium carbonate. There is indeed, from the mineralogy, no reason why the limestone bands should not owe their present character largely to processes of segregation. In thin-section, most of the carbonate is recrystallised but the local presence of thin curved strips of glassy calcite, which are almost certainly fragments of shells, together with numerous pellet-like objects, suggests that carbonate migration was governed by the presence of small areas in the shales which were initially rich in calcium carbonate owing to the presence of organisms (probably thin-shelled lamellibranchs).

ii) Trace element content

The trace element content of the rocks is shown in Table 15. Cobalt again is below the detection limit and lead is close to it.

a. THE LIMESTONE, C1D

Fig. 4.19 compares the trace element content of the nodular limestone

TABLE 15

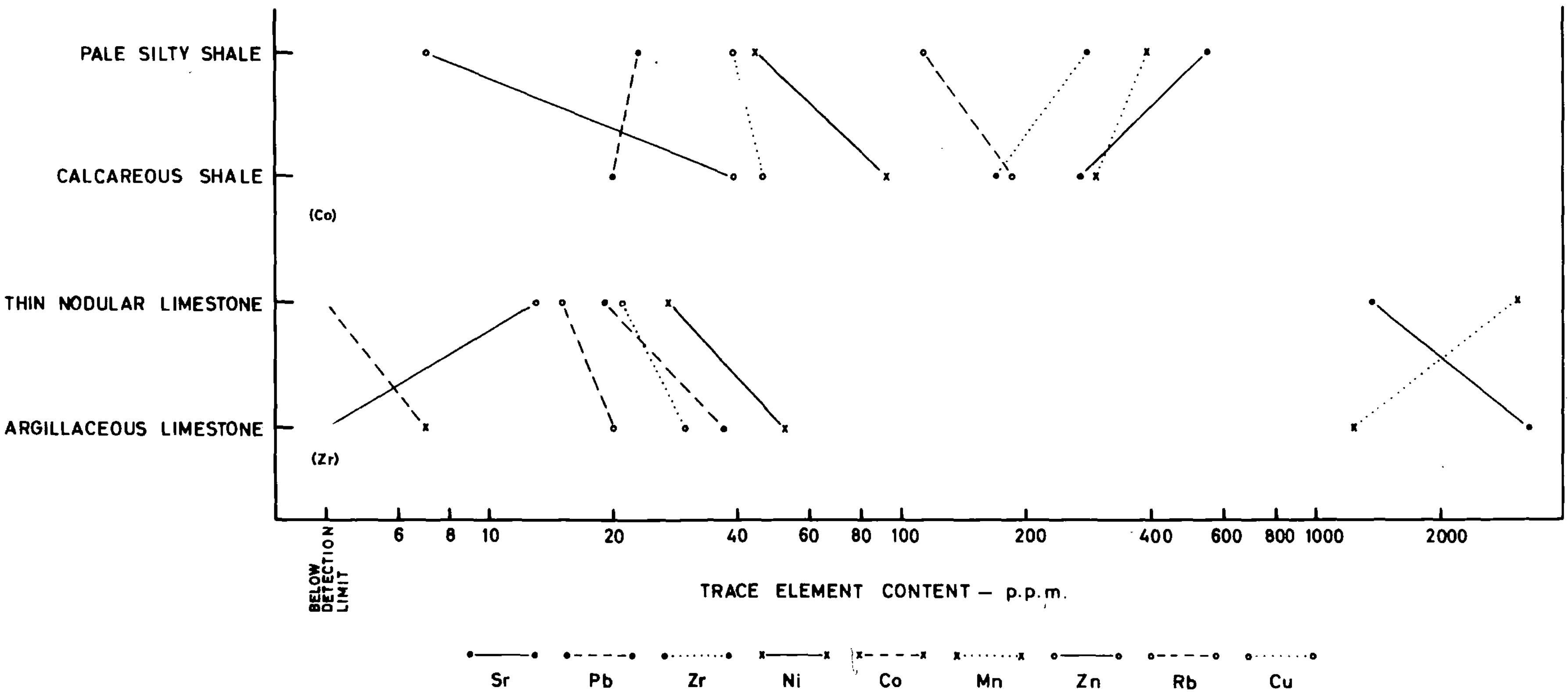
Trace element content in parts per million

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Mn
C1D	-	1368	15	(19)	13	21	27	3073
C2D	279	550	113	(23)	(7)	39	44	390

The trace element content of some strata above the Maulds Meaburn Limestone

Figure 4.19

COMPARISON OF TRACE ELEMENT CONTENT OF MARINE AND POSSIBLE NON MARINE IMPURE LIMESTONES AND CALCAREOUS SHALES



with that of the argillaceous limestone, C31LS, and, with two exceptions, manganese and zinc, their content is lower in the former. Manganese is greatly more abundant in C1D because of the presence of siderite and it is interesting that there is more than twice as much manganese in this rock than in the argillaceous sandstone, C6H, which, from the height of the main X-ray diffraction peak, has almost as much siderite. It was suggested (page 194) that there may have been special manganese enrichment in the siderite of concretions and, if so, this would lend further support to the theory that the nodular limestone band, C1D, owes its present form to redistribution of carbonate and not to primary precipitation. The lower content of strontium may be attributed both to the slightly smaller quantity of calcium carbonate present in C1D and to the absence of the probably rather special conditions which led to the fixing of very large amounts of strontium in the horizons of which C31LS is an example (page 167 et seq.). The two horizons appear to contain similar total amounts of clay minerals, which are probably the principal reservoirs of the remaining trace elements, but the significance of the general decreased abundance in C1D is not known. It will be partly due to differences in the proportions of the various clay minerals but additional variation may be the result of either differences in the source area or, for the non-detrital fraction, the removal of lesser amounts from solution at the site of deposition. This could be due to deposition from a solution of lower ionic strength, i.e. fresher water, or merely to more rapid deposition. Zinc is of interest in that it occurs here in amounts well above the detection limit in contrast to all other of the calcareous horizons studied. However, because of the uncertainties mentioned above and the probability that the nodular limestone bands are partly secondary, it is unsafe to attach any environmental significance to the variations.

b. THE SHALE, C2D

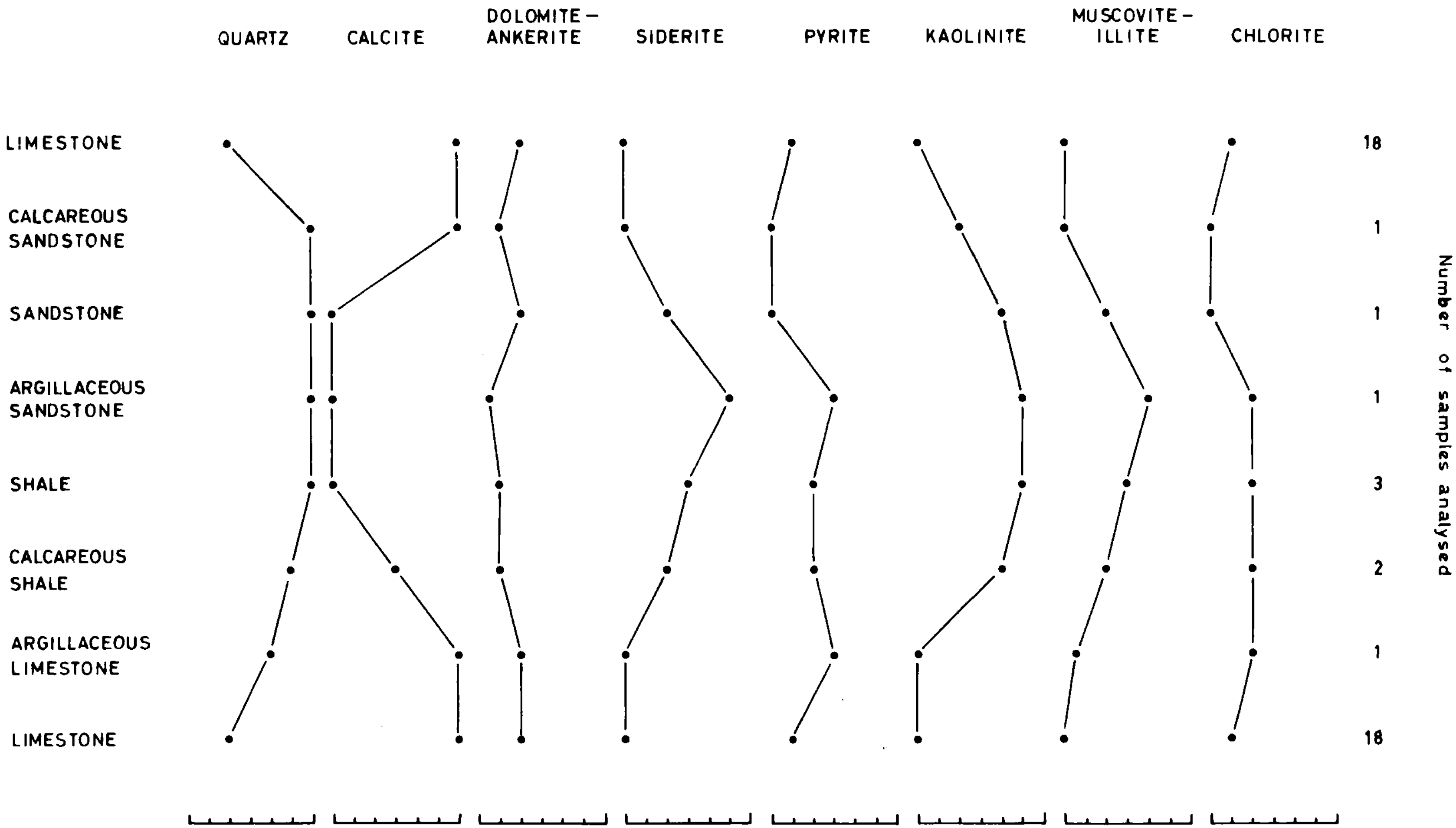
Trace element variations between the pale silty shale and the average of the two calcareous shales is shown in Fig. 4.19. The higher quantity of strontium in C2D can probably be largely attributed to the greater amount of calcite in this rock, and much manganese must be incorporated in this mineral as well as in the ankerite in order to explain its relatively high content in spite of the fact that there is much more siderite in the fossiliferous shales. The greater content of zirconium in C2D results from the abundance of silt-grade detrital material which must include some zircon. Cobalt is below the detection limit in both cases and the remaining elements, except for lead which is not significantly different, all decrease in abundance in the silty shale. The greatest decrease is shown by zinc and, although this has almost certainly been concentrated in the calcareous nodular bands (see above), they comprise so small a part of the shales that the latter must, as a whole, be impoverished in this element. As in the nodular limestones, rubidium, copper and nickel are less abundant than in the comparable fossiliferous horizons. Again, this can be interpreted in terms of differing clay mineralogy, weathering differences at the source and more rapid deposition, but also these elements may have been less abundant in the depositing medium and, clearly, detailed investigation of this possibility could be rewarding.

F. VARIATION THROUGH A STANDARD CYCLOTHEM

The mineralogical and trace element studies encompass a varied set of strata which, in the Yoredale Series, tend to be grouped in an often repeated sequence, termed a cyclothem. Because of lack of exposure and the necessity of obtaining fresh samples wherever possible, no complete series of samples through any one cyclothem could be obtained, but it is useful to group the lithological types from different horizons into a 'hypothetical' or standard cyclothem in order to gain a picture of the overall changes which take place through each major unit of deposition. It must be remembered, however, that very little significance can be attached to many of the values because they result from the analysis of only one example of that particular rock type.

The nature of the mineralogical changes is illustrated in Fig. 4.20 which brings out several important features. Quartz and calcite tend to be antipathetic and the horizons in which they occur together in large quantities are, in terms of thickness, of very minor significance; also the gradual quartz increase and slow reduction in calcite content is in marked contrast with their relatively sudden termination and appearance respectively at the top of the cycle. Dolomite-ankerite varies irregularly, being generally more common in the limestones and sandstones than in the shales, but is quantitatively unimportant. Siderite, in contrast, is commonest in the shales, absent from most limestones and appears to reach its greatest abundance in the transitional beds between shales and sandstones - the thinly interlaminated argillites and very fine micaceous sandstones. Pyrite shows a rather similar distribution, being most abundant in rocks of transitional facies except for the calcareous sandstone which tends to be rich in goethite, but it is quantitatively less important and is absent from the main sandstone bodies (though probably in part owing to weathering). The kaolinite is largely secondary and its distribution merely reflects that of suitable primary material. The peak

Figure 4.20



MINERAL VARIATION THROUGH A HYPOTHETICAL CYCLOTHEM of the muscovite-illite distribution at the argillaceous sandstones is due to the abundance of well-crystallised muscovite here, as is its high concentration in the sandstone. Chlorite is most abundant in the shales and largely absent from the sandstones.

The average trace element content of these different lithological types is shown in Table 16 and Fig. 4.21. The strontium distribution closely follows that of calcite but with its presence in the clay minerals being apparent where this dies out. Manganese varies greatly, with highest values in the transitional rock types; it depends partially on the siderite content but is, for a reason not fully understood, common in the argillaceous limestone and there are very small and large quantities respectively in the sandstone and calcareous sandstone the significance of which is discussed elsewhere (pages 182 and 186).

Manganese generally behaves geochemically in a similar way to iron; unfortunately the major element content of the rocks has not been determined but some idea of the distribution of iron has been obtained from the traces which were run on the spectrograph for some samples. Fig. 4.22 shows total manganese plotted against the height of the iron K_{α} peak. Clearly there is no strong coherence between the two elements and high contents of both occur only where siderite (C1D and C6H) or ankerite (C5MM) are common. The remaining samples occur in widely separated areas - the argillaceous rocks with high iron and low manganese, unaltered limestone with small quantities of both elements, and the dolomitised rocks which have received much manganese but little iron.

Zirconium, because of its occurrence in detrital zircon, closely follows the quartz distribution, whilst the group of elements, rubidium, zinc and nickel, primarily associated with the clay minerals is clearly indicated. Copper shows the same tendency but remains much more constant throughout and must also be incorporated in the carbonates or possibly the sulphide phase. Cobalt lies too close to the detection limit for its variation to be significant, but it

TABLE 16

Trace element content in parts per million

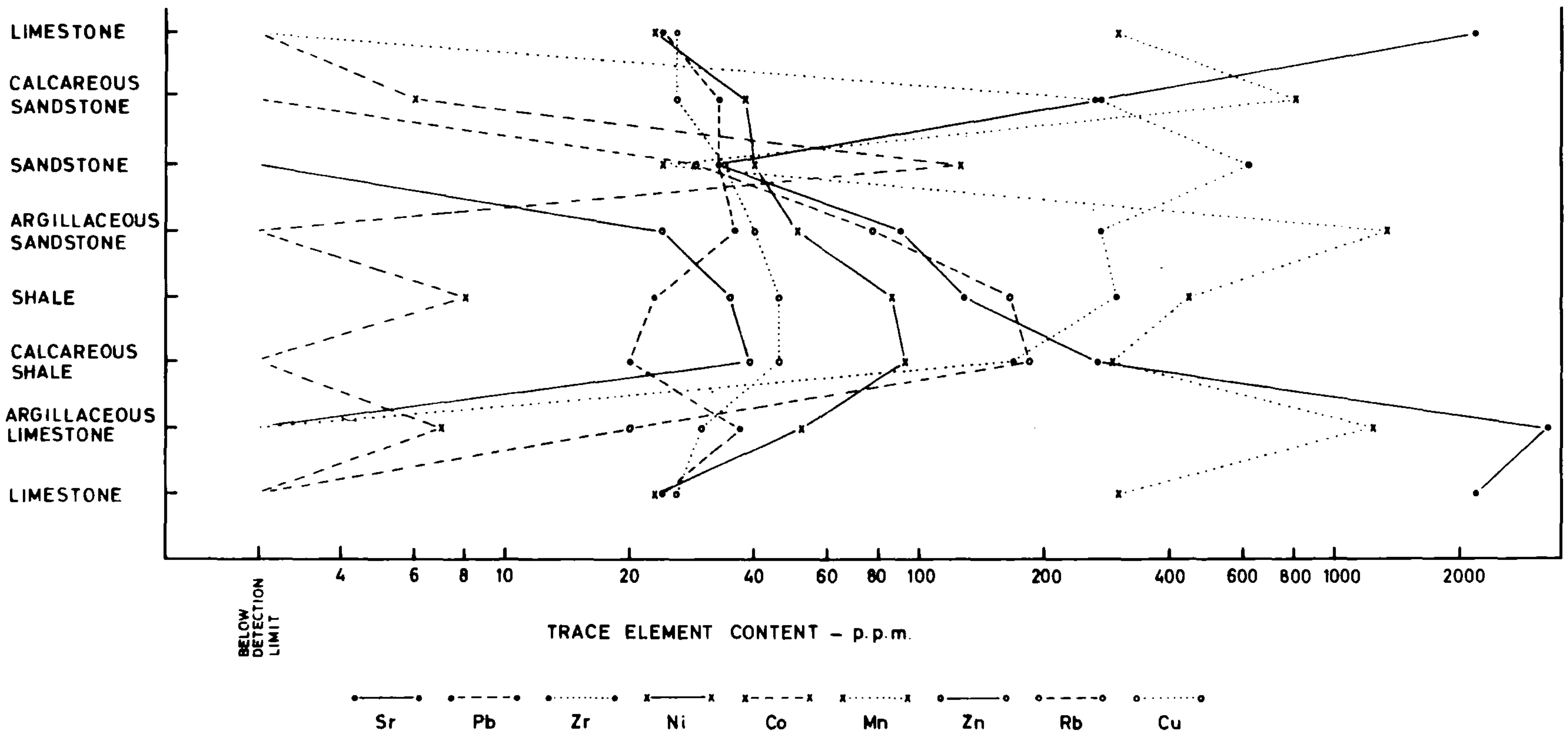
	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
(1) Calcareous Sandstone	267	276	-	33	-	26	38	(6)	812
(1) Sandstone	622	33	29	33	-	34	40	126	24
(1) Argillaceous Sandstone	274	90	77	36	24	40	51	-	1352
(3) Shale	300	129	166	(23)	35	46	86	(8)	446
(2) Calcareous Shale	169	270	185	(20)	39	46	92	-	293
(1) Argillaceous Limestone	-	3279	20	37	-	30	52	(7)	1241
(18) Limestone	-	2194	-	(24)	-	26	23	-	304

(The figures preceding the rock names refer to the number of samples analysed)

The trace element content of rocks of different lithologies

Figure 4.21

TRACE ELEMENT VARIATION THROUGH A HYPOTHETICAL CYCLOTHEM



must primarily be associated with the clay minerals. Lead, in contrast, is at a minimum in the argillaceous rocks and reaches its greatest quantities in the argillaceous limestone and argillaceous sandstone, as does pyrite, so that a chalcophile tendency is indicated.

For comparison, Table 17 shows the mean abundance of the elements studied for limestones, shales and sandstones, as given by Turekian and Wedepohl (1961). Between the limestones, the most important differences are the low content of zinc and the high content of copper (though partly because of contamination) and the very high content of strontium, in the Yoredale rocks. Manganese is also low, probably because, included in the average limestone are samples containing dolomite, ankerite and siderite. Manganese is again higher in the average shale, as is zinc, suggesting the possibility of a definite deficiency in this latter element during the time of formation of the strata studied. The average shale may include calcareous shales in view of the close similarity with the strontium and zirconium contents of the calcareous shales of the Yoredale Series. The fact that only one sandstone was examined prohibits a comparison with the values for the average sandstone except to point out the obviously atypical cobalt content.

TABLE 17

Trace element content in parts per million

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
Sandstone	220	20	60	7	16	-	2	0.3	-
Shale	160	300	140	20	95	45	68	19	850
Limestone	19	610	3	9	20	4	20	0.1	1100

The mean content of some trace elements in sandstones, shales and limestones

(from Turekian and Wedepohl, 1961)

CHAPTER 5

ASPECTS OF THE MINERALOGY AND CHEMISTRY OF SOME YOREDALE STRATA WHICH HAVE UNDERGONE EXTENSIVE ALTERATION

A. DOLOMITISED LIMESTONE

At Lookingflatt, the Great Strickland Limestone immediately underlies the New Red Sandstone unconformity and is extensively dolomitised as well as having a reddened base. Fig. 5.1 shows the location of a series of samples representative of this alteration which has given the strata a buff or orange tint and produced, especially near the top, many tiny cavities and some large vugs lined with carbonate crystals.

In thin-section, the original textures are largely obscured though fossil ghosts, especially crinoid ossicles, are always present. The rest of the rock is made up mainly of a carbonate ground-mass which may be very fine-grained as in C18G or consist of a mosaic of larger crystals which sometimes are poorly-defined (C13G) but which may also have distinct boundaries (C19G) and exhibit rhombic shape (C15G) (Plate 32). Red translucent and occasionally opaque hematite, weathering to brown goethite, is present in most of the samples, and in hand specimen there is usually a dark mottle due to fine crystals of a black mineral which, on account of its often dendritic habit is thought to be pyrolusite. At the base, quartz occurs as detrital grains, making up about 20% of C11G, but near the top it forms groups of anhedral interlocking crystals with undulose extinction and is present only in widely-spaced pockets, some of which are large and clearly visible to the naked eye. The rock is cut by numerous calcite veins which post-date the dolomitisation (Plate 53).

i) Mineralogical variation

The mineralogy at different levels in the limestone is shown in Fig. 5.2 where it is also compared with the variation found in the little-

Figure 5.1

LOCATION OF SAMPLES FROM THE GREAT STRICKLAND LIMESTONE

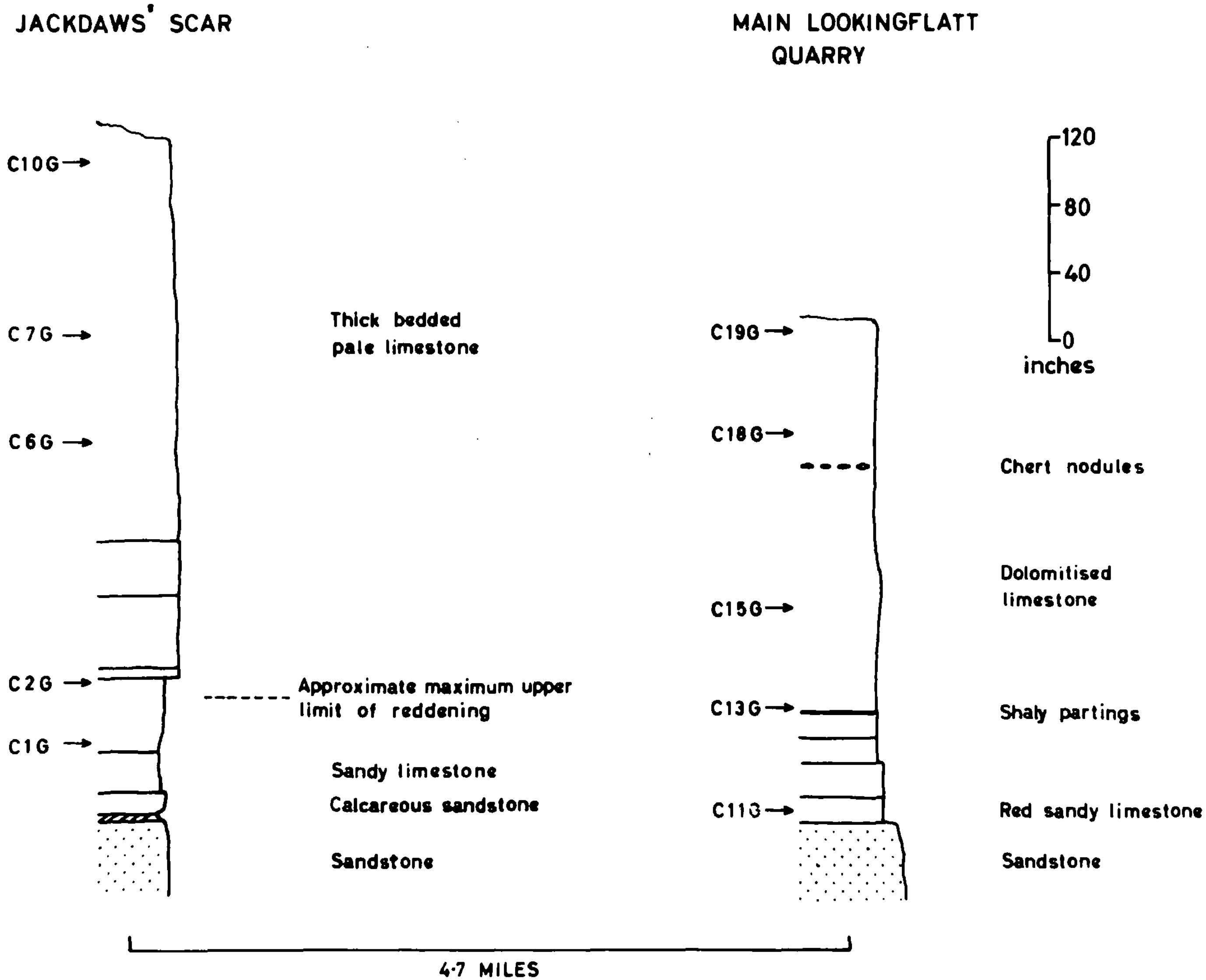
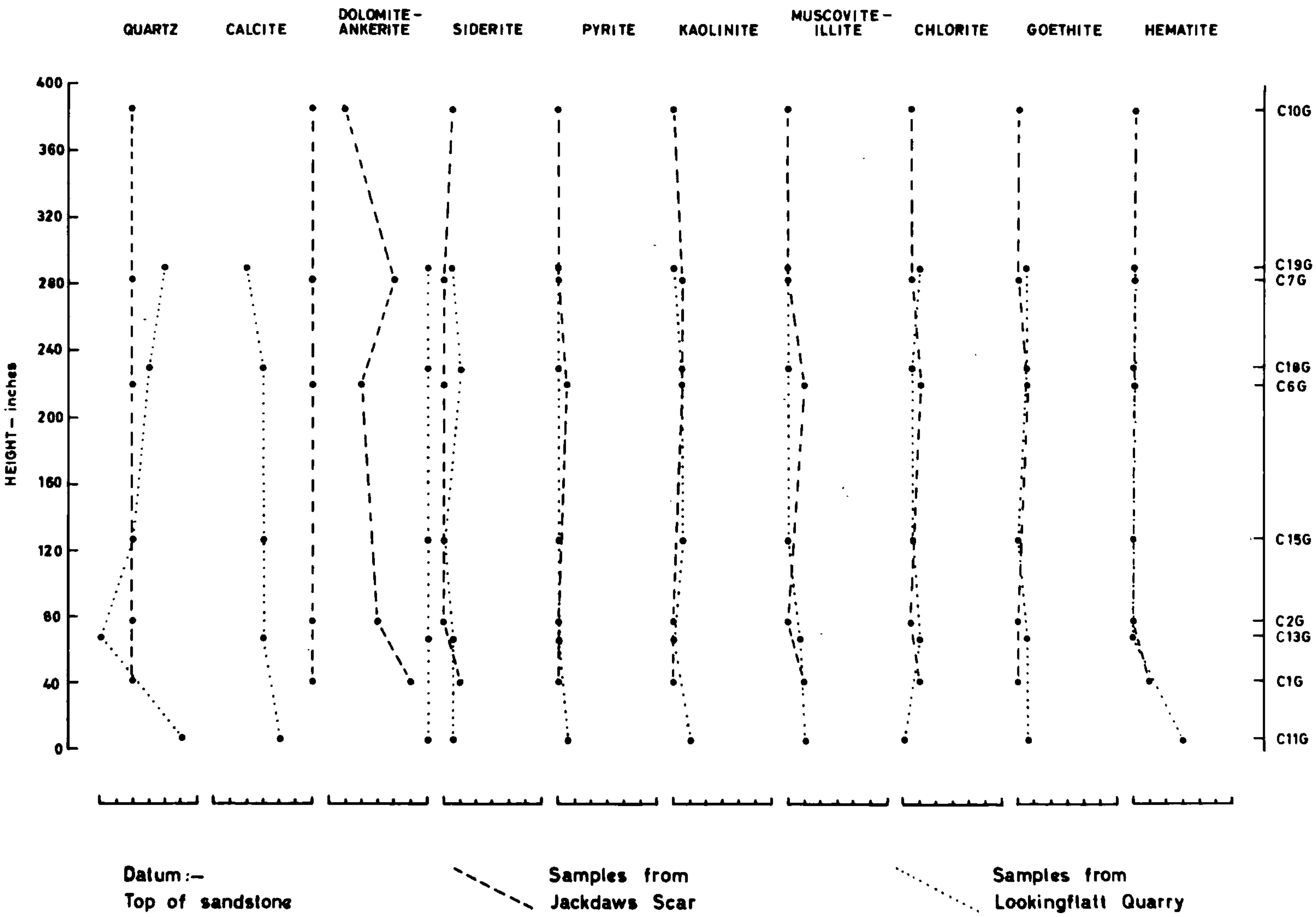


Figure 5.2

MINERAL VARIATION THROUGH THE GREAT STRICKLAND LIMESTONE



altered limestone of Jackdaws' Scar.

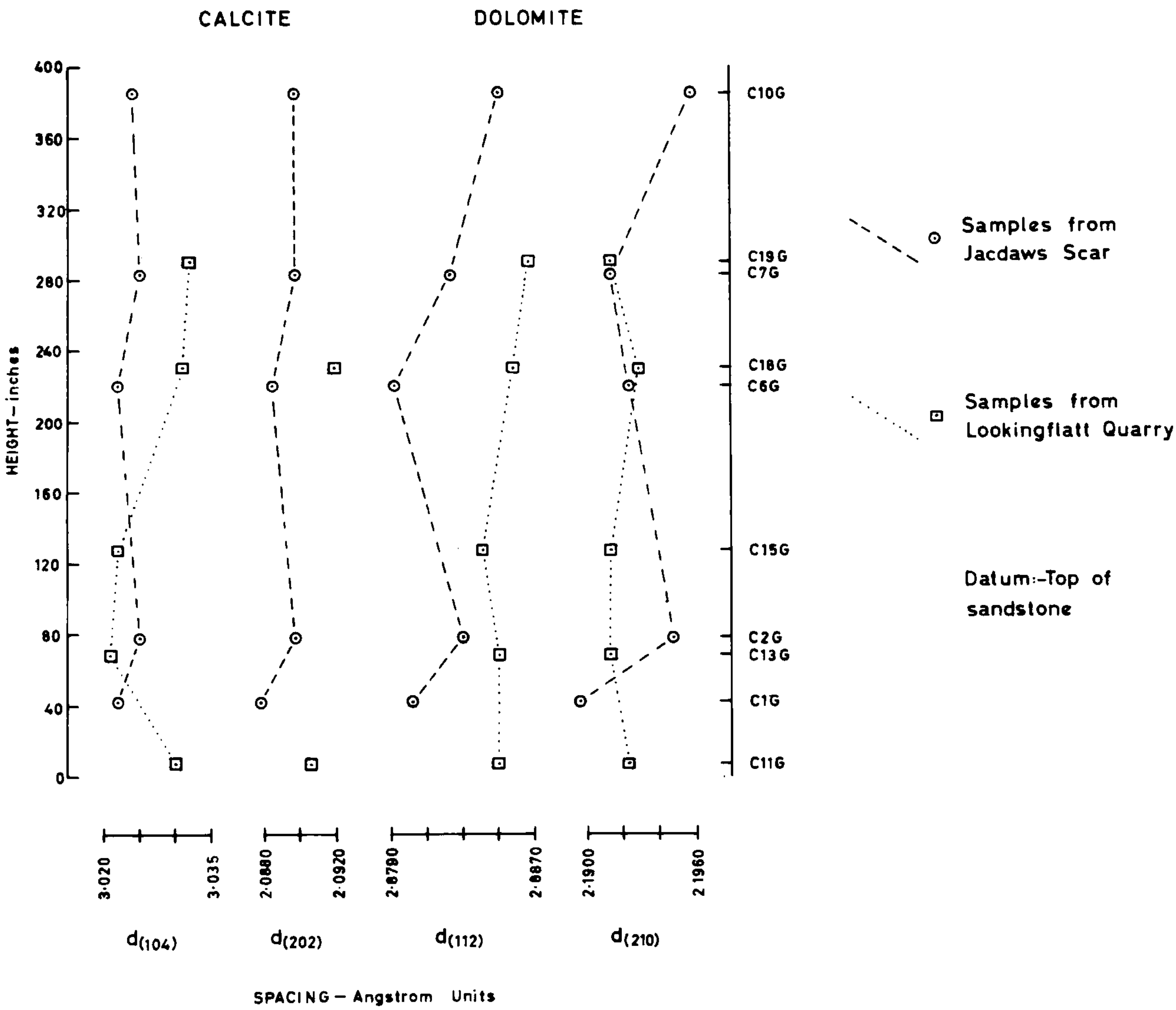
The most striking changes are shown by the carbonates, dolomite-ankerite being the major constituent throughout at Lookingflatt, and calcite being reduced to a minor role except at the base where a moderate amount still remains. At higher levels some of the calcite is secondary, occurring as it does in veins, but some fossils and possibly part of the groundmass must also be undolomitised. The steady upwards decrease in calcite content is the result of its increasing conversion to dolomite and is one of the several pieces of evidence, all of which point to the conclusion that the dolomitising agents acted from above. The quartz distribution is also important in this respect; whereas in the fresh limestone it occurs throughout in uniformly small quantities, at Lookingflatt (excluding the sandy base) it is entirely absent low in the succession but gradually increases upwards so that in C19G, from just below the unconformity it is present in moderate amounts. This strongly suggests that it was extensively redistributed, having been dissolved from horizons low in the limestone and precipitated nearer the New Red Sandstone erosion surface.

Clay minerals are present in very small quantities and are difficult to identify but chlorite (and possibly, locally, some magnesian septechlorite) is undoubtedly present throughout as are mixed-layer illites. Clay minerals with spacings between 19 Å and 15 Å are relatively common in C11G, C13G and C18G and may be montmorillonoids in various stages of hydration; except perhaps in the sandy limestone the presence of kaolinite is doubtful.

The remaining minerals are present in very small quantities and show no important variation or much difference in distribution from that in the Jackdaws' Scar section. There is no definite evidence that either

Figure 5.3

VARIATION IN CARBONATE COMPOSITION THROUGH THE GREAT STRICKLAND LIMESTONE



siderite or pyrite are present at any level; hematite is very common at the base but becomes rare upwards and is absent from the top, whilst small amounts of goethite occur throughout. Feldspar is only important in the basal sandy limestone, whilst calcium phosphate is found at higher levels but may have been partially replaced by a magnesium-bearing phosphate as a result of the dolomitisation; for the same reason, a trace of magnesite may also occur.

The effect of the dolomitisation on the d-spacing of some of the carbonate peaks is illustrated in Fig. 5.3. Apart from C13G and C15G which have no significant change in spacing, the calcium carbonate is apparently slightly purer after dolomitisation. Probably the foreign ions were partially removed during this process and incorporated into the magnesium-bearing carbonate, which seems intermediate in composition between dolomite and ankerite and less pure than the corresponding carbonate from the limestone at Jackdaws' Scar. The absence of significant variation in d-spacing of the largely newly-formed dolomite-ankerite may indicate that some overall unifying factor was operative, although there is evidence (below, page 206) that compositional uniformity is not maintained.

ii) <u>Trace element distribution</u>

The strong variation in the content of many of the trace elements and important differences from what would have been expected in the absence of dolomitisation are clearly seen in Figs. 5.4, 5.5 and 5.6. Basically two patterns of distribution are present and are essentially independent of any mineral variation; strontium, zinc, nickel cobalt and manganese have their maximum abundance near the middle of the succession (C15G) or

TABLE 18

Trace element content in parts per million

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
C10G	-	1024	-	(20)	-	27	23	-	300
C7G	-	896	-	(22)	-	29	22	-	581
C6G	-	949	-	-	-	25	20	-	513
C2G	-	1261	-	(25)	-	28	23	-	472
C1G	-	360	(7)	37	-	22	24	6	1658
C19G	-	75	11	(23)	-	29	35	10	1983
C18G	-	63	(8)	37	-	27	31	-	1972
C15G	-	98	-	(25)	11	18	54	26	11392
C13G	-	119	(7)	31	14	23	40	12	8499
C11G	125	79	12	26	-	26	37	-	1214

The trace element content of samples from the Great Strickland Limestone.

TABLE 19

Trace element content in parts per million

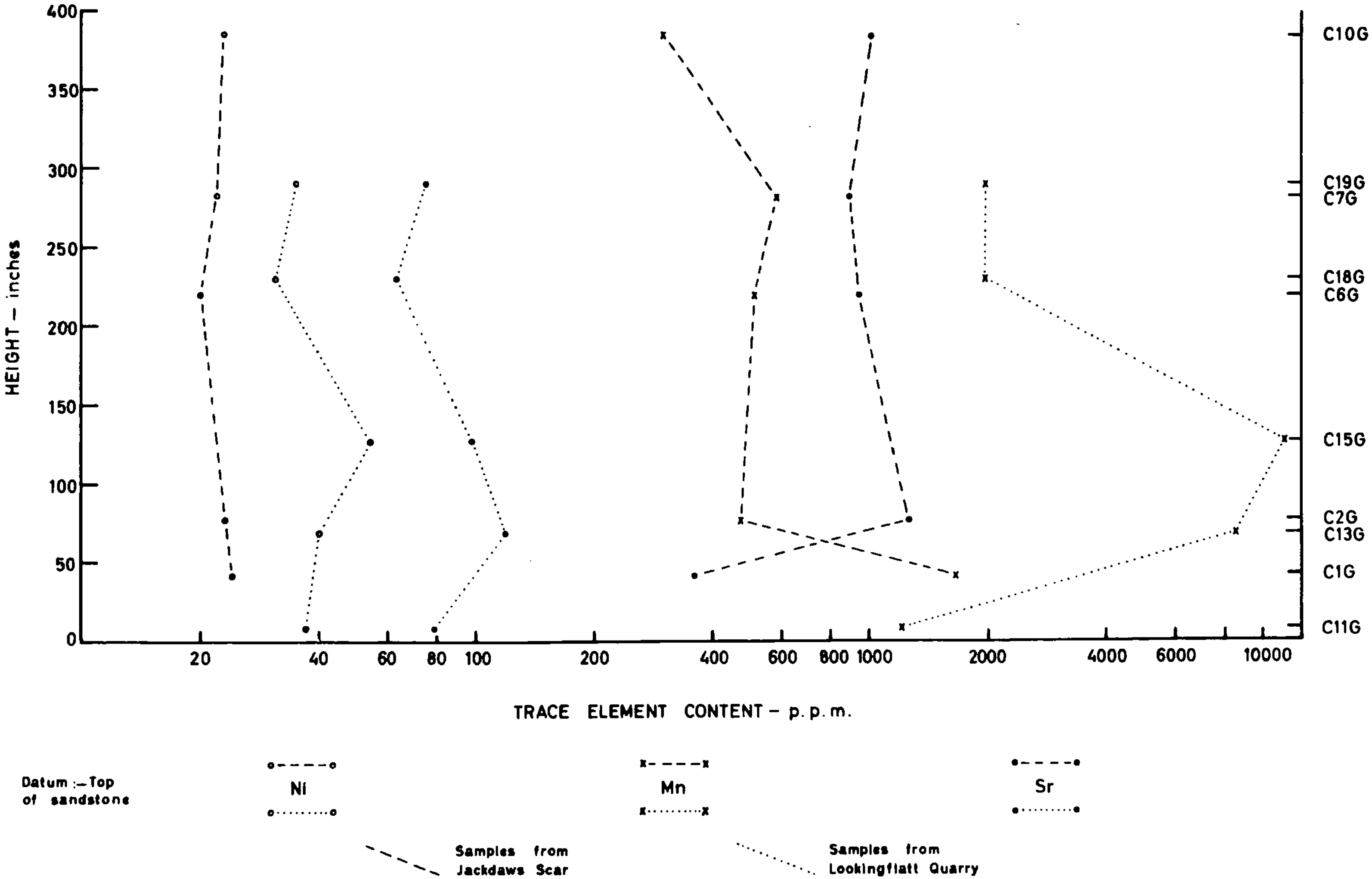
	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn
Dolomitised Limestone	89	(8)	29	(6)	24	40	13	5962
Mean C2G — C10G	1034	-	(20)	-	27	22	-	467

The trace element content of dolomitised and relatively fresh limestone.

(C1G & C11G excluded from the mean values)

Figure 5.4

VARIATION IN MANGANESE, NICKEL AND STRONTIUM THROUGH THE GREAT STRICKLAND LIMESTONE



just below (C13G), whilst the other four elements have a minimum at this level. Table 18 shows the contents of the different horizons.

The slightly higher abundance of most of the elements in the dolomitised limestone as compared with the relatively unaltered limestone (Table 19) is probably only a relative enrichment resulting from the substitution of magnesium for the heavier calcium ions, and does not mean that extra quantities of these elements have been added to the rock; this does not apply to the very large difference in manganese content.

a. STRONTIUM

With a mean abundance of only 89 ppm, large quantities of strontium have clearly been removed from the Limestone as the calcite was converted into dolomite which, with its smaller cell-size, is capable of holding much less of the element. The present distribution bears no relation to that of calcite (though this mineral probably contains most of the small quantity which remains) but is the result of the powerful dolomitisation process which has re-assembled many of the trace elements in conformity with the first of the two patterns described above.

b. MANGANESE

Large quantities of manganese have been added to all horizons except, perhaps, the sandy base of the sequence, during dolomitisation and in the middle it constitutes over 1% of the rock. In contrast to occurrences in unaltered rocks, the manganese variation now follows an essentially parallel course to that of strontium and the two must result from the same process of redistribution. Presumably the manganese is largely

Figure 5.5

VARIATION IN COPPER, ZIRCONIUM AND LEAD THROUGH THE GREAT STRICKLAND LIMESTONE

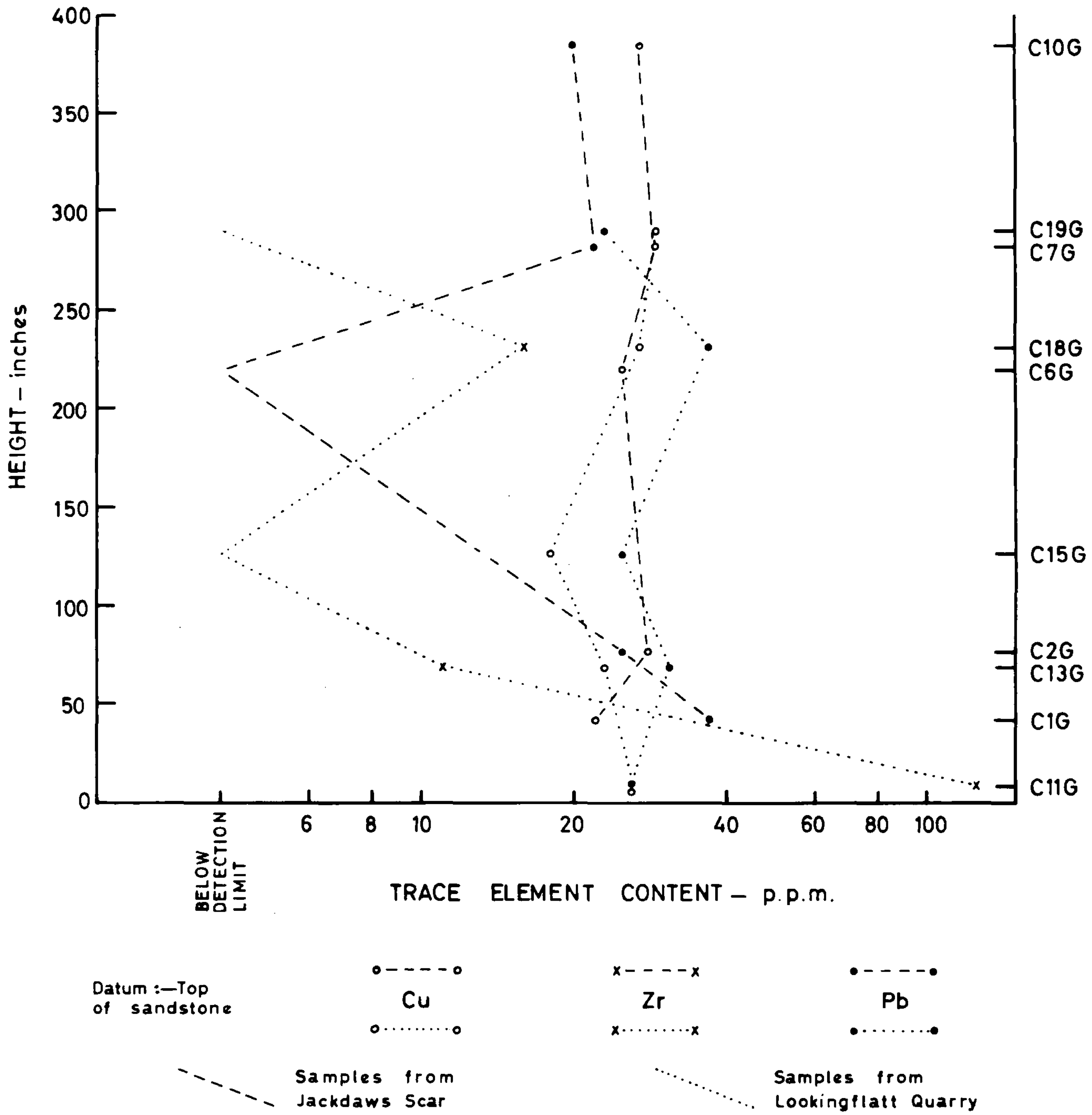
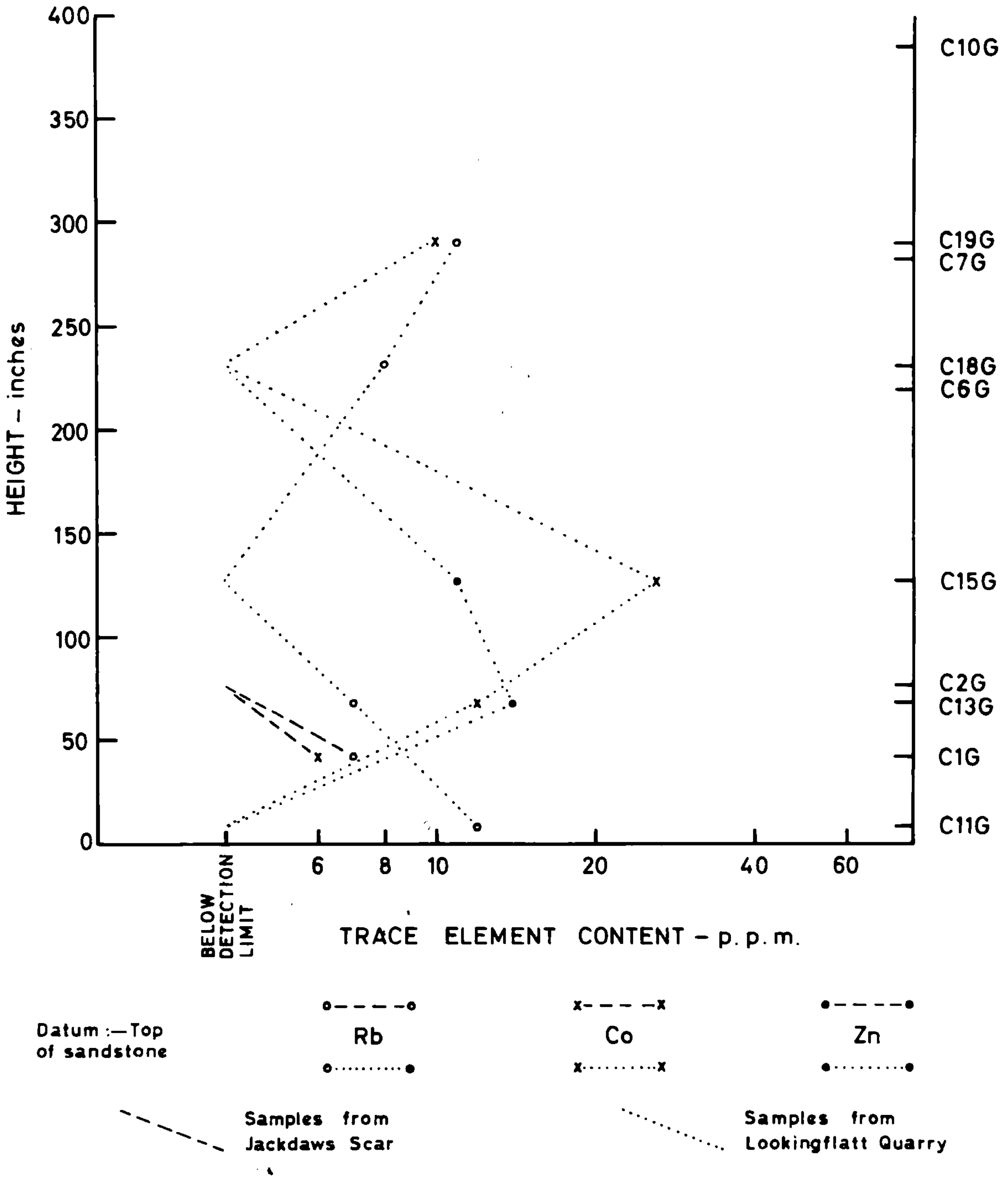


Figure 5.6

VARIATION IN COBALT, ZINC AND RUBIDIUM THROUGH THE GREAT STRICKLAND LIMESTONE



associated with dolomite-ankerite but this scarcely varies in abundance so that it must contain vastly different quantities of the element at different levels. Although a little iron has been added to the rock the presence of manganese ions must, to an important extent, account for the relatively large d-spacing of the dolomite (Fig. 5.3). It is, in fact, unusual that in spite of the very high contents of manganese which the dolomite of C13G and C15G must contain, their d_{102} values are almost the same as those of the other dolomites at this locality. The reason, perhaps, is that at this level the manganese substitutes not only for the small magnesium ion but also for the larger calcium, so that the resulting changes in cell-size are partially compensatory.

c. ZINC, NICKEL, COBALT

All three elements are relatively enriched in the dolomitic limestone, though there is no reason to believe that quantities have been added during the dolomitisation. This process has, however, caused a strong redistribution and concentration of the elements at the same levels (C13G and C15G) as with strontium and manganese. In addition, cobalt is enriched at the top of the succession.

d. RUBIDIUM

Rubidium has a completely different distribution, increasing in abundance symmetrically about a minimum at C15G. It is uncertain whether this is entirely produced by the same process which caused the redistribution of the other elements or if it is, at least in part, a reflection of primary differences, related to the clay (and especially the montmorillonite) content.

e. LEAD, COPPER

The small variation of these elements is probably not significant and there has been little or no change during dolomitisation, except probably the loss of a little copper. The fact that both now have low values at C15G is presumably the effect of the lack of redistribution of these elements combined with the great increase of several others, most notably manganese, at this horizon.

f. ZIRCONIUM

Zirconium is below the detection limit in all except the sandy limestone where it will be principally due to the presence of detrital zircon. It has been shown in Fig. 5.5 also at the two levels where it appears to be over 10 ppm to illustrate the similarity of its distribution with that of lead but, again, there is some doubt as to whether this has any real significance.

B. REDDENED LIMESTONE

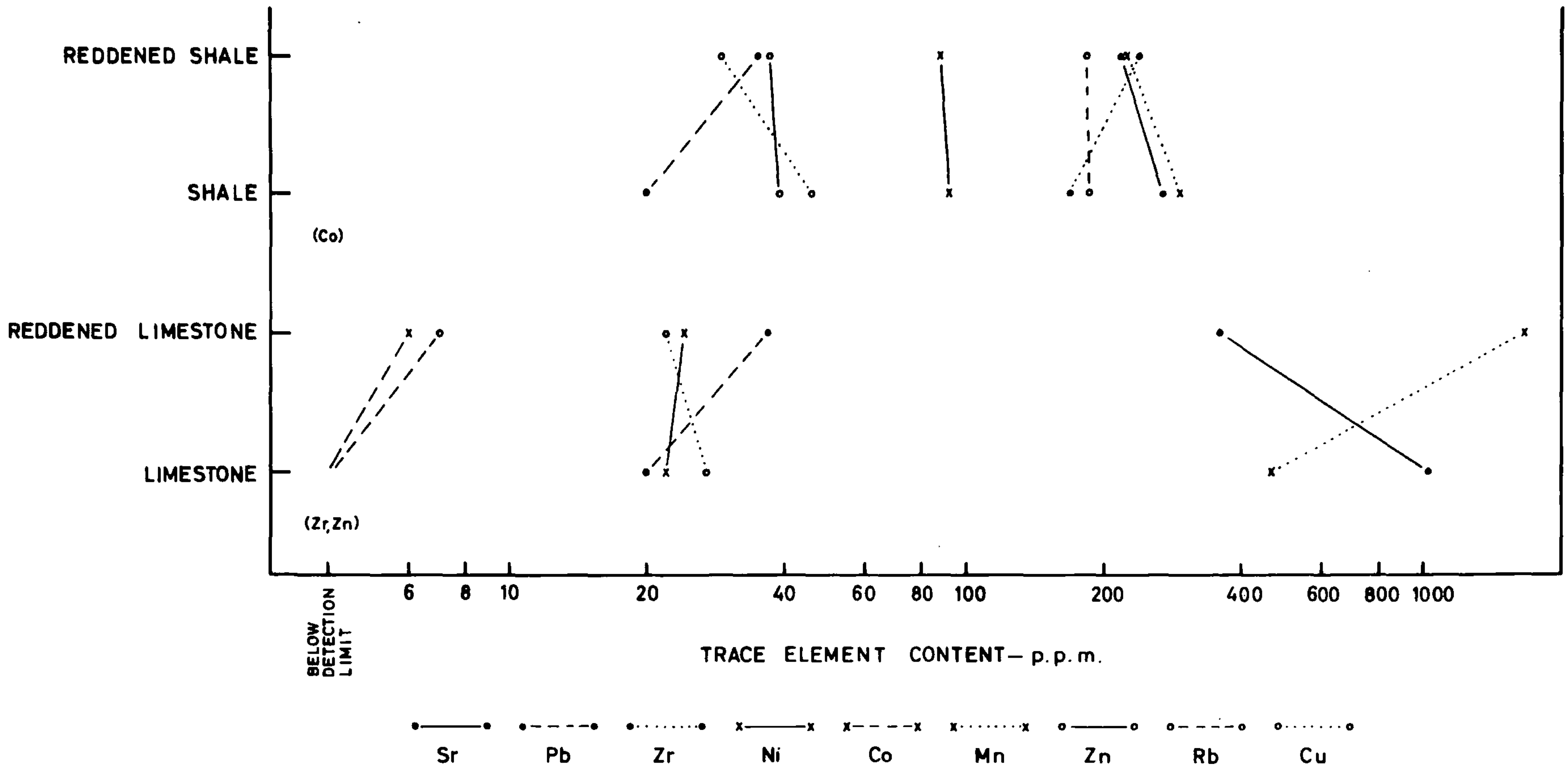
None of the major limestones is reddened throughout but several of the highest in the succession have a strongly reddened zone at the base and some red flecks above. Unfortunately, these same limestones have invariably been partly dolomitised and, although the two processes were probably unrelated and did not take place together, it is impossible to be sure in most cases, especially with respect to the trace element variation, which was the dominant process in bringing about the observed changes.

The relatively unaltered Great Strickland Limestone at Jackdaws' Scar was studied in an attempt to elucidate the changes involved in the reddening process but, as can be seen in Fig. 5.2, the reddened limestone, C1G, contains more dolomite-ankerite than the higher part of the succession, so that the differences between them could be largely the result of the more intense dolomitisation which the reddened limestone has undergone. Mineralogically there seems no significant change consequent upon the reddening apart from the extensive production of hematite from the iron-bearing minerals, in this case mainly from the dolomite-ankerite. It is difficult to say if the oxygenating fluids carried additional iron into the reddened rock because, although spectrograph traces suggest that the rock contains more iron than the fresh limestone, it lies quite near the base of the limestone - a level at which iron is normally primarily concentrated in any case.

A comparison of the trace element content of C1G and the average of the four higher samples is shown in Fig. 5.7 and the values are included in Tables 18 and 19 respectively. The large differences in the contents of strontium and manganese are in the same direction (and of the correct

Figure 5.7

COMPARISON OF TRACE ELEMENT CONTENT OF REDDENED AND NON-REDDENED STRATA



magnitude) as the changes brought about by dolomitisation so that any independent effect accompanying the reddening cannot be assessed. The appearance of cobalt and rubidium and, to a lesser extent, the fall in copper content in C1G may also be attributed to dolomitisation. This process would have been expected to produce a relative increase in abundance of nickel and its constant value may indicate that a little has been removed during reddening. The latter process might have caused a concentration of lead since this element seems to undergo a lesser increase during dolomitisation (Table 19). However, there is no evidence that the percolation of oxidising fluids which were responsible for the reddening had any major effect upon the trace element content of the limestone.

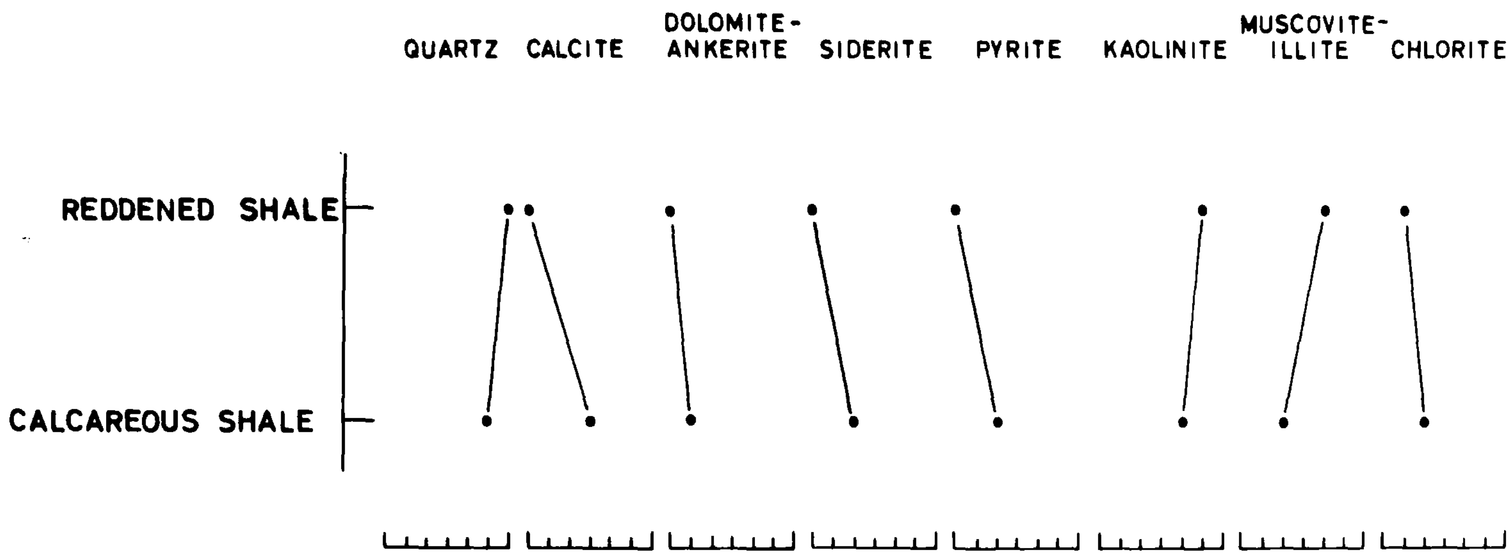
C. REDDENED SHALE

Reddened shale (C1L) from a short distance above the Great Strickland Limestone has been studied to determine any mineralogical or trace element changes as compared to non-reddened shale. No fresh material from the same horizon occurs so a comparison has been made with the average of the two calcareous shales sampled from the Askham clastic succession. The calcareous shales were chosen because of the probably original calcareous nature of the reddened shale, in view of the presence of fossil traces and abundant ironstone nodules.

i) Mineralogy

Fig. 5.8 compares the mineralogy of the two rock types, the greatest difference being in the loss of all of the carbonates from the reddened shale with a resulting relative increase in the quartz content and the appearance of large quantities of hematite, probably an important part of which is iron derived from these carbonates. Pyrite is another source of the iron and is absent from the reddened shale. The height of the iron K peak on the spectrograph traces indicates that the reddened shale does not contain more of this element than do the non-reddened calcareous shales. Mixed-layer clays and 14 Å chlorite almost vanish and their place seems to be taken by a 7 Å chlorite mineral but the abundance of kaolinite, which is even richer in the reddened shale than in the calcareous shales, makes identification difficult. The apparent increase in 10 Å minerals is probably due to the presence of a greater proportion of muscovite and an increase in crystallinity as a result of the alteration.

Figure 5.8



COMPARISON OF MINERALOGY OF REDDENED AND NON-REDDENED SHALE

ii) Trace element content

The trace element content of reddened and non-reddened shale is shown in Fig. 5.7 and Table 20, but, because the samples are from completely different horizons, they must be interpreted with caution. No significance can be attached to the very slight fall in the contents of rubidium, zinc and nickel in the reddened shale and the increase in zirconium is thought to imply only that there is more detrital zircon at this particular horizon. Strontium has, in part, been removed along with the carbonates but it has not fallen to a level typical of the other shales examined and some must have been incorporated in the newly-formed or regenerated clay minerals. The decrease in manganese, too, is attributable to the loss of the carbonates, especially the siderite.

The large differences in the copper and lead contents, not paralleled in the non-calcareous shales and therefore not solely owing to the loss of calcite, seem to be the most significant changes brought about by the reddening process. They are presumably located in the clay minerals which appear, therefore, to gain lead and to lose copper - differences which were noted as occurring in the reddened limestone.

TABLE 20

Trace element content in parts per million

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Mn
Reddened Shale	240	219	183	35	37	29	88	224
Calcareous Shale	169	270	185	(20)	39	46	92	293

The trace element content of reddened and non-reddened shale

D. REDDENED SIDERITE CONCRETIONS

The trace element content of an oxidised siderite concretion (C3L) and the shale immediately surrounding it (C2L) (Fig. 5.9 and Table 21) was determined to study the differences with comparable non-reddened rocks. Sample C1L (above) is from the same horizon but is not adjacent to a concretion.

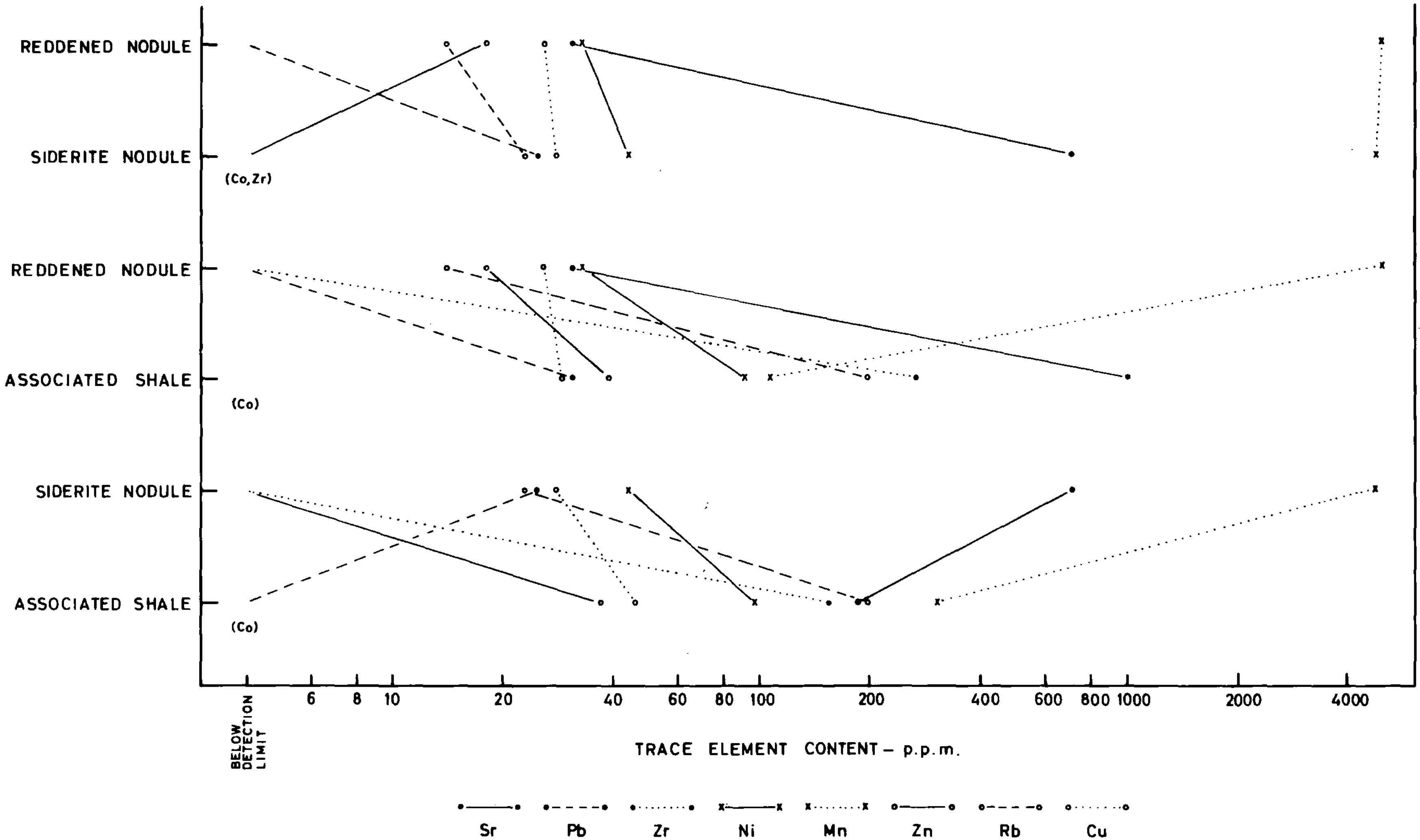
Mineralogically, the oxidised concretions differ from normal ironstone concretions in that the siderite is replaced by hematite, although in the rock studied a trace of siderite remained. Minor quartz and kaolinite (which occurs in small white veins) and traces of pyrolusite and pyrochroite are the only other minerals present apart from a little goethite resulting from the hydration of hematite.

The strontium content, as in other reddened strata, is greatly reduced as compared to that of the fresh concretions owing to the loss of carbonates but, in contrast, manganese, because it is readily oxidised and immobilised as manganic oxides, has not been removed. It probably also occurs in solid solution with Fe^{++} in the hematite which, from its large d_{104} spacing, must contain foreign ions. No significant change occurs in the copper and nickel contents, the former being in contrast to the fall associated with the reddening of shale. Both rubidium and lead may have been removed and the reddening process has effected a definite concentration only of zinc.

The reddened concretion, in comparison with the associated shale, is poorer in all except manganese and so the relationship of the trace elements differs little from that displayed by the fresh concretions and their associated shales, shown in the same Figure. The exceptions are strontium which has been lost from the reddened concretion together with

Figure 5.9

TRACE ELEMENT CONTENT OF IRONSTONE NODULES AND ASSOCIATED SHALE



the carbonates, and lead which appears to have been transferred from the reddened concretion to the nearby shales, in contrast to the unaltered rocks where it has been segregated into the siderite concretions.

There is very little difference in trace element content between the red shale immediately around the concretion and that further away (Table 21, C2L and C1L).. The concentration of manganese into the concretion is indicated by the much lower content of this element in the shale nearest to the concretion and the process is probably accomplished during the reddening since the same relationship is not shown by the equivalent non-reddened shales (C8H and C1H, Table 13). The difference in strontium is also interesting, the very much higher quantities in the red shale near the concretion (C2L) indicating that, although this element was removed from the concretion itself, it was not carried more than a few inches away and must have been taken up rapidly by the clay minerals.

TABLE 21

	Zr	Sr	Rb	Pb	Zn	Cu	Ni	Mn
Siderite Concretion (C7H)	-	710	23	(25)	-	28	44	4796
Oxidised Concretion (C3L)	-	31	14	-	18	26	33	4949
Associated Red Shale (C2L)	268	1006	197	31	39	29	91	106
Red Shale (C1L)	240	219	183	35	37	29	88	224

<u>The trace element content of reddened ironstone concretions and their associated shale</u>

CHAPTER 6

SEDIMENTARY ENVIRONMENT

A. THE CARBONIFEROUS

The Carboniferous succession, though less than a thousand feet thick, includes a great variety of lithofacies indicative of a frequently changing depositional environment and, in itself, stronly suggestive of a shallow water origin for the sediments. Basically, an alternation of predominantly chemical, and predominantly detrital, sedimentation can be recognised and, as noted by numerous workers, the strata are a record of the delicate interplay of these fundamentally different types of deposition. The probable nature of the most often recurring environments is discussed below but insufficient data are available to consider adequately all of the varied micro-environments which, from what is known about contemporary shallow water sedimentation, must have existed.

i) The major limestones

a. SOURCE AND TRANSPORT

The main Yoredale Limestone horizons contain, through most of their thickness, more than 98% of carbonates which have been derived from the water of the depositional area, both directly as precipitates and with the aid of organisms. Ultimately it has been produced by the chemical weathering of bordering land areas and entered the basin of deposition in solution, essentially as the bicarbonate, in river water. No carbonate of detrital origin, other than rare intraclasts having an intra-basinal source, is known.

b. PHYSICO-CHEMICAL CONDITIONS

For its precipitation, calcium carbonate requires an environment which is alkaline; in acid solution, the solubility product of $CaCO_3$ is not exceeded owing to the conversion of carbonate anions into bicarbonate and undissociated carbonic acid:-

$$CO_3^{--} + H^+ \rightleftharpoons HCO_3^-$$
$$HCO_3^- + H^+ \rightleftharpoons H_2CO_3$$

According to Krumbein and Garrels (1952) calcium carbonate only occurs in minor quantity if the pH is between 7 and 7.8 and consequently the major limestones must have been deposited in water whose pH exceeds this latter value. Since large bodies of water having a pH greater than 8.5 do not occur, a pH in the vicinity of 8 may reasonably be expected to have prevailed at this time.

The redox conditions can be deduced with less accuracy but, because of the presence of an abundant benthonic fauna, the waters must have been oxidising and, by analogy with present day seas, an Eh of 0.1 to 0.4 is probable. However, below the depositional interface, any trapped organic material is likely to have produced reducing conditions; these were responsible for the preservation of the organic compounds which give many of the limestones their bituminous smell when broken, and for the ferrous state of the iron present. In particular, where pyrite occurs the Eh within the sediment may have been as low as −0.3 (Fig. 6.1).

The fauna is of a type which today is found in saline waters having a mean salinity of the order of 35‰. The same general conditions of salinity probably prevailed during limestone deposition, there being no faunal element suggestive of brackish water nor any chemical precipitates

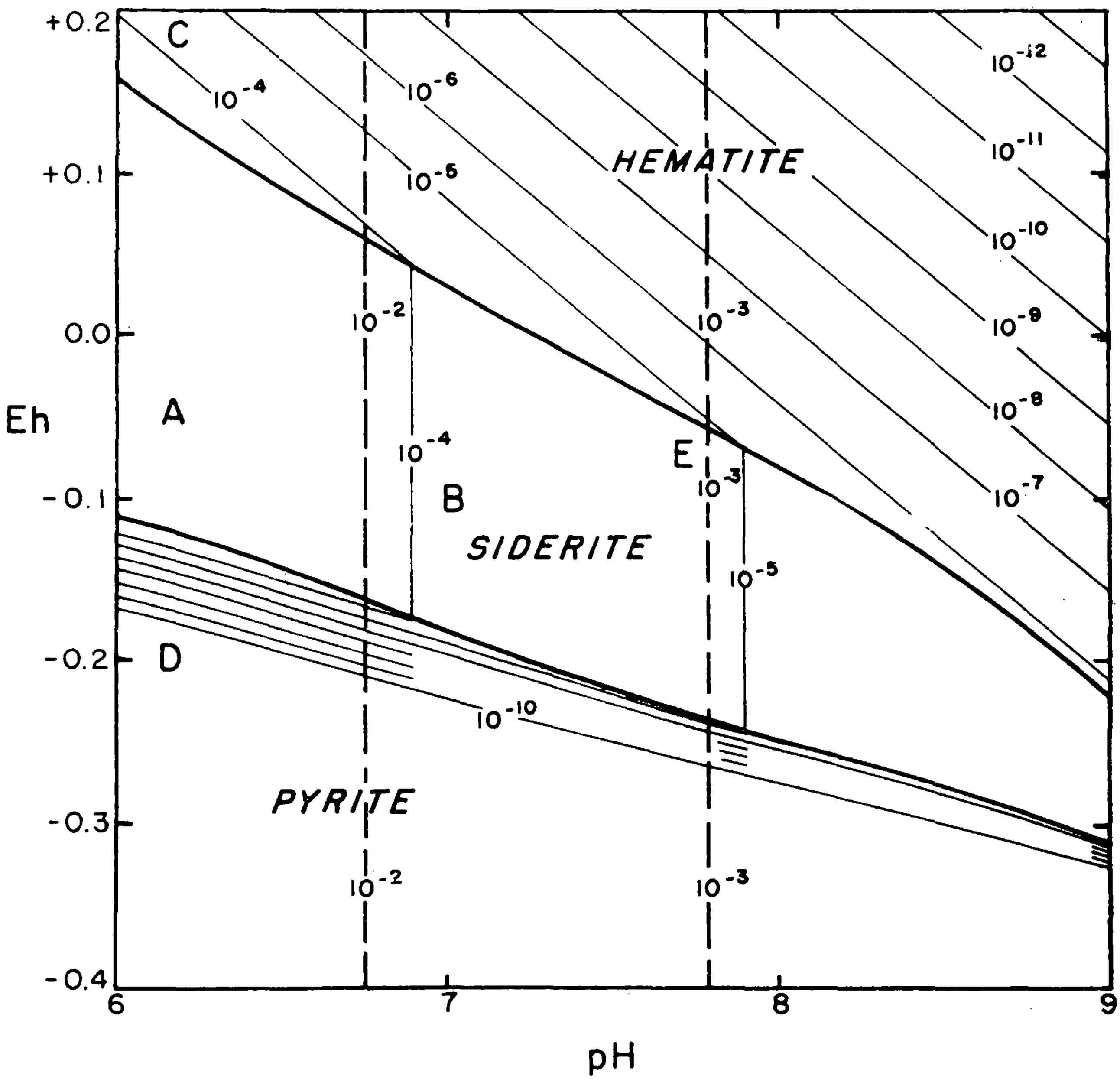


Figure 6.1

(after Krumbein and Garrels 1952)

which could indicate the existence of a more saline environment. The varied fauna and the frequent occurrence of corals, which today thrive only in tropical and sub-tropical waters, as well as the presence of chemically precipitated carbonate, indicate that the water was warm throughout the year, probably being between 20°C and 30°C. Similar considerations are suggestive of a depth of water such that sunlight could penetrate in strength to the bottom; 100 feet to 150 feet is a probable maximum, with much deposition occurring at shallower depths.

c. NATURE OF THE ENVIRONMENT

The deduced conditions of sedimentation can only be provided by an entirely marine environment and, if present day parallels are a guide, one which lay in tropical or sub-tropical regions. Terrestrial influences were essentially absent, largely because the limestones accumulated at a considerable distance from the shore. In addition however, land-derived material would tend to be excluded if, there lay, between the source of this material and the areas of thick limestone deposition, regions of greater subsidence which could trap much detritus. The Northumberland Trough (page 122 and Fig. 2.24) and the regions south and west of the Craven Faults may well have behaved in this manner. If limestone deposition were accompanied by a rising base-level of erosion due to, say, regional subsidence, a similar reduction in the quantity of detritus would be effected.

A combination of these circumstances resulted in the deposition of chemical sediments with an average of less than 1½% of sand and mud. The latter represents the finest detrital material which was able to remain in suspension over a long period of time or was carried over the sea by winds; locally, strong currents may have been responsible for some of the sand but winds are a more likely alternative and much may be from siliceous organisms, the shell material of which would be concentrated into small patches of opal and subsequently recrystallised to quartz.

The warm shallow and saline water was able to support much life and large but varying proportions of the limestones are made up of their remains, the most common of which are the now completely fragmented and redistributed crinoids. Entire fossils, especially the colonial corals and Productids, normally occur in thin but widespread bands where they appear to be in situ and may indicate small favourable changes in the environment such as the occurrence of a stronger current bringing in increased supplies of nutrients. Horizons with abundant algal nodules are common in the older limestones and may be indicative of particularly shallow water or even lagoonal conditions as suggested by Garwood (1912). They are said to characterise the upper part of the limestones (Hudson 1929) but in those studied they are probably more frequently found towards the base.

Organisms are undoubtedly also indirectly responsible for the precipitation of some of the remaining carbonate because, during photosynthesis, plants remove carbon dioxide from the water, thereby reducing the hydrogen ion concentration and increasing the quantity of CO_3^{--} present. In spite of this, there is no reason to believe that much of the carbonate mud was not precipitated inorganically as the saturated water becomes heated, perhaps in passing into shallower regions. Illing (1954) has suggested such a mechanism for the origin of much of the non-skeletal calcium carbonate on the Bahama Banks.

It is not however possible to draw too close a parallel with the very specialised Bahaman environment where large areas of water with a depth not exceeding 30 feet are surrounded by deeps reaching over 12,000 feet. There were no similar deeps surrounding the shelf seas of north England in Carboniferous times and most of the limestone was deposited in a lower energy environment as is evidenced by the absence of oolitic limestones and the almost universal occurrence of calcareous ooze. For their formation, ooliths require the winnowing-away of ooze and constant agitation by strong currents and consequently these must have been absent. Certainly, there is no evidence for the existence of features of strong relief on the sea-floor or of small cays with beaches, both of which, by virtue of tidal movements, might be expected to produce strong currents.

On the other hand, it is not suggested that currents were absent since water movements of some strength are required to cause the extensive redistribution of crinoid and other fossil fragments, though these, at the time of deposition, would be relatively light, their pores not having been in-filled. The abundance of ooze can be attributed not only to the absence of strong currents but also to a high rate of precipitation and the difficulty, characteristic of most fine-grained sediment, of returning it to suspension once settling has occurred. Evidence has been presented (pages 167 to 171) to show that both calcite and aragonite mud were deposited and it is thought that the latter was favoured in areas of the shelf where currents were at a minimum. This could have been where the water was deep and still but, in view of the necessity to achieve supersaturation, is more likely to have occurred in shallow low-energy environments where the water could become especially warm. At the present day, aragonite mud is precipitated in the lea of large islands in the Bahamas and similar restricted conditions are envisaged for the Visean limestones though probably with submerged banks of organic material rather than islands serving to reduce current strengths.

Periods of stronger current action are indicated by horizons with sparry calcite instead of ooze but they are restricted to thin bands at or near the base of the limestones before the general limestone-depositing conditions had been fully established. At higher levels, only the bedding-planes remain as evidence for increased current activity (see Schwarzacher 1958) which then appears to have been strong enough to prevent deposition and also probably led to some erosion. The alternative, that precipitation was prohibited by a reduction in the pH, is unlikely in the absence of any supporting evidence. This is not, of course, true when a marl parting occurs since then there is definite evidence of a temporary terrestrial influence which may well have brought in fresher and less alkaline water. Usually however, the concentration of crinoid and shell debris just below bedding-planes is more suggestive of increased current action and this is certainly the case where erosion surfaces of some relief are developed as in the Grayber and Bewley Castle Limestones. Irrespective of the precise nature of the change in environment which results in the production of bedding-planes, there is no doubt, from their often wide lateral extent, that this change was contemporaneous over a large area of the shelf-sea; their importance for correlation purposes cannot be over-emphasised.

d. MINOR PRECIPITATED PHASES

Further information concerning the nature of the environment can be obtained from some of the minerals present in only small quantities, especially if they are locally concentrated; they are discussed individually below.

Pyrite

Since the benthonic fauna shows that the depositional environment was oxidising, the pyrite present in some of the limestones must have developed below the sea floor. Here, aerobic decomposition of the organic matter to produce carbon dioxide soon exhausts the oxygen supply and the environment becomes suitable for anaerobic bacteria which extract oxygen from sulphates in the pore solutions and in organic compounds. This results in the production of hydrogen sulphide and causes the precipitation of any iron in the solutions as ferrous sulphide, hydrotroilite $FeS.nH_2O$, largely giving rise to the dark colour of much of the limestone. Light coloured limestone will, therefore, be favoured where there is a better supply of oxygen to decaying organic matter, either because of the presence of stronger ventilating currents or because it is not liable to rapid burial. The overall upward rise in pyrite content through the Little Strickland Limestone seems to indicate a gradual decrease in the capacity of the environment to bring about the oxidation of organic matter on the sea-floor. This is only partially due to the existence of shallow restricted areas (as indicated by high strontium contents) and is also thought to indicate a progressive deepening of the basin of deposition.

Calcium phosphate

Phosphorite is precipitated under similar conditions to calcium carbonate, the PO^{--} ion being strongly pH dependent (Krumbein and Garrels 1952). It has been suggested (op.cit.) that a relatively low pH would precipitate the phosphate without calcite, but it occurs in the Yoredale limestones in such small quantities that co-precipitation with calcium carbonate is sufficient to explain its presence. In the absence of a knowledge of the precise variation in the solubility of phosphorite with pH, the significance of the upward increase in quantity found in the Little Strickland Limestone cannot be assessed. Possibly, because the mineral is relatively insoluble, most is precipitated as soon as it reaches water with a sufficiently high pH, leaving only very small quantities to be precipitated towards the centre of the basin.

Dolomite-ankerite

The iron-bearing dolomite found in very small quantities in the unaltered limestones is almost certainly of secondary origin, being the result of redistribution of the magnesium occurring in the fossils. Chave (1954) has shown that the shells of most organisms contain some magnesium carbonate, which often constitutes 5% to 10% of the material and may reach nearly 30% in some algae. If organic material with an average magnesium carbonate content of 7½% made up 40% of a typical limestone then, provided that none has been removed, the rock will now contain 3% of magnesium carbonate or about 6% of dolomite. This is certainly sufficient to account for the presence of dolomite-ankerite peaks in the X-ray diffractometer traces. It has remained scattered through the limestone except locally where it occurs in irregular ferruginous-weathering patches. The general absence of siderite suggests that the amount of iron present in these marine waters was almost invariably so small that it was able to be incorporated in the other carbonate minerals.

The Johnny Hall's Trees Limestone with its abundant dolomite is a special case. The cavities suggest that the dolomite was not a primary precipitate, whilst the lack of dolomitisation in the adjacent limestones seems to preclude a late secondary origin. The equivalents of the

Limestone throughout much of the northern Pennines show the same characteristics, indicating that penecontemporaneous dolomitisation at this horizon was widespread and that for a brief interval there existed conditions somewhat different from those which produced the typical limestone horizons. The nature of this special environment remains uncertain but high salinity induced perhaps by decreased subsidence giving rise to extensive shallows may have been an important contributory factor. According to Teodorovich (1961) dolomite will replace calcite under conditions of high CO_2 pressure and low pH, whilst Ingerson (1962) records that dolomite is forming in lagoons in South Australia, probably penecontemporaneously, under pH conditions ranging from 8.5 to 9.2, high temperature and a salinity up to four times as great as that of the sea. Similar extensive shallows at the time of formation of the Johnny Hall's Trees Limestone in which there occurred many organisms with magnesium-rich skeletal material and plants whose photosynthesis produced alkaline conditons may explain the unusual nature of this deposit.

Silica

A component which appears in the limestone horizons at and above the level of the Grayber Limestone is silica, usually in the form of layers of nodules but occasionally as thin banded cherts, as those in the upper leaf of the Newby Mill Limestone.

At present, both rivers and the sea contain less silica in solution than is required to saturate the water with amorphous silica (Krauskopf 1956) and it is likely that the same situation prevailed in the Visean seas and rivers. Consequently, normal precipitation resulting from, say, pH or temperature changes cannot have been an important factor, especially since the solubility of silica is not much influenced by pH changes in the range of 2 to 9 (Krauskopf op.cit.). Biological agencies are the most likely cause, therefore, for the appearance of the silica, which may have been largely in the form of opaline radiolarian tests but has been redistributed to form the nodules. In addition, some silica may have been in colloidal form though at present this is not characteristic of river water. In either case, most precipitation would be expected to occur close to regions where water was discharged into the sea and would explain those deposits, seen especially in districts to the south-east of the area studied (see, for example, Wells 1955), in which chert succeeds the limestones and a strong terrestrial influence might be expected. However, siliceous deposits appear to occur only in association with these higher limestones and it is probable that silica was much more common in the river water at this time, perhaps due to a difference in the mode of weathering of the source rocks.

Glauconite

In the strata studied, glauconite has a distribution which is similar to that of silica and seems to occur where there is evidence that movements of water were on a greater scale than during the deposition of most of the limestones (page 137). In this respect, the absence of thin-shelled foraminifera from the glauconite-rich horizons may be significant. A stronger flow of water could result in the reduced rate of deposition claimed by many workers as essential for glauconite production (Cloud 1955, Burst 1958) though the presence of ooze precludes the possibility of very strong current agitation. The Eh conditions implied by its presence are the subject of some disagreement, for Van Andel and Postma (1954) state that glauconite requires well-oxygenated shallow water, whereas Takahashi (1939) lists reducing conditions as one of its environmental requirements in view of its close association with pyrite.

The association of glauconite with pyrite is a feature of most of the occurrences in the Shap-Appleby area and has also been recognised by Hemingway in the Three Yards Limestone of the Askrigg Block (personal communication 1964) which is the equivalent of the Grayber Limestone. Burst (1958) records that the mineral commonly has an Fe^{+++}/Fe^{++} ratio of 7 so that it must be thought of as indicative of semi-oxidising conditions, probably being formed close to the sediment/water interface where pore solutions are well oxygenated but where included organic material has locally reduced the Eh and allowed the existence of some iron in the ferrous state. The pH in the sediments may have also been slightly reduced due to the presence of carbon dioxide since, with the good oxygen supply in the sea above, some of the organic matter would undergo aerobic decomposition. A lowered pH would reduce the stability of calcium carbonate and might explain the tendency for the glauconite to replace shell and crinoid material.

ii) The coarsening-upward sequence

a. SOURCE AND TRANSPORT

The major limestone of the cyclothem is most frequently succeeded by a thick series of argillites and fine-grained sandstones which show an overall upward increase in grain size. They represent the encroachment of extra-basinal detritus into the zone of formation of biogenic and chemically formed rocks.

The detritus is overwhelmingly of relatively fine grain size, is usually well sorted and is poor in feldspar and rock fragments, so that a source area of strong relief close to the basin of deposition can be ruled out. The terrigenous material has a mature aspect indicative of prolonged transport in rivers and has also probably undergone some marine reworking, especially in the case of the clean-washed sandstones. Absence of ferromagnesian constituents and the restricted suite of other heavy minerals is suggestive of an origin from pre-existing sedimentary rocks for much of the material, the Old Red Sandstone, of which there is little sign in the north of England and south of Scotland, being perhaps the major source. Only in the coarser feldspar-rich horizons in the upper part of the succession is there likely to have been a major influx of first-cycle material.

The general absence of montmorillonite may suggest that weathering was accomplished under acid and poorly oxidising conditions such as might be expected to occur in a wet tropical region with an abundant vegetation cover. Similar conditions were deduced by Loring (1960) to have prevailed in the source area for a group of Coal Measure strata.

b. PHYSICO-CHEMICAL CONDITIONS

Both calcite and siderite are most soluble in acid water (Krumbein and Garrels 1952, Fig. 6.1) but siderite has a much lower solubility so that few Fe^{++} ions are able to disperse far into the basin of deposition. Increasing iron content may, therefore, be taken as an indication of the approach of a marginal facies of deposition.

The steady decrease in calcite content through the upward-coarsening cycle (Fig. 4.20) is a clear indication of the increasing acidity of the waters from which the sediment was deposited. This appears to have fallen from 8 to 7 during the deposition of the calcareous shales and to have been below 7 at higher horizons where calcite is absent. The decreasing pH also had the effect of reducing the amount of life on the sea-floor (aided perhaps by the appearance of increasing quantities of detritus) with the result that the content of magnesium-bearing carbonate is also reduced.

These same changes brought about an increase in the amount of siderite precipitated, which is essentially absent from the limestones, most of the iron having been removed closer to the shore. During limestone deposition, any iron removed from solution was either incorporated in the carbonate minerals directly or oxidised and precipitated as the hydroxide, but in the calcareous shale environment, greater quantities of ferrous ions were present and the lower Eh allowed siderite to precipitate alongside the calcite in small amounts. However, presumably because siderite solubility is most sensitive to pH changes in relatively acid conditions, it becomes more abundant at higher levels where a pH of say 7 would indicate an Eh range as low as 0 to -0.1 (Fig. 6.1), though this probably reflects bottom-water conditions rather than the upper more agitated layers. Within the sediment, organic debris has caused the Eh to be still lower and resulted in the production of small quantities of pyrite.

b. NATURE OF THE ENVIRONMENT

The Eh-pH changes outlined above may be envisaged as occurring as the result of the appearance of a freshwater influence on the saline marine environment; this influence became steadily stronger as the wedge of clastic sediment was progressively extended. Such river-derived water, with its high CO_2 content, organic acids and decaying plant material, would have both a lower pH and a lower Eh than the sea and would be able to carry the large amounts of iron, mainly in the form of ferrous bicarbonate, required to produce the siderite and pyrite of the argillites.

The arrival of this terrestrial influence is first apparent, not by its chemical effects, but by the admixture of fine mud at the top of the limestones and is suggestive of quiet and probably relatively deep water. Absence of oxygenating currents is also indicated by the occurrence of a higher content of pyrite at this horizon (Fig. 4.20). No examples are known of the abrupt replacing of the open sea marine influence, with the possible exception of the upper limit of the Maulds Meaburn Limestone at some localities. Normally the calcite and fauna die out gradually and often the limestone gives way to fossiliferous shale by alternation.

It was recorded (page 172) that the argillaceous limestone studied contains unusually large quantities of trace elements; this appears sometimes to be a feature of strata deposited close to shorelines (Hirst 1962), where trace elements in solution are incorporated in flocculating clay minerals. However, there is no independent evidence that the impure upper parts of the limestones were deposited in proximity to the shore or under any significantly different physico-chemical conditions to the purer limestone below. Rather, the high content of some trace elements may be largely due to a slow rate of deposition coinciding here with the availability of material (the clay minerals) capable of their sorption.

As the detrital sediment accumulated on the sea-floor and chemical sedimentation became subordinate, the rate of deposition appears to have exceeded that of subsidence. This allowed a progressive advance of the terrestrial deposits, bringing shallower water and increased current activity, shown by the gradually increasing grain size, and culminating in the deposition of a thick body of sandstone. The existence of stronger currents is not only exhibited by the absence of fine detritus, the decrease in muscovite content, and the increase in the scale of the cross-laminations, but also by the big reduction in pyrite content (Fig. 4.20), although its general absence is probably partly owing to the ease of subsequent oxidation. Even at this stage in the cycle, the occurrence of siderite suggests that the environment was not of a high energy oxidising type and this is borne out by the lack of coarse detritus.

It should be emphasised that there is no evidence in the form of, say, beach deposits that this sequence straddles any shoreline; there is a continuity of deposition which implies that the whole succession was deposited in the sea, though one in which rapid sedimentation was occurring and where the influx of fresh water was such as to reduce its salinity and pH very considerably. Brackish conditions would prevail and at times of very strong rainfall it may have been almost fresh. These factors combined to prohibit virtually all invertebrate life. Conditions in many respects similar to those envisaged have been described from the essentially landlocked Gulf of Paria, which never exceeds 100 feet in depth and lies between Trinidad and the South American mainland, by Van Andel and Postma (1954).

iii) Fining-upward sequences

In the Middle Limestone Group, fining-upward sequences are uncommon and are usually confined to small thicknesses of sediment. Apart from a few instances in which thin silt and shale bands occur at the top of the sandstone of the coarsening-upward cycle, they are all characterised by having abrupt erosional bases, above which there is often evidence of intrabasinal erosion in the form of included mud-flakes.

The Littlebeck Sandstone, details of which are included in Chapter 2 (pages 82 to 86), is the most widespread of these erosive horizons, although locally some of the other sandstone bodies have sharp lower contacts. Invariably beds at or near the base are coarser and often richer in feldspar than those at higher levels, which may however contain lenses of relatively coarse rock. At the top, frequently succeeding a ganister, a thin series of siltstones shales and thin coals sometimes followed by calcareous silts, is present. Such deposits can probably be attributed to fluvial deposition (Pattinson 1964, page 242 et seq.) and must represent the rapid extension of an area whose depositional regime is under exclusively terrestrial influence. Channel-like erosion surfaces, except on a small scale, have not been found but from the disposition of the rock types it is reasonable to suppose that the deposits have filled channels produced by the gradual extension into the shelf-sea of the main sediment-carrying streams. The cutting of the channels and some of the infilling may have occurred beneath the sea but the frequent development of ganister at the top indicates that terrestrial conditions ultimately became established. The coarse and feldspathic Littlebeck Sandstone is somewhat different in that it has an erosive base over a very wide area. Actual uplift of part of the basin of deposition as well as strong uplift of the source areas could explain these characteristics and it may have been deposited entirely under non-marine floodplain conditions.

A very different type of fining-upward unit is represented by some thin fossiliferous sandstones in the Maulds Meaburn and Little Strickland cycles. The former, the calcareous 'grit' of Drybeck, abruptly overlies pale silts and shales and contains varying proportions of brachiopod shells in the lower few inches as well as coarse quartz, feldspar and micrite intraclasts; it passes up into a very fine calcareous sandstone with small-scale cross-laminations. The similar deposit in the overlying cycle is of finer grain size at the base but is again crowded locally with shells and it becomes an argillaceous limestone towards the top before being succeeded by shale. Clearly these deposits are minor marine, rather than fluvial, transgressions and are probably thin beach deposits.

iv) Variable sequences

The thin marine transgressive deposits described above form part of groups of strata which are very variable, both vertically and laterally. They include thin argillaceous and arenaceous limestones, shales, sometimes calcareous and often of pale colour, sandstones, ganisters and thin coals. They normally occur above the main sandstone unit of a cycle and are of small thickness, but in the Maulds Meaburn and Johnny Hall's Trees cyclothems they may comprise the major part of the succession.

The great variability, as well as the frequent location above a thick sandstone body are both suggestive of deposition in an area of very shallow water after the main locus of deposition had moved elsewhere. A coastal environment liable to frequent changes in the position of the shoreline is indicated. Most deposition probably occurred in lagoons and marshy tidal areas, often colonised by vegetation, where salinity would generally be low and normal marine life excluded. The rarity of beach deposits testifies to the absence of strong currents and favours the existence of extensive areas with a very gentle depositional slope. The occasional definite marine transgressions, giving rise to fossiliferous sandy and argillaceous limestones, can be attributed to local compaction and possibly regional subsidence which were temporarily not balanced by the concurrent sedimentation of river-derived material. This could occur, as suggested by Moore (1958) when the established depositional pattern was disturbed by crevassing of river banks resulting in a transference of deposition to neighbouring areas.

The only strata from these environments which have been studied in detail are thin nodular limestones and pale silty shale from above the Maulds Meaburn Limestone (pages 195-8). Their mineralogy and trace element content, although not conclusive, support the impression gained from the field study that they could be of non-marine origin. In particular, the abundance of siderite is not typical of normal marine deposits, a pale colour is thought by Degens, Williams and Keith (1957) to be more characteristic of fresh-water shales than marine ones, and the low contents of rubidium and nickel are in agreement with the findings of these authors in their studies on non-marine shales. The absence of pyrite from the beds studied suggests that deposition of these particular horizons was in well circulating water, but many of the associated rock types, especially the plant-bearing sandstones, are rich in this mineral and are indicative of stagnant conditions.

Where such strata follow a thick limestone, as in the Maulds Meaburn cyclothem, it is postulated that the normal deepening of the sea during limestone deposition did not occur. A shallow lagoonal environment was then able to be established immediately upon the arrival of terrestrially derived material and its accompanying fresher water.

v) The re-establishment of open-sea conditions

In the Yoredale cycles studied, the most common form of the sandstone-limestone transition is where a ferruginous-weathering limestone rests on a thin layer of calcareous sandstone which is separated above and below by well marked bedding-planes. This sequence is clearly seen at the base of the Maulds Meaburn Limestone where it has been studied in detail at Iron Hill (pages 180 to 187; Plate 47).

These features are suggestive of rapid and extensive marine transgression since terrigenous regressive deposits are essentially absent. It is true that the retreat phase of terrestrial sedimentation would be expected to be represented by only a small thickness of deposits because rising base-level will cause a much reduced amount of sediment to pass into the sea, but in the Middle Limestone Group it generally appears to have been entirely cut off. Even fine-grained material is rare in the basal limy deposits and the calcareous sandstone, with its admixture of crinoid and shell fragments is thought to be the result of the reworking of material on the sea-floor. In most cases, any ganister, coal or argillaceous beds which may have occurred above the sandstone have been removed but occasionally, perhaps when currents were less active, they are present and the lower part of the limestone has largely argillaceous impurities. Re-working is also thought to have been absent in those cases, as at the top of the Askham cyclothem near Harberwain Rigg, where sandstone passes up into limestone without the intervention of persistent bedding-planes (Plate 49); shell fragments get progressively more common upwards in the sandstone and deposition appears to have been continuous throughout.

The rapid spread of marine waters must have resulted in a sudden

PLATE 49. The complete transition from sandstone into the base of the Bank Moor Limestone at Harberwain Rigg.

increase of the pH and ferrous ions would be present in excess of their solubility in the presence of carbonate and hydroxyl ions. The almost universal occurrence of ferruginous beds at the bases of the limestone may thereby be explained. In the active oxygenated environment of the initial transgression represented by the calcareous sandstone, there is some evidence that the iron was precipitated as the hydroxide, but thereafter, with a deepening of the sea, the Eh conditions were sufficiently reduced to allow the formation of the carbonates. If the Maulds Meaburn Limestone is a guide, these are rich in calcium and magnesium rather than being pure siderite, which is perhaps not surprising considering the relative abundance of these ions in normally saline marine waters.

B. THE NEW RED SANDSTONE

i) The Brockram

The coarsely detrital and very poorly sorted nature of the basal New Red Sandstone conglomerates , together with the general absence of all but well separated lensoid bedding-planes, leaves no doubt that they are largely piedmont deposits and formed an alluvial fan spreading out at the foot of a mountain range. The illustration of the Bishop Conglomerate, a piedmont deposit from Wyoming U.S.A. in Dunbar and Rodgers (1957 page 30) appears indistinguishable from numerous exposures of the Brockram. McKee (1953) reports that alluvial fan stratification is usually less than 10 degrees and, although Brockram dips generally now exceed this value, it must be remembered that a tilt, averaging 6 degrees, in the approximate direction of the depositional dip of the conglomerate has subsequently been imposed. However some exposures, notably in Hoff Beck, show Brockram which must have had an initial dip of between 20 and 30 degrees, though passing in only a few yards into normally-dipping beds. Here it probably forms a talus slope, the rounding of the limestone pebbles being largely due to chemical weathering, much of which may have been subsequent in deposition.

The depositional conditions are well summarised in the words of Gilligan (1926) who suggested that there were:-

> "steep hillsides trenched by deep gullies down which torrents plunged in the rainy season, carrying vast quantities of detritus and spreading this out on the low ground at the base".

All of the material examined could have been derived locally from the Yoredale strata and the orientation of the wadi-like channels indicates that it was transported from the south and south-west. A southerly direction for the source areas is also supported by the fact that most pre-New Red Sandstone erosion has occurred in this direction, the basal New Red Sandstone, towards Kirkby Stephen, coming to rest upon progressively older rocks and ultimately reaching the D_1 limestones.

By analogy with regions where today similar deposits are forming, it seems likely that arid conditions predominated at the time of formation of the Brockram but that very heavy rains occasionally occurred.

ii) The Penrith Sandstone

Where, at the base, the sandstone is interbedded with Brockram, it may be considered to be water-lain, being the product of deposition from waning currents following torrential floods. The main mass, however, because of its undoubted dune-bedding (Shotton 1956) is an aeolian deposit, and, because of the large area of deposition, can only have been formed in a desert. The arid climate and lack of vegetation is also indicated by the fact that hematite brought into the basin from the reddened source rocks was not hydrated or reduced.

The hematite was probably transported as part of the material of the dust storms which must have been quite common in such an environment. Although most would be carried beyond the sand desert and deposited with the other fine detritus as red marls, some, settling on the dunes, has been re-distributed, probably at times of occasional rain and possibly even with the aid of dew, and has been deposited as a thin pellicle around the quartz grains on evaporation of the coating of water.

Yoredale strata, partially reddened, may again be thought of as the source rocks and it appears that the processes occurring at the time of formation of these rocks resulted in strong sedimentary differentiation.

Yoredale limestones produced the Brockram, the sandstones were transported further to give the Penrith Sandstone and the shales were removed entirely from the area of study and deposited as the marls in the Carlisle Basin.

C. THE RHYTHMIC REPETITION

Numerous hypotheses concerning a mechanism for the development of cyclothems have been advanced since Hudson first discussed the problem in 1924. They are summarised by Moore (1958) and Wells (1960) both of whom suggest further theories. All, as is generally agreed could lead to a form of cyclothemic sedimentation but there is no unanimity as to which is likely to have been the most important mechanism influencing Visean sedimentation, although theories involving eustatic sea-level change appear to be gaining favour.

In studying the mechanism problem it is useful to consider probable variation in the depth of the sea. The fact that there occurred a net accumulation of shallow water sediment shows that the basin underwent sinking throughout the period but an important question is whether or not this was steady or erratic. If the latter was the case, this could be the cause of the rhythmic sedimentation but if there was a gradual subsidence an additional mechanism is required.

In a typical cycle it is probably reasonable to assume that limestone deposition occurred in a few tens of feet of water and since the rate of accumulation of limestone is normally relatively slow, any sinking of the basin could well have produced a deepening of the sea. Evidence has been presented above which suggests that the sea did indeed reach a maximum depth at the time of deposition of the upper parts of the limestones (page 227) but subsequently this would become reduced by the much more rapid deposition of the mass of clastic sediments; at this time sinking may have been slow but there is no reason to believe that it ceased altogether.

The fact that many of the clastic sequences end in terrestrial or very shallow water conditions, as evidenced by the occurrence of seat-earths, suggests that it resulted in the almost complete filling of the basin so that the water depth at the time of onset of clastic sedimentation cannot have greatly exceeded the thickness of the clastics. Although compaction will now have reduced the thickness of the sediment this effect will have been offset by any subsidence which occurred, since this would reduce the initial depth of water requirements. For this reason, the average thickness of 55 feet for the clastic material in the cyclothems of the Shap-Appleby area may not be very much smaller than the mean maximum depth in which their deposition started.

There is strong evidence (pages 232 and 233) that the highest clastic sediments were rapidly followed by the deposition of limestone in wide-spread open sea conditions; if there had been steady subsidence through-out the cycle it is difficult to understand this apparently sudden change. Moore's suggestion (1958) of a change in the main locus of sedimentation would be adequate to give rise to the thin calcareous horizons but it is unlikely to have produced the major limestones which, as far as can be ascertained, are continuous throughout most of the area of outcrop of the Yoredale Series. This is especially true when there is evidence that deposition occurred under conditions which bear no more than superficial resemblance to those in the delta complex of the Mississippi, from a consideration of which Moore was able to formulate his crevassing theory.

It is difficult to avoid the conclusion that the period of advance of clastic sedimentation was brought to an end by a relatively sudden rise in sea level but none of the theories postulating eustatic sea level changes seems entirely satisfactory in explaining why this should have occurred at fairly regular intervals. On the whole, the probable depth changes can be best understood if they result from both sedimentary and tectonic controls and in the latter connection it should be remembered that the deposits were formed during a period of crustal instability when isostatic changes following the Caledonian orogeny would be accompanied by early Hercynian movements. A theory of crustal readjustment which would involve periodic uplift of source areas and uneven subsidence of adjacent basins has been advanced by Bott (1964) who envisages a periodic flow of mantle material towards areas having negative gravity anomalies and rising intermittently as a result of isostacy. The expected results of such movements on sedimentation correspond so well with what is observed in the Yoredale succession that there is at least a strong probability that they are a basic cause of these deposits, especially since the inter-continental scale of rhythmic deposition at this time is also thereby explained.

CHAPTER 7

THE POST-DEPOSITIONAL HISTORY OF THE YOREDALE STRATA

A. PRE-NEW RED SANDSTONE UPLIFT

The period of time between the deposition of the lower part of the Upper Limestone Group and the Brockram is not now represented by any strata in the Shap-Appleby district but the presence of Coal Measures both in west Cumberland and near Brough-under-Stainmore suggests the probability that a much more complete Upper Carboniferous succession was once present. During this time, and probably in the late Carboniferous after Coal Measure deposition, important changes in the geography took place.

The earliest recognisable event was an uplift which converted the basin of deposition into an upland area in which erosion soon diversified the relief. In the absence of major folding, the uplift may be thought of as being of epeirogenic rather than orogenic type, and the region was broken by a series of faults, downthrowing usually to the east and north-east, of which the Inner Pennine Fault is the most important. In the area studied, smaller parallel dislocations, of which the Barwise Fault is the largest, can be recognised, as well as several striking approximately at right-angles to this north-north-westerly direction and generally having a northerly downthrow. They may not be contemporaneous with the Inner Pennine Fault but demonstrably occurred prior to the deposition of the local New Red Sandstone and they appear to be the product of a similar stress field.

B. JOINTS

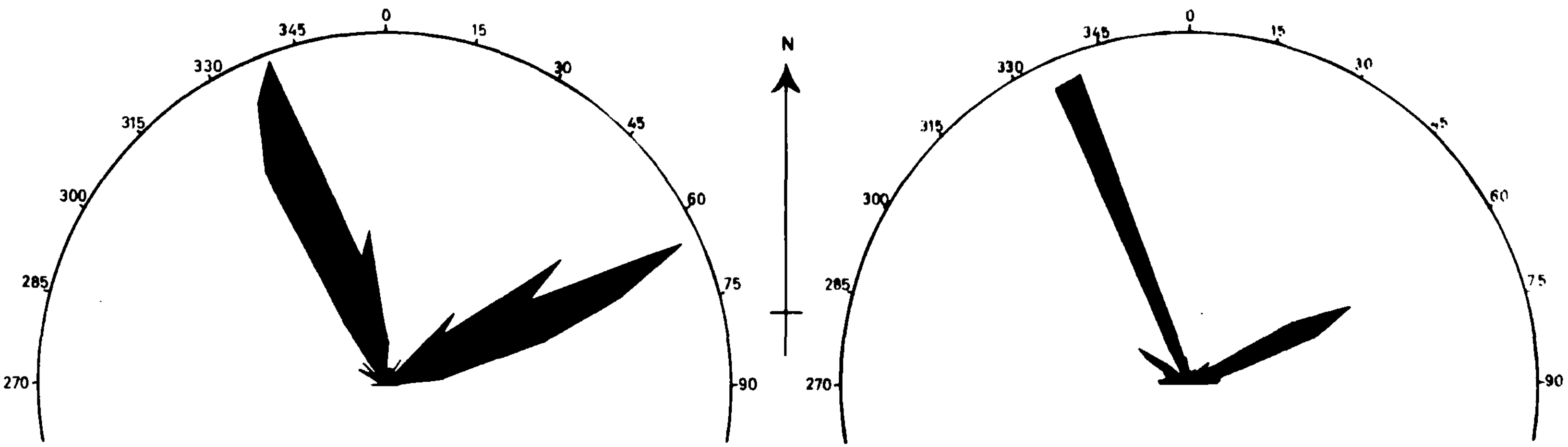
Well developed joints are present in the more competent members of the succession, especially the limestones. They are essentially perpendicular to the bedding, form a rectangular pattern and are now usually open fractures. Some displace the strata a few inches vertically and slickensides indicate that horizontal movements have taken place.

The 233 joint readings taken during the field study are shown in the form of a rose diagram in Figure 7.1. The principal modes are at 340 degrees and 65 degrees and compare with values of 335-340 degrees and 60-70 degrees obtained by Dunham (1933) from the Great Limestone of Weardale (Fig.7.1). In the Shap-Appleby district, subsidiary peaks are recognisable at 355 and 55 degrees and when values are broken down into individual sub-areas this is found to be due to the predominance of joints in these directions in the Reagill-Morland sub-area. The remaining sub-areas show a slight but definite anticlockwise shift in the positions of the majority of the readings in going from the north-west to the south-east of the region.

The joint pattern helps to emphasise the structural unity of the study area and the Alston Block and indicates that when they were formed very similar stress fields existed in both areas, and that either the jointing was essentially contemporaneous over the whole region or that stress patterns changed little over long periods of time.

Dunham (1933) considers that they are shear joints associated with a regional stress field older than the Whin Sill whereas Trotter (1944) and Spears (1961) favour a tensional origin and link them with the uplift and doming of the Alston Block. Trotter considered this to be of Tertiary age but Dunham (1933) has demonstrated that the mineralising fluids used the pre-existing joints and recent studies leave no doubt that this mineralisation

Figure 7.1



VALE OF EDEN—233 readings

ALSTON BLOCK: WEARDALE—2000 readings

(Dunham 1933)

DIRECTION-FREQUENCY OF JOINTS

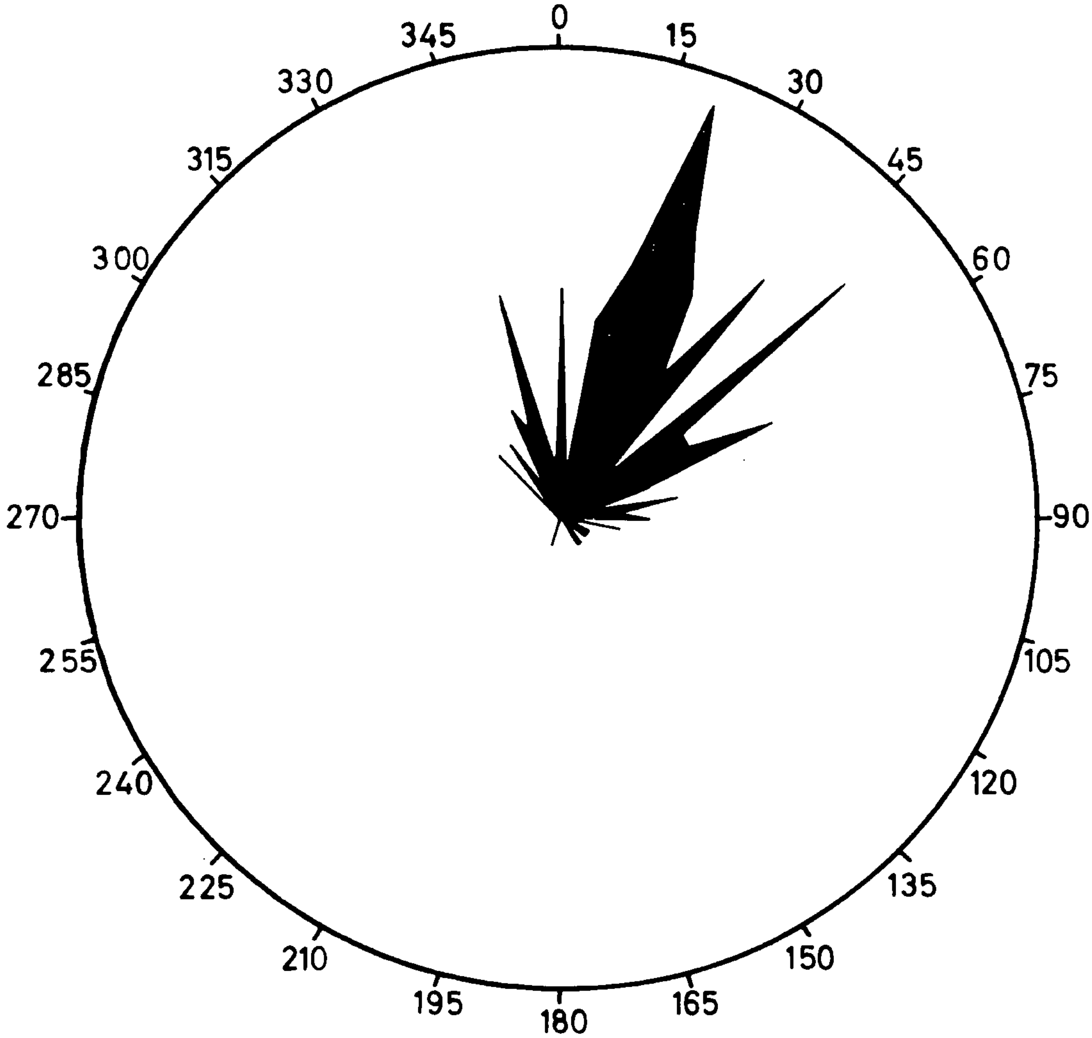
has a broadly Hercynian date (Moorbath 1959). Spears believes the joints to be younger than the Whin Sill because he has shown this to have the same joint pattern but, as Dunham has pointed out (discussion in Spears 1961), there is abundant evidence that similar stress patterns had recurred since the Lower Palaeozoic.

In the Shap-Appleby area, the Whin Sill does not occur so that there is no direct evidence as to the relative dates of joint formation and sill intrusion. On the other hand, the relationship between the joint directions and the dip of the strata (Fig.7.2) suggests that the two are intimately related. Although there is a wide scatter of dip directions, the modal value of 20 degrees lies exactly mid-way between the azimuths of the major joints and there is the same tendency for an anticlockwise shift in the predominant dip direction in going towards the south-easterly part of the region. A theory involving the Tertiary tilting of strata which had a joint pattern developed during the Hercynian movements, seems therefore unlikely. More reasonable is the possibility that tilting has taken place periodically in post-Carboniferous times as a result of the existence of a persistent positive area nearby in the Lake District; this has produced radial dips in the Carboniferous and New Red Sandstone strata surrounding it, the greater part of which seems to post-date the New Red Sandstone. The jointing is thought to have occurred in response to this same regional stress pattern but was probably largely completed at an early stage in the tilting.

Less frequently seen are gently curving joints, having low dips and dying out in bedding-planes which are separated vertically by only a few feet. They usually displace those bedding-planes which they cut by a few inches and re-crystallised calcite on the joint-planes has often been striated by subsequent movements; they have only been found in the lower parts of limestones (Plate 50). Their form suggests that they have a different origin to that of

Figure 7.2

DIRECTION - FREQUENCY OF DIPS



SHAP - APPLEBY AREA

158 readings

the major joints and they appear to be the result of lateral compression which has locally caused bedding-plane slip and set up stresses in the intervening strata. It is noticeable that in the Great Strickland Limestone of Lookingflatt, the reddening, normally confined to the basal few inches, locally occurs on either side of higher bedding-planes and is also extended upwards by these curving joints, though it is not associated with the major joints. Unless the latter were tightly closed fractures throughout the time of reddening (which does not appear likely since the area had been uplifted and, on the evidence of the common normal faulting, was in a tensional structural setting) it is difficult to escape the conclusion that a period of reddening occurred between the times of formation of the two types of joints. This particular phase of reddening is thought to post-date the Penrith Sandstone (page 248) so that a late Permian or Triassic age for the jointing is indicated.

C. DOLOMITISATION

Limestones lying immediately below the New Red Sandstone and also those in the same vicinity at a lower stratigraphical level but which are adjacent to major fractures such as the Barwise Fault have been extensively dolomitised. A similar distribution of dolomitisation has also been described by Trotter (1939) in the Carlisle basin to the north where, as in the Shap-Appleby area, it dies out rapidly with depth. This is particularly well seen in the Lyvennet section where only very slightly altered Great Strickland Limestone is probably within 100 ft. of the unconformity. Trotter goes no further than to state that the dolomitisation seems to be connected with the pre-New Red Sandstone surface, with the implication that it pre-dates the deposition of the strata immediately above this surface.

An important feature to be considered in postulating a time and mechanism for the dolomitisation process, is a source for the large quantities of magnesium which have been added to the rock. Although the Yoredale limestones undoubtedly contained enough magnesium when deposited to produce the amount of dolomitisation now visible, much if not all has remained in these limestones and they contain no evidence of upward migration of magnesium ions; nor is any process of concentration of this element in surface limestones by sub-aerial weathering known. The only major source of magnesium which satisfactorily explains the Vale of Eden occurrences of dolomite is the sea, and it is known that the sea which deposited the Permian limestones east of the Pennines spread into the Appleby district shortly after the deposition of the Penrith Sandstone leaving a thin horizon of Magnesian Limestone.

That the dolomitisation process post-dates the basal New Red Sandstone deposits is confirmed by the presence of dolomitised pebbles in the Brockram; although some conceivably could be derived from a previously dolomitised

PLATE 50. Low-angled joint picked out by weathering; Maulds Meaburn Limestone, Scalebeck Quarries.

PLATE 51. Cavernous pebbles at the base of the Brockram, Whirly Lum.

limestone, others (Plate 51) with hollow centres can only have been altered in place. Although, therefore, the Magnesian Limestone itself is not present to the west of the River Eden, the alteration of limestone close to the New Red Sandstone unconformity, both above and below, bears testimony to its transgression into this region. The fact that high ground occurred in the south and west of the area makes it probable that the margin of the sea lay close to Appleby and the non-dolomitised nature of the limestones in the rest of the area results from their never having lain below the floor of the Permian sea. How far above the exposed New Red Sandstone rocks the sea-floor and any Magnesian Limestone deposit was, is unknown, but the strong process of alteration suggested notably by its intensive redistribution of silica and trace elements (Chapter 5, pages 203 to 207) implies that no thick mass of Penrith Sandstone intervened between it and the Carboniferous.

D. REDDENING

Hematite is present locally at all levels in the succession studied, including the Knipe Scar Limestone, some 800 ft. stratigraphically below the lowest point to which the New Red Sandstone can be seen to cut in the area mapped. Deep penetration of oxidising conditions is clearly indicated, but that this was most effective near the unconformity is shown by the occurrence here of strongly reddened shales and completely reddened thin limestones or bands at the base of the major limestones.

In view of the otherwise normal lithology, the fossil content of the strata, and the occurrence of non-red beds of the same age only a few miles away in the Pennines, the possibility of the material being red on deposition can be discarded. So too can theories involving the introduction of red iron oxide from the overlying New Red Sandstone strata for four reasons:-

1. In County Durham, the Carboniferous is reddened in spite of the occurrence of drab coloured Permian above (Anderson and Dunham 1953).

2. When iron is introduced from outside, the most porous rocks will be the most strongly reddened and little change will occur in the argillites except along joints. This will be especially true if, as is generally supposed, the iron was moved in the form of solid hematite particles. In the Vale of Eden Carboniferous it is the argillites which are the most consistently stained.

3. The iron in the Penrith Sandstone is in the form of a hematite pellicle which is now impossible to remove, even with strong acids, because it is under a deposit of authigenic silica. This was precipitated at an early stage of diagenesis (Shotton 1956) and it is doubtful if sufficient time elapsed prior to this, or that suitable conditions existed, for the transference of the iron.

4. The occurrence of red limestone pebbles alongside normal grey limestone in the Brockram, recognised by Trotter (1939) and confirmed at many localities in the Appleby district, proves that extensive reddening of the Carboniferous had occurred before any New Red Sandstone was deposited.

It may be concluded that the reddening is due to the <u>in situ</u> oxidation of Carboniferous iron (c.f. Bailey 1926); the most strongly reddened beds are those, the shales and the base of limestones, which may reasonably be expected to have contained the most iron when deposited. Redistribution of the iron has, however, also occurred as in the cases of red and white colour banding in the sandstones and although addition of iron is not necessarily implied, it seems probable that some has been brought in from outside. This could be from higher Carboniferous strata undergoing oxidation (Trotter <u>op.cit.</u>) or, more probably, by upwards migration into the strongly oxidising zone from deeper Carboniferous rocks.

As Trotter suggests, no support for the traditional method of derivation of the west Cumberland hematite ores from the New Red Sandstone is lent by the evidence of reddening from the Vale of Eden. A process of limestone replacement by Carboniferous-derived iron is more likely. Both the nature of this process and the reason for the absence of hematite deposits in the Knipe Scar Limestone on the eastern side of the Lake District are of considerable interest but are beyond the scope of the present study.

Evidence, as was suggested above (page 135), indicates that the reddening cannot be assigned to a single period. That much occurred before the local New Red Sandstone was deposited is proved by the occurrence of reddened rocks in the Brockram and there is no doubt that the red colour of the New Red Sandstone originates in a source region which had previously undergone deep weathering. A consideration of present-day environments in which red soils are produced suggests that such a region was a well drained upland which was both hot and wet (Dunham 1952). These conditions favour deep chemical weathering but rapid oxidation is most likely to occur when there is a short dry season during which organic matter, which must have been abundant, can be removed as carbon dioxide, so prohibiting any reduction of the iron which could lead to its removal in solution.

Hot and wet conditions would also favour strong bacterial activity in the soils, which van Houten (1948) believes to be important in producing the red pigment. This is thought to appear as the result of the ageing of brown hydrous colloidal ferric oxide, $Fe_2O_3.nH_2O$ (Turgite), which by loss of water and increasing size of particles changes to a red colour. Normal processes of oxidation, which produce the hydrated oxide, goethite $HFeO_2$, are unlikely to have been important because this oxide requires greater than normal temperature and pressure for its conversion to hematite.

The uplifted Shap-Appleby district and areas to the south and west may, therefore, be thought of as having undergone deep oxidation in a humid tropical climate in late Carboniferous times to produce the source material for the local New Red Sandstone. Increased aridity during the early Permian led to pronounced erosion and the eventual accumulation of the conglomerates and sandstones of Edenside in semi-desert and desert conditions. It is thought however that reddening of the underlying strata had not completely ceased during this time. This is suggested by the strata at the base of the Great Strickland Limestone at Lookingflatt (page 134) where the most likely interpretation is that dolomitised limestone has been reddened (Plate 52); at the same locality there also are examples of dolomite which has re-crystallised next to late stage calcite veins and which has had its contained iron oxidised to hematite (Plate 53). Oxidation following dolomitisation is also indicated by the presence of much pyrolusite in the upper part of the same Limestone. This could not have been produced during the main

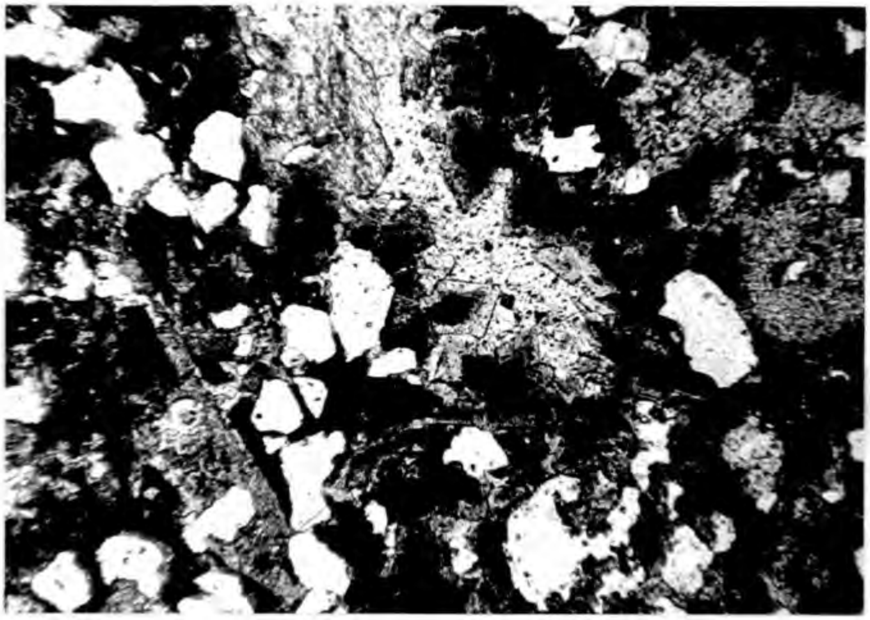


PLATE 52. Sandy base of the Great Strickland Limestone at Lookingflatt. Dolomite rhombs can be recognised and some have hematite cores. (x 28)

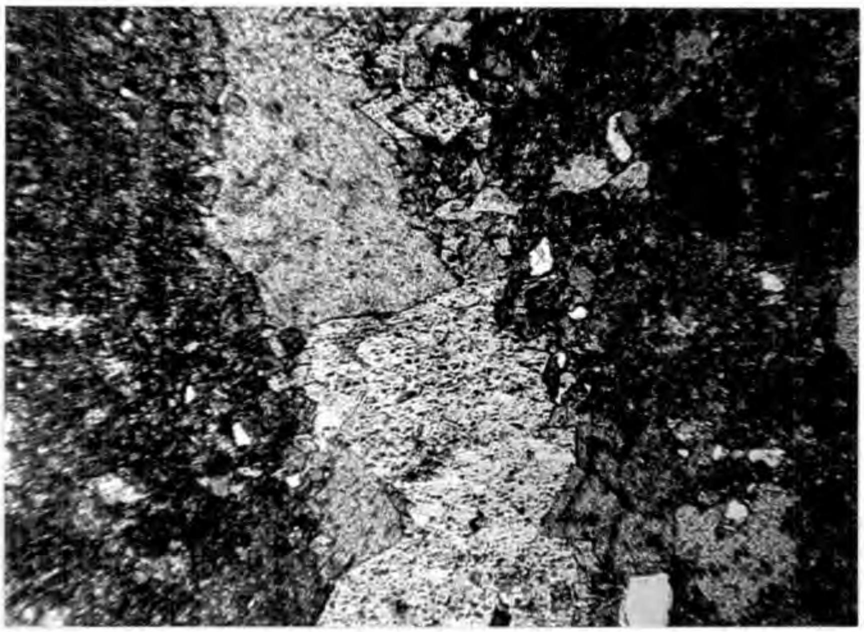


PLATE 53. Broad calcite vein in dolomitised Great Strickland Limestone at Lookingflatt. Recrystallisation has produced dolomite rhombs adjacent to the vein; they contain zones of hematite. (x 28)

early period of reddening because the necessary manganese was introduced only during the conversion of the original calcite to dolomite. This is clearly shown by the comparison of the manganese contents of the Great Strickland Limestone in its fresh and in its dolomitised states (Table 18).

E. REGIONAL TECTONICS

The Vale of Eden is a region with a complex structural history, dating at least from Lower Pälaeozoic times, which has received the attention of numerous geologists and especially of Shotton whose tectonic studies were presented in 1935. Since that time relatively little has been added to our knowledge of the structure of the area, though Versey (1939) has expressed doubt about some aspects of the generally accepted views. The present study is concerned with a structurally relatively simple part of the region but several points have emerged which require consideration.

The structural unity of the Alston and Shap areas during the deposition of the Carboniferous strata is clearly revealed by a comparison of the stratigraphy of the two areas (Fig.2.24). There is no similar sediment-ological evidence for the following Period since no New Red Sandstone now remains on the Pennines but several facts suggest that the histories of the two areas differed considerably in post-Carboniferous times. Both Turner (1927) and Shotton (1935) show that the Inner Pennine Fault is of Hercynian age and that it threw the Alston Block down with respect to the Lake District; this resulted in the latter becoming an area of erosion. The westerly source for the New Red Sandstone which follows from this fact is confirmed by the present study, although this by no means excludes a southerly origin for some of the material as favoured by Versey (1960). He also believes that there may have been an easterly source and this possibility deserves careful consideration, involving, as it almost certainly does, the date of movement of the Outer Pennine Fault system. This is generally thought to be of Tertiary age and certainly to be entirely post-Triassic, but it is difficult not to agree with Versey (discussion of his paper of 1939) that it is impossible to prove that the whole of the throw occurred at one period. Indeed, three observations suggest the opposite:-

1. The occurrence of pebbles of the Whin Sill in the Upper Brockram of George Gill (Dunham 1932). Provided that the identification is correct, even though the pebbles are exceedingly rare, this can only mean that some of the material at this time was derived from the east since the intrusion did not penetrate into the region to the west. An uplift to the ~~west~~ east of the region is thereby implied and the only known fractures with the correct direction of throw are the Outer and Middle Pennine Faults.

2. The easterly origin of the Penrith Sandstone is deduced from the dip of the cross-bedding in the barchan dunes (Shotton 1956) combined with the very great thickness of the Sandstone of the Vale. Even though there is probably much truth in the theory of Versey (1939) that the sand is derived from detritus eroded west of the Pennines, spread out on the depressed Alston Block, and blown back by easterly winds, this would not have accumulated to such a great thickness unless rapid downward movement was taking place to make room for it. There is no evidence that a thick development of sandstone at this horizon was present to the east; the subsidence was probably, therefore, only very localised. If it had been on a regional scale, either a thick sandstone development in County Durham (Yellow Sands) or an early transgression of the Permian sea would have resulted. In the absence of a broad region of westerly dips east of the Vale of Eden, one may postulate that its depression resulted from faulting and that the Outer Pennine Fault system had already been initiated. Because there is no reason to believe that the Carboniferous strata in the study area had received much of their present north-easterly tilt by this time, the trough is likely to have been margined by faults in this direction too. Some are now exposed but others probably still lie below the New Red Sandstone, by which they

were overstepped; one such has, in fact, recently been recorded (Turner 1964) in a borehole at Appleby.

3. The presence of dolomitised Carboniferous limestones immediately to the east of the Outer Pennine Fault, altered, according to Turner (1927) by the Permian sea. This suggests a situation comparable to that in the area studied with the dolomitised limestone occurring close to the margin of the main Penrith Sandstone basin. An earlier large easterly downthrow of the Inner Pennine Fault, which lies to the east of these outcrops, explains the absence of dolomitisation in equivalent horizons on the Block (Turner op.cit.) which had a thick cover of younger rocks but, in the absence of any fault delimiting the eastern side of the basin, the dolomitised limestones would be under about 1000 ft. of strata when dolomitisation occurred.

There is reason to suppose, therefore, that the New Red Sandstone deposits accumulated in a north-north-westerly elongated trough in which subsidence roughly kept pace with deposition and which had an essentially faulted eastern margin at about the position of the present Outer Pennine Fault. In this connection, it should be remembered that this period in Britain is characterised by the development of such elongated and fault-bounded troughs, especially in the general area of the Vale of Eden where the basins of Stranraer and Dumfries afford good examples.

Although most of the material was derived from the uplands to the south and west, erosion accompanying the initiation of the uplift of the Alston Block would contribute some detritus, including the Whin pebbles. These have been derived either from the very attenuated Sill which may have intruded the strata between the Inner and Outer Pennine Faults, or from the Whin dykes from this same zone or even, perhaps, from further to the east. In either case, the scarcity of the pebbles is understandable.

There is no reason why such an early uplift of the Alston Block should have given rise to a major fault scarp and the objections of several authors, notably Shotton (in Versey 1939) and Turner (1927) to a theory of the Permian movement of the Outer Pennine Fault are not necessarily valid. Erosion could have kept pace approximately with deposition and only a minor topographic feature need have occurred during most of the time when the New Red Sandstone was accumulating. The problem of the apparent formation of barchan dunes close in the lee of a mountain range does not, therefore, arise and the absence of a coarse conglomerate comparable with the brockrams in exposures close to the Outer Pennine Fault (in Hayber and Crowdundale Becks) would be expected. In any case, much post-Triassic movement along the same line has taken place and the beds now in contact with the older rocks were not deposited against them.

Of some economic interest is the question of the age of the highest Carboniferous rocks underlying the New Red Sandstone of the Vale. Gilligan (1926) believed that they are unlikely to be as young as the Coal Measures but the present work has lead to the conclusion that it is by no means impossible that a concealed coalfield may lie beneath part of the Eden Trough.

Unfortunately, calculations and vertical sections can throw little light on the problem because of the impossibility of obtaining the necessary data concerning the regional dips of the two formations and because of the variables in the form of faulting and the shape of the unconformity surface, involved (see section in folder at back of thesis). The average value of the Carboniferous dips measured is 6.3 degrees in a direction N 28° E; if this is maintained across the Vale from Sideway Bank to the Outer Pennine Fault near Knock, a distance of 5 and 3/4 miles, it can be calculated that the Great Strickland Limestone will reach a depth of approximately 3500 ft. However, a more reliable average dip value is that of the whole of the Middle Limestone Group across the area mapped which has been calculated as 3°32'; this would produce less than 2000 ft. of strata above the Great Strickland Limestone where it reaches the Outer Pennine Fault. But, because of the absence of reliable readings of the regional dip in the cross-stratified New Red Sandstone deposits as well as the uneven nature of the surface of unconformity, the critical question of the depth at which the top of the Carboniferous strata lie cannot be answered. On the other hand, thickness estimates of the New Red Sandstone generally put the Penrith Sandstone alone at about 1000 ft. so that, on this basis, at the maximum there are probably no more than 1000 ft. of Carboniferous strata younger than the Great Strickland Limestone underlying the Vale in this region. Pattinson (1964) has mapped about 700 ft. of the Upper Limestone Group above the Upper Little Limestone of the Alston Block and since allowance must be made for the youngest Namurian strata ('Millstone Grit') there seems little chance on this basis that Coal Measures will be present.

In the study area the New Red Sandstone and the Carboniferous frequently have very similar dips with the larger values tending to occur in the former. This factor cannot, therefore, be expected to result in the occurrence of Carboniferous rocks under the New Red Sandstone any younger than those seen at Appleby, which themselves may be largely attributed to two independent factors. These are the existence of important faults down-throwing to the east-north-east and the occurrence of major irregularities on the unconformity surface which must have been erosion residuals isolated from the main upland mass. Provided that these features continue to the east there is a good chance that Coal Measures will have been preserved, though they imply that the outcrop will be broken and perhaps even partially isolated into areas separated by barren channels of red sandstone and conglomerate.

Much of course will depend on the exact time of the faulting which, it has been postulated, allowed the subsidence of the basin; in order that the youngest possible rocks should be preserved it is necessary that faulting should have occurred soon after the downthrow of the Alston Block so that a probable westerly spread of a piedmont zone from the Inner Pennine Fault had insufficient time to remove all of the youngest Carboniferous strata. Early downthrow is also important in order to protect the coal seams from the strong alteration which they would be liable to undergo as part of an upland subject to the intense oxidation characteristic of the Carboniferous-New Red Sandstone interval (see, for example, Mykura 1960).

Given the early development of trough subsidence in the Vale of Eden, it is undoubtedly possible to imagine situations in which Coal Measures might be preserved beneath the New Red Sandstone. This may be especially true north of the region studied, where the distance between the exposed Carboniferous of the Upper Limestone Group and the Outer Pennine Fault greatly increases, thereby making available more space for the necessary faulting. In this same direction, however, the thickness of strata overlying any coal reserves would almost certainly be greatly increased, possibly precluding exploitation.

F. GLACIAL FEATURES

No strata younger than the Trias are present in the Vale of Eden other than the Pleistocene deposits, which are the subject of comprehensive papers by Hollingworth (1931) and Trotter (1929). If strata of intervening ages were deposited, all trace has now been removed apart from the small Lias outlier to the north near Carlisle. During this time, a gradual evolution may be envisaged which involved uplift of the neighbouring areas of general mass-deficiency with their major granite bodies (the Lake District and the Alston Block) and possibly a further slight sinking of the Vale itself. Such movements may have been accentuated during the unstable Tertiary Period and probably resulted in the development of the Pennine scarp as it is known today.

All but the major relief features of the area depend to a large extent upon the changes which occurred during the Pleistocene glaciation. Most of the deposits, according to Hollingworth (1931), belong to the advance which followed the main glaciation of Britain and they are widespread in the area mapped which forms part of the classic drumlin belt of the Vale of Eden.

Purely depositional features such as eskers and kames are absent but composite erosional-depositional masses, often with a drumlin form, occur over most of the lower ground and may be up to 75 ft. in height (Plate 54). As pointed out by Hollingworth (op.cit.) these bodies sometimes consist of solid rock rather than boulder-clay and it is impossible to distinguish between the two types on form alone. There is a very strong alignment of the drumlins parallel to the general trend of the Eden Valley i.e. N 30° W and usually the steepest end is to the south-east, indicating that the

PLATE 54. Large drumlin east of Dryevers. It rises above a broad alluvial flat which extends south-south-east of the farm.

PLATE 55. View southwards from the Dryevers drumlin towards Hoff Moor. The flat alluvial area in the middle distance was probably a tarn in glacial times.

basal ice, at the time of their formation, moved down the valley towards Carlisle. A few do, however, face in the opposite direction, the largest being that at Morland Bank and its immediate neighbour to the west; they were formed, perhaps, at a time when the ice was moving in a southerly direction towards the Stainmore or Lune exits and the build-up of ice in the Vale was at a maximum.

Even where drumlins are absent, a variable layer of drift generally obscures much of the solid geology, thicknesses of 10 to 20 ft. being commonly found. It is normally of grey and brownish colours but sometimes becomes a deeper red-brown colour near reddened Carboniferous strata, and, where derived from the Penrith Sandstone, is very even-textured and orange in colour. Erratics occur over all but the highest ground; as well as blocks of Carboniferous material, lavas from the Lake District and, in particular, Shap Granite boulders are conspicuous.

Purely erosional features are present only in the highest parts of the area to the south and west where rock pavement, sometimes with striations, may occur. Glacial action has also accentuated the bench-like features in the sides of some of the major valleys, especially in cutting back the soft shale (Goodchild 1887).

Small tarns, due to the blocking of normal channels of drainage by boulder-clay when the ice retreated, were probably once present south-south-east of Dryevers (Plate 55) and west-south-west of Barwise Hall but they have since been filled with alluvium. Small drift-filled channels in the Askham Limestone of Gaythorn Plain are the only probable overflow channels observed, and major water-eroded features are absent in contrast to the region east of the Eden (Trotter 1929) where the ice was retreating towards lower, rather than higher, ground. The deep and youthful valleys of the main north-flowing streams and the steepness of some of their tributaries can, however, be attributed to the action of glacial meltwaters which are also probably responsible for the higher of the river terraces.

FOSSIL LIST

KNIPE SCAR LIMESTONE

Girvanella nodules.

Dibunophyllum bourtonense Garwood and Goodyear.
Lithostrotion martini Edwards and Haime group.
L. minus McCoy.
Palaeosmilia murchisoni Edwards and Haime.

Bryozoa indet.

Buxtonia sp.
Chonetes papilionacea Phillips.
Gigantoproductus maximus (McCoy).
Productus sp.
Spirifer sp.

ASKHAM LIMESTONE

Girvanella nodules.

Saccamminopsis fusulinaformis (McCoy).

Chaetetes septosus (Fleming).
Diphyphyllum sp.
Lithostrotion junceum (Fleming).
L. maccoyanum Edwards and Haime.
L. martini Edwards and Haime group.
Lonsdaleia floriformis (Martin).
Syringopora sp.

Crinoid columnals up to 15 mm. diameter.

Chonetes (? *Megachonetes*) juv.
Chonetes sp.
Dictyoclostus sulcatus (J.Sowerby).
Gigantoproductus juv.
Schuchertella sp.

Sanguinolites sp.

ASKHAM CLASTICS

Haploid coral indet.

Crinoid columnals up to 16 mm. diameter.

Bryozoa indet.

Dictyoclostus sp.

Lamellibranch ? *Schizodus*.

BANK MOOR LIMESTONE

Girvanella nodules.

Caninia sp.
Lithostrotion junceum (Fleming).
L. martini Edwards and Haime group.
L. cf. scoticum Hill.
Haploid coral indet.

Edmondia cf. expansa Hind.

Bellerophontid.

MAULDS MEABURN LIMESTONE

Aulophyllum fungites (Fleming).
Caninia bemberbensis Lewis group.
Chaetetes septosus (Fleming).
Dibunophyllum bipartitum (McCoy).
? Koninckophyllum sp.
Lithostrotion junceum (Fleming).
L. martini Edwards and Haime group.
Lonsdaleia floriformis (Martin).
Nemistium edmondsi S. Smith.
Palaeosmilia murchisoni Edwards and Haime.
Syringopora sp.

Fenestella sp.

Athyris sp.
Brachythyris sp.
Dictyoclostus pugilis (Phillips).
Dictyoclostus sp.
Gigantoproductus giganteus (Martin) group.
G. latissimus J. Sowerby.
Overtonia fimbriata (J. de C. Sowerby).
Productus sp.
Spirifer bisulcatus J. de C. Sowerby.

MAULDS MEABURN CLASTICS

Annelid trails.

Orthotetid.

LITTLE STRICKLAND LIMESTONE

Girvanella nodules.

Saccamminopsis fusulinaformis (McCoy).

Diphyphyllum fasciculatum (Fleming).
Lithostrotion junceum (Fleming).
L. martini Edwards and Haime group.
L. pauciradiale (McCoy).
Orionastraea placenta (McCoy).
Syringopora sp.

Camarotoechia pleurodon (Phillips).
Composita sp.
Dictyoclostus sp.

Eomarginifera sp.
Phricodothyris sp.
Productus (Echinoconchus) cf. punctatus (Martin).
Schuchertella sp.

Gastropod indet.

Fish teeth.

LITTLE STRICKLAND CLASTICS

Productus sp.
Spirifer sp.

Lamellibranch indet.

JOHNNY HALL'S TREES LIMESTONE

Crinoid columnals up to 21mm. diameter.

JOHNNY HALL'S TREES CLASTICS

Dibunophyllum sp.
Lithostrotion pauciradiale (McCoy).

Gigantoproductus giganteus (Martin) group.

MAULDS MEABURN EDGE LIMESTONE

Girvanella nodules.

Saccamminopsis fusulinaformis (McCoy).

Lithostrotion junceum (Fleming).
Syringopora sp.

Pugnax pugnus (Martin).

BRACKENSLACK LIMESTONE

Stick bryozoa.

GRAYBER LIMESTONE

Haploid coral indet.

Stenopora sp.

NEWBY MILL LIMESTONE

Haploid coral indet.

Gigantoproductus latissimus J. Sowerby.
Spirifer bisulcatus J. de C. Sowerby.

Trilobite pygidium indet.

NEWBY MILL CLASTICS

Productus concinnus J. Sowerby.

Aviculopecten planoclathratus McCoy.
Eumicrotis sp.

Cycloceras sp.

GREAT STRICKLAND LIMESTONE

Dibunophyllum sp.
Diphyphyllum lateseptatum (McCoy).
Lonsdaleia floriformis laticlavia S. Smith.

Spirifer ? trigonalis (Martin).

UPPER LIMESTONE GROUP (excluding Great Strickland and Bewley Castle Limestones)

Fenestella sp.

Productus sp.
Spirifer ? trigonalis (Martin).

Coleolus sp.

Cycloceras sp.

BEWLEY CASTLE LIMESTONE

Hyalostelia parallela McCoy.

Zaphrentid indet.

Fenestella sp.
Bryozoan indet.

Dictyoclostus sp.
Echinoconchus sp.
Eomarginifera sp.
Orbiculoidea nitida (Phillips).
Orthotetid indet.
Spirifer bisulcatus J. de C. Sowerby.

Lamellibranchs indet.

Euphemites urei (Fleming).

Cycloceras sp.
Nautiloid indet.

REFERENCES

ANDERSON, W. and DUNHAM, K.C. 1953. Reddened beds of Carboniferous age beneath the Permian of Durham and south Northumberland. Proc. Yorks. Geol. Soc., 29, 21-32.

BAILEY, E.B. 1926. Subterranean penetration by a desert climate. Geol. Mag., 63, 276-280.

BLAND, J.S. 1862. On the Carboniferous rocks in the neighbourhood of Shap and Crosby Ravensworth. Trans. Manch. Geol. Soc., 4, p. 44.

BLAND, J.S. 1910. The Vale of Lyvennet. Wilson, Kendal. 90 pp.

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.

BOTT, M.H.P. 1964. Formation of sedimentary basins by ductile flow of isostatic origin in the upper mantle. Nature, Lond., 201, 1082-84.

BURST, J.F. 1958. Mineral heterogeneity in " glauconite pellets ". Amer. Min., 43, 481-497.

CAPEWELL, J.G. 1955. The post-Silurian pre-marine Carboniferous sedimentary rocks of the eastern side of the English Lake District. Quart. J. Geol. Soc. Lond., 111, 23-46.

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

CHAVE, K.E. 1954. Aspects of the biogeochemistry of magnesium. 1. Calcareous marine organisms. Journ. Geol., 62, p. 266.

CLOUD, P.E. 1962. Behaviour of calcium carbonate in sea water. Geo. et Cosmo. Acta, 26, 867-884.

CLOUD, P.E. Jr. 1955. Physical limits of glauconite formation. Bull. Amer. Assoc. Petrol. Geol., 39, 484-492.

DAKYNS, J.R., TIDDEMAN, R.H. and GOODCHILD, J.G. 1897. The goelogy of the country between Appleby, Ullswater and Haweswater. Mem. Geol. Surv. U.K.

DEER, W.A., HOWIE, R.A. and ZUSSMAN, J. 1962. Rock forming minerals. Vol. 5. Non-silicates. Longmans, London. 307 pp.

DEGENS, E.T., WILLIAMS, E.G. and KEITH, M.L. 1957. Environmental studies of Carboniferous sediments. 1: Geochemical criteria for differentiating marine from freshwater shales. Bull. Amer. Assoc. Petrol. Geol., 41, 2427-2455.

DEGENS, E.T., WILLIAMS, E.G. and KEITH, M.L. 1958. Environmental studies of Carboniferous sediments. 2: Application of geochemical criteria. Bull. Amer. Assoc. Petrol. Geol., 42, 981-997.

DUNBAR, C.O. and RODGERS, J. 1957. Principles of stratigraphy. Wiley, New York. 356 pp.

DUNHAM, K.C. 1932. Quartz-dolerite pebbles (Whin Sill type) in the Upper Brockram. Geol. Mag., 69, p. 425.

DUNHAM, K.C. 1933. Structural features of the Alston Block. Geol. Mag., 70, 241-254.

DUNHAM, K.C. 1948. Geology of the northern Pennine orefield, Vol. 1, Tyne to Stainmore. Mem. Geol. Surv. U.K. 344pp.

DUNHAM, K.C. 1952. Red colouration in desert formations of Permian and Triassic age in Britain. XIX Int. Geol. Congr., Pt. vii, 25-32.

EASTWOOD, T. et al. 1931. The geology of the Whitehaven and Workington district. Mem. Geol. Surv. U.K.

EDMONDS, C. 1922. The Carboniferous Limestone Series of west Cumberland. Geol. Mag., 59, 74-83, 117-131.

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

GARWOOD, E.J. 1912. The Lower Carboniferous succession in the north-west of England. Quart. J. Geol. Soc., Lond., 68, 449-586.

GILLIGAN, A. 1919. The petrography of the Millstone Grit of Yorkshire. Quart. J. Geol. Soc., Lond., 75, p. 251.

GILLIGAN, A. The geology of the Appleby district. 1926.

GOODCHILD, J.G. 1874. Note on the Carboniferous conglomerates of the basin of the Eden. Quart. J. Geol. Soc., Lond., 30, 394-400.

GOODCHILD, J.G. 1887. Ice work in Edenside and some of the adjoining parts of north-west England. Trans. Cumb. Westm. Assoc., 11, 111-167.

GOODCHILD, J.G. 1889. An outline of the geological history of the Eden Valley or Edenside. Proc. Geol. Assoc., 11, 258-284.

GOODCHILD, J.G. 1891. Observations on the New Red Series of Cumberland and Westmorland with especial reference to classification. Trans. Cumb. Westm. Assoc., 17, 1-24.

GRAF, D.L. 1962. Minor element distribution in sedimentary carbonate rocks. Geoch. Cosmoch. Acta, 26, 849-856.

GROVES, A.W. 1951. Silicate analysis. Edition 2. Allen and Unwin, London.

HAWKES, L. and SMYTHE, J.A. 1935. Ankerites from the Northumberland coalfield. Min. Mag. , 24, p. 65.

HIRST, D.M. 1962. The geochemistry of modern sediments from the Gulf of Paria. II: Location and distribution of trace elements. Geoch. Cosmoch. Acta, 62, 1147-1187.

HOLLINGWORTH, S.E. 1931. Glaciation of western Edenside and adjoining areas and the drumlins of Edenside and the Solway Basin. Quart. J. Geol. Soc., Lond., 87, 281-359.

HOWIE, R.A. and BROADHURST, F.M. 1958. X-ray data for dolomite and ankerite. Amer. Min., 43, p. 1210.

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. 1929. A Carboniferous lagoon deposit with sponges. Proc. Yorks. Geol. Soc., 21, 181-196.

HUDSON, R.G.S. 1938. The general geology......and the Carboniferous rocks. In 'The geology of the country around Harrogate'. Proc. Geol. Assoc., 49, 295-330.

ILLING, L.V. 1954. Bahaman calcareous sands. Bull. Amer. Assoc. Petrol. Geol., 38, 1-95.

INGERSON, E. 1962. Problems of the geochemistry of sedimentary carbonate rocks. Geoch. Cosmoch. Acta, 26, 815-847.

JOHNSON, G.A.L. 1958. Biostromes in the Namurian Great Limestone of northern England. Palaeontology, 1, 147-157.

JOHNSON,G.A.L. 1959. The Carboniferous stratigraphy of the Roman Wall district in western Northumberland. Proc. Yorks. Geol. Soc., 32, 83-130.

JOHNSON,G.A.L. and DUNHAM, K.C. 1962. The geology of Moor House. Monograph of the Nature Conservancy, No. 2, H.M.S.O., London. 168pp.

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

KENDALL, P.F. 1902. On the Brockrams of the Vale of Eden and the evidence they afford of an inter-Permian movement of the Pennine Faults. Geol. Mag., 39, 510-513.

KRAUSKOPF, K.B. 1956. Dissolution and precipitation of silica at low temperatures. Geoch. Cosmoch. Acta, 10, 1-26.

KRUMBEIN, W.C. and GARRELS, R.M. 1952. Origin and classification of chemical sediments in terms of pH and oxidation-reduction potentials. Journ. Geol., 60, 1-33.

LORING, D.H. 1960. Some aspects of the geochemistry of certain Carboniferous rocks. Ph. D. Thesis, Manchester.

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

MACCARTHY, G.R. 1926. Colours produced by iron in minerals and the sediments. Amer. Journ. Sci., Series 5, 12, 17-36.

McKEE, E.D. 1953. Report on studies of stratification in modern sediments and in laboratory experiments. Office of Naval Research, Project No. 164 (00), 61 pp.

MARR, J.E. 1907. The geology of the Appleby district, Westmorland. Proc. Geol. Assoc., 20, 129-148.

MILLER, A.A. and TURNER, J.S. 1931. The Lower Carboniferous succession along the Dent Fault and the Yoredale beds of the

Shap district. Proc. Geol. Assoc., 42, 1-38.

MOORBATH, S. 1959. Isotopic composition of lead from British mineral deposits. Nature, London, 183, 595-596.

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

MYKURA, W. 1960. The replacement of coal by limestone amd the reddening of Coal Measures in the Ayrshire Coalfield. Bull. Geol. Surv. G.B., 16, 69-109.

NICHOLLS, G.D. 1958. Sedimentary geochemistry. A possible future method for the correlation of strata. Petroleum.

ODUM, H.T. 1951. The stability of the world strontium cycle. Science, 114, 407-411.

PATTINSON, R. 1964. Stratigraphy and sedimentation of the Namurian strata in the Coalcleugh-Rookhope district, northern Pennines. Ph.D. Thesis, Durham.

PETTIJOHN, F.J. 1957. Sedimentary rocks. (2nd. Edition). Harper, New York. 718 pp.

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

RAMBERG, H. 1952. The origin of metamorphic and metasomatic rocks. Chicago, Univ. Chicago Press.

RANKAMA, K. and SAHAMA, T.G. 1950. Geochemistry. Univ. Chicago Press. 912 pp.

RAY,S., GAULT,H.R. and DODD, C.G. 1957. The separation of clay minerals from carbonate rocks. Amer. Min., 42, 681-686.

RAYNER, D.H. 1953. The Lower Carboniferous rocks in the north of England: a review. Proc. Yorks. Geol. Soc., 28, 231-315.

SCHWARZACHER, W. 1958. The stratification of the Great Scar Limestone in the Settle district of Yorkshire. Lpool Manchr. Geol. J., 2, 124-142.

SHOTTON, F.W. 1935. The stratigraphy and tectonics of the Cross Fell Inlier. Quart. J. Geol. Soc., Lond., 91, 639-704.

SHOTTON, F.W. 1956. Some aspects of the New Red desert in Britain. Lpool Manchr. Geol. J., 1, p. 450.

SMYTHE, F.S. and DUNHAM, K.C. 1947. Ankerites and chalybites from the northern Pennine orefield and the north-east coalfield. Min. Mag., 28, p. 53.

SPEARS, D.A. 1961. Joints in the Whin Sill and associated sediments in upper Teesdale, northern Pennines. Proc. Yorks. Geol. Soc., 33, p.21.

TAKAHASHI, J. 1939. Synopsis of glauconitisation; in 'Recent marine sediments'. Amer. Assoc. Petrol. Geol., Tulsa, 503-512.

TEODOROVICH, G.I. 1961. Authigenic minerals in sedimentary rocks. (Translation from the Russian). New York. 120 pp.

TROTTER, F.M. 1929. Glaciation of east Edenside, the Alston Block and the Carlisle Plain. Quart. J. Geol. Soc. Lond., 85, 549-612.

TROTTER, F.M. 1939. Reddened Carboniferous beds in the Carlisle Basin and Edenside. Geol. Mag., 76, 408-416.

TROTTER, F.M. 1944. The age of the ore deposits of the Lake District and of the Alston Block. Geol. Mag., 81, p. 223.

TUREKIAN, K.K. 1955. Palaeoecological significance of the strontium/ calcium ratio in fossils and sediments. Bull. Geol. Soc. Amer., 66, 155-158.

TUREKIAN, K.K. and KULP,L . 1956. The geochemistry of strontium. Geoch. Cosmoch. Acta, 10, 245-296.

TUREKIAN, K.K. and WEDEPOHL, K. 1961. Distribution of elements in some major units of the earth's crust. Bull. Geol. Soc. Amer., 72, 175-192.

TURNER, J.S. 1927. The Lower Carboniferous succession in the Westmorland Pennines and the relations of the Pennine and Dent Faults. Proc. Geol. Assoc., Lond., 38, 339-374.

TURNER,J.S. 1956. Some faunal bands in the Upper Visean and early Namurian of the Askrigg Block. Lpool Manchr. Geol. J., 1, 410-419.

TURNER, J.S. 1963. A boring through the Lower Brockram at Appleby, Westmorland. Trans. Leeds Geol. Assoc., 7, 127-130.

van ANDEL, Tj.H. and POSTMA, H. 1954. Recent sediments of the Gulf of Paria; in Reports of the Orinoco Shelf Expedition, Vol.1. Kon. Nederl. Akad. Wetensch. Verh., Vol. 20, No. 5.

VAN HOUTEN, F.B. 1948. Origin of red-banded early Cenozoic deposits in the Rocky Mountains region. Bull. Amer. Assoc. Petrol. Geol., 32, 2083-2126.

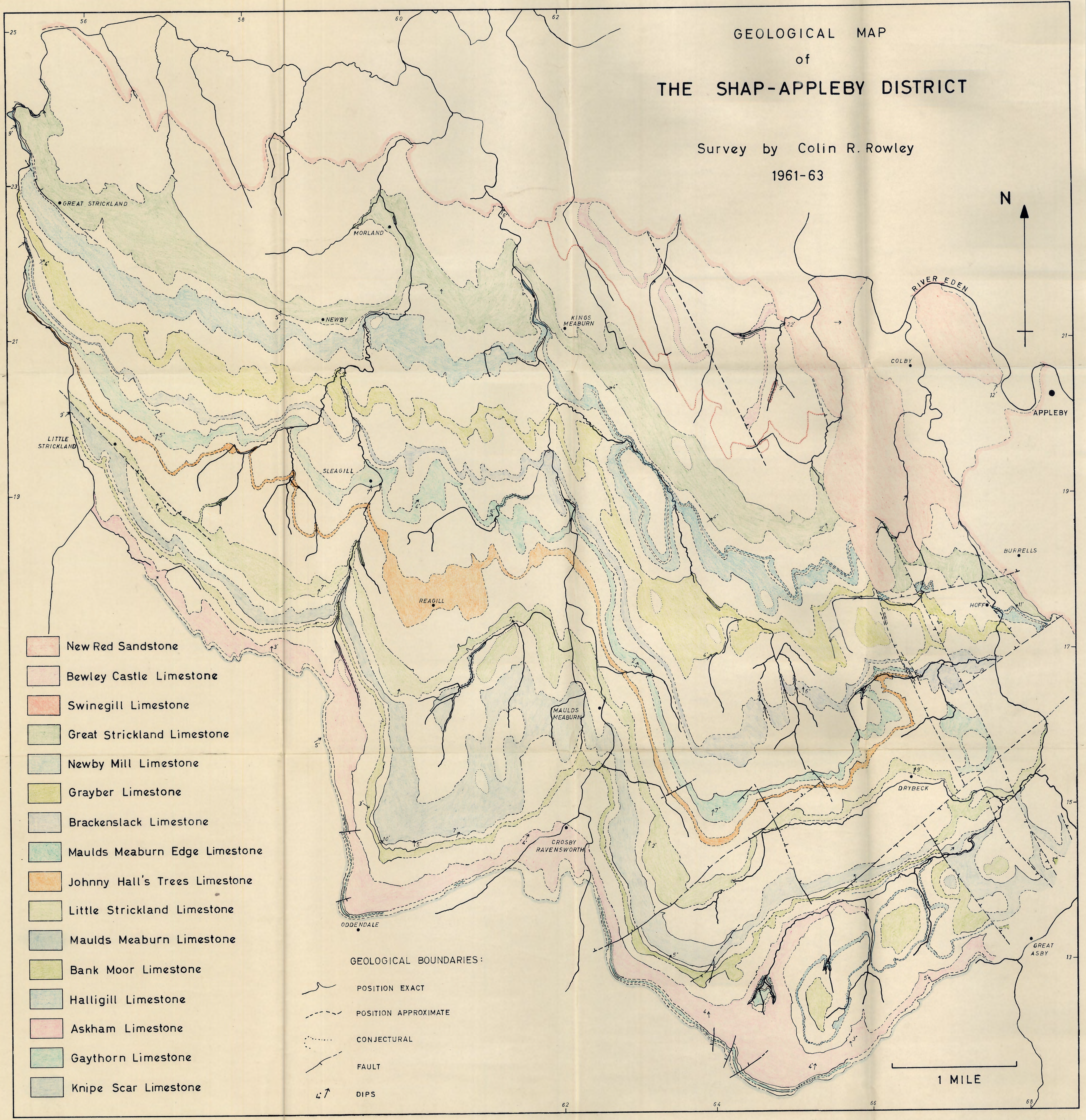
VERSEY, H.C. 1939. The petrography of the Permian rocks in the southern part of the Vale of Eden. Quart. J. Geol. Soc. Lond., 95, p. 275.

VERSEY, H.C. 1960. Geology of the Appleby district. (4th. edition). Appleby. 40 pp.

WELLER, J.M. 1930. Cyclical sedimentation of the Pennsylvanian Period and its significance. Journ. Geol., 38, p. 97.

WELLS, A.J. 1955. The development of chert between the Main and Crow Limestones in north Yorkshire. Proc. Yorks. Geol. Soc., 30, 177-198.

WELLS, A.J. 1960. Cyclic sedimentation: a review. Geol. Mag., 97, 389-403.


GEOLOGICAL MAP
of
THE SHAP-APPLEBY DISTRICT
Survey by Colin R. Rowley
1961-63
N
RIVER EDEN
GREAT STRICKLAND
MORLAND
NEWBY
KINGS MEABURN
COLBY
APPLEBY
LITTLE STRICKLAND
SLEAGILL
REAGILL
BURRELLS
HOFF
MAULDS MEABURN
DRYBECK
CROSBY RAVENSWORTH
ODDENDALE
GREAT ASBY
New Red Sandstone
Bewley Castle Limestone
Swinegill Limestone
Great Strickland Limestone
Newby Mill Limestone
Grayber Limestone
Brackenslack Limestone
Maulds Meaburn Edge Limestone
Johnny Hall's Trees Limestone
Little Strickland Limestone
Maulds Meaburn Limestone
Bank Moor Limestone
Halligill Limestone
Askham Limestone
Gaythorn Limestone
Knipe Scar Limestone
GEOLOGICAL BOUNDARIES:
POSITION EXACT
POSITION APPROXIMATE
CONJECTURAL
FAULT
DIPS
1 MILE
56
58
60
62
64
66
68
25
23
21
19
17
15
13

SECTION THROUGH THE STRATA IN THE SHAP-APPLEBY DISTRICT