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SEDIMENTOLOGY, PALAFONTOLOGY AND DIAGENESIS OF THE MUCH WENLOCK LIMESTONE FORMATION

KENNETH THOMAS RATCLIFFE

Doctor of Philosophy

ASTON UNIVERSITY

October 1987

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ASTON UNIVERSITY

SEDIMENTOLOGY, PALAFONTOLOGY AND DIAGENESIS OF THE MUCH WENLOCK LIMESTONE FORMATION

by

Kenneth Thomas Ratcliffe

Submitted for the degree of Doctor of Philosophy at Aston University
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Summary

Lithofacies distribution indicates that the Much Wenlock Limestone Formation of England and South Wales was deposited on a shelf which was flat and gently subsiding in the north, but topographically variable in the south. Limestone deposition in the north began with 12m of alga-rich limestone, which formed an upward shoaling sequence. Deepening then led to deposition of calcareous silty mudstones on the northern shelf. The remainder of the formation in this area formed during a shelf-wide regression, culminating in the production of an E to W younging sandbody. Lithofacies distribution on the southern shelf was primarily controlled by local subsidence. Six bedded lithofacies are recognised which contain 14 brachiopod/bryozoan dominated assemblages, of which 11 are in situ and three consist of reworked fossils. Microfacies analysis is necessary to distinguish assemblages which reflect original communities from those which reflect sedimentary processes. Turbulence, substrate-type, ease of feeding and other organisms in the environment controlled faunal distribution. Reefs were built dominantly by corals, stromatoporoids, algae and crinoids. Coral/stromatoporoid (Type A) reefs are common, particularly on the northern shelf, where they formed in response to shallowing, ultimately growing in front of the advancing carbonate sandbody. Algae dominate Type B and Type C reefs, reflecting growth in areas of poor water circulation. Lithification of the formation began in the marinephreatic environment with precipitation of aragonite and high Mg calcite, which was subsequently altered to turbid low Mg calcite. Younger clear spars post-date secondary void formation. The precompactional clear spars have features which resemble the products of meteoric water diagenesis, but freshwater did not enter the formation at this time. The pre-compactional spars were precipitated by waters forced from the surrounding silty mudstones at shallow burial depths. Late diagenetic products are stylolites, compaction fractures and burial cements.

Key Words

Silurian, limestone, sedimentology, palaeontology, diagenesis.

TITLE PAGE1
THESIS SUMMARY2
CONTENTS3
LIST OF FIGURES8
CHAPTER 1 INTRODUCTION
CHAPTER 2 LITHOFACIES, MICROFACIES AND DEPOSITIONAL
ENVIRONMENTS OF THE MUCH WENLOCK LIMESTONE
FORMATION20
2.1 ABSTRACT20
2.2 INTRODUCTION
2.3 LITHOFACIES
2.3.1 Wavy-bedded crinoidal grainstone lithofacies24
2.3.2 Interbedded limestone and silty mudstone
lithofacies24
2.3.3 Thick-bedded oncoid-rich lithofacies29
2.3.4 Ferruginous crinoidal grainstone lithofacies30
2.3.5 Nodular limestone lithofacies30
2.3.6 Silty micrite lithofacies31
2.3.7 Reef lithofacies31
2.3.8 Lithofacies distribution32
2.4 MICROFACTES35
2.4.1 Carbonate mudstones
2.4.2 Wackestones
2.4.3 Packstones38
2.4.4 Grainstones40
2.4.5 Boundstones41
2.4.5.1 Bindstones41

2.4.5.2 Framestones41
2.5 DEPOSITIONAL ENVIRONMENT OF LITHOFACIES42
2.5.1 Wavy-bedded crinoidal grainstone lithofacies42
2.5.2 Interbedded limestone and silty mudstone
lithofacies45
2.5.3 Thick-bedded oncoid-rich lithofacies47
2.5.4 Nodular limestone lithofacies48
2.5.5 Ferruginous crinoidal grainstone lithofacies49
2.5.6 Reef lithofacies50
2.6 DEPOSITIONAL HISTORY OF THE MUCH WENLOCK LIMESTONE
FORMATION52
2.7 REFERENCES
CHAPTER 3 ONCOIDS AS ENVIRONMENTAL INDICATORS IN THE MUCH
WENLOCK LIMESTONE FORMATION OF THE WEST MIDLANDS65
3.1 ABSTRACT65
3.2 INTRODUCTION
3.3 SEDIMENTOLOGY OF THE LOWER QUARRIED LIMESTONE69
3.3.1 Reef lithofacies69
3.3.2 Bedded lithofacies71
3.4 ALGAE IN THE LOWER QUARRIED LIMESTONE
3.5 ONCOIDS IN THE LOWER QUARRIED LIMESTONE
3.6 ONCOIDS AS ENVIRONMENTAL INDICATORS80
3.7 CORRELATION AND PALAFOGEOGRAPHY84
3.8 REFERENCES
CHAPTER 4 PALAEOECOLOGY OF BRACHIOPOD/BRYOZOAN DOMINATED
COMMUNITIES IN THE MUCH WENLOCK LIMESTONE FORMATION93

4.1	ABSTRA	ACT93
4.2	INTROI	DUCTION95
4.3	SAMPLI	ING PROCEDURES98
4.4	SEDIM	ENTOLOGY99
	4.4.1	Interbedded limestone and silty mudstone
		lithofacies100
	4.4.2	Thick-bedded oncoid-rich lithofacies101
	4.4.3	Nodular limestone lithofacies102
	4.4.4	Ferruginous crinoidal grainstone lithofacies102
4.5	PALAE	OECOLOGY103
	4.5.1	Composition of faunal assemblages103
		4.5.1.1 Sedimentary overprint103
		4.5.1.2 Minor elements of the fauna104
		4.5.1.3 Poor taxonomic knowledge of Silurian
		bryozoans119
	4.5.2	Environmental significance of faunal assemblages.121
		4.5.2.1 Assemblage 1
		4.5.2.2 Assemblage 2124
		4.5.2.3 Assemblage 3
		4.5.2.4 Assemblage 4
		4.5.2.5 Assemblage 5
		4.5.2.6 Assemblage 6
		4.5.2.7 Assemblage 7
		4.5.2.8 Assemblage 8
		4.5.2.9 Assemblage 9130
		4.5.2.10 Assemblage 10131

4.5.2.11 Assemblage 11131
4.5.3 Sedimentary faunal assemblages132
4.5.3.1 Assemblage A132
4.5.3.2 Assemblage B
4.5.3.3 Assemblage C134
4.5.4 Distribution of assemblages135
4.5.4.1 Silty mudstone/limestone fauna135
4.5.4.2 Laterally equivalent collections138
4.5.4.3 Bed-by-bed variation138
4.5.4.4 Regional and stratigraphic variation of
assemblages138
4.6 CONCLUSIONS142
4.7 REFERENCES
APPENDIX I- COLLECTION LOCALITIES149
CHAPTER 5 THE WENLOCK REEFS OF ENGLAND
5.1 ABSTRACT153
5.2 INTRODUCTION
5.3 REEF MICROFACIES
5.3.1 Wackestones, packstones and grainstones155
5.3.2 Boundstones
5.4 REEF DESCRIPTIONS
5.4.1 Type A reefs157
5.4.1.1 Sedimentology160
5.4.1.2 Palaeontology160
5.4.1.3 Sedimentology of surrounding lithofacies.161
5.4.1.4 Relief
5.4.2 Type B reefs

5.4.2.1 Sedimentology162
5.4.2.2 Palaeontology165
5.4.2.3 Sedimentology of surrounding lithofacies.165
5.4.2.4 Relief
5.4.3 Type C reefs166
5.4.3.1 Sedimentology and palaeontology166
5.4.3.2 Sedimentology of surrounding lithofacies.169
5.4.3.3 Relief169
5.5 REEF GROWTH
5.5.1 Type A reefs169
5.5.2 Type B reefs
5.5.3 Type C reefs
5.6 FACTORS CONTROLLING REEF DISTRIBUTION
5.7 REFERENCES
CHAPTER 6 MARINE: SHALLOW-BURIAL: DEEP-BURIAL DIAGENESIS OF A
SILURIAN LIMESTONE
6.1 ABSTRACT183
6.2 INTRODUCTION
6.3 CEMENT DESCRIPTION
6.3.1 Micritic envelopes187
6.3.2 Micritic and iron oxide cements190
6.3.3 Turbid sparry cements190
6.3.4 Secondary voids and neomorphism199
6.3.5 Inclusion-free cements199
6.3.5.1 Pre-compactional clear cements199
6.3.5.2 Post-compactional clear cements205

	6.3.6	Pressure solution and late-stage vein fill206
	6.3.7	Dolomitisation207
	6.3.8	Silicification207
6.4	DIAGE	VETIC ENVIRONMENTS208
	6.4.1	Diagenetic environments of micritic and turbid
		spar cements208
	6.4.2	Diagenetic environments of pre-compactional clear
		cements
	6.4.3	Diagenetic environments of post-compactional
		cements218
6.5	DIAGE	NETIC HISTORY OF THE MUCH WENLOCK LIMESTONE
	FORMA!	PICS
6.6	REFER	ENCES
CHA	PIER 7	OONCLUSIONS
	APPEN	DIX II233
	APPEN	DIX III

1.1	Locality mapl
2.1	Locality and palaeogeographic maps2
2.2	Correlation of lithofacies across the West Midlands2
2.3	Correlation of lithofacies in the Welsh Borders2
2.4	Schematic representation of Daw End railway cutting3
2.5	Correlation of lithofacies sequences in the West
	Midlands and on Wenlock Edge
2.6	Microfacies composition of the Much Wenlock Limestone
	Formation
2.7	Triangular plots for cement vs. clast vs. matrix
	for each lithofacies4
2.8	The sequence of lithofacies variation in the West
	Midlands5
2.9	Depositional environments of the Much Wenlock
	Limestone Member5
2.10	Depositional environments on the late Wenlock shelf5
3.1	Locality map and generalized stratigraphy6
3.2	Microfacies distribution in the Lower Quarried
	Limestone Member7
3.3	Microfacies composition of the Lower Quarried
	Limestone Member
3.4	Algae and oncoids in the Much Wenlock Limestone
	Formation
3.5	Ratio of maximum cortex thickness to minimum cortex
	thickness vs. circumference of oncoids from borehole
	R37
3.6	Composition of three oncoid morphotypes

3.7	sequential variation of oncord morphotypes in the
	Lower Quarried Limestone Member
3.8	Lithological correlation of the Much Wenlock Limestone
	Formation from Walsall to Dudley8
3.9	Refined lithological correlation of the Lower Quarried
	Limestone Member made available by studying changes in
	oncoid morphology8
4.1	Locality map9
4.2	Faunal composition of collections from Daw End railway
	cutting10
4.3	Faunal composition of collections from the Lower
	Quarried Limestone Member and the lower part of the
	Nodular Beds Member at Wren's Nest10
4.4	Faunal composition of collections from the upper
	part of the Nodular Beds Member at Wren's Nest11
4.5	Faunal composition of collections from Hobb's Ridge in
	the May Hill inlier11
4.6	Faunal composition of collections from Eastnor Quarry
	in the Ledbury Hills11
4.7	Faunal composition of collections from the Woolhope
	inlier11
4.8	Faunal composition of collections from the Usk inlier.11
4.9	Method adopted for removing minor faunal elements from
	the raw data12
4.10	Correlation matrix for comparison of collections from
	Eastnor Castle Quarry12
4.11	Brachiopod composition of assemblages 1-1112

4.12	Faunal variation between silty mudstone and adjacent
	limestone beds13
4.13	Faunal variation between laterally equivalent
	collections13
5.1	Locality map15
5.2	Microfacies distribution in Type A reefs
5.3	Microfacies distribution in Type B reefs16
5.4	Microfacies distribution in Type C reefs16
5.5	Growth of Type A reefs17
5.6	Growth of Type B reefs
5.7	Growth of Type C reefs
6.1	Locality map
6.2	Micritic, ferroan and early marine cements18
6.3	Marine cement fabrics and their probable precursors19
6.4	Sparry marine cements19
6.5	Sparry marine cements and silicification features19
6.6	Carbon/oxygen isotope plot for spars, micrites and
	allochems20
6.7	Dissolution features and pre-compactional cements20
6.8	Distribution of secondary voids and pre-compactional
	clear spars20
6.9	Organic matter degredation related to organic matter
	dewatering21
6.10	Mixing systems within the Much Wenlock Limestone
	Formation created during shallow burial21
6.11	Timing of deep burial diagenetic products22
6 12	Diagenetic history of the Much Wenlock Limestone

Formation

CHAPTER 1

INTRODUCTION

Wenlock rocks crop out widely in Britain (Fig. 1.1), those deposited in the Welsh Borderland, English Midlands and South Wales forming part of the Silurian shelf sequence which accumulated on the SE margin of the Tapetus Ocean. Limestones are locally important within shelf sequences, and the Much Wenlock Limestone Formation is the most notable of these. The formation crops out on Wenlock Edge, in the English Midlands, the southern Welsh Borders and South Wales (Fig.1.1). Exposure in the type area is greatly enhanced by quarrying which is still active today. Limestone was quarried and mined from the inliers in the Midlands, southern Welsh Borders and South Wales in the past but these activities have now largely ceased. However, small, overgrown quarries and stall and pillar mines are common, providing practically the only exposure of the formation in the inliers. The mine systems extend under much of the West Midlands and core material is produced from holes sunk to determine the location of these underground caverns.

In the Wenlock type area on Wenlock Edge, the formation is the uppermost lithostratigraphic division of the Wenlock Series (Bassett 1974) and belongs to the <u>ludensis</u> Biozone of the Homerian (Bassett et al. 1975), but the base descends to the <u>lundgreni</u> Biozone in the West Midlands (Fig.1.1). Field descriptions of the formation are common and date back to the middle of the last century (see Riding 1981 for review of early work). Detailed descriptions of the formation have

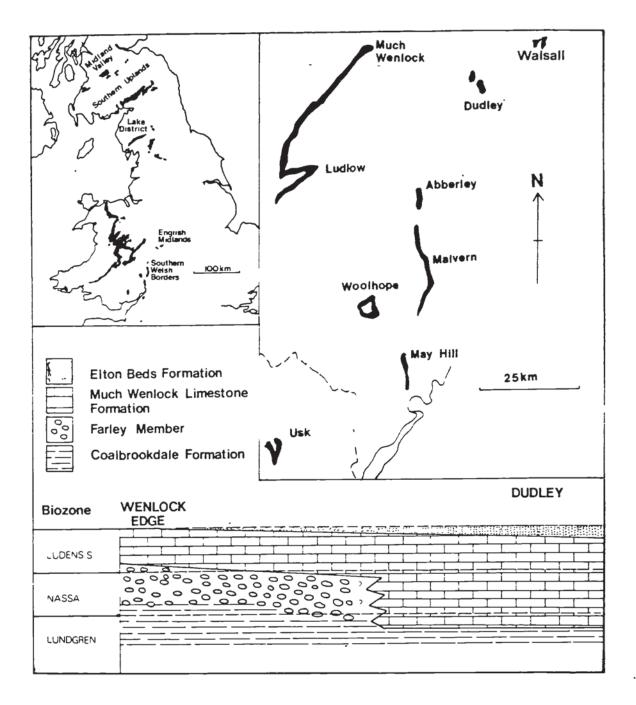


Fig. 1.1 Locality map. Upper left inset shows the outcrop of Wenlock rocks on mainland Britain (after Thomas 1978). In the Southern Uplands the outcrop given is that of the Ludlow and Wenlock. In the Midland Valley the entire Silurian outcrop is shown. The inset on the right shows the outcrop of the Much Wenlock Limestone Formation in the English Midlands and the Welsh Borders. The lower diagram is a schematic cross-section of Homerian rocks, taken E-W from Dudley to Wenlock Edge.

been made more recently by Shergold & Bassett (1970) and Scoffin (1971) leading to a palaeogeographic reconstruction in which the formation at Wenlock Edge occupied a shelf edge position; deep water muds were deposited to the W and shallow shelf deposits to the E (Scoffin 1971, p. 215). The stratigraphy and field appearance of the formation have been described in the English Midlands (Butler 1939, Oliver 1981, Dorning 1983), in the Abberley, Malvern and Ledbury Hills (Phipps & Reeve 1967), around May Hill (Lawson 1954, Lawson 1955) and Usk (Walmsley 1959), but little detailed sedimentological or environmental interpretation was made.

Fossils from the Much Wenlock Limestone Formation were described and illustrated as early as 1750 (Thomas 1978, p. 3) and the formation has since become renowned for its diverse and generally well preserved fauna. More recently some shelly faunal elements have been the subjects of detailed taxonomic and stratigraphic studies (see Bassett 1970, p. 2 and Thomas 1978, p. 3 for references), some of which are still unpublished (Powell 1980). Palaeoecological work has concentrated mainly on brachiopods (Hurst 1975), corals (Abbott 1974, Powell 1980) and stromatoporoids (Powell 1980). The coral and stromatoporoid fauna was only extensively studied by these authors on Wenlock Edge, study in the inliers being patchy. The only published account of the diagenesis of the Much Wenlock Limestone Formation (Oldershaw & Scoffin 1967) concentrated on Wenlock Edge and was published before cathodoluminescence and stable isotope techniques were generally used in diagenetic studies.

The chapters in this thesis concentrate on the sedimentology, palaeontology and diagenesis of the less well studied inliers of the

English Midlands, southern Welsh Borders and South Wales. Each chapter is presented as a self contained paper adopting the format of the Journal of the Geological Society, London in order to be consistent with chapter 3 which has already been accepted for publication there. Chapters 2 and 3 present and interpret lithofacies and microfacies data from core material from the West Midlands and from surface exposure. Chapters 4 and 5 concentrate on the palaeoecology; chapter 4 describes the faunas of the bedded lithofacies and chapter 5 the reef palaeoecology. Chapter 6 describes the sequence of diagenetic environments through which the formation passed subsequent to its deposition.

The data base for the work was derived largely from field work and core logging. Cores were cut through the centre as far as possible and then logged. Field work in the first year, totalling approximately 4 weeks, involved compilation of sedimentary logs for the formation using locality data from Bassett (1970) and Thomas (1978). This was followed in the second year with a further 4 weeks field work in which palaeoecological collections were made and detailed reef maps prepared. The latter were done by photographing selected reefs and then superimposing the lithofacies on to photographic prints. Palaeoecological samples from bedded lithofacies consisted of 2 - 6 kg of fossiliferous beds. These were then split in the laboratory and thin sections prepared for microfacies analysis. Approximately 250 thin sections were prepared and studied during the research. Coral and stromatoporoid specimens had acetate peels taken from cut, polished and etched surfaces for identification. Thin sections were studied using a Technosyn cold cathodoluminescence model II lumnoscope for

diagenetic studies. Powders for isotope study were prepared from polished slabs using a high powered binocular microscope.

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CHAPTER 2

LITHOFACIES, MICROFACIES AND DEPOSITIONAL ENVIRONMENTS OF THE MUCH WENLOCK LIMESTONE FORMATION

2.1 ABSTRACT.

Based on bedding styles and the proportion of silty mudstone as opposed to limestone, 7 lithofacies are identified in the Much Wenlock Limestone Formation of the West Midlands and southern Welsh Borders. Lithofacies distribution indicates that the late Wenlock shelf was gently subsiding in the north but unstable and topographically variable in the south. Using microfacies analysis, the depositional environment of each lithofacies is determined. Then, by considering the sequential variation of lithofacies, the depositional history of the formation is traced. Limestone deposition began during a local regression in the West Midlands, when 12m of limestone was deposited in a mid-shelf setting. During this period the rest of the shelf was still dominated by siliciclastic deposition. Following the early limestones the West Midlands was returned to deeper water low-energy conditions. From this time onwards lithofacies across the whole of the northern shelf formed an upward shallowing sequence. The regression suggested by these sequences culminated in deposition of a grainstone sandbody in an environment frequently reworked by wave action. This sandbody migrated from E to W transgressing adjacent sediments which had been deposited on the lower shelf in deeper water. Reefs developed in front of the advancing sandbody and wash-over sediments were

deposited immediately behind it to form the uppermost parts of the formation. This model indicates that the formation is diachronous on the northern shelf, being older in the West Midlands than it is around Wenlock Edge. On the southern shelf lithofacies sequences are less laterally extensive, probably reflecting local variations in subsidence rates rather than regional sea level fluctuations.

2.2 INTRODUCTION

The Much Wenlock Limestone Formation is an impure limestone unit which was deposited on part of the SE margin of the gradually closing Iapetus Ocean. The study area includes Dudley, Walsall, the Malverns, Woolhope, May Hill, Fastnor and Usk (Fig. 2.1). Exposure in these areas is generally poor when compared with Wenlock Edge, but borehole data from the English Midlands are plentiful. Most previous workers have concentrated on the Wenlock Edge area due to relatively good exposure. It was there that the similarity of "ballstones" to modern coral reefs was noted in the late 19th century. Crosfield & Johnson (1914) considered the palaeoenvironment analogous to a present day back reef or lagoonal setting. Colter (1957), from work over the whole outcrop area, concluded that deposition took place in a warm tropical sea no more than 30m deep. In the formation around Wenlock Edge Shergold & Bassett (1970) defined 8 lithofacies but made made no environmental interpretations. Scoffin (1971) described 6 lithofacies and proposed a model in which the reefs around Hill Top (Wenlock Edge) were part of a barrier reef complex with the formation elsewhere being deposited in a back reef environment. Since then however, the base of the formation has been shown to be diachronous (Bassett 1974), necessitating a new model. It has been suggested that the top of the formation is older in the West Midlands than on Wenlock Edge (Bassett 1974), but recently this has been disputed (Dorning & Bell 1987, see also Bassett 1976). The field appearance and stratigraphy of the formation in the West Midlands, the Malverns, Woolhope, May Hill and Usk have been described respectively by Butler (1939), Phipps & Reeve (1967), Squirrell & Tucker (1960), Lawson (1955) and Walmsley (1959),



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Figure 2.1 Locality and palaeogeographic maps. Diagram to left is a reconstruction of the Wenlock palaeogeography (data from Cocks & Fortey 1982). The stippled parts are areas interpreted to be land. The right hand map outlines the outcrop of the Wenlock Series in England and South Wales with the Much Wenlock Limestone Formation highlighted in black. An inset of the British Isles shows the area on the locality map.

but without comment on the depositional environments. The stratigraphy of the Wren's Nest Inlier (West Midlands) was formalised by Dorning (1983) who, based on Butler's (1939) original three—fold division of the formation, named the following members; the Lower Quarried Limestone, the Nodular Beds and the Upper Quarried Limestone. Recent sedimentological work was carried out at Wren's Nest by Oliver (1981), but this was restricted to surface exposure.

The depositional environment of the Much Wenlock Limestone is modelled using comparison of lithofacies sequences studied by me with those described from Wenlock Edge. This model refines understanding of the palaeogeographical evolution of the late Wenlock shelf. It indicates that the shelf was divided into a stable northern part and an unstable southern part. On the northern part the formation is younger in the W than it is in the E. Sedimentation on the southern shelf was controlled by local variation in subsidence rates.

2.3 LITHOFACIES

The term lithofacies is used to describe a rock type whose field appearance allows it to be distinguished from any other in the formation. Each lithofacies is composed of a number of microscopically discrete lithologies, termed microfacies. The Much Wenlock Limestone Formation of the West Midlands and southern Welsh Borders is composed of 7 lithofacies which are broadly comparable with those described from Wenlock Edge (Scoffin 1971, Shergold & Bassett 1970).

2.3.1. Wavy-bedded crinoidal grainstone lithofacies

Over 95% of this lithofacies is composed of wavy, pale-grey beds of well-sorted crinoidal grainstones which contain rip-up clasts of carbonate mudstone. The beds are 20-500mm thick, generally continuous and occasionally cross-laminated. This lithofacies occurs towards the top of the formation in the West Midlands and northern Malverns (Figs 2 2 & 2.3). It closely resembles Scoffin's Facies D, and non-red-weathering parts of Shergold & Bassett's gingerbread lithofacies.

2.3.2. Interbedded limestone and silty mudstone lithofacies

This lithofacies is composed of continuous limestone beds 20mm-

.

Figure 2.7 Triangular plots of cement vs. clast vs. matrix for each lithofacies. A). Wavy-bedded and ferruginous crinoidal grainstone lithofacies. Dominantly grainstones with MF. 6 representing the in situ shell banks of the ferruginous crinoidal grainstone lithofacies. B). interbedded limestone and silty mudstone lithofacies. MF. 11 8 12 are grainstones from the mud-poor parts of this lithofacies. MF. 7 is a skeletal packstone which with incresing proportions of spar grades into MF. 11. MF. 3 & 4 are wackestones composed respectively of in situ bioclasts and locally reworked bioclasts. MF. 2, pure carbonate mudstone, represents the more distal products of reworking. C). Thickbedded oncoid-rich lithofacies. Composed dominantly of oncoidal wackestones (MF. 5) with beds of skeletal packstone grading into grainstone (MF. 7-11) and oncoidal packstone (MF. 8) D). Nodular limestone and silty micrite lithofacies. MF.1 are Quartzose mudstones forming the equidimensional nodules. MF. 6 & 7 are packstones with in situ and reworked bioclasts respectively. For other microfacies see 2). B). Reefal lithofacies. MF. 12 is mottled micrite with few clasts. MF. 13 and 14 are framestones. MF. 7 and 10 are skeletal packstones and grainstones respectively, composed dominantly of crinoid ossicles. Each point represents a count from a single section where n=2000.

FIGURE 2.2

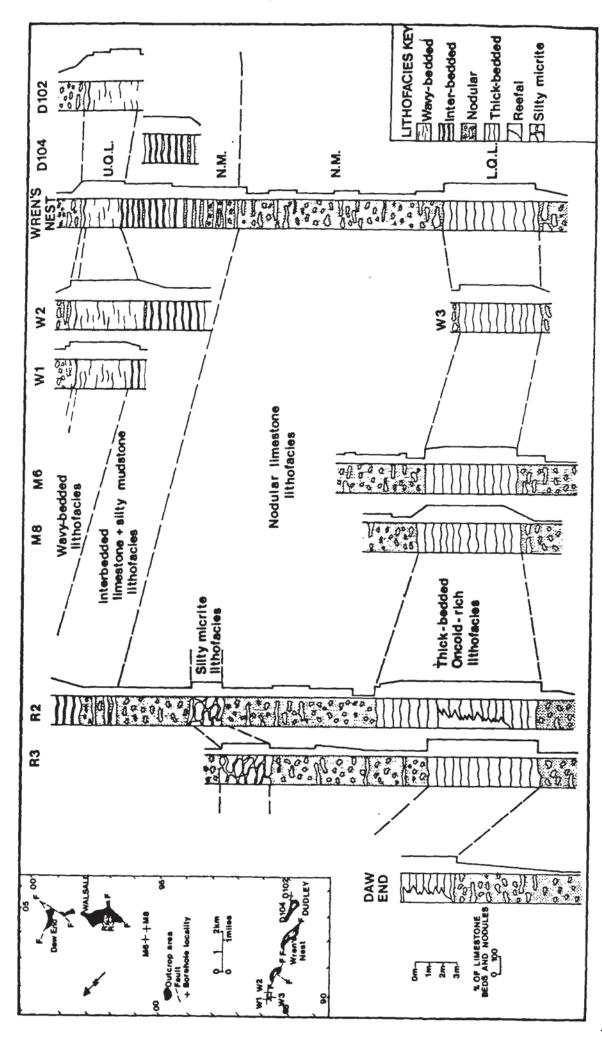
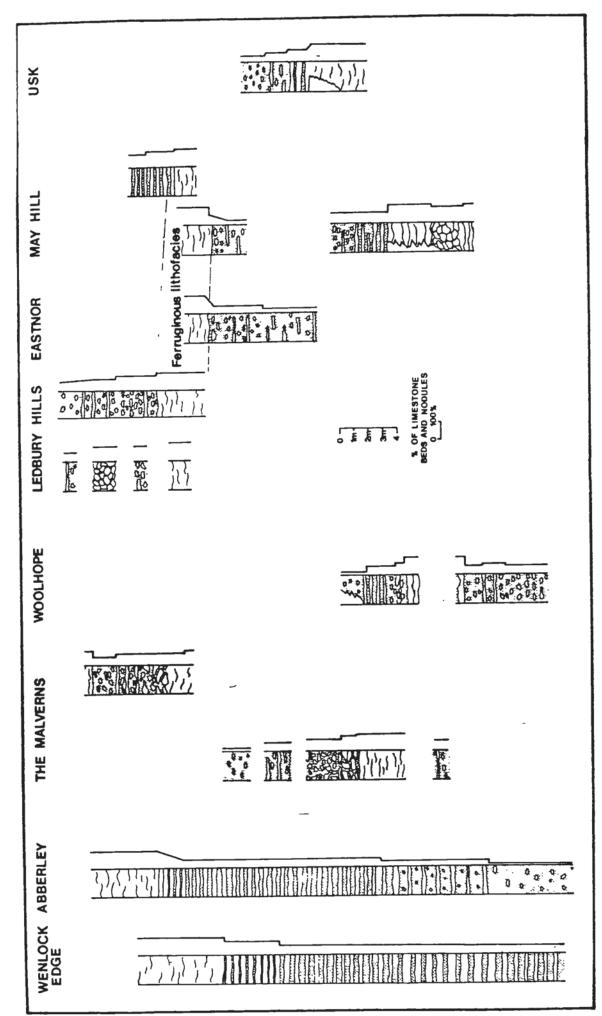


Figure 2.2 Correlation of lithofacies across the West Midlands. The members in the West Midlands are; L.Q.L. Lower Quarried Limestone, N.M. Nodular Beds and U.Q.L. Upper Quarried Limestone. In addition to the surface exposures at Wren's Nest Hill (SO 922 938 and Daw End railway cutting (SP 0C3 034) boreholes from the following localities were studied; Dudley Sports Ground, D102 & D104 (SO 954 903 & SO 952 908), Cinder Hill Cemetery, W1, W2 & W3 (SO 9391 9183, SO 9417 9185 & SO 9414 9196), junction 10 of M6 motorway, M6 & M8 (SO 9903 9801 & SO 9912 9949) and Walsall railway station, R2 & R3 (SP 0112 9848 & SP 0123 9856). Left inset shows localities within the West Midlands, right inset is the key, which also applies to Fig. 2.3. The solid line to the right of the lithological columns indicates the percentage of limestone nodules and beds as opposed to silty modstone.



0.4m thick, separated by silty mudstone beds 20mm-300mm thick. The mudstone component comprises 60% of rock volume when the limestone beds are brown and relatively thin. These thin limestone beds are generally skeletal wackestone with occasional grainstone beds. When the limestone beds are thick and pale grey as little as 10% of the lithofacies is composed of silty mudstone. In this mud-poor part of the lithofacies the limestone beds are composed of peloidal and skeletal grainstones, skeletal wackestones and packstones, and carbonate mudstones. Symmetrical ripples are common and planar and trough cross-lamination occur at some horizons. This lithofacies forms the upper part of the Nodular Beds Member and the top metre of the Lower Quarried Limestone Member in the West Midlands (Fig. 2.2). It is also common throughout the southern Welsh Borders (Fig. 2.3). The mudpoor parts of this lithofacies are comparable with Scoffin's Facies C, and the mud-rich parts with his Facies A. Similarly the interbedded limestone and silty mudstone lithofacies is comparable with Shergold & Bassett's bluestone and measures lithofacies.

2.3.3. Thick-bedded oncoid-rich lithofacies

Pale grey continuous limestone beds, 0.1-0.8m thick, composed of oncoidal wackestones and packstones constitute most of this lithofacies. Thin mudstone partings are rare, but do occur where this lithofacies grades into muddier lithofacies. Parallel- and cross-lamination is present, but very rare. The Lower Quarried Limestone of the West Midlands is composed of this lithofacies (Fig. 2.2), as is the lower part of the May Hill section (Fig. 2.3). While no directly comparable sediments have been described from Wenlock Edge, without

close inspection this lithofacies could be mistaken for parts of the interbedded lithofacies.

2.3.4 Ferruginous crinoidal grainstone lithofacies

This red, rubbly, wavy-bedded lithofacies occurs at the top of the formation around Eastnor and May Hill. The limestone beds are composed of occasionally cross-laminated crinoidal grainstones with silty mudstone rip-up clasts. Unbedded masses up to 0.5m wide, composed of brachiopods in life position surrounded by dark green silty mudstone, are scattered throughout this lithofacies (chapter 4). At Wenlock Edge Shergold & Bassett (1970) referred to this lithofacies as the crinoidal grainstone lithofacies. Red, rubbly parts of their gingerbread lithofacies appear similar.

2.3.5. Nodular limestone lithofacies

The nodules in this lithofacies vary in shape from equidimensional to highly elongate and are composed of silt-rich carbonate mudstone, skeletal wackestone or occasionally skeletal packstone. The equidimensional nodules are generally subspherical and less than 100mm in diameter. The elongate nodules are usually less than 70mm thick but up to a few metres long. Parts of the lithofacies composed of equidimensional nodules contain of up to 90% silty mudstone. Where the lithofacies contains elongate beds the silty mudstone content can be as little as 30%. With a gradual decrease in silty mudstone content, and with the appearance of continuous beds, the nodular limestone lithofacies grades into the interbedded limestone and silty mudstones lithofacies. From the base to the top of the Nodular Beds Member in the West Midlands all the variations of the nodular limestone lithofacies are seen (Fig. 2.2). It is also a common

lithofacies in the Welsh Borders (Fig. 2.3), including Wenlock Edge where it is equivalent to Scoffin's Facies B and Shergold & Bassett's nodular lithofacies.

2.3.6. Silty micrite lithofacies

Large pale grey coalesced nodules of silty carbonate mudstone form this hard, poorly-bedded lithofacies. The nodules, up to 0.5m wide, are tightly packed, generally with no intervening silty mudstone. This is not a common lithofacies. It usually forms laterally impersistent units within mud-rich parts of the nodular limestone lithofacies (Fig. 2.2). It resembles Shergold & Bassett's Jack's Soap lithofacies but contains less silty mudstone.

2.3.7. Reef lithofacies

The term reef is used here to refer to a product of the actively building and sediment-binding biotic constituents which have the capacity to erect topographic features (Reijers & Hsu 1986). In the Much Wenlock Limestone Formation reefs are less common in the West Midlands and southern Welsh Borders than they are around Hill Top, Wenlock Edge. They are either massive uniform bodies composed dominantly of pale grey micrite, or they are poorly bedded masses made of 2m wide limestone lenses encased in mudstone. Reefs are present at Daw End, Wren's Nest, Woolhope and May Hill. At Daw End and May Hill they are composed dominantly of micrite and occur within thick-bedded oncoid rich lithofacies. At Wren's Nest, Woolhope and Usk they are composed of large limestone lenses. They occur in interbedded limestone and silty mudstone lithofacies at Wren's Nest and Usk but in nodular limestone lithofacies at Woolhope (chapter 5).

2.3.8.Lithofacies distribution

The lithofacies successions for the sections studied are shown in Figures 2.2 & 2.3. In the West Midlands the Much Wenlock Limestone Formation is uniform in thickness. The non-reef lithofacies within it are traceable for tens of kilometres across the English Midlands (Fig. 2.2), showing only minor local variations. One such variation is seen at Daw End railway cutting where the wavy-bedded crinoidal grainstone lithofacies, typical of the Lower Quarried Limestone Member, grades laterally within 100m into the nodular limestone lithofacies (Fig. 2.4). Local variations also occur in the Nodular Beds Member where the silty micrite lithofacies is laterally impersistent. The non-reef lithofacies to the north of Hill Top at Wenlock Edge appear to be laterally persistent (Scoffin 1971 p. 179; Fig.2) and, apart from the Lower Quarried Limestone Member of the West Midlands, they show a similar vertical sequence to the formation in the West Midlands and northern Malverns (Fig. 2.5). The uniformity of the formation in these areas suggests the northern part of the shelf was stable and relatively flat.

Due to poor exposure in the southern Welsh Borders the lateral extent of many of the lithofacies is difficult to determine, but they appear to be impersistent. This may be expected since the formation in the southern Welsh Borders shows rapid lateral thickness changes (Bassett 1974). Some lithofacies are traceable for up to 15km; for example from May Hill to Eastnor the top of the formation is marked by the ferruginous crinoidal grainstone lithofacies (Fig. 2.3). However, the general lack of internal continuity and rapid changes in formation thickness suggest that the southern shelf had variable relief.

Figure 2.4 Schematic representation of Daw End section (SO 003 C34) showing local lithofacies variation in the West Midlands. The Lower Quarried Limestone Member in the W is composed of thick-bedded oncoid-rich lithofacies, but to the E passes into nodular limestone lithofacies.

Figure 2.5 Vertical lithofacies distribution at Wenlock Edge (Scoffin 1971, p.179, fig.2) and in the West Midlands, with lithofacies correlation between the two.

FIGURE 2.4

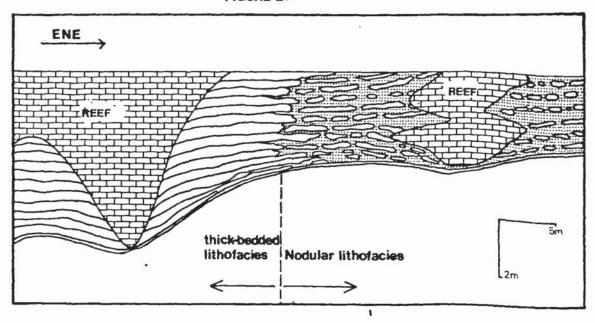
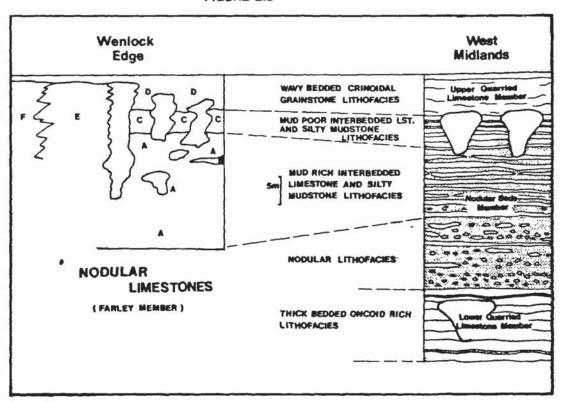


FIGURE 2.5



resulting in laterally impersistent depositional environments. This implies that different parts of the southern shelf had different subsidence rates, suggesting that it was less tectonically stable than the northern shelf.

2.4 MICROFACIES

Carbonate mudstones, wackestones, packstones, grainstones (Dunham 1962) and boundstones (Embry & Klovan 1972) are all present in the Much Wenlock Limestone Formation. The first four of these textural subdivisions form a sequence which represents an increase in depositional energy. Boundstones are sediments which were bound together or had a self-supporting framework. Within each textural subdivision a number of microfacies are recognised; each is described below (Fig. 2.6) and their depositional environments discussed.

2.4.1 Carbonate mudstones

MF.1. Quartzose carbonate mudstones

This microfacies comprises silt-grade quartz grains and clay minerals, encased in carbonate mudstone. Together these components form equidimensional nodules or sandwich packstone and wackestone beds. Laminae within nodules are widely spaced compared with their equivalents in the surrounding mudstones. Hence the nodules formed prior to compaction as early diagenetic carbonate concentrations. Prior to carbonate mobilisation the lithology was a parallel-laminated, muddy, calcareous siltstone typical of low-energy depositional environments.

MF.2. Pure carbonate mudstones

Very little insoluble residue is present in this microfacies.

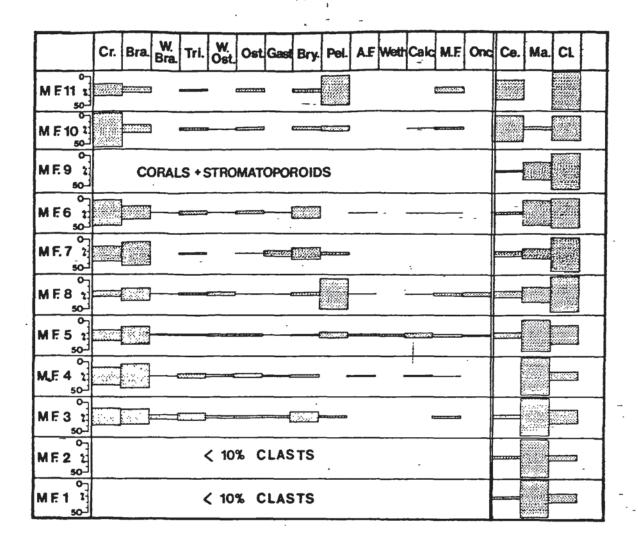


Figure 2.6 Microfacies composition of the Much Wenlock Limestone Formation. Left hand column refers to microfacies in the text. Cr, crinoid ossicle; Bra, brachiopod; W. Bra, whole brachiopod; W. Ost, whole ostracode; Ost, ostracode; Gast, gastropod; Bry, bryozoa; Pel, peloid; A.F., algal fragment; Weth, Wetheredella sphere; Calc, calcisphere; MF., micritised fragment; Onc, oncoid; Ce, cement; Ma, matrix; Cl, clast. Percentage allochems from counting 500 grains. Percentage clast/matrix/cement from point counts where n=2000.

Allochems, generally fragmentary and well-sorted, are concentrated into laminae 2-3mm thick and pockets 3-4mm wide. The abundance of carbonate mud suggests deposition in a low-energy environment, but the broken and well-sorted nature of the bioclasts suggests they had a high-energy source area. Beds of this microfacies probably resulted from settling of fine carbonate debris which was produced by a high-energy event some distance from the site of deposition. The laminae rich in broken bioclasts represent the coarser debris which settled from suspension first. Small scale slumping of these laminae was responsible for forming the small pockets of bioclasts.

2.4.2 Wackestones

The bioclasts in the wackestones, packstones and grainstones are composed dominantly of brachiopod, crinoid and bryozoan remains. The exact proportion of each is not usually important environmentally. Therefore "skeletal" prefixes the textural description and mention is made of the exact composition only when it is environmentally significant.

MF.3. Skeletal wackestones with articulated bioclasts

Many of the brachiopods are articulated and contain geopetal structures which indicate they are in life position and suggest there was little reworking. However one bed in the lower part of the Daw End section contained geopetal structures in which the internal sediment overlay the spar, indicating the fossils were reworked subsequent to deposition of the geopetal fill. This microfacies was generally formed in a low-energy environment where carbonate mud settled from suspension and slowly buried the fauna, reworking was uncommon.

MF.4. Skeletal wackestones with broken bioclasts

Bioclasts in this microfacies are generally large but fragmentary and float in a carbonate mudstone matrix. The mixture of high-energy grains and low-energy matrix, with no evidence for density flows, implies deposition in a low-energy environment subsequent to a period of reworking. This is supported by the frequent occurrence of this microfacies at the bases of carbonate mudstone beds. Despite the bioclasts being fragmentary they do not have rounded or heavily abraded edges. This indicates they were of local origin.

MF.5. Oncoidal wackestones

Allochems in this microfacies consist of large irregular oncoids, skeletal remains, algae, peloids and micritised grains. Both articulated and fragmentary allochems occur floating in a micrite matrix. This microfacies was deposited within the photic zone, above storm wavebase but below normal wavebase. This resulted in intermittent high-energy events in an otherwise low-energy environment (sections 3.6 & 3.7).

2.4.3 Packstones

MF.6. Skeletal packstones with articulated bioclasts

This microfacies occurs as unbedded bodies, up to 0.5m wide, composed of tightly packed brachiopods in life position separated by dark green silty mudstones. These build-ups of brachiopods are analogous to modern oyster or mussel banks (section 4.5.2.11).

MF.7. Skeletal packstones with broken bioclasts

These packstones form elongate nodules and beds composed of tightly packed and fragmentary bioclasts. The percentage of carbonate mudstone decreases as these packstones grade into grainstones.

Fragmentary bioclasts suggest a relatively high-energy environment,

but the presence of an interstitial muddy matrix indicates a lack of traction currents. This microfacies therefore represents a resedimented deposit, similar to MF. 4, which formed in a low-energy environment subsequent to local reworking. The abundance of spar in some examples indicates gentle current winnowing.

Another type of skeletal packstone with disarticulated bioclasts occurs in the interbedded limestone and silty mudstone lithofacies of the Much Wenlock Limestone Formation. Beds composed of this second type of packstone are continuous and have smooth upper surfaces but irregular lower surfaces, with burrows penetrating the underlying sediment. In these beds the bioclasts are tightly packed, often lacking both matrix and cement but interparticulate stringers of pyrite sometimes occur. The bioclasts, a high proportion of which are bryozoans, are often bored. The features of these beds are characteristic of hardgrounds (Leeder 1982, Scoffin 1987), but diagnostic characters (Bathurst 1975, Reijers & Hsu 1986) are lacking. The lack of matrix indicates constant winnowing of the sediment, and the abundance of encrusting bryozoans suggests that the beds formed hard-bottom substrates (sensu Bassett 1984). Such beds are interpreted to represent slowly deposited, frequently reworked shell lags.

MF.8. Oncoidal packstones

The oncoidal packstone microfacies contains small subspherical oncoids, algae, peloids, micritised grains and skeletal debris. It was deposited close to wavebase in an area where wave energy was low and the sediment was constantly, but gently, reworked (chapter 2).

MF.9. Coral/stromatoporoid packstones

This microfacies contains both rolled and in situ colonial organisms which are surrounded by a skeletal packstone matrix. The rolled fauna occurs close to similar organisms which are in life position. Coupled with the lack of evidence for long distance transport, this suggests a local origin for the bioclasts. This microfacies formed in an area of high organic activity with little or no current reworking. Although some of the colonial organisms are in life position they are too widely spaced to form a framework.

2.4.4 Grainstones

MF.10. Skeletal grainstones

Skeletal grainstones in the Much Wenlock Limestone Formation are composed dominantly of crinoid ossicles. Brachiopod debris is generally small and fragmentary, indicating a high-energy depositional environment. The presence of pale grey carbonate mudstone rip-up clasts up to 50mm long supports a high-energy environment, and also indicates a local source of carbonate mudstone. Some crinoidal grainstones have early iron oxide cements which have weathered red to form the ferruginous crinoidal grainstone lithofacies. Some coarse skeletal grainstones grade from MF.7 with a loss of matrix. They contain large but disarticulated brachiopod fragments. The grainstones were winnowed by traction currents capable of removing carbonate mud but not capable of reworking skeletal fragments.

MF. 11 Peloidal grainstones

These are well sorted, fine to medium sand-grade, commonly crosslaminated peloidal grainstones. The peloids grade into micritised fragments which are recognisable as skeletal debris, suggesting that the peloids are abraded and micritised allochems rather than diagenetic precipitates. Symmetrical cross-lamination and wave ripples are the most abundant sedimentary structures but decimetre scale planar— and trough—cross stratification are present in the upper metre of the Upper Quarried Limestone Member in the West Midlands. It is a high—energy microfacies deposited dominantly under the influence of wave action. However, the presence of planar— and trough—cross stratification at the top of the Upper Quarried Limestone Member indicates that the environment at the close of limestone deposition in the West Midlands was affected by unidirectional currents.

2.4.5 Boundstones

2.4.5.1 Bindstones

MF.12. Mottled micrite

Mottled micrites are most common in reef lithofacies where they can form complete reef masses. They commonly have a grumose texture (sensu Pettijohn 1975) with isolated algal tubules floating in the denser parts of the micrite suggesting that it is largely of algal or cyanobacterial origin. This is supported by the similarity of fine, wavy lamination in this microfacies to the cryptalgal structures described by Monty (1976).

2.4.5.2 Framestones

While the palaeoecology of individual species is outside the scope of this paper (chapter 5) the framestones can be subdivided, depending on the growth morphology of the fauna.

MF.13. Upright framestones

Upright framestones occur as pockets within reefs at Daw End,
Wren's Nest and Woolhope. They are composed of upright branching coral
colonies which trapped micrite between their branches. The growth

morphology (Powell 1980) and abundant micrite indicate that this microfacies was formed in a low-energy environment.

MF.14. Laminar framestones

Laminar framestones occur toward the tops of reefs at Wren's Nest. They were constructed by laminar encrusting corals and stromatoporoids which grew over sediment, or dead parts of their own colonies. Where they grew on sediment such organisms acted as stabilisers. This growth morphology is indicative of high-energy conditions (Powell 1980).

2.5 DEPOSITIONAL ENVIRONMENT OF LITHOFACIES

By considering the microfacies distribution within each lithofacies (Fig. 2.7) the depositional environment of the lithofacies can be determined (Fig. 2.8).

2.5.1 Wavy-bedded crinoidal grainstone lithofacies

The wavy-bedded crinoidal grainstone lithofacies is composed entirely of grainstone microfacies 10 and 11, indicating a high-energy depositional environment. Although now texturally homogeneous, rip-ups within MF.11 suggest that carbonate mudstone beds existed during deposition of this lithofacies but were reworked. Low-energy conditions therefore existed between the high-energy periods of grainstone deposition. The abundance of wave ripples in this lithofacies indicates that the high-energy conditions were created by frequent wave action, in an environment above wavebase.

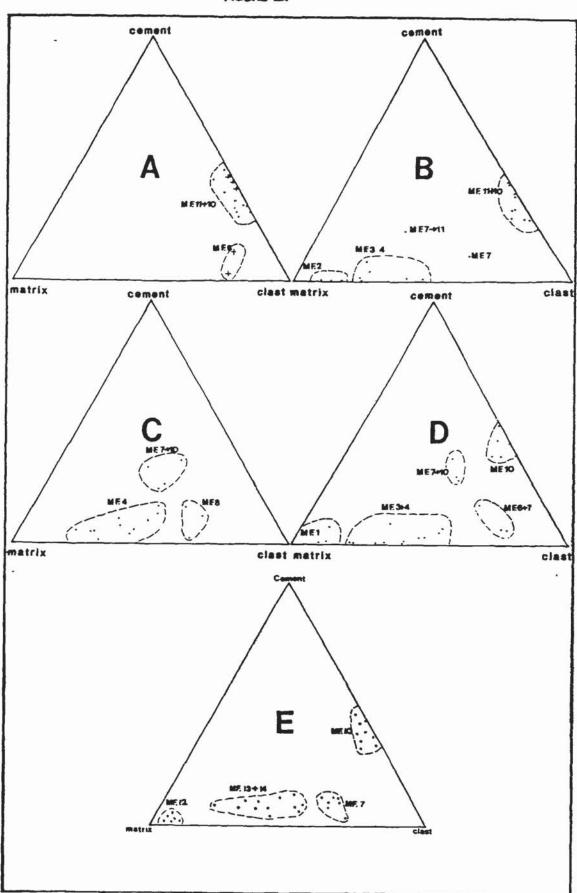
The wavy-bedded crinoidal grainstone lithofacies occurs close to the top of the formation at Wenlock Edge (Shergold & Bassett 1970, Scoffin 1971), throughout the West Midlands and in the northern -

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Figure 2.7 Triangular plots of cement vs. clast vs. matrix for each lithofacies. A). Wavy-bedded and ferruginous crinoidal grainstone lithofacies. Dominantly grainstones with MF. 6 representing the in situ shell banks of the ferruginous crinoidal grainstone lithofacies. B). interbedded limestone and silty mudstone lithofacies. MF. 11 8 12 are grainstones from the mud-poor parts of this lithofacies. MF. 7 is a skeletal packstone which with incresing proportions of spar grades into MF. 11. MF. 3 & 4 are wackestones composed respectively of in situ bioclasts and locally reworked bioclasts. MF. 2, pure carbonate mudstone, represents the more distal products of reworking. C). Thickbedded oncoid-rich lithofacies. Composed dominantly of oncoidal wackestones (MF. 5) with beds of skeletal packstone grading into grainstone (MF. 7-11) and oncoidal packstone (MF. 8) D). Nodular limestone and silty micrite lithofacies. MF.1 are Quartzose mudstones forming the equidimensional nodules. MF. 6 & 7 are packstones with in situ and reworked bioclasts respectively. For other microfacies see 2). E). Reefal lithofacies. MF. 12 is mottled micrite with few clasts. MF. 13 and 14 are framestones. MF. 7 and 10 are skeletal packstones and grainstones respectively, composed dominantly of crinoid ossicles. Each point represents a count from a single section where n=2000.

FIGURE 2.7



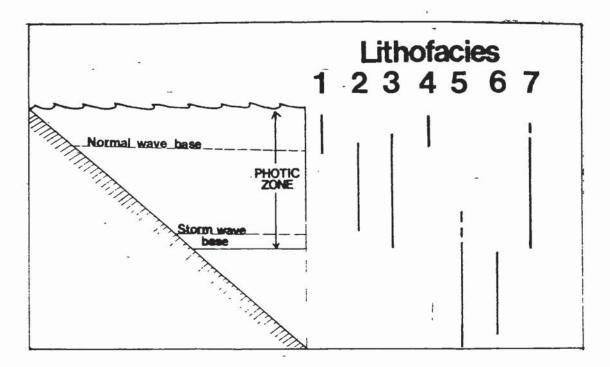


FIGURE 2.8. Depositional environments of lithofacies in the Much Wenlock Limestone Formation. 1 - Wavy-bedded crinoidal grainstone lithofacies, 2 - Interbedded limestone and silty mudstone lithofacies, 3 - Thick-bedded oncoid-rich lithofacies, 4 - Ferruginous crinoidal grainstone lithofacies, 5 - Nodular limestone lithofacies, 6 - Silty micrite lithofacies, 7 - Reef lithofacies.

Malverns. Assuming open sea lay to the W (Bassett 1974), high wave energy could not have been maintained from Wenlock Edge to the West Midlands. It is therefore suggested that this lithofacies represents a migrating front of maximum wave energy. Before the direction of migration can be determined the associated lithofacies must be be considered.

2.5.2. Interbedded limestone and silty mudstone lithofacies

A wide variety of microfacies are present within this lithofacies (Fig. 2.7), paralleling its variable field appearance. Where it contains little silty mudstone the thick pale grey limestone beds are composed of grainstones (MF. 10 & 11), pure carbonate mudstones (MF.2) and occasional skeletal wackestones (MF. 3 & 4). The brown limestone beds in the mud-rich parts of this lithofacies are dominantly wackestones (MF.3 & 4) and packstones (MF.7), with occasional skeletal grainstones (MF. 11). The fine grained often parallel laminated, nature of the silty mudstones around the beds and nodules is typical of deposition in a relatively low-energy environment.

The mud-poor parts of this lithofacies occur both below and above the wavy-bedded crinoidal grainstone lithofacies, into which they grade by progressive loss of fine grained interbeds. This suggests that the high-energy events, which deposited MF. 10 & 11, were less frequent and/or less erosive than during deposition of the wavy-bedded crinoidal grainstone lithofacies. The abundance of wave ripples in the peloidal grainstones indicates that the high-energy conditions resulted primarily from wave action. In the West Midlands planar and trough cross-stratification at the top of the Upper Quarried Limestone Member indicate that the area was dominated by unidirectional traction currents during final limestone deposition. Between high-energy events the sea floor was colonised by brachiopods, crinoids and bryozoans, forming beds of MF.3. Reworking of these on a local scale resulted in deposition of MF. 4 & 7. Beds of pure carbonate mudstone (MF. 2) were deposited from suspension as distal products of high-energy events. A likely source for the fine carbonate was an environment in which frequent reworking sent abundant sediment into suspension. Such an

environment existed during deposition of the wavy-bedded crinoidal grainstone lithofacies. It is therefore suggested that the mud-poor parts of the interbedded limestone and silty mudstone lithofacies were deposited adjacent to areas where the wavy-bedded crinoidal grainstone lithofacies was forming. On a carbonate shelf the change from an environment which is occasionally wave affected to one which is frequently wave-affected occurs as the environment shallows. The wavy-bedded crinoidal grainstone lithofacies therefore formed higher on the shelf than the contemporaneous mud-poor interbedded limestone and silty mudstone lithofacies

In the mud-rich parts of the interbedded limestone and silty mudstone lithofacies peloidal grainstones and cross-lamination are absent. The abundance of silty mudstone indicates a constant supply of terrigenous material. Faunal activity sporadically exceeded the terrigenous input and beds of MF. 3 formed. Occasional reworking concentrated skeletal material into beds of MF. 4 and 7 or rarely MF.

11. This part of the lithofacies was deposited in a lower energy environment than the mud-poor section. The sediment was only sporadically reworked, implying that the mud-rich interbedded limestone and silty mudstone lithofacies formed in a deeper environment than the mud-poor parts.

2.5.3. Thick-bedded oncoid-rich lithofacies.

The depositional environment of the most studied thick-bedded concoid-rich lithofacies, the Lower Quarried Limestone Member of the West Midlands, is fully described in sections 3.6 and 3.7. Oncoidal wackestones (MF. 5), oncoidal packstones (MF. 8) and skeletal packstones (MF. 6) constitute this lithofacies. The abundance of algae

suggests that this lithofacies was deposited within the photic zone. Most commonly in this lithofacies algae encrust allochems to form oncoids. Three types of oncoid are defined in section 3.4 based on morphological variation. Type III are typical of low-energy conditions, Type II are typical of an environment with intermittent rolling and Type I of an environment in which there was constant but gentle reworking. The sequential variation in oncoid types indicates that shallowing took the sea floor from below wavebase to above storm wavebase, and ultimately to a position close to normal wavebase. The lack of very high-energy microfacies indicates that the wave-energy in the West Midlands was low, probably as a result of a large expanse of shallow sea to the W (section 3.7).

2.5.4. Nodular limestone lithofacies

Equidimensional nodules composed of MF. 1, frequently with a core of MF.3, and elongate nodules composed of MF. 3,4 & 7, float in silty mudstone. Some of the elongate nodules occur along particular horizons to form discontinuous beds. Occasionally continuous beds of skeletal grainstone occur.

The equidimensional nodules formed during early diagenesis when carbonate migrated toward areas of skeletal concentration. The original sediment was a calcareous silty mudstone deposited in a low-energy environment. Elongate nodules composed of fragmentary bioclasts were formed by gentle current activity which concentrated skeletal dobris into distinct lenses. Elongate nodules containing articulated bioclasts represent in situ faunal buildups. The discontinuous beds of tightly packed packstone were reworked in a relatively high-energy environment before being resedimented. The beds thus deposited were

bioturbated to give their present discontinuous nature. The change from equidimensional nodules through elongate nodules to discontinuous beds represents an increase in energy of depositional environment.

2.5.5.Ferruginous crinoidal grainstone lithofacies

The bedded parts of this lithofacies are composed of grainstone MF. 10 & 11, being texturally identical to the wavy-bedded crinoidal grainstone lithofacies. It is therefore a high-energy deposit formed close to wavebase. Rip-ups in the skeletal grainstones suggest the presence of micaceous green silty mudstones prior to reworking. Green silty mudstone is also present in the unbedded masses of in situ brachiopods suggesting the small shell banks, which they represent (section 4.5.2.11 & 4.5.4.4), formed during low-energy periods when deposition of fine sediment occurred. The banks must have been sufficiently rigid to prevent reworking in the subsequent high-energy conditions.

The red colouration of this lithofacies is caused by weathering of iron oxide cements which fill crinoid stereome systems. These iron oxide cements pre-date marine turbid spars and must have been precipitated before the sediment was lithified. The iron oxides could be a product of the recent weathering of other iron minerals, but there are no remnants to support this even in relatively fresh samples. This suggests a primary iron oxide mineralogy. To precipitate iron oxide the eh of the environment must be low and ferrous ions must be abundant. Both these conditions are met in subaerial environments. Consequently red-stained lithologies are frequently interpreted to represent subaerial exposure. However this lithofacies lacks other features, such as karstic topography, evidence of palaeosol

development or vadose cements, which are diagnostic of subaerial exposure. Low eh also exists in shallow, well aerated water where crinoidal grainstones are typically deposited. The restriction of the ferruginous crinoidal grainstone lithofacies to the southern Welsh Borders suggests a local source of iron in these areas. Where this lithofacies occurs it is underlain by the nodular limestone lithofacies which contains silty mudstones rich in pyrite. Where the texturally similar wavy-bedded crinoidal grainstone lithofacies occurs, the underlying sediments are the mud-poor parts of the interbedded limestone and silty mudstone lithofacies which contain little iron. This suggests that the iron staining may have resulted from local erosion of pyrite-rich silty mudstones with precipitation in an oxidising, turbulent, shallow water environment. In this case the rate of deposition must have been slow and reworking frequent.

This lithofacies occurs near the top of the formation at both Eastmor and May Hill, in an equivalent position to the wavy-bedded crinoidal grainstone lithofacies in the north. The shallowing which resulted in deposition of these grainstone lithofacies must have been more rapid in the south than in the north, since no high-energy interbedded limestone and silty mudstone lithofacies underlie the ferruginous crinoidal grainstone lithofacies at May Hill or Eastmor. 2.5.6. Reef lithofacies

Reefs occur at Daw End (Walsall), Wren's Nest (Dudley), Wenlock Edge, Woolhope, May Hill and Usk. At Daw End reefs occur in the Lower Quarried Limestone Member. This member is composed of thick-bedded oncoid-rich lithofacies deposited during a local regression. The reef bases there are composed of upright framestones (MF. 14) indicating

that growth began in a low-energy environment. Overlying the upright framestones are crinoidal packstones (MF. 7) that commonly contain articulated stems, and represent a sediment-trapping crinoid-thicket. Overlying these and forming the bulk of the reefs are mottled micrites (MF. 12), indicating that the reefs were formed dominantly by calcareous algae or cyanobacteria. Occasional in situ laminar colonies of <u>Labechia</u> sit on top of 1-2mm thick silty mudstone partings within the mottled micrite. These laminar colonies probably represent recolonisation of the reef surface after a storm events. By considering the local increase in thickness of the Lower Quarried Limestone Member where the reefs are present, and the amount of preferential compaction of the bedded sediments, the original relief on these algal reefs is estimated to have been 1-2m (see also section 5.4.2.4).

At Wren's Nest reef growth began in the low-energy nodular limestone lithofacies and ends in the high-energy interbedded limestone and silty mudstone lithofacies. These reefs are composed of large elongate limestone lenses separated by silty mudstone. In the lowest parts of the reefs the lenses consist of coral/stromatoporoid packstones (MF. 14) deposited in a low-energy environment. The percentage of colonial organisms in the lenses increases upward, until upright framestones (MF. 13) dominate the middle parts of the reefs. The top of each reef is composed of laminar framestones (MF. 14) and crinoidal grainstones (MF. 10), typical of high-energy conditions.

Apart from small pockets of crinoidal grainstones the reefs at May Hill are composed entirely of mottled micrite. Estimation of

relief on these reefs suggests that they stood up to 0.5m above the sediment surface during deposition (section 5.3.4.3).

2.6 DEPOSITIONAL HISTORY OF THE MUCH WENLOCK LIMESTONE FORMATION

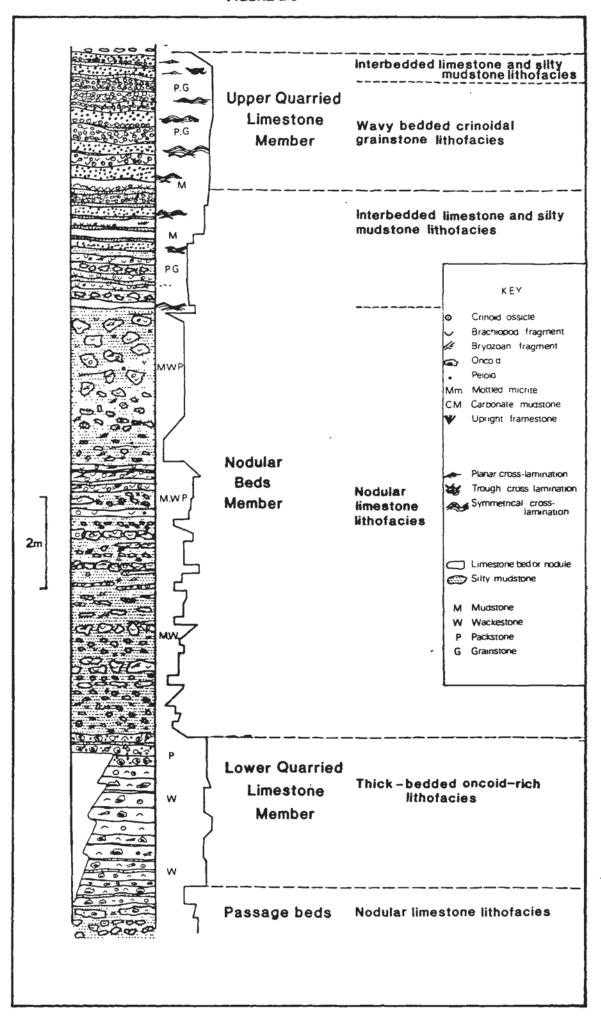
Deposition of the Much Wenlock Limestone Formation began in the West Midlands (Bassett 1974) with the deposition of the thick-bedded oncoid-rich lithofacies and the reefal lithofacies of the Lower Quarried Limestone Member (Fig. 2.9). The depositional environments of this member are fully discussed in chapter 3. The extent of limestone deposition to the N and E is unknown due to lack of outcrop but, around Wenlock Edge and in the southern Welsh Borders, calcareous silts and muds were being deposited at this time. Deposition of the Lower Quarried Limestone Member began below wavebase but within the photic zone (Fig. 2.10a). Oncoidal wackestones containing Type III oncoids were deposited and clumps of upright framestones marked the future sites of algal reefs. As deposition continued local shallowing took the environment above storm wavebase (Fig. 2.10b). Within this environment oncoidal wackestones with Type III and Type II oncoids were deposited between low algal reefs. Between the reefs at Daw End the thick-bedded oncoid-rich lithofacies of the Lower Quarried Limestone Member passes laterally into the nodular limestone lithofacies, while retaining the same microfacies (Fig. 2.4), suggesting that the reefs exerted an influence on the surrounding sediment. This increase in the silty mudstone content of the Lower Quarried Limestone Member may be due to local current variations created between the reefs and/or the ability of reef organisms to shed

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Figure 2.9 The sequence of lithofacies variation in the West Midlands. Lithological column shows detailed sedimentological variation within the Much Wenlock Limestone Formation. The solid line to the right of the column represents the percentage (0-100%) of limestone beds and nodules as opposed to silty mudstone. The names of the members and their component lithofacies are given on the right.

FIGURE 2.8



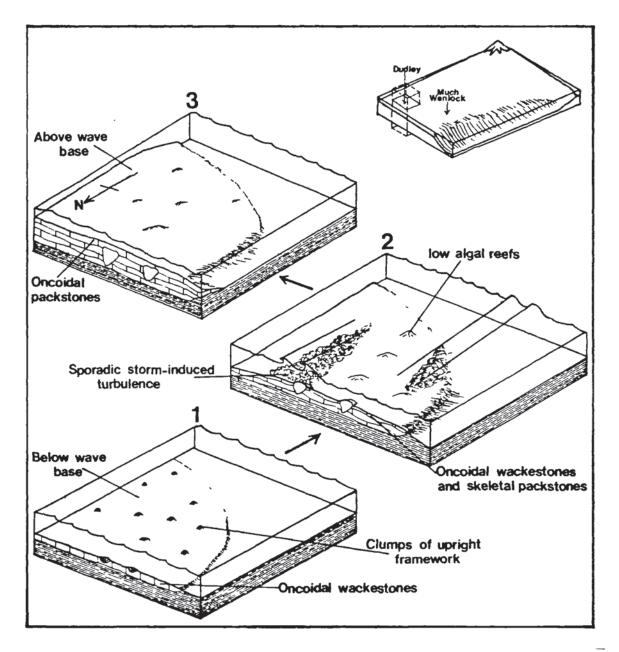


Figure 2.10 Depositional environments of the Lower Quarried Limestone Member. Upper inset shows extent of area represented in larger diagrams. The Lower Quarried Limestone Member is not seen in sections to the W and SW, and there is no control on its extent in other directions. Stage 1. Onset of Lower Quarried Limestone deposition, below wavebase, in which microfactes 5 was deposited. Small clumps of upright framestones (MF.13) mark future sites of algal reefs. Stage 2. Local shallowing has moved the sea bed above storm wavebase and MF. 5 and 7-11 form. Low algal reefs now give the otherwise flat sea floor slight local relief. Stage 3. Shallowing has now taken the environment close to normal wavebase resulting in deposition of MF. 8.

silt and mud from their surfaces. The reefs were swamped by oncoidal packstones during deposition of the uppermost parts of the member. The depositional environment during this period was close to wavebase resulting in constant but gentle reworking of the sediment surface (Fig. 2.10c). The lack of very high-energy microfacies in the Lower Quarried Limestone Member indicates that wave energy in the area was low. This was due to the large expanse of shallow shelf to the W of the West Midlands. The Lower Quarried Limestone Member therefore represents a carbonate build-up of uncertain extent in a mid-shelf setting, on a shelf otherwise dominated by siliciclastic deposition. The onset of carbonate deposition on the mid-shelf was probably brought about by local shallowing, taking the environment to within the photic zone and allowing calcareous algae to flourish.

Following deposition of the Lower Quarried Limestone Member in the West Midlands the mid-shelf was temporarily returned to an environment dominated by siliciclastics (Fig. 2.9). During this period calcareous silty mudstones were deposited over the whole shelf. These became the nodular limestone lithofacies which now form the lower part of the Nodular Beds Member in the West Midlands and the Farley Member on Wenlock Edge. Above the Lower Quarried Limestone Member in the West Midlands the nodular limestone lithofacies grades firstly into mud-rich then mud-poor interbedded limestone and silty mudstone lithofacies to form the Nodular Beds Member (Fig. 2.9). This is cverlain by the wavy-bedded crinoidal grainstone lithofacies which forms the bulk of the Upper Quarried Limestone Member, the very top being composed of the interbedded limestone and silty mudstone lithofacies. This sequence of lithofacies represents an upward

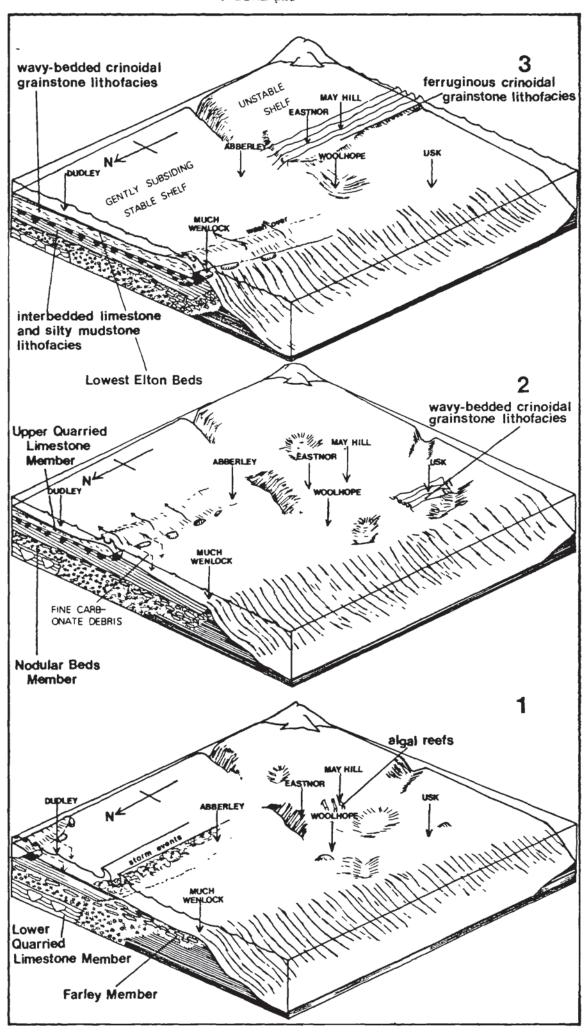
increase in depositional energy, caused by an increase in the frequency with which the sea floor was affected by storm events. Such a change in depositional environment on a shelf is caused by upward shallowing. A similar sequence of lithofacies interpreted as the result of a regression is seen at Wenlock Edge, where the Farley Member passes up initially into interbedded limestone and siltstone lithofacies and ultimately into wavy-bedded crinoidal grainstone lithofacies (Fig. 2.5). The high-energy conditions necessary for deposition of the wavy-bedded crinoidal grainstone lithofacies, equivalent to Scoffin's Facies C, could not have been maintained over the whole area. The zone of maximum wave energy must therefore have migrated from E to W, overlapping the lower-shelf deposits (Fig. 2.11) represented by the interbedded limestone and silty mudstone lithofacies. Reefs developed directly in front of this advancing carbonate sandbody (Fig. 2.11). They are now seen at Wren's Nest, terminating below the Upper Quarried Limestone Member, and at Wenlock Edge where their abundance reflects their shelf-edge position. Behind the sandbody, washover deposits formed the unidirectional crosslaminated parts of the interbedded limestone and silty mudstone lithofacies at the top of the Upper Quarried Limestone Member.

Carbonate sedimentation ceased behind this high-energy zone, allowing siliciclastics to dominate once again. The siltstones deposited behind the sandbody form the lowest Elton Beds (= the Eirmingham Siltstone Formation of Hurst 1975). Due to the lower sedimentation rates of these silty mudstones local shelf subsidence became greater than the regional rate of regression, causing the

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Figure 2.11 Depositional environments on the late Wenlock shelf. The topography and timing of events on the southern shelf cannot be shown accurately due to lack of control. Stage 1 (lundgreni to nassa Biozones). On the northern shelf the wavy-bedded crinoidal grainstone lithofacies was deposited in the far east, while the interbedded limestone and silty mudstone lithofacies was deposited lower on the shelf to the W. The interbedded limestone and silty mudstone lithofacies was sporadically affected by storm events, and also received reworked sediment from higher on the shelf. The southern shelf had variable topography. Algal reef development at May Hill. Stage 2 (nassa to ludensis Biozones . On the northern shelf the zone of maximum wave energy had advanced to the W depositing the Upper Quarried Limestone Member in the West Midlands. Behind the advancing carbonate sand body wash-over deposits initially formed but eventually gave way to siliciclastics. In front of the sand body reefs grew. On the southern shelf the onset of limestone deposition at Usk was marked by high-energy conditions. In other areas nodular limestone lithofacies formed plus reefs at Woolhope. Stage 3 (top <u>ludensis</u> Biozone). The wavy-bedded crinoidal grainstone lithofacies was deposited at Wenlock Edge. Behind this zone shelf subsidence allowed continued shallow water deposition despite the overall regressive regime. On the southern shelf the end of limestone deposition in the Ledbury Hills and May Hill regions was marked by high-energy depositional environments which produced the ferruginous crinoidal grainstone lithofacies.

FIGURE 2.10



environment to deepen. Limestone deposition was terminated by a rapid regional transgression leading to the deposition of organic-rich mudstone (Shergold & Shirley 1968, Shergold & Bassett 1970).

This succession of lithofacies is not seen in the southern Welsh Borders. The lithofacies were deposited in similar environments on the southern part of the shelf but their distribution was controlled by shelf topography. This makes the timing of deposition in the southern Welsh Borders difficult to correlate the northern part of the shelf, a problem increased by poor exposure. At May Hill the middle part of the formation comprises the thick-bedded oncoid-rich lithofacies and vertical-sided algal reefs. The overlying nodular limestone lithofacies indicates low-energy depositional environments. The equivalent part of the formation at Eastnor is also composed of nodular limestone lithofacies. High-energy ferruginous crinoidal grainstone lithofacies overlie the nodular limestone lithofacies at both May Hill and Eastnor, indicating a rapid shallowing of the environment. The abruptness of this transition suggests that the shallowing affect of the regional regression was locally enhanced by uplift. The base of the formation in the Woolhope inlier is a highenergy crinoidal grainstone. The middle of the formation there is composed of the thick-bedded oncoid-rich lithofacies overlain by the low-energy nodular limestone lithofacies with a reef. At Usk the lowermost part of the Much Wenlock Limestone Formation is composed of the wavy-bedded crinoidal grainstone lithofacies which grades up into the interbedded limestone and silty mudstone lithofacies and ultimately into the nodular limestone lithofacies. This is clearly a transgressive succession. Locally, parts of the nodular limestone

lithofacies are replaced by wavy-bedded crinoidal grainstone lithofacies emphasising the rapid lateral changes in depositional environment on this southern part of the shelf.

The model shown in Fig. 2.11 explains the distribution of lithofacies in the Much Wenlock Limestone Formation. It shows that in addition to the base of the formation being diachronous (Bassett 1974), the top of the formation also youngs to the W. As the Lower Quarried Limestone Member was being deposited in the West Midlands, muds of the Coalbrookdale Formation were being deposited on Wenlock Edge. Deposition of the Lower Quarried Limestone Member began towards the top of the <u>lundgreni</u> Biozone (Bassett 1974) and probably ended within the nassa Biozone. During deposition of the upper parts of the the Nodular Beds Member in the West Midlands, calcareous silts and muds, later to become the nodular Farley Member, were being deposited on Wenlock Edge (stage 1 on Fig. 2.11). This took place during the nassa and lower part of the <u>ludensis</u> Biozones. The Upper Quarried Limestone Member of the West Midlands was deposited within the ludensis Biozone (stage 2 on Fig. 2.11). Contemporaneously, the interbedded limestone and silty mudstone lithofacies was being deposited on Wenlock Edge. By the top of the <u>ludensis</u> Biozone limestone deposition had ended in the West Midlands and silty mudstones of the lowest Elton Beds were being deposited. The carbonate sandbody represented by the wavy-bedded crinoidal grainstone lithofacies had migrated as far as Wenlock Edge by the top of the ludensis Biozone (stage 3 on Fig. 2.11). Hurst's (1975) attempt to correlate transgressive and regressive cycles from north to south is shown in this model to be invalid; lithofacies distribution in the

south was dominantly controlled by local subsidence rather than the mid-late Silurian regressive event.

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CHAPTER 3

ONCOIDS AS ENVIRONMENTAL INDICATORS IN THE MUCH WENLOCK LIMESTONE FORMATION OF THE ENGLISH MIDLANDS

3.1. ABSTRACT

The Much Wenlock Limestone Formation of the West Midlands was deposited in a mid-shelf setting and is divisible into three members; the Upper and Lower Quarried Limestone members being separated by the more argillaceous Nodular Beds Member. Oncoids, composed predominantly of micritic fabrics with Rothpletzella and Girvanella. occur commonly in the Lower Quarried Limestone Member. These oncoids vary from subspherical bodies up to 5 mm in diameter to forms with a highly irregular and branched upper surface which reach 70 mm across. Each form is indicative of a different depositional environment, which is also reflected in the sediment enclosing the oncoid. Equidimensional oncoids in peloidal packstones, were formed by continuous rolling, whereas the larger branched forms enclosed in loosely packed wackestones, developed in quieter conditions below wavebase. The distribution of oncoid morphotypes in the Lower Quarried Limestone Member shows that small variations in relative sea level were superimposed on the overall mid to late Wenlock regressive episode during which the Much Wenlock Limestone Formation was deposited. The uniformity of the formation throughout the West Midlands indicates that the sea floor was essentially planar over a

large area. Vertical variation of oncoid morphology within the Lower Quarried Limestone Member can be traced throughout the area, allowing accurate correlation of relative sea-level variations.

3.2 INTRODUCTION

In latest Wenlock times, carbonate-dominated deposition took place to the E of the Welsh Basin producing the rocks of the Much Wenlock Limestone Formation. This formation crops out in a roughly triangular area defined by Much Wenlock (Shropshire), Walsall (West Midlands) and Usk (South Wales) (Fig. 3.1). To the S and W the lateral equivalents of the limestone are shallow water sandstones and basinal shales. The subsurface extent of the formation to the N and E is unknown.

In the the Much Wenlock Limestone Formation of the English Midlands three members were recognized by Dorning (1983) based on Butler's (1939) original subdivision. The basal Lower Quarried Limestone Member (8-12 m thick), is composed of 20-100 mm thick peloidal packstone beds and skeletal wackestone beds which are rich in oncoids, separated by 1-5 mm thick silty mudstone partings. The overlying Nodular Beds Member (18-20 m thick) comprises pale grey nodules of carbonate mudstone and loosely packed skeletal wackestones embedded in dark grey to black silty mudstones. Thin but continuous, sharp-based beds of skeletal crinoidal packstones also occur in this member, particularly towards the top. The highest member, the Upper Quarried Limestone (5-7 m thick), is bedded on a similar scale to the lowest member, but the dominant lithology is peloidal packstone, which is cross-laminated and wave-rippled. Crinoidal grainstones occur as 20 to 500 mm thick beds within the peloidal packstone. Unbedded to irregularly bedded limestone mounds up to 6 m thick occur within both the Lower Quarried Limestone and upper part of the Nodular Beds Member.

The vertical distribution of the three members is best studied in



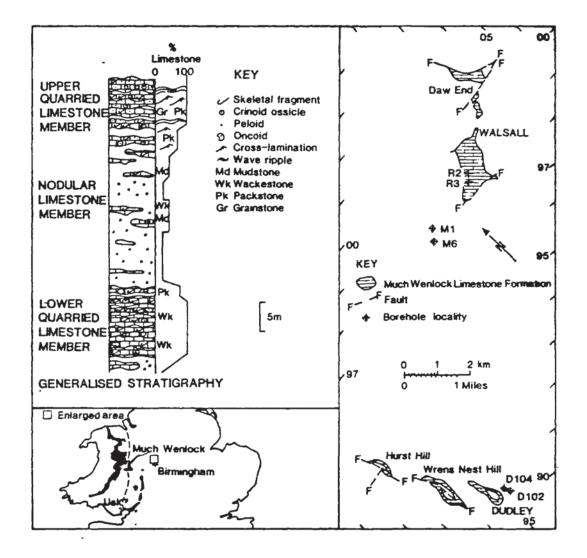


Fig. 3.1. Location map and generalized stratigraphy. Lower left inset shows the outcrop of the Wenlock Series in England and Wales; the Much Wenlock Limestone Formation occurs to the east of the dashed line.

Main map shows outcrop of the formation in the West Midlands and the position of boreholes: Walsall Railway Station, (R2, SP 011984; R3, SP 012985), Junction 10 of the M6 motorway, (M1, SO 993984; M6, SO 990980) and Dudley sports ground, (D104, SO 952908; D102, SO 954903). Upper left inset shows generalized stratigraphy of the Much Wenlock Limestone Formation in the West Midlands. The solid line to the right of the lithological column represents the percetage of carbonate nodules and beds (0-100%) as opposed to silty mudstones.

six boreholes (Fig. 3.1), two each from Walsall railway station, (R2 and R3), from junction 10 of the M6 motorway, (M1 and M6), and from Dudley sports ground, (D104 and D102). Detailed lateral field relationships however, can only be seen at surface exposure, of which Wren's Nest Hill(SO 936920, all National Grid References are prefixed SO or SK) and Daw End Railway Cutting(SK 034003) are the only extensive examples in the region (Fig. 3.1). Due to quarrying at Wren's Nest the Lower Quarried Limestone Member is best studied at Daw End railway cutting, which is the only section where unbedded masses of limestone in this member are accessible.

The sedimentology of the Much Wenlock Limestone Formation in the West Midlands indicates an increase in energy of depositional environment reflecting the overall mid to late Wenlock regression evidenced throughout the Welsh Borders by both sedimentology (Scoffin 1971) and faunal variations (Hurst 1975). Oncoid distribution and microfacies variation indicate that minor sea-level fluctuations are superimposed on the overall regressive pattern.

3.3 SEDIMENTOLOGY OF THE LOWER QUARRIED LIMESTONE

Oncoids are restricted almost entirely to the Lower Quarried Limestone Member, in which their morphology varies between different lithofacies. Two broad lithofacies—groups are distinguished: the reef and the bedded lithofacies (Fig. 3.2).

3.3.1 Reef lithofacies

The term 'reef' is used here to refer to mound-like structures, either layered or massive, which stood above the surrounding

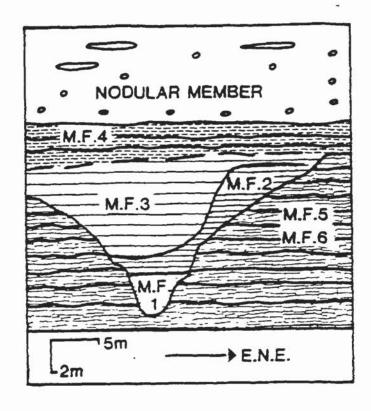


Fig. 3.2. Microfacies distribution in the Lower Quarried Limestone Member. M.F.1- Coralline framestones. M.F.2- Crinoidal grainstones. M.F.3- Algal micrites. M.F.4- Peloidal packstones. M.F.5- Skeletal packstones and wackestones. M.F.6- Loosely packed skeletal wackestones.

contemporaneously deposited sediment and were formed by sedentary calcareous organisms (Bates & Jackson 1980). In the Lower Quarried Limestone Member the reefs, which are here massive limestones extending 6 m vertically and 30 m laterally, are composed of three microfacies labelled MF. 1-3 (Fig. 3.2).

Microfacies 1 (MF. 13 in chapter 2) comprises coralline framestones composed dominantly of in situ colonies of <u>Halysites</u>, <u>Palaeofavosites</u> and <u>Heliolites</u>, with branched and/or domal morphology. They are embedded in micrite.

Microfacies 2 (MF. 10 in chapter 2) is tightly packed crinoidal grainstones, in which articulated stems up to 100 mm long are found.

Microfacies 3 (MF. 12 in chapter 2) contains mainly mottled micrite with grumose texture (sensu Pettijohn 1975), fenestral fabric and occasional algal tubules, suggest that much is of algal or cyanobacterial origin. Within the micrite, in situ laminar colonies of Labechia and Stelliporella sit directly above 1 to 2 mm thick silty mudstone partings.

3.3.2 Bedded lithofacies

The bedded lithofacies of the Lower Quarried Limestone Member are divided into three microfacies, labelled MF. 4-6 (Figs 3.2 & 3.3).

Microfacies 4 (MF. 8 in chapter 2) comprise oncolitic peloidal packstones, in which the peloids are discrete grains which do not merge into clotted textures. The peloids do, however, grade into micritized fragments recognizable as skeletal debris. Articulated brachiopods and unbroken grains are rare, most allochems consisting of fragmentary skeletal debris. The matrix is composed of silt-grade fragments and micrite. This microfacies dominates the upper few metres of the member, and overlies both reefs and MF. 5 and 6 (Fig. 3.2).

Microfacies 5 (MF. 6 in chapter 2) is composed of skeletal

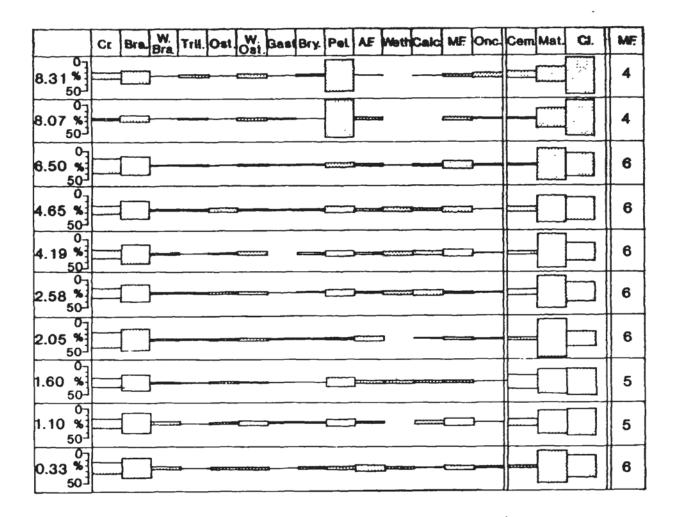


Fig. 3.3. Lithological composition of the Lower Quarried Limestone Member. Left hand column is height in metres of specimen above base. Cr, crinoid ossicle; Bra, brachiopod fragment; W. Bra, whole brachiopod; Tril, trilobite fragment; Ost, ostracode fragment; W. Ost, whole ostracodes; Gast, gastropods; Bry, bryozoans; Pel, peloids; A.F., algal fragment; Weth, Wetheredella sphere; Calc, calcisphere; M.F., micritised fragment; Onc, oncoid; Cem, cement; Mat, matrix; Al, allochems. Final column shows the microfacies to which the specimens are assigned. Percentage allochems obtained by counting 500 grains. Percentage allochems, matrix and cement based on point counts where n-2000.

packstones and wackestones, commonly containing articulated brachiopods and abundant complete valves. Micrite is less abundant in this microfacies than in any other Lower Quarried Limestone microfacies(Fig. 3.3). Brachiopods are dominantly rhynchonellids and spiriferids forming an assemblage which approximates to Hurst's (1975) high-energy subassemblage of the Sphaerirhynchia Community. Oncoids are relatively rare in this microfacies. Microfacies 5 occurs as sharp-based beds 20 to 50 mm thick within microfacies 6.

Microfacies 6 (MF. 5 in chapter 2) is loosely-packed, poorlysorted oncolitic skeletal wackestones. Articulated brachiopods and
other whole fossils are common, but comminuted debris is also
abundant. The grains float in micritic matrix which contains isolated
algal tubules associated with clotted textures. Peloids are diffuse
and often grade into clotted zones. This microfacies is, with the
included beds of microfacies 5, the lateral equivalent of the reef
lithofacies (Fig. 3.2).

3.4 ALGAE IN THE LOWER QUARRIED LIMESTONE

Algae in the Much Wenlock Limestone Formation were first described by Wethered (1893), who thought that the variously sized tubules in a particular oncoid represented different species of Girvanella.

Rothpletz (1913), who assigned Wethered's oncoids to Sphaerocodium, on the other hand considered different types of tubule to be vegetative and reproductive cells of the same species. This approach of assigning morphologically different albeit intertwining filaments to the same genus has led to confusion in classification. Wood (1948) re-examined Rothpletz's material, recognizing Girvanella and naming

two new genera, Rothpletzella and Wetheredella. These three genera are the dominant forms in the Much Wenlock Limestone Formation in the West Midlands. The present examples of Girvanella and Rothpletzella (Figs 3.4e & f) closely resemble the forms described by Wood (1948). Wetheredella specimens however, sometimes differ from the material described by him, which have an average diameter of 0.1 mm and wall thickness of 0.03 mm. In addition to typical Wetheredella there are large forms which have 1 mm external diameters and 0.1 mm thick walls (Fig. 3.4d). There is a complete gradation in size from these large forms into others identical to those described by Wood (1948). This, combined with the similarity in radial pore structure, warrants classification of the larger forms as Wetheredella. Spheres 0.2 to 1.0 mm in diameter commonly occur in the sediment surrounding Wetheredella-rich oncoids. These have a wall thickness and structure identical to the Wetheredella occurring as encrusting forms in the oncoids, suggesting that the spheres are non-encrusting forms of the same genus.

Girvanella is now accepted as a cyanophyte (Riding 1984), but the taxonomic positions of Rothpletzella and Wetheredella are less certain. Riding (1984) regarded Rothpletzella as probably a cyanophyte and Wetheredella a cyanophyte or chlorophyte.

In the Lower Quarried Limestone Member Rothpletzella and Girvanella occur in both the reef and bedded lithofacies. In the reefs they encrust colonial organisms and occur as isolated patches in the mottled micrite (section 5.4.2). In the bedded lithofacies the algae most commonly encrust allochems to form oneoids.

f

Fig. 3.4. Algae and oncoids in the Much Wenlock Limestone Formation.

a-c, oncoid types in the Much Wenlock Limestone Formation. a) Type C,

polished slab. b) Type B, polished slab. c) Type A, negative print

from stained peel. d-f, photomicrographs of three alga-types. d).

Wetheredella. e). Girvanella f). Rothpletzella.

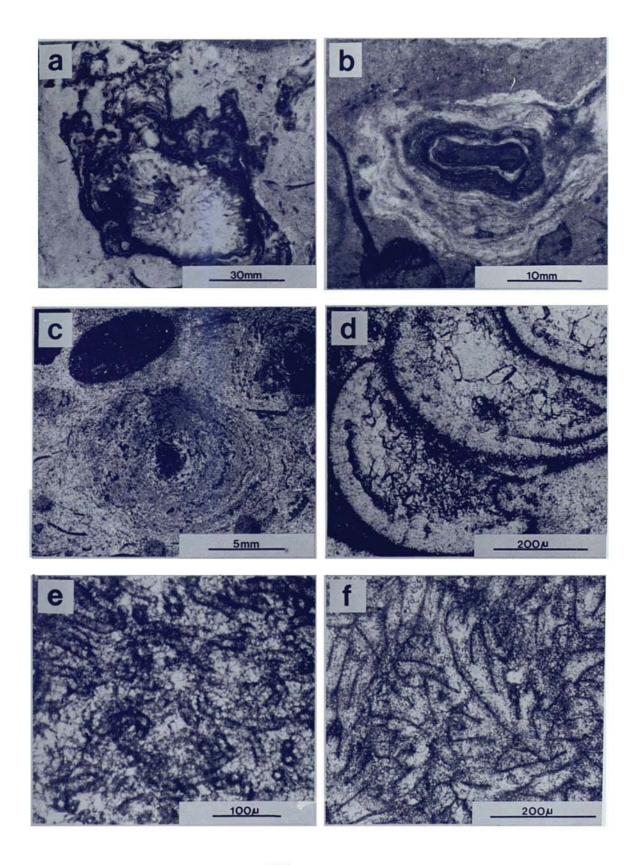


FIGURE 3.4

3.5 ONCOIDS IN THE LOWER QUARRIED LIMESTONE

The oncoids were studied in sectioned cores so that only two dimensional representations of three dimensional objects were seen. To guard against bias, the core sections were orientated randomly and a large population was studied.

The Lower Quarried Limestone Member oncoids are composed of micrite and spar which form spongiostromate fabrics, and cyanobacterial tubules which form porostromate fabrics (Monty 1981). The tubules always exhibit encrusting growth morphologies, never forming upright bushes. Despite this, the most obvious feature of the oncoids is their morphological variation, forming a continuous series from small (5-10 mm) subspherical forms to large (up to 70mm) branched forms. For descriptive purposes the oncoids are divided into three morphological Types, A, B and C (Figs 3.4 & 3.5):

Type A oncoids are small, smooth-surfaced, spherical to subspherical and composed dominantly of concentrically laminated spongiostromate fabric (Fig. 3.4c). Discontinuous lenses of porostromate fabric occur but are not abundant (Fig. 3.6). When the ratio of maximum cortex thickness to minimum cortex thickness is calculated, Type A oncoids have a low value (Fig. 3.5). Type A oncoids dominate in the peloidal packstones of microfacies 4 at the top of the Lower Quarried Limestone Member (Fig. 3.7).

Type B oncoids have a greater size range than Type A. Their cortex is continuous and composed of irregular and often discontinuous laminae of spongiostromate and porostromate fabrics (Fig. 3.4b). Successive laminae have their maximum thicknesses at different places within the cortex. Type B oncoids contain a higher proportion of spongiostromate

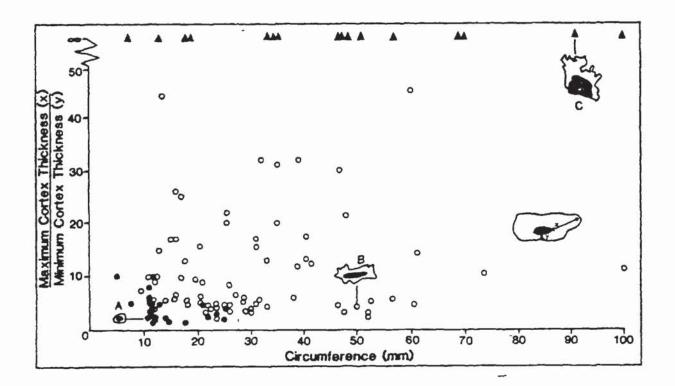


Fig. 3.5. Ratio of cortex to circumference of oncoids from borehole R3, Walsall Railway Station (SP 012985). Typical forms of each oncoid type, A, B and C, are shown, taken from tracings of the oncoids on polished slabs. Cortex ratio obtained by dividing maximum cortex thickness (X) by minimum cortex thickness (Y), see bottom right inset of schematic oncoid. n=140. - type A, O - type B, A - type C.

fabric than Type A choolds but a lower proportion than Type C.

Rothpletzella is the dominant taxon (Fig. 3.6).

Type C oncoids are composed dominantly of porostromate fabric which coats only the upper surfaces of allochems (Fig. 3.4a). Hence, Type C

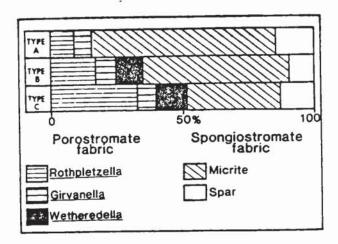


Fig. 3.6. Composition of the three oncoid morphotypes. Based on point counts of 20 oncoids, each count consisted of 1000 points.

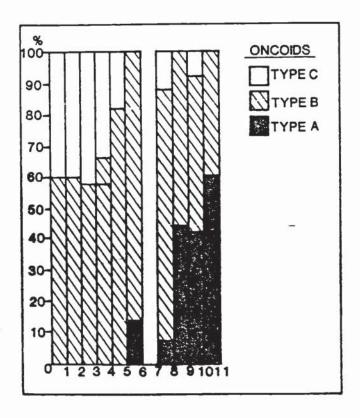


Fig. 3.7. Sequential variation of oncoid morphotypes in the Lower Quarried Limestone Member. Each column represents the percentage of different oncoid types per metre of core, where 0 is the base of the member and 1-11 are metres above the base. Poor core recovery accounts for the lack of oncoids at 6-7 m. n=140.

oncoids plot at infinity on the cortex-ratio axis of figure 3.5, Rothpletzella again being the most abundant cyanobacterium. The cortex is irregular and often branched, even though it is composed of encrusting, not upright, tubule growth forms. Types B and C occur in the skeletal packstones and wackestones of microfacies 5 and 6. Type C dominates in the basal parts of the Lower Quarried Limestone Member and Type B in the intermediate parts (Fig. 3.7).

3.6 ONCOIDS AS ENVIRONMENTAL INDICATORS

By definition, oncoids are constructed by algae and will therefore only form in conditions suited to the growth of those organisms.

Algae are generally accepted to be indicative of shallow water deposits (Swinchatt 1969; Lauritzen & Worsley 1974), although they have now been found at depths of 1000 m in the Indian Ocean (Bernard & Lecal 1960). Caution must thus be taken when using algae as depth indicators. Despite this, optimum growth conditions for algae are within the photic zone, generally less than 50 m depth (Riding 1975, Wray 1977) on marine carbonate shelves (Riding 1984).

In order to determine the environmental significance of oncoids, Peryt (1981) considered the sediments in a variety of oncoid-bearing sequences. He concluded that all oncoids are associated with slow sedimentation rates, and that oncoids composed of spongiostromate fabrics typify high-energy conditions whereas those with porostromate fabrics are generally associated with quiet water conditions. It has also been noted that due to abrasion, the percentage of porostromate fabric preserved in oncoid cortices decreases as depositional energy increases (Dahanayake 1978, Peryt 1983, Wright 1983).

The abundance of algae and oncoids in the Lower Quarried
Limestone Member, and their close association with a shelf fauna
including a relatively high-energy brachiopod assemblage, indicates
that the member was deposited in a shallow marine environment, within
the photic zone. The depth to which the photic zone extended locally
cannot be estimated accurately, but the abundance of micrite in this
member suggests the water may have been cloudy, restricting the photic
zone to a few tens of metres. Within this general framework
morphological, variations in the oncoids and the relative abundance of
various forms within the member enable more detailed analysis of
environments.

Type C oncoids could not have formed in an environment where rolling occurred, as their branches would have been broken. Since Rothpletzella and Girvanella are probably cyanobacteria, optimum growth conditions would have been in well-lit areas, particularly the upper surfaces of allochems. Therefore the absence of cortex from the undersides of Type C oncoids indicates that only one side of a grain was exposed at the sediment/water interface during its growth, confirming that Type C oncoids formed in a non-turbulent environment. This interpretation is supported by the close similarity of Type C oncoids to "tender" oncoids (Fuchtbauer 1968) and Sphaerocodium (Rothpletz 1890), both thought to have formed in low-energy conditions (Peryt 1977). Morphologically, Type C oncoids resemble Wright's (1983) "irregular Garwoodia" oncoids, interpreted as a low-energy growth form. The abundance of micrite in the surrounding microfacies supports the low-energy depositional environment suggested by oncoid morphology. As the upper surfaces of Type C oncoids often coincide

with the base of a silty mudstone parting, their growth termination is thought to be due to an increase in sedimentation rate.

Type B oncoids have continuous cortices. Jones & Wilkinson (1978) stated that in some conditions a continuous cortex may grow around an allochem with no rolling. However, they also considered that greatest algal growth occurs in well-lit waters and that, when present, cortices are thin on the undersides of oncoids. The change in position of the maximum thickness of successive laminae in Type B oncoids indicates that different parts of each oncoid were exposed to optimum growth conditions at the sediment surface at different times. This means that the oncoids must have been intermittently rolled during their growth. The presence of both whole fossils and comminuted debris in the skeletal wackestones of microfacies 6, suggests that periods of quiet deposition were occasionally interrupted by periods of turbulence. This interpretation also explains the co-existence of Type B and Type C oncoids within microfacies 6. As deposition proceeded Type B oncoids became more abundant, due to the increasing frequency of turbulent events. occurrence within microfacies 6 of sharp-based brachiopod-rich beds of microfacies 5 (skeletal wackestones and packstones) indicative of periodic high-energy conditions, supports the interpretation of intermittent turbulence. Additional evidence is seen in the laterally equivalent reefs, where horizons of the opportunistic stromatoporoid Labechia reflect periods of recolonization and stabilization (Powell 1980) following turbulent events (section 5.4.2).

Type A oncoids have concentric laminae suggesting they were frequently, if not continuously rolled during formation (Wright 1983).

Supporting this is the rarity of algal tubules, a common feature of oncoids formed in relatively high-energy conditions (Dahanayake 1977, Peryt 1983, Wright 1983). Type A oncoids are very similar to Dahanayake's Type II oncoids and Wright's "dense oncoids" both interpreted by those authors to be relatively high-energy forms. Surrounding Type A oncoids, the peloidal packstones of microfacies 4 contain very few whole fossils, suggesting an environment in which the sediment was agitated. However, they also contain micrite, indicating that the environment was not sufficiently energetic to remove all the fine-grained sediment. The peloids in this microfacies do not resemble peloidal cements (Macintyre 1984). They do grade into micritised but recognizable skeletal fragments, suggesting the peloids are abraded and micritised skeletal debris.

In the Lower Quarried Limestone Member the change of microfacies from base to top (Figs 3.2 & 3.3) indicates an increase in energy of depositional environment. This is matched by the change in relative abundance of different oncoid types (Fig. 3.7). Initially the environment was low-energy with little turbulence, producing dominantly Type C oncoids, but as deposition proceeded intermittent periods of turbulence became more frequent, favouring the formation of Type B oncoids. At the top of the member constant but gentle rolling produced Type A oncoids. Such changes on a shallow carbonate shelf are best explained by upward shallowing. The lowest parts of the member were deposited in an environment within the photic zone, but below wavebase. Shallowing took the sea-bed above storm wavebase resulting in sediments which show evidence of sporadic turbulence in an otherwise quiet environment. As deposition continued the turbulent

events became more common, probably as a result of continued shallowing taking the environment above the wavebase of progressively weaker storms. At the top of the member the sea-floor was close to wavebase resulting in constant agitation. Whilst the peloidal packstones of microfacies 4 show evidence of agitation, they also contain micrite indicating that the agitation was gentle and implying that wave energy was low.

3.7 CORRELATION AND PALAEOGEOGRAPHY

Lithological correlation of the Much Wenlock Limestone Formation in the West Midlands is facilitated by the lack of lateral variation (Fig. 3.8). The regression reflected in the sedimentology of the formation can be correlated across the area and related to the overall mid to late Wenlock regressive event. The sedimentology of each member is almost the same in every section, and even the relatively small variations reflected by oncoids in the Lower Quarried Limestone Member can be traced laterally for 10 km. This allows more detailed lithological correlation than has been previously possible (Fig. 3.9). The lack of lithological variation across the area indicates that environmental changes affected the sea-floor uniformly, suggesting the sea bed was essentially planar. Supporting this is the relative uniformity in thickness of the formation in the West Midlands, which also suggests that the area was tectonically stable. Hence, the West Midlands was part of a stable carbonate shelf, whose known extent covers an area of 8 km by 10 km. Its extent outside this area is uncertain, but as the Much Wenlock Limestone Formation is diachronous, becoming younger to the W (Bassett 1974), the outer shelf was

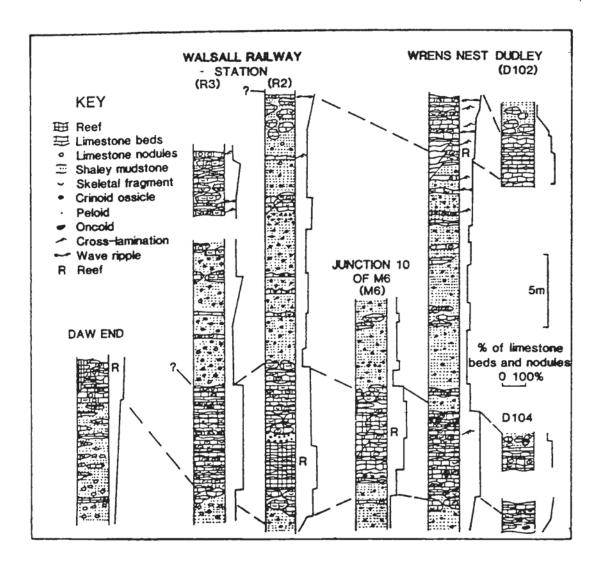


Fig. 3.8. Lithological correlation of the Much Wenlock Limestone

Formation from Dudley to Walsall. The solid line to the right of the

lithological columns represents the percentage of carbonate nodules

and beds as opposed to silty mudstone. For locations see Fig. 31.

dominated by fine grained siliciclastics during deposition of at least the lower parts of the formation in the West Midlands. When carbonate sedimentation did begin in the Welsh Borders it was marked by rapid lateral variations in both sedimentary facies and formation thickness, indicating that this area differed from the stable mid-shelf environment which existed in the West Midlands.

A previous attempt to recreate the palaeogeography during deposition of the Much Wenlock Limestone Formation (Scoffin 1971) concentrated on Wenlock Edge, Shropshire; only a generalized representation of the West Midlands was shown. The data presented here allows a more detailed palaeogeographic reconstruction for the West Midlards at that time. When Lower Quarried Limestone Member deposition was initiated, the West Midlands lay in a shallow marine environment below wavebase. The planar sea-bed was muddy and algarich. The only break in the monotonous sea-floor would have been upright, in situ coral colonies. By the time the sediment was being affected by storm waves the sea floor still lacked significant topography, although reefs had developed. Although estimation of the relief on the reefs is outside the scope of this paper, correlation of the oncoids above and below the reefs, with oncoids in the surrounding sediments, reveals that 4-5 m of unbedded limestone corresponds to 2-3 m of bedded limestone. This, combined with the local 1-2 m increase in thickness of the member where reefs occur implies that the relief was in the order of 1-2 m. This figure is probably an overestimate due to compaction of the argillaceous component of the non-reef facies (section 5.4.2.4). During the period that the sea-bed was being sporadically affected by storm waves the sediments would generally have been alga-rich containing relatively few other organisms. Succeeding a storm event however, the sea-floor was colonized by brachiopods and the reefs by stromatoporoids. Such periods are respectively represented by the skeletal packstones and wackestones of

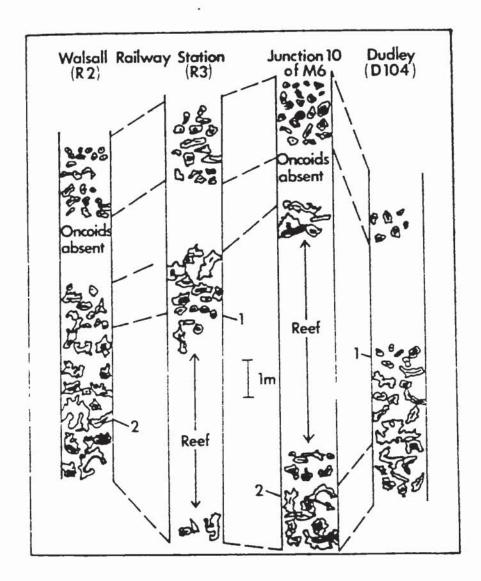


Fig. 3.9. Refined lithological correlation of the Lower Quarried
Limestone made available by studying changes in oncoid morphology. For
locations see Fig.31.

microfacies 5, and the thin layers of mudstone overlain by colonies of in situ Labechia in the reefs. By the time the upper parts of the member were being deposited the reefs had been covered and the seafloor was again essentially planar, and with water perhaps only a few metres deep over the whole of the West Midlands area, any strong wave action would have been rapidly expended, leaving only a gentle rolling effect to disturb sediment close to wavebase.

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CHAPTER 4

PALAFOECOLOGY OF BRACHIOPOD/BRYOZOAN DOMINATED COMMUNITIES IN THE MUCH WENLOCK LIMESTONE FORMATION

4.1 ABSTRACT

Four lithofacies in the Much Wenlock Limestone Formation contain brachiopod/bryozoan dominated faunas. Fourteen discrete assemblages are recognised; microfacies analysis indicates that 11 of these are composed of in situ faunas which reflect ecological parameters but three consist of reworked faunas which reflect sedimentary processes. The assemblages of in situ fauna can only be differentiated from sedimentary faunal assemblages by thin section analysis. Single beds sampled can occasionally be a composite of several microfacies and, unless detected by microfacies analysis, this will cause the faunal assemblages to intergrade. Consideration of the component taxa of the 11 in situ assemblages shows that turbulence, substrate type, ease of feeding and the presence of other organisms in the sediment were the main ecological controls on faunal distribution. While some of these controls were loosely depth-related, it is an overgeneralisation to suggest that the faunas are depth-controlled. Sequential variation of the assemblages indicates that faunal variation closely parallels lithofacies distribution. In high-energy lithofacies the sample interval needs to be decreased in order to increase the probability of sampling an in situ fauna. Microfacies analysis in such lithofacies must be particularly rigorous to prevent reworked faunas being

interpreted as original communities. The rapidity of faunal variation shows that the traditionally adopted palaeoecological practice of defining broad palaeocommunities is of limited value in the Much Wenlock Limestone Formation.

4.2 INTRODUCTION

The Much Wenlock Limestone Formation was deposited on a relatively shallow shelf which lay to the E of the Welsh Basin in late Wenlock times. It contains a diverse and well-preserved biota dominated by crinoids, brachiopods and bryozoans. The outcrop of the formation is shown on Fig. 4.1, with summary logs of each section studied. The formation is composed of varying proportions of limestone beds and nodules surrounded by silty mudstone. Changes in the proportion of silty mudstone and in bedding style allow 7 lithofacies to be recognised in the West Midlands and southern Welsh Borders (section 2.3). Of these lithofacies only 5 are sufficiently fossiliferous to allow palaeoecological work. Brachiopods and bryozoans are abundant in the interbedded limestone and silty mudstone lithofacies, thick-bedded oncoid-rich lithofacies, nodular limestone lithofacies and ferruginous crinoidal grainstone lithofacies, but only occasionally occur in reefs. The coral\stromatoporoid and algal biotas characteristic of the reef lithofacies are described in chapter 5.

Most palaeoecological studies of Silurian faunas have concentrated on brachiopods, a fact reflected in the naming of many communities after brachiopod taxa. Palaeoecological work on other organisms has generally been very restricted (see Thomas 1978 for list of references on the British Wenlock, Bassett & Lawson 1981 for current work on the autecology of Silurian organisms). In many cases bryozoans and crinoids outnumber the brachiopods in the Much Wenlock Limestone Formation and bioturbation suggests soft-bodied organisms were common. However, brachiopods are common in most Silurian shelly

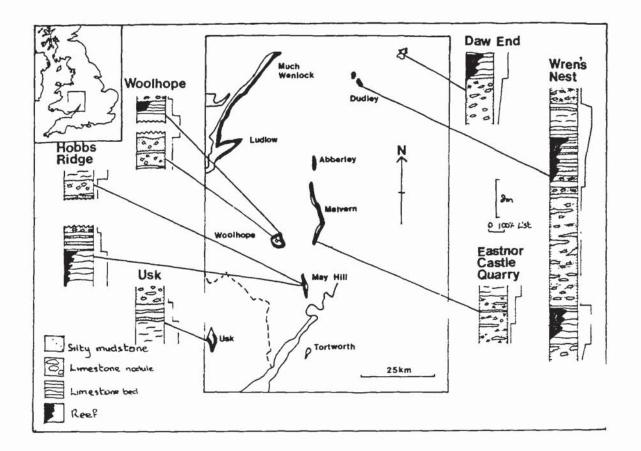


Figure 4.1 Locality map. The outlined areas mark the outcrop of the Wenlock Series in England and South Wales with the Much Wenlock Limestone Formation highlighted in black. Summary logs for each section sampled are shown.

faunas, they are often well preserved and taxonomically well characterised. These factors make them ideal for palaeoecological studies.

Ziegler (1965) pioneered palaeoecological study of Silurian communities with work on Llandovery siliciclastic faunas. This work was extended by Cocks (1967) and Ziegler et al. (1968), and the British Wenlock and Ludlow siliciclastics have been studied in a similar manner (Calef & Hancock 1974, Lawson 1975). Hurst (1975)

described 4 recurrent brachiopod palaeocommunities from the Silurian limestones of England; Visbyella, Eoplectodonta, Isorthis and Sphaerirhynchia. The practice of defining a small number of broad communities has been criticised by Lawson (1975), who argued that in Ludlow siliciclastics, detailed, and probably palaeoecologically important, data are lost when using this approach. Hurst (1975), like Ziegler, Cocks and Calef & Hancock, considered the distribution of communities to be depth related, with Visbyella being the deepest and Sphaerirhynchia the shallowest. Subsequent work has shown this to be an overgeneralization (Lawson 1975, Bassett 1984, section 4.5). All the sections studied in the current work were sampled by Hurst (1975). The majority of collections processed approximated to his Sphaerirhynchia Community, but strict assignment of a collection to one of Hurst's communities is not possible, a common difficulty of palaeocommunity work. From figures 4.2-4.8 it is clear that four communities cannot adequately describe the variations in the shelly faunas of the Much Wenlock Limestone Formation. The variations are to some degree enhanced by post-mortem redistribution, a feature considered unimportant by Hurst (1975, p. 229). Microfacies analysis, however, shows that sedimentary processes were important in distributing bioclasts and that different processes produce distinct faunal assemblages. Where winnowing affected the sediment the lighter and/or more easily transported elements were removed, leaving a fauna which reflected the sedimentary process not the original community. The finer bioclasts from the winnowed lag were later deposited forming an association of smaller faunal elements. In some cases transported assemblages are evident in the field and for ecological

reconstructions can be ignored, but more often they cannot be separated from in situ assemblages without thin section analysis. Of the 59 collections processed, 39 were composed of locally derived or in situ fossils, 12 were composed of reworked faunas and 8 were a mixture of the two. Interactive study of faunal variations and sedimentology is rarely carried out during palaeoecological research. Without this interactive study, collections which reflect sedimentary processes rather than palaeoecology are likely to incorporated into community or assemblage data. The paucity of sedimentological data in Hurst (1975) is also responsible for the apparent lack of correlation between his faunal distribution and lithofacies.

4.3 SAMPLING PROCEDURES

Prior to sampling a section for palaeoecological work it was logged and the major lithofacies identified. As far as faunal distribution allowed collections were made from the top and base of each lithofacies, with as many samples from intermediate parts as possible. This vertical sampling was supplemented by laterally equivalent samples as far as exposure permitted. Ideally, to allow the rapidity of faunal changes to be determined, bed by bed collecting is necessary (Lawson 1975, Bassett 1976). Successive beds in the Much Wenlock Limestone Formation are rarely sufficiently fossiliferous to allow such sampling. The separation of successive collections varied from adjacent beds to beds tens of metres apart. Silty mudstone interbeds were generally poorly fossiliferous and were only sampled where the fauna was relatively abundant. The samples, consisting of

individual beds, were split parallel to bedding in the laboratory, each macrofossil being identified as far as taxonomic understanding allowed. Brachiopods were identified to generic level (Bassett 1970, 1972, 1974a & 1977), bryozoans were grouped into orders (Murray 1985, P.D. Taylor pers. comm.) and corals into morphologically similar groups. Thin sections were made for over 80% of the samples and these were point counted to provide a basis for microfacies analysis. The number of brachiopods in each collection was calculated by adding the number of articulated specimens to the number of pedicle or brachial valves present, depending which was most abundant. Bryozoans were only recorded when they showed no evidence of extensive breakage. The first 200 individuals found were recorded. Plotting the diminishing rate of appearance of new species for a range of collections shows that 50-150 individuals provide an approximation of the preservable parent populations in the Much Wenlock Limestone Formation.

4.4 SEDIMENTOLOGY

The stratigraphy and general sedimentology of the Much Wenlock Limestone Formation have been described by Lawson (1955), Colter (1957), Walmsley (1959), Squirrell & Tucker (1960), Phipps & Reeve (1967), Shergold & Bassett (1970), Scoffin (1971), Bassett (1974b) and Oliver (1981). In the West Midlands the vertical variation in lithofacies, first described by Butler (1939), has recently been formalised (Dorning 1983) into the Lower Quarried Limestone, the Nodular Beds and the Upper Quarried Limestone Members. Detailed lithofacies and microfacies composition of the Much Wenlock Limestone Formation is discussed in sections 2.3 and 2.4.

4.4.1 Interbedded limestone and silty mudstone lithofacies

Those parts of the interbedded limestone and silty mudstone lithofacies which are composed of thin brown limestone beds separated by thick silty mudstones, were deposited in relatively low-energy environments (section 2.5.2). Evidence for sporadic storm events becomes more common where the limestone beds are thicker and the silty mudstone less abundant, suggesting that the mud-poor parts of the lithofacies were deposited in a shallower water environment than the mud-rich parts (section 2.5.2). The limestone beds of this lithofacies vary from carbonate mudstones with no bioclasts through skeletal wackestones and packstones into skeletal grainstones. The limestone beds are surrounded by parallel-laminated silty mudstone which is typical of a low-energy depositional environment. The sparse fauna in the silty mudstone will therefore have been subjected to little postmortem reworking, and should reflect accurately the original preservable faunal components. Beds of skeletal wackestone with articulated bioclasts should also contain a record of original faunal composition, as the high percentage of articulated brachiopods indicates limited post-mortem transportation. Skeletal wackestones and packstones containing disarticulated bioclasts can also be useful in recreating original faunal compositions. The bioclasts frequently lack evidence of long distance transport, suggesting that the fauna is of local origin. In such wackestones and packstones the broad faunal content of the palaeoenvironment is preserved but detailed lateral and vertical variations are homogenised. Skeletal packstones which contain a high percentage of spar often contain bioclasts which show little evidence of transportation. The abundance of calcite spar in these

beds indicates winnowing, however, and the fauna is a concentration of heavy and difficult to transport bioclasts. By contrast, skeletal grainstones which do show evidence of transportation have an abundance of smaller bioclasts. The pure carbonate mudstones contain abundant micrite, suggesting a low-energy depositional environment, and the fauna could reasonably be expected to be of local origin. Thin section study, however, shows that many of the carbonate mudstone beds resulted from settling of fine carbonate debris subsequent to a storm event higher on the shelf. The significance of resedimented and winnowed assemblages is discussed in section 4.5.4, where they are referred to as sedimentary faunal associations.

4.4.2 Thick-bedded oncoid-rich lithofacies

The thick-bedded oncoid-rich lithofacies contains abundant algae indicating that it was deposited within the photic zone. The Lower Quarried Limestone Member is composed of this lithofacies and variations in oncoid morphology show it to be a shoaling-upward sequence (section 3.5). Deposition of the member began below storm wavebase, the intermediate parts were deposited above storm wavebase and the top of the member close to normal wavebase.

Oncoidal wackestones, oncoidal packstones and skeletal packstones/grainstones occur in the thick bedded oncoid-rich lithofacies. The oncoidal packstones contain few identifiable fossils, most having been broken by gentle wave action. Oncoidal wackestones contain a mixture of articulated and fragmentary bioclasts but there is no evidence for long distance transport. The fragmentary nature of some of the bioclasts is attributed to local reworking during sporadic

storm events (section 3.7). The fauna in this microfacies probably broadly reflects the original faunal composition but detailed lateral and vertical variations have been homogenised. Sharp-based beds of skeletal packstone with a high percentage of calcite spar are winnowed shell lags and therefore contain large, heavy bioclasts.

4.4.3 Nodular limestone Lithofacies

The nodular limestone lithofacies is a low-energy deposit, most of the nodules being early diagenetic concretions. Some current activity is evidenced by the presence of elongate nodules composed of skeletal debris (section 2.5.4). Limestone nodules of skeletal wackestone, skeletal packstone and quartzose carbonate mudstone are surrounded by varying proportions of silty mudstone in this lithofacies. The fauna of the silty mudstones suffered little postmortem reworking. Nodules of quartzose carbonate mudstone are diagenetic concretions in the silty mudstones, and therefore contain a largely in situ fauna. Nodules composed of skeletal wackestone with articulated bioclasts represent patchy colonization of the sea floor with no post-mortem redistribution. In nodules where the bioclasts are fragmentary, the fauna has been redistributed by gentle current activity.

4.4.4 Ferruginous crinoidal grainstone lithofacies

The ferruginous crinoidal grainstone lithofacies was deposited above wavebase in a dominantly high-energy environment (section 2.5.5). Rip-up clasts in some beds indicate the former presence of silty mudstone. The high-energy conditions in which the crinoidal

grainstones were deposited were therefore separated by quiescent periods in which fine sediment was allowed to settle, prior to being reworked (section 2.5.5). Unbedded shell banks formed during these low-energy periods. Brachiopods in these banks are often articulated, show little sign of sorting or abrasion and geopetal infills suggest that they are in life position. Thus the fauna may reflect low-energy conditions rather than the high-energy conditions in which the grainstones were deposited.

4.5. PALAEOECOLOGY

4.5.1 Composition of faunal associations

Comparison of collections seen on figures 4.2 to 4.8 is hampered by sedimentary overprint, minor elements of the fauna and poor taxonomic understanding of bryozoans.

4.5.1.1 Sedimentary overprint.

Only by detailed microfacies analysis can the fauna of a sample be proved to be of local origin. Articulated brachiopods are assumed to have undergone little post-mortem transportation, particularly since common geopetal structures suggest that the articulated brachiopods are in life position. Disarticulated brachiopods are only interpreted to be of local origin if they show no signs of breakage and/or abrasion. The collections which contain obviously transported bioclasts have a fauna comparable with some of the in situ assemblages. Without sedimentological data such sedimentary faunal associations could be mistaken for assemblages of in situ fauna. The

significance of the sedimentary faunal associations is discussed separately (4.5.3).

4.5.1.2 Minor elements of the fauna

Comparison of the collections is further hindered by the sporadic occurrence of rarer taxa which do not form a significant part of any collection. These rarer faunal elements were removed to facilitate comparison. This was done by plotting graphs of both cumulative percentage and abundance percentage of the species in each collection, starting both graphs with the most abundant taxon (Fig. 4.9). From the cumulative plot the number of taxa necessary to make up 90% of the collection can be obtained. By plotting this number on the percentage abundance curve the value below which a taxon becomes insignificant at the 90% level can be calculated. In most cases this value is approximately 1.5% of the total fauna in any collection (Fig. 4.9). The elements present in a collection below this value were then omitted for comparative purposes.

Figure 4.2 Faunal composition of collections from Daw End railway cutting, Walsall. For figures 4.2-4.8 the sedimentary log for the section is shown on the left with lines to indicate the positions of samples. The vertical line to the right of the columns represents the percentage of limestone beds and nodules. A brief description of the collection is given on the right. The following abbreviations are used in figures 4.2 - 4.8: Res. - Resserella, Is. - Isorthis, Dal. - Dalejina. Ske. - Skenidioides, Lep. - Leptaena, Sc. - Scammnomena. Am. -Amphiostrophia, Lept. - Leptostrophia, Cool. - Coolinia, Strop. -Strophonella, Phol. - Pholidostrophia, Kat. - Katastrophomena, Lean. -Leangella, Eop. - Eoplectodonta, Prot. - Protochonetes, Pent. -Pentlandina, R.a. - Ribbed atrypid, Gl. - "Glassia", Nuc. - Nucleospira, Whit. - Whitfieldella, Atr. - Atrypa, Eos. - Eospirifer, How. - Howella, Kow. - Kozlowskiellina, Stri. - Striispirifer, Spin. - Spinella, Hom. -Homeospira, Mer. - Meristina, Gyp. - Gypidula, An. - Anrhynchonella, Rh. -Rhynchotreta, Mic. - Microsphaeridiorhynchus, Sph. - Sphaerirhynchia, R.T.- Ramose trepostome, E.T.- Encrusting trepostome, Fen.-Fenestella, Fist. - Fistulipora, R.C. - Rhabdomesine cryptostome, P.T. -Ptilodictine cryptostome, Tril.- Trilobite, Gast.- Gastropod, S.c.-Solitary coral, St.c.- "stick" coral, Br.c.- Branching coral, M.c.-Massive coral, N.A.- Non articulate, Tent.- Tentaculites.

FIGURE 4.2

П	pe	p	P	P		pec .	
	Limestone bed	Limestone bed	Limestone bed	Laterally equivalent limestone bed	Limestone bed	Limestone bed	
	imest	imest	imes	Laterally equivaler limeston	imes.	imes	
Tent.	_	.		~~~		-	
A. M.c.							
Br.c. St.c.							
S.c.							
Tril.							
R.C. Fist.			1	<u> </u>	1 1	1 1	
Fen. E.T.		1	1	п	П	П	
R.T. Sph. Mic.				11		k.i	
Rh An	- H						
Gyp Mer							
Hom. Spin.	ı	0		I			
Stri. Kow.	•	Ĭ	_		-		
How. Eos.				\ \ \ \		4	
Cyr. Atr.		ł		ſ			
Nuc. Whit.		п	П	, —	п		
GI. R.a.							
Pent. Prot. Eop.	ı	l	ı				
Leen. Kat.	·				•		
Phol. Strop.				, , , , , , , , , , , , , , , , , , ,		I	
Cool. Lept.			l n	\$100 B	1	į	
Am. Sc. Lep.	1	1	I		1	i i	
Ske. Dic.							
Dal.		1	1		Π		
Res.	<u>'</u>			EEE	Ĭ		
5 × 6	DEH	DEG	, j	DEE	DEB	DEA	
				11/10/1000 000000	*	10011	
		100	MM	THIND OF LOG	00 100	1 100 DE	
	<u> </u>			o € ∾			

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Figure 4.4 Faunal composition of collections from the upper parts of the Nodular Beds Member from Wren's Nest

FIGURE 4.3

			URE 4.3
	Limestone/silty mudstone couplet	Limestone bed	Limestone bed Limestone bed Limestone bed
Tent.			
Strom.			
Br.c. Bt.c. S.c.	0 1	b	
Gas.			
Tril. P.C.			
R.C. Fiet.		ł	
Fen.	. 1		
E.T. M.T.	<u> </u>		
Sph. Mic.		H	
Rh.	*		
An. Gyp.	·	A	
Mer. Hom.			
Spin. Strl.			0 🗆
Kow.			Д Д Д
How.	п Д	ñ	- Y
Cyr. Atr.	I LI		1 ' 1
Nuc.			1 1
Whit.		_0_	
R.a. Pont.	$-\Pi$		
Prot. Esp. Loon.		849	
Ket.			•
Phol. Strop.	1 8	W2-W	
Cool	1,	zus	1 1
Am		Į.	1
Sc. Lop.			
Ske. Dic.	======================================		
Del.	년 [4	
le. Res.	<u> </u>		
5 F 8	BWN 18	BWN 19	BWW 13N
		0000000	
		Mark the second	6 f A

Figure 4.4 Faunal composition of collections from the upper parts of the Nodular Beds Member from Wren's Nest

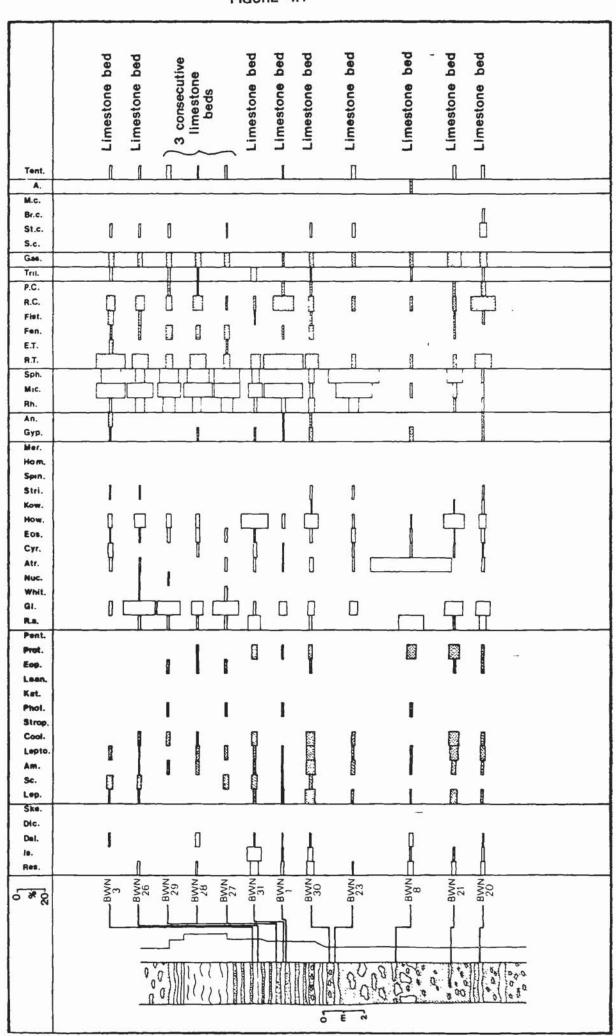


Figure 4.5 Faunal composition of collections from Hobb's Ridge in the May Hill Inlier.

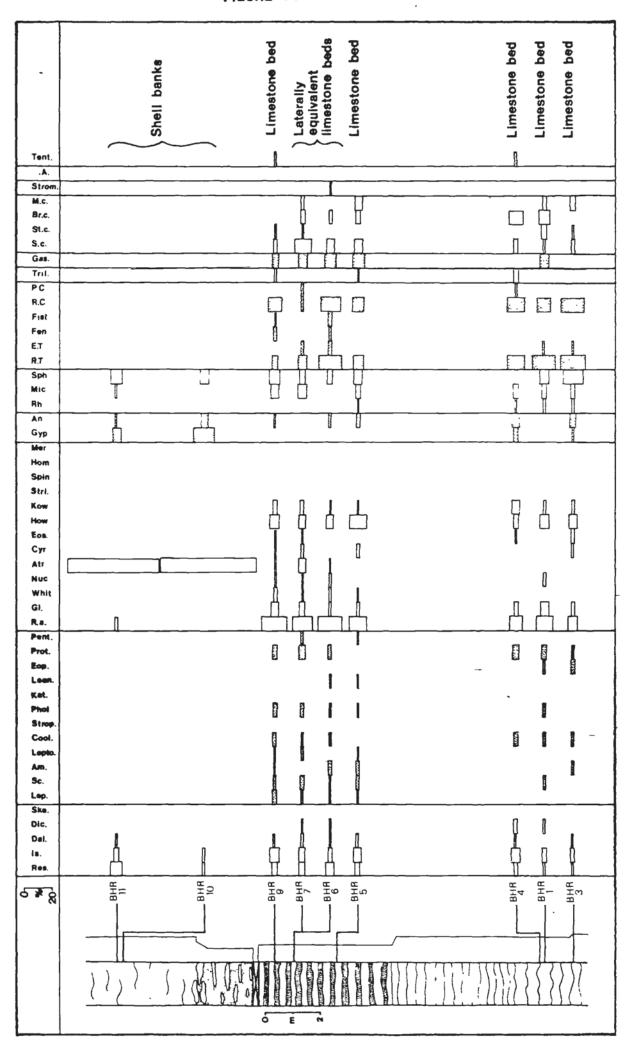
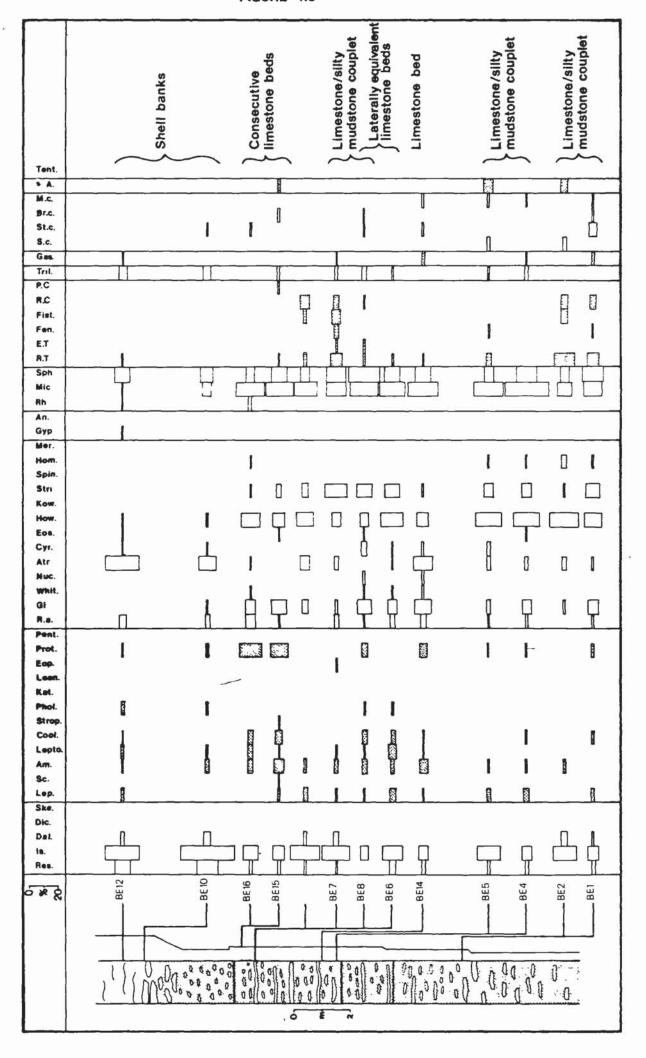


Figure 4.6 Faunal composition of collections from Eastnor Quarry in the Ledbury Hills.

FIGURE 4.6



2

Figure 4.7 Faunal composition of collections from the Woolhope Inlier.

FIGURE 4.7

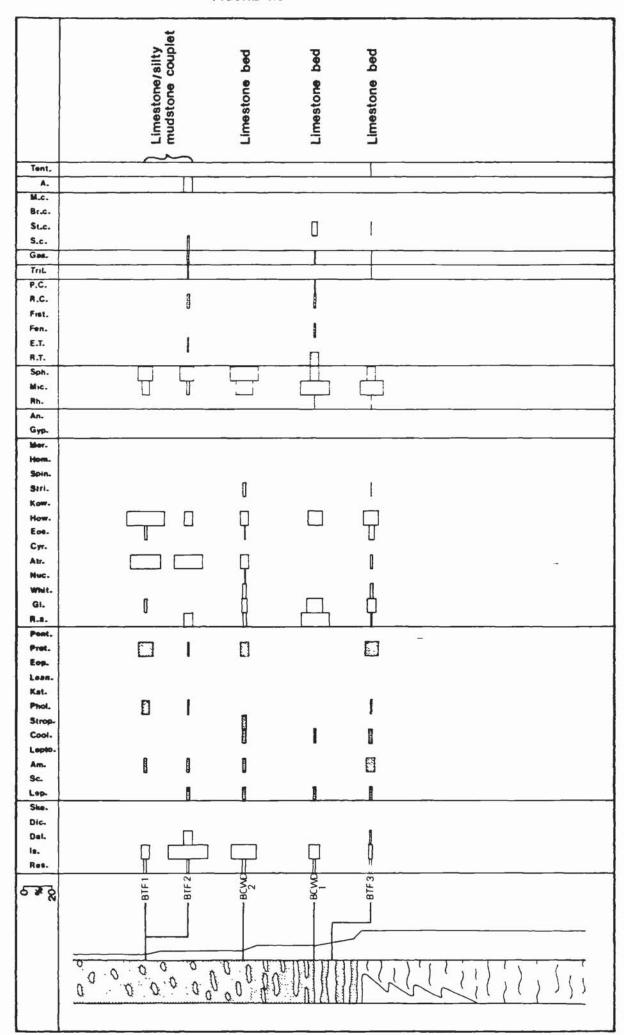
	FIGURE 4.7	
Tont.	Reef lithofacies	Limestone bed Limestone bed Limestone bed
.A. M.c. Br.c. St.c. \$.c. Tril.	7 1 1	
P.C. R.C. Fist. Fen. E.T. R.T. Sp. Mic. Rh.		
An- Gyp. Mer. Hom. Spin. Stri. Kow. How.		
Cyr. Atr. Nuc. Whit. Gi. R.a. Pent.		
Eop. Lean. Kat. Phol. Strop. Cool. Lepto. Am. Sc. Lep.		
Ske. Dic. Dal. Is. Res.	BW0 12 18 18 18 18 18 18 18 18 18 18 18 18 18	B WA B 3 A D D D D D D D D D D D D D D D D D D

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Figure 4.8 Faunal composition of collections from the Usk Inlier.

FIGURE 4.8



4.5.1.3 Poor taxonomic knowledge of Silurian bryozoans

The current state of Silurian bryozoan taxonomy does not allow specific or generic identification of each specimen. While the subdivision used here is of environmental significance it does not facilitate comparison of collections. This problem is overcome by recalculating the percentage of brachiopod species so that the total brachiopod abundance is 100%.

By applying the above techniques to the raw data displayed in figures 4.2 to 4,8, a new data set is obtained which shows the percentage of common brachiopods present in each collection. The collections can then be grouped together into visually similar assemblages. To numerically test the similarity of two collections the sum of the differences between the species in each collection was calculated. The smaller the resulting figure the closer the correlation. By preparing matrices of these correlation indices for visually similar collections, those with a numerically similar brachiopod assemblage can be identified (Fig. 4.10). Two collections are considered to be numerically similar if their correlation coefficient is 65 or below, and numerically different it is above 65. Those collections which contain a visually and numerically similar fauna were averaged to produce an assemblage. This method allows discrete assemblages to be defined which can be compared to any subsequent collections. This method also prevents the grouping together of collections which are broadly similar but have one particularly abundant taxon, a common feature of some community analyses. The eleven discrete assemblages composed of in situ or

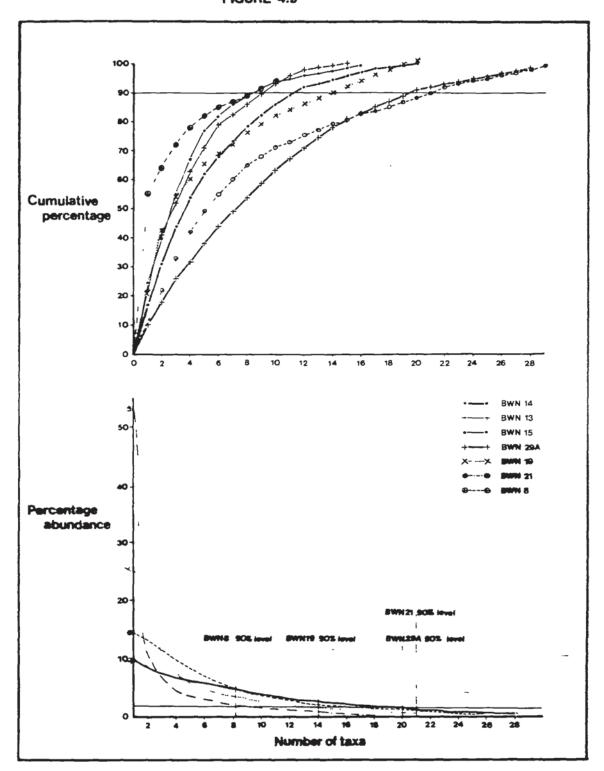


Figure 4.9 Method adopted for removing minor faunal elements from the raw data. The upper graph shows the diminishing rate of appearance of new species with increasing sample size. From this graph the minimum number of taxa necessary to make up 90% of a collection can be calculated. The lower graph plots the percentage of each taxon within a collection in order of decreasing abundance. From this graph the percentage below which a taxon can be rejected as insignificant at the 90% level can be calculated. This is generally about 1.5%.

BE10	56											
BE16	116	113		_								
BE15	113	143	57									
BE14	95	93	61	112								
BE9	80	75	85	82	75	}						
BE8	125	149	81	51	60°	111]					
BE7	75_	82	99	90	81	46	86					
BE6	111	109	59	62	69	65	53	54				
BE5	103	99	80	71	108	48	76	41	43		_	
BE4	113	143	_78	63	65	74	65	60	50	46		
BE3	92	_88	101	103	87	56	112	39	85	56	38	
BE2	101	129	71	57°	61°	74	50	54 °	36 °	56 *	42°	94
	BE11	BE10	BE16	BE15	BE14	BE9	BES	BE7	BE6	BE5	BE4	BE3

Figure 4.10 Correlation matrix for comparison of collections from Eastnor Castle Quarry. Each number represents the sum of the differences between percentage abundance of taxa in the collections being considered. Dots indicate values less than 65 which are considered to represent collections which are numerically similar.

locally derived brachiopods are shown graphically on Fig. 4.11.

4.5.2 Environmental significance of faunal assemblages

4.5.2.1 Assemblage 1

Collections BWN 3 and 23 belong to this assemblage. The brachiopod fauna is dominated by Microsphaeridiorhynchus and Sphaerirhynchia wilsoni. Microsphaeridiorhynchus is thick shelled.

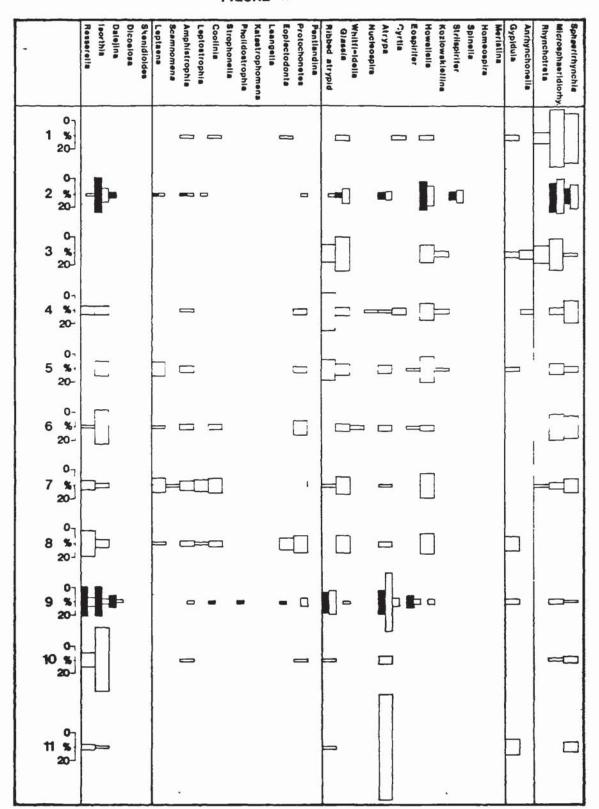


Figure 4.11 Brachiopod composition of assemblages 1-11. Each assemblage is the average of the component collections after recalculation to remove bryozoans and minor faunal elements.

Assemblages 2 and 9 come from collections where the adjacent silty mudstones were sampled and the black bars represent the average of the faunas from the silty mudstones.

heavily ribbed and had a functional pedicle throughout ontogeny, all of which are morphological adaptations to living in turbulent environments (Rudwick 1964, Fursich & Hurst 1975). It also had a spirolophous lophophore (Rudwick 1970, Fursich & Hurst 1975) which would have enabled it to live in areas where feeding was difficult. Difficult feeding for brachiopods can result when the organic content of the water is low. This is generally considered to occur in deeper water, or where the relative abundance of organics is diluted by sediment in suspension (Rudwick 1970). The latter is most likely to occur in very shallow water. The dominance of brachiopods with morphological adaptations to a turbulent environment suggest that this assemblage formed in very shallow water. Smaller individuals of Sphaerirhynchia wilsoni are similar to Microsphaeridiorhynchus and probably lived in similar environments. Larger individuals are usually globose, thick shelled, sulcate and have atrophied pedicles. Such morphological adaptations in Sphaerirhynchia are thought to have formed in response to an ambitopic life style with the umbones partially buried in soft sediment (Westbrock et al. 1975, Fursich & Hurst 1981) This life strategy would have been better suited to a lower energy environment than the more common pedunculate morphology of rhynchonellides. It would also have restricted the adults to soft substrates (Thayer 1974). The individuals of Sphaerirhynchia wilsoni in assemblage 1 are small, thick-shelled and had functional pedicles. Bryozoans are also common in this assemblage (Fig. 4.4). The palaeoecology of Silurian bryozoans is as poorly understood as their taxonomy. They needed a firm substrate for their larvae to settle on, but small skeletal fragments may have been adequate. Forms with

laminar—encrusting and massive to domal growth morphologies are more abundant in high—energy environments than ramose and articulated forms (Brood 1984). The only numerically abundant bryozoans found in the collections are ramose and articulated forms. The similarity in distribution of ramose trepostomes and rhabdomesine cryptostomes in this and other assemblages suggests the two occupied similar ecological niches. Trepostomes are slightly more abundant in rhynchonellide—rich collections, suggesting that their robust nature made them better suited to higher energy conditions than the rhabdomesine cryptostomes. This assemblage therefore contains a fauna typical of a high—energy, shallow water environment with hard substrates.

4.5.2.2 Assemblage 2

Collections BE 2,4,6,8 and 14 are assigned to this assemblage. It is rich in rhynchonellides (27%), which again suggests a relatively shallow water, turbulent environment with a hard substrate. The other common brachiopods are Howellella elegans (13%), "Glassia" (10%) and Isorthis (10%). Howellella elegans had a functional pedicle throughout ontogeny, allowing it to attach to hard substrates. Large individuals had flat interareas similar to such spiriferides as Cyrtia exporrecta, which sat on soft substrates. Hence H. elegans may have lived on soft sediment as well as hard substrates. The efficient spiriferide lophophore of Howellella elegans would have enabled it to live in areas where feeding was difficult but its heavily ribbed, thick shell would also have made it suited to shallower turbulent water. Howellella therefore appears to have been able to thrive in a

wide variety of environments on both hard and soft substrates. "Glassia" is a broad name given to small smooth spiriferides which cannot be assigned to another taxon. They had a functional pedicle throughout ontogeny indicating that they were capable of living on hard substrates, but their small size may also have allowed them to attach to small fragments in otherwise soft sediment. Orthides had a simple lophophore (Williams & Wright 1965, Fursich & Hurst 1975) which would have restricted them to areas where feeding was easy. Isorthis is most common in collections from silty mudstones, which during deposition, would have formed a relatively soft substrate with a lack of attachment points for a plenipedunculate brachiopod. Isorthis has no preserved morphological adaptations to soft substrates, yet shows a marked increase in abundance in silty mudstones. It may be that the pedicle of Isorthis was rhizopedunculate, allowing individuals to anchor themselves into soft sediments. This pedicle morphology occurs in modern brachiopods (Rudwick 1961, Curry 1981) but its existence is difficult to prove in fossils. While rhizopedunculate brachiopods are capable of rooting themselves in soft sediment they can also tether themselves to a hard substrate, which would explain the occurrence of Isorthis in most collections. The dominance of rhynchonellides in this assemblage therefore indicates that this assemblage formed in a relatively high-energy environment, but the occurrence of genera less well adapted to turbulence suggests that conditions were lower-energy than during the formation of assemblage 1. Despite the occurrence of hard substrates during the formation of this assemblage, bryozoans are rare.

4.5.2.3 Assemblage 3

This assemblage contains BWN 13 and 15. Rhynchonellides, spiriferides and pentamerides are the only brachiopod orders in this assemblage. Microsphaeridiorhynchus (22%), Howellella elegans (13%), "Glassia" (24%) and a ribbed atrypid (13%) make up most of the fauna. Once again the abundance of rhynchonellides indicates a relatively shallow water, turbulent environment. Algal tubules are abundant in the matrix of these collections, suggesting that the sea floor was colonized by algae. Under these conditions an organism lying with its anterior margin close to, or partly buried in, the sediment would have been rapidly encrusted by algae, probably leading to the death of the animal. Howellella elegans was capable of resting on its umbones with its anterior margin raised above the sediment surface (section 4.5.2.2). Individuals of Sphaerirhynchia wilsoni in this assemblage generally show the features described for an ambitopic life style (4.5.2.1), living with their anterior margins raised off the sediment surface. The ribbed atrypid is of uncertain affinity. It closely resembles the atrypids described by Worsley & Broadhurst (1975) from Norway. The heavily ribbed thick-shelled atrypid described by them lived in an almost upright position, with its umbones partially buried in the sediment and its pedicle acting as an anchor to give extra stability. The ribbed atrypid in the Much Wenlock Limestone Formation may have had a similar life strategy. The common brachiopods in this assemblage all lived with their anterior margins raised off the sediment surface, and thereby prevented their commisures from being colonised by algae. Bryozoans are absent from this assemblage. This

may be due to any available hard substrates being encrusted more rapidly by algae than by bryozoan larvae.

4.5.2.4 Assemblage 4

Collections EHR 1, 4, 5, 6, 7, 9 and EWO 9 are assigned to this assemblage. Spiriferides dominate, a ribbed atrypid (31%) being the most abundant taxon and Howellella elegans (14%) also being common. Ramose trepostome and upright articulated rhabdomesine cryptostome bryozoans are common, as are corals (Fig. 4.5). Apart from the occurrence of orthides, the brachiopod fauna of this assemblage resembles that of assemblage 3. Both assemblages come from the thickbedded oncoid-rich lithofacies which contains thin silty mudstone interbeds at May Hill that are absent from the lithofacies in the West Midlands (the Lower Quarried Limestone Member). The orthides in this assemblage probably originated from the silty mudstone interbeds (section 4.5.4.1) that occur in the section at May Hill. Apart from the orthides the brachiopods in this assemblage are forms which lived with their anterior margins off the sediment surface, again suggesting that this may have been a life style favourable to life in an algarich carbonate mudstone. The abundance of bryozoans is anomalous considering the alga-rich nature of the sediment, but may be due to corals providing a large area for the bryozoans to colonize.

4.5.2.5 Assemblage 5

This assemblage contains collections BWA 1, BWO 1 and BWO 6.

Howellella elegans (18%), a ribbed atrypid (14%), Resserella (11%) and

Leptaena (10%) contribute significantly to the brachiopod fauna. These

collections all come from lenses of coral/stromatoporoid packstones and therefore contain abundant colonial organisms. Ribbed atrypids lived with their umbones partially buried in the sediment (section 4.5.2.3). The sharp geniculation of Leptaena's shell and occasional presence of a trail imply a quasi-infaunal life style (Rudwick 1970, Bassett 1984), suggesting that Leptaena preferred a soft substrate into which it could partly sink. It must have colonized low-energy environments or the sediment in which it lived would have been frequently reworked, leaving the animal exposed in an unstable concave-upward position. Resserella is most abundant in skeletal wackestone and packstone beds. It occurs in association with other brachiopods which show some morphological adaptations to turbulent environments but is never abundant in rhynchonellide-rich collections. This suggests it preferred hard substrates in an environment of intermediate energy. It is thought that the brachiopods in this assemblage lived on, or in, the sediment at the base of crinoid thickets. The microfacies created in this environment was a crinoidal packstone which would have formed a hard substrate, but the thicket would also have trapped carbonate mud creating a soft substrate locally.

4.5.2.6 Assemblage 6

Collections BTF 3 and BCM 2 belong to this assemblage. It is dominated by Microsphaeridiorhynchus (18%), small individuals of Sphaerirhynchia wilsoni (15%) and Isorthis (23%). Spiriferides are relatively rare and bryozoans almost entirely absent. This assemblage appears to be a mixture of high-energy, hard-bottom and low-energy,

soft-bottom faunas. The collections come from the nodular limestone lithofacies composed of elongate nodules. The nodules sampled had cores of skeletal wackestone surrounded by quartzose mudstones of diagenetic origin (section 2.4.1). The fauna in the diagenetic part of the nodule would have been orthide-rich, typical of the silty mudstones (section 4.5.4.1). The mixture of two environmentally different assemblages is therefore a combination of the fauna from the silty mudstones and the limestone beds.

4.5.2.7 Assemblage 7

Collections BWN 21 and 29A are assigned to this strophomeniderich assemblage. Howellella elegans (17%) and "Glassia" (12%) are the most abundant taxa, but Leptaena (9%), Amphistrophia funiculata (7%), Leptostrophia filosa (9%) and Protochonetes minimus (7%) are relatively common. Strophomenides had narrow body cavities suggesting that they were inefficient feeders, restricting them to areas where feeding was easy. Amphistrophia funiculata has a sharply geniculated shell similar to Leptaena and is interpreted to have lived partly buried in soft sediment in relatively low-energy environments (Bassett 1984). Leptostrophia filosa adopted an ambitopic life style early in ontogeny (Bassett 1984), its broad flat morphology providing a large surface area which enabled it to rest on soft substrates (Thayer 1974). This would have been a relatively unstable position, restricting Leptostrophia filosa to non-turbulent environments. Protochonetes minimus also shows morphological adaptations to lying on the surface of soft sediment. The development of spines would have given it extra stability, possibly allowing it to live in slightly

higher energy conditions than the larger strophomenides (Bassett 1984). The abundance of strophomenides in this assemblage therefore indicates a soft substrate in a relatively low-energy environment. This is supported by the rarity of bryozoans in this assemblage.

4.5.2.8 Assemblage 8

DEE and DED belong to this assemblage. Howellella elegans (15%),
"Glassia"(12%), Resserella (19%) and Protochonetes minimus (12%) are
its main constituents. Ramose trepostomes and rhabdomesine
cryptostomes are present but not abundant. Howellella elegans was
capable of living in a variety of environments (section 4.5.2.2).
Protochonetes minimus lived on soft substrates and could withstand
some turbulence. "Glassia" and Resserrella lived on hard substrates.
This assemblage therefore formed in a relatively low energy
environment where both hard and soft substrates existed.

4.5.2.9 Assemblage 9

Collections EWN 8,17 and19, DE B and EWA 1 form this assemblage. It is dominated by Atrypa reticularis (40%) and a ribbed atrypid (17%). Other taxa are rare. Atrypa reticularis is not present in all assemblages but where it does occur, it tends to dominate the fauna. Where large numbers are found individuals are large, globose and sulcate with an atrophied pedicle. The lack of pedicle indicates that adults were free living and preferred low-energy conditions. Their large globose nature suggests they had a large lophophore making them suited to areas where feeding was difficult. The ability to feed efficiently would have allowed them to live in environments where

other forms could not, explaining their scattered distribution and local abundance. This assemblage therefore formed in a low energy environment with soft substrates where feeding was difficult, probably in deeper water than the other assemblages.

4.5.2.10 Assemblage 10

This assemblage contains collections BE 10 & 11. It is dominated by Isorthis (46%) but Resserella (10%) is common. The brachiopods colonized the area during the low-energy periods which existed between deposition of the crinoidal grainstones (section 2.5.5). The environment was probably close to wavebase and the water sediment laden. Isorthis probably had a rhizopedunculate pedicle (section 4.5.2.2) making it suited to colonisation of the silty mudstones which were deposited during quiescent (section 2.5.5) periods. The dominance of Isorthis may be due to local settling of larvae.

4.5.2.11 Assemblage 11

Collections EHR 10 & 11 belong to this assemblage. It is dominated by Atrypa reticularis (75%) with a significant proportion of Gypidula galeata (11%). The individuals of A. reticularis are generally typical ambitopic forms (4.5.2.9). They would therefore have been suited to living on a soft substrate in a relatively low-energy environment. This seems to contradict the sedimentological evidence; the ferruginous crinoidal grainstone lithofacies in which they occur is a shallow, wave-influenced grainstone. However, rip-ups of silty mudstone within the grainstone microfacies indicate that silty mudstone beds were deposited under low-energy conditions before being

reworked. The presence of mudstone between the brachiopods of the shell banks suggests that they formed during the quiescent periods. This explains the presence of typical low-energy brachiopods in what appears to be a high-energy environment. Individuals of Gypidula galeata have strongly incurved umbones which made the pedicle non-functional. The umbones also became greatly thickened which must have made the posterior of the shell relatively heavy. Pentamerides with these features lived in a posterior-down position and were well-suited to colonizing poorly sorted sands in a shallow water environment sporadically affected by wave action (Ziegler et al. 1966, Anderson & Makurath 1973) explaining their abundance in this assemblage. The abundance of Atrypa reticularis suggests that feeding was difficult. This difficulty was probably due abundant fine sediment in suspension, which resulted from turbulence in a shallow water environment

4.5.3. Sedimentary faunal assemblages

In addition to the 11 assemblages described, there are 3 others with faunas which reflect sedimentary processes rather than the original community. These sedimentary faunal assemblages are described below.

4.5.3.1 Assemblage A

This assemblage contains collections BWN 27,28,29 and 1. The brachiopod fauna is dominated by Microsphaeridiorhynchus (38%), Sphaerirhynchia wilsoni (25%) and "Glassia" (21%). The collections within this assemblage contain abundant bryozoans, dominantly ramose and articulated forms. This assemblage closely resembles the rhynchonellide-rich assemblage 1, which occurs near to the top of the

formation in the West Midlands. Thin sections of beds of this assemblage contain broken, abraded and well sorted bioclasts. Some of the beds grade up into fine carbonate mudstone which settled from suspension following a storm event (section 2.4.1). This indicates that the beds which contain assemblage A were resedimented lower on the shelf after a storm event reworked the sediments in shallower water. The high percentage of rhynchonellides does not represent colonization of a high energy environment, but reflects the relative ease with which the small shells were transported. Bryozoans on death must have been relatively light and therefore also easily transported. The source area of assemblage A may have been rhynchonellide-rich but it could also have contained a varied fauna with only the smaller components being transported long distances.

4.5.3.2 Assemblage B

This assemblage contains collections BE 15 and 16, EWA 2 and 4 and EWN 31. It is dominated by Microsphaeridiorhynchus (20%), Howellella elegans (16%), Protochonetes minimus (11%) and Isorthis (10%). It also contains a relatively high proportion of large strophomenides but bryozoans are rare. The fauna is typical of an assemblage which colonized a low-energy soft substrate, similar to assemblage 7. The beds from which the component collections came belong to MF. 7-11, skeletal packstones to grainstones. These beds were winnowed by gentle traction currents which removed carbonate mud. Therefore the fauna in this assemblage is composed of the larger and/or less easy to transport elements. Protochonetes minimus and Microsphaeridiorhynchus appear at first to be anomalous in a winnowed microfacies. However, Protochonetes had anterior spines which would

have made it relatively difficult to transport.

Microsphaeridiorhynchus, although common, is less abundant in assemblage B than it is in the collections from equivalent non-winnowed limestone beds, suggesting it was preferentially removed.
4.5.3.3 Assemblage C

DEH, DEG and DEF are assigned to this assemblage. It contains abundant ribbed atrypids (16%), Atrypa reticularis (12%), Gypidula (9%), and Microsphaeridiorhynchus (14%). The beds from which the collections were made were winnowed, yet their fauna is different from assemblage B. The collections composed of in situ fauna from the same part of the section belong to assemblage 3 which only contains spiriferides, pentamerides and rhynchonellides. Therefore the winnowed assemblage contains a concentration of those faunal elements in that fauna which were more difficult to transport.

The remaining 8 collections are a mix of reworked and in situ faunas. BWN 26 is composed of well-sorted skeletal grainstones and skeletal wackestones with articulated bioclasts. From figure 4.4 BWN 26 can be seen to be a mixture of assemblages 1 and A. Similarly BWN 20 is a mixture of well-sorted skeletal grainstone, skeletal wackestones with articulated bioclasts and quartzose carbonate mudstones (Fig. 4.4). BWO 7 is a mixture of crinoidal grainstone and crinoidal packstones, the resulting fauna resembling a partially winnowed assemblage 5. The top of the bed containing DE A was dominated by an in situ fauna rich in small rhabdomesine cryptostomes. The interior of the bed is a mixture of quartzose carbonate mudstone and skeletal wackestone with disarticulated bioclasts. The remaining 4 collections probably represent a mixture of in situ and reworked

assemblages, but small sample size prevented thin sections being made.

This again stresses the need for 100% thin section coverage of the faunal collections.

4.5.4 Distribution of the assemblages

Before regional and stratigraphic variations in the faunas can be considered the degree of local variation needs to be determined. The difference between silty mudstone and limestone faunas, the lateral persistence of assemblages and bed-by-bed faunal variations are discussed below.

4.5.4.1 Silty mudstone/limestone fauna

Collections of silty mudstone faunas were made in the 5 cases where the silty mudstone surrounding the limestone beds and nodules was sufficiently fossiliferous. The fauna of the silty mudstones parallels that of the adjacent limestone beds, but with significant variations in the proportions of some taxa (Fig. 4.12). The orthides, particularly Isorthis and Dalejina, are more abundant in the silty mudstones, and the rhynchonellides more abundant in the limestones. Other variations occur but are less systematic (Fig. 4.12). A similar compositional variation occurs between the argillaceous and biomicrite assemblages of Hurst's Sphaerirhynchia Community. The relative decrease in rhynchonellides within the silty mudstones is to be expected as there would have been few attachment points for pedunculate brachiopods. Orthides are also pedunculate but Isorthis may have had a rhizopedunculate pedicle which would have suited a life style anchored in soft sediment (section 4.5.2.2). Dalejina is

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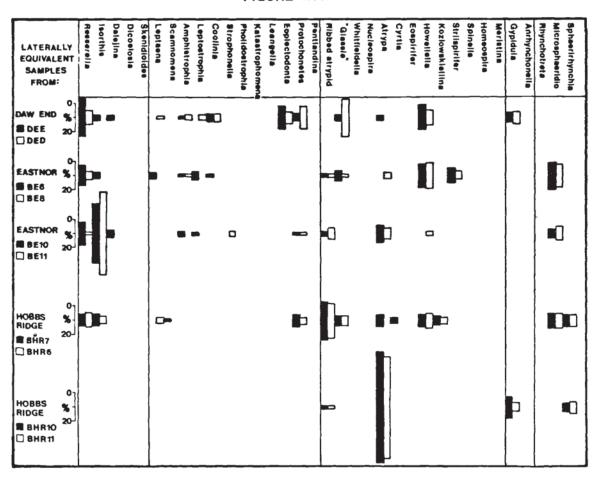
Figure 4.12 Faunal variation between silty mudstones and adjacent limestone beds. The upper, heavily stippled bars show the percentage of genera present in the silty mudstones but not in the limestone beds. The lower bars show the percentage of genera in the limestone beds but not in the silty mudstones. The silty mudstone fauna from Eastnor belongs to collections BE 2, 5, and 7, and limestone fauna from BE 4, 6, 8, 9 and 14. The silty mudstone fauna from Usk comes from collection BTF 2, and the limestone fauna from BTF 1. The silty mudstone fauna from BTF 1 and the limestone fauna from BTF 1. The silty mudstone fauna from BTF 1 and the limestone fauna from BTF 1.

Figure 4.13 Faunal variations between laterally equivalent collections. Each pair of black and white bars represents two collections which are lateral equivalents of one another. The collection numbers are given in the left hand column.

FIGURE 4.12

IN SHALE I		Resserella	Isorthie	Dalejina	Dicoeloeia	Skenidioides	Leptaena	Scamnamena	Amphiostrophia	Leptostrophia	Coolinia	Strophonella	Pholidostrophia	Katastrophomena	Leangella	Eoplectodonta	Protochonetes	Pentlandina	Ribbed atrypid	Glassia	Whitfieldella	Nucleospira	Atrypa	Cyrtia	Rospiriter	Howellella	Kozlowskiellina	Striispiriter	Spinella	Homeospira	Meristina	Gypidule	Anrhynchonella	Rhynchotreta	Microephaeridio.	Sphaerirhynchia
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WREN'S NEST	ONE							_		1	-t f.s				- 1	্নীকু ক -			· (2)				- Carrier	*												
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WREN'S NEST	6- %- 10-							!					-			[E						1					[

FIGURE 4.13



morphologically similar to <u>Isorthis</u> and has a very similar distribution, suggesting it may also have had a rhizopedunculate pedicle.

4.5.4.2 Laterally equivalent collections

Four pairs of laterally equivalent samples were processed from a variety of lithofacies and localities (Fig. 4.13). Three of the pairs are very similar. The two laterally equivalent collections from Daw End are similar, but show some variation between the proportions of certain taxa. The fauna in this bed is of local origin and the slight variation therefore probably reflects sedimentary processes. All the laterally equivalent collections were sufficiently similar to warrant inclusion in the same assemblage.

4.5.4.3 Bed-by-bed variation

Successive limestone beds in the Much Wenlock Limestone Formation are rarely sufficiently fossiliferous to allow bed-by-bed collecting. In each case where they were sufficiently fossiliferous (BWN 27, 28 & 29 and BE 14 & 15) thin sections showed them to belong to sedimentary faunal assemblages. This indicates that the same sedimentary processes deposited the beds but does not provide a control on the rapidity of changes in the original communities.

4.5.4.4 Regional and stratigraphical variation of assemblages.

The distribution of lithofacies indicates that the late Wenlock shelf was divisible into stable northern and unstable southern parts. Faunal variations in the two areas are described separately.

Because of the good exposure in the West Midlands, collections can be made from throughout the formation. The lowest part, the passage beds (Butler 1939), is there composed of nodular limestone

lithofacies. Assemblages 8 & 9, typical of soft substrates occur in these beds. Assemblage 9 occurs in the lowest part of the passage beds suggesting that the water was relatively deep.

Overlying the passage beds is the Lower Quarried Limestone

Member, composed of thick-bedded oncoid-rich lithofacies. Assemblage 3

at the base of the member indicates that hard substrates were

available, and suggests that conditions were more turbulent than

during deposition of the passage beds. This is supported by the

presence of Assemblage C which reflects winnowing by current activity.

The increase in environmental energy is probably the result of

shallowing, evidenced by the sudden appearance of abundant algae at

the base of the Lower Quarried Limestone Member (section 3.4).

The lowest shell—rich horizons in the Nodular Beds Member occur 8m above its base, within the nodular limestone lithofacies. This middle part of the member is dominated by assemblage 9 suggesting deeper water, low—energy conditions with soft substrates. This is supported by the lack of current—reworked assemblages. The fauna in this part of the section is very similar to that in the lower parts of the passage beds which are composed of the same lithofacies. The whole of the section described so far was assigned to one community by Hurst (1975), emphasising the difficulty of displaying faunal variations utilising only four communities. In the middle part of the Nodular Beds Member there is a transition from the nodular limestone lithofacies to the interbedded limestone and silty mudstone lithofacies. This transitional zone contains assemblages 7 % 9, both of which typify low—energy conditions with soft substrates. However, the abundance of strophomenides in assemblage 7 suggests that feeding

was becoming easier, probably as a result of shallowing. Assemblage A also occurs within this part of the section. Without microfacies analysis its occurrence suggests a turbulent, possibly shallow water environment with a hard substrate, but petrography indicates that it is a sedimentary faunal assemblage and that its fauna includes resedimented, easy to transport bioclasts. The upper part of the Nodular Beds Member is composed of mud-poor interbedded limestone and silty mudstone lithofacies containing assemblages 1 and 7. Assemblage 1 suggests that the environment was relatively high-energy with hard substrates while the presence of assemblage 7 indicates that periods of low-energy also existed. During these periods carbonate mud, which had been sent into suspension by high-energy events, settled to form a soft substrate suitable for strophomenides to colonize. Assemblages A and B are common toward the top of the Nodular Beds Member indicating that winnowing and resedimentation were becoming more common. Because of these processes the sampling interval must be decreased to enhance the likelihood of in situ assemblages being collected. Under such circumstances microfacies analysis is particularly important to prevent a collection being interpreted as an in situ collection when it belongs to a sedimentary faunal assemblage.

In the southern Welsh Borders the only vertically extensive sections sampled were at May Hill, Eastnor, Woolhope and Usk. At May Hill the lowest exposed part of the formation is composed of the thick-bedded oncoid-rich lithofacies with a fauna belonging to assemblage 4. Both the sedimentology and the fauna of this lithofacies resemble the Lower Quarried Limestone Member of the West Midlands. The main difference between the two faunas is the presence of orthides at

May Hill. These were probably derived from the beds of silty mudstone which occur there. The fauna in the lower parts of the May Hill section therefore reflects deposition in an algally dominated, shallow water environment with some turbulence. The top of the Much Wenlock Limestone formation at May Hill is composed of ferruginous crinoidal grainstone lithofacies with shell banks composed of assemblage 11. The dominance of one species is typical of a high-stress environment. The abundance of Atrypa reticularis in this lithofacies indicates that feeding was difficult, possibly due to suspended sediment.

At Eastnor the lower part of the section is composed of nodular limestone lithofacies which contains a fauna of assemblage 2. This assemblage formed in relatively high-energy conditions. Assemblage B is common indicating that winnowing currents occasionally affected the sediment. The upper part of the section at Eastnor is composed of the ferruginous crinoidal grainstone lithofacies with a fauna dominated by Isorthis. Again the dominance of one taxon indicates a high-stress environment but the ecological reason for the dominance of Isorthis is uncertain.

At Woolhope the nodular limestone lithofacies beneath the Much Wenlock Limestone Formation contains an in situ fauna belonging to assemblage 9. This suggests deposition in a low-energy environment in which feeding was difficult. Assemblage B also occurs in this part of the section at Woolhope indicating that gentle currents winnowed the sediment during deposition. The middle of the formation at Woolhope is composed dominantly of the thick-bedded oncoid-rich lithofacies overlain by the nodular limestone lithofacies, both of which are sparsely fossiliferous. The thick-bedded oncoid-rich lithofacies

contains assemblage 4 which indicates a shallow water, alga-rich environment, similar to that prevailing during deposition of this lithofacies at May Hill and in the West Midlands. A small reef occurs within the nodular limestone lithofacies. The reef yields brachiopods of Assemblage 5 which lived in the sediment at the base of a crinoid thicket. The thicket created a low-energy environment and trapped fine carbonate mud, providing a soft substrate.

At Usk the wavy-bedded crinoidal grainstone lithofacies at the base of the formation contains no identifiable macrofossils. The lower parts of the overlying nodular limestone lithofacies contains assemblage 6, indicating a relatively high-energy environment with a hard substrate. The upper parts of the nodular limestone lithofacies at Usk contain assemblage 9, suggesting that the depositional environment became lower-energy during deposition, possibly as a result of deepening.

4.6. CONCLUSIONS

1. By removing minor elements of the fauna, taxonomically poorly defined elements and the affects of sedimentary overprint, 11 palaeoecologically significant faunal assemblages were defined. The sequential variation of these assemblages in the Much Wenlock Limestone Formation allows a more accurate interpretation of faunal variation than the previously adopted approach of broad community definition. The definition of discrete assemblages also allows any further samples to be conveniently compared with existing assemblages.

- 2. Sedimentary processes are a major influence in distributing the fauna within the formation. The importance and affects of sedimentary processes can only be determined by combining palaeoecological work with detailed microfacies analysis. This interactive approach prevents the interpretation of reworked fossils as ecological indicators. It also stops the faunas of beds composed of more than one microfacies being considered as parts of one original community. Failure to recognise these composite beds can lead to the averaging of two assemblages, causing the defined communities to completely intergrade.
- 3. Reworked faunal assemblages are more common in high-energy lithofacies. Therefore the distance between successive samples in such lithofacies needs to be decreased to enhance the probability of collecting an in situ fauna.
- 4. The variation in faunal content closely reflects lithofacies distribution in the Much Wenlock Limestone Formation, as would be expected since both are both environmentally controlled. The failure to recognise this correlation by some earlier workers was probably the result of inadequate sedimentological characterization.
- 5. Turbulence, substrate-type, ease of feeding and other organisms in the sediment are controlling factors in the distribution of faunal assemblages. Turbulent environments most commonly occur in, but are not restricted to, shallow water. Soft substrates are common in deeper, lower energy environments, but also occur in shallower, higher-energy lithofacies. Difficult feeding conditions for brachiopods can exist in both shallow and deep water. The presence of algae in the sediment produces a distinctive assemblage which, within the restriction of the photic zone, is not depth-controlled. The

distribution of assemblages is therefore loosely depth-related, but cannot be interpreted as depth-controlled.

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APPENDIX - COLLECTION LOCALITIES.

DAW END RAILWAY CUTTING, WALSALL.

- 1. DEA SK 0389 0035. Nodular limestone lithofacies (passage beds). 600m ENE of where canal crosses railway line.
- DEB SK 0389 0035. Nodular limestone lithofacies (passage beds). 5m
 WSW of collection 1.
- DED SK 0354 0031. Nodular limestone lithofacies (passage beds).
 200m WSW of collection 2.
- 4. DEE SK 0354 003.1 Nodular limestone lithofacies (passage beds). Same bed as collection 3 but 10m WSW.
- 5. DEF SK 0345 0030. Thick-bedded oncoid-rich lithofacies (Lower Quarried Limestone Member)
- 6. DEF SK 0345 0030 Thick-bedded oncoid-rich lithofacies (Lower Quarried Limestone Member) 0.4m above collection 5.
- 7. DEG SK 0345 0030 Thick-bedded oncoid-rich lithofacies (Lower Quarried Limestone Member) 0.1m above collection 6.

WREN'S NEST HILL, DUDLEY.

- 8. BWN 1 SO 9353 9200. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member) W side of Wren's Nest Hill.
- 9. BWN 3 SO 9353 9195. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member) W side of Wren's Nest Hill, 50m south of collection 8.
- 10. BWN 8 SO 9358 9200. Nodular limestone lithofacies (Nodular Beds Memeber) W side of Wren's Nest Hill.
- 11. BWN 13 SO 9380 9212. Thick-bedded oncoid-rich lithofacies (Lower Quarried Limestone Member). Trench section, E side of Wren's Nest Hill.
- 12. BWN 14 SO 9380 9212. Nodular limestone lithofacies (passage beds). Trench section, E side of Wren's Nest Hill. 5m W of collection 11.
- 13. BWN 15 SO 9380 9212. Thick-bedded oncoid-rich lithofacies (Lower Quarried Limestone Member). Trench section, E side of Wren's Nest Hill. 5m E of collection 11.
- 14. BWN 17 SO 9382 9212. Nodular limestone lithofacies (Nodular Beds Member). Trench section, E side of Wren's Nest Hill. 20m E of collection 11.
- 15. BWN 18 SO 9382 9212. Nodular limestone lithofacies (Nodular Beds Member). Trench section, E side of Wren's Nest Hill. Silty mudstone on top of collection 14.
- 16. BWN 19 SO 9382 9212. Nodular limestone lithofacies (Nodular Beds Member). Trench section, E side of Wren's Nest Hill. 3m to the W of collections 14 and 15.
- 17. BWN 20 SO 9383 9212. Nodular limestone lithofacies (Nodular Beds Member). Trench section, E side of Wren's Nest Hill. 11m E of collection 17.
- BWN 21 SO 9383 9212. Nodular limestone lithofacies (Nodular Beds Member). Trench section, E side of Wren's Nest Hill. lm E of collection 17.
- 19. BWN 23 SO 9385 9212. Nodular limestone lithofacies (Nodular Beds Member). Trench section, E side of Wren's Nest Hill. 20m E of collection 18.
- 20. BWN 26 SO 9353 9210. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member). W side of Wren's Nest Hill.

- 21. BWN 27 SO 9350 9190. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member). W side of Wren's Nest Hill.
- 22. BWN 28 SO 9350 9190. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member). W side of Wren's Nest Hill. Bed above collection 21.
- 23. BWN 29 SO 9350 9190. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member). W side of Wren's Nest Hill. Bed above collection 22.
- 24. BWN 30 SO 9355 9218. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member). W side of Wren's Nest Hill.
- 25. BWN 31 SO 9350 9190. Interbedded limestone and silty mudstone lithofacies (Nodular Beds Member). W side of Wren's Nest Hill. HOBB'S RIDGE, MAY HILL.
- 26. BHR 1 SO 6945 1943. Thick-bedded oncoid-rich lithofacies. Base of section in old quarry.
- 27. BHR 3 SO 6945 1940. Thick-bedded oncoid-rich lithofacies.

 Approximately same horizon as collection 26, but 28m S.
- 28. BHR 4 SO 6945 1945. Thick-bedded oncoid-rich lithofacies. Base of section at N end of old quarry.
- 29. BHR 5 SO 6945 1940. Thick-bedded oncoid-rich lithofacies. Above collection 27.
- 30. BHR 6 SO 6945 1940. Thick-bedded oncoid-rich lithofacies. 1.5m S of collection 29.
- 31. BHR 7 SO 6945 1939. Thick-bedded oncoid-rich lithofacies. Approximately same horizon as collection 30 but 1m S.
- 32. BHR 9 SO 6945 2935. Thick-bedded oncoid-rich lithofacies.
- 33. BHR 10 SO 6905 1924. Ferruginous crinoidal grainstone lithofacies. Most easterly quarry in a line of old workings.
- 34. BHR 11 SO 6904 1924. Ferruginous crinoidal grainstone lithofacies. 10m W of collection 33.
- EASTNOR CASTLE QUARRY, LEDBURY HILLS. (All collections from small quarry at SO 7322 3629).
- 35. BE 1. Nodular limestone lithofacies.
- 36. BE 2. Nodular limestone lithofacies.
- 37. BE 4. Nodular limestone lithofacies.
- 38. BE 5. Nodular limestone lithofacies. Silty mudstone from directly on top of collection 37.
- 39. BE 6. Nodular limestone lithofacies. 3m E of collections 4 and 5.
- 40. BE 7. Nodular limestone lithofacies. Silty mudstone from directly on top of collection 39.
- 41. BE 8. Nodular limestone lithofacies.
- 42. BE 10. Ferruginous crinoidal grainstone lithofacies.
- 43. BE 12. Ferruginous crinoidal grainstone lithofacies. 5m E of collection 42.
- 44. BE 14. Nodular limestone lithofacies.
- 45. BE 15. Nodular limestone lithofacies. Bed above collection 43.
- 46. BE 16. Nodular limestone lithofacies.
- WOOLHOPE INLIER.
- 47. BWA 1. SO 3552 6254. Base of Much Wenlock Limestone Formation.
- 48. BWA 2. SO 3552 6254. Nodular limestone lithofacies. Transition between the Coalbrookdale Formation and the Much Wenlock Limestone Formation. 1.5m E of collection 46.

- 49. BWA 3. SO 3552 6254. Nodular limestone lithofacies. Transition between the Coalbrookdale Formation and the Much Wenlock Limestone Formation. O.3m E of collection 47.
- 50. BWA 4. SO 3552 6253. Nodular limestone lithofacies. Transition between the Coalbrookdale Formation and the Much Wenlock Limestone Formation. 8m E of collection 48.
- 51. BWO 1. SO 6039 3861. Reef lithofacies.
- 52. BWO 6. SO 6039 3861. Reef lithofacies. 2m above collection 50.
- 53. BWO 9. SO 6039 3861. Thick-bedded oncoid-rich lithofacies below reef-base.
- 54. BWO 12. SO 6039 3861. Reef lithofacies. 0.5m above collection 51. USK INLIER.
- 55. BTF 1. SO 3315 0189. Nodular limestone lithofacies.
- 56. BTF 2. SO 3315 0189. Nodular limestone lithofacies. Silty mudstone on top of collection 54.
- 57. BTF 3. SO 3315 0189. Interbedded limestone and silty mudstone lithofacies.
- 58. BCMD 1. 3660 9900. Nodular limestone lithofacies.
- 59. BCMD 2. 3660 9900. Nodular limestone lithofacies. Approximately same horizon as collection 58, but 3m to the W.

CHAPTER 5

THE WENLOCK REEFS OF ENGLAND

5.1 ABSTRACT

Three types of reef are recognised in the Much Wenlock Limestone Formation based on shape, microfacies distribution and faunal content. Type A reefs are the most abundant and are composed of large limestone lenses separated by silty mudstone. The fauna of Type A reefs is dominated by corals and stromatoporoids which commonly formed a rigid framework. These reefs grew on a shallow open shelf in front of an E to W migrating carbonate sandbody. Type B and Type C reefs were constructed mainly by algae, but Type B reefs grew outwards while Type C reefs have vertical sides. This difference in shape is controlled by the rate of reef growth compared with sedimentation rate. The algal reefs grew in an environment where water circulation was low, thereby preventing extensive coral growth. Wenlock reefs in England are restricted to the thick-bedded oncoid-rich lithofacies and the interbedded limestone and silty mudstone lithofacies, where their distribution was controlled by the availability of stable substrates on which coral or algal growth could begin. Reef growth in other lithofacies was inhibited variously by excessive turbulence, restricted water circulation and high sedimentation rate.

5.2 INTRODUCTION

The Much Wenlock Limestone Formation is a Silurian carbonate unit deposited on a relatively shallow shelf that lay on the SE margin

of the gradually closing Iapetus Ocean. The formation is composed dominantly of limestone beds and nodules surrounded by silty mudstone, together with unbedded or poorly bedded reef masses. In the West Midlands and southern Welsh Borders reefs are seen at Wren's Nest, Daw End, May Hill, Woolhope and Usk (Fig. 5.1). They have also been reported from Abberley (Penn 1971) but are no longer exposed there. Wenlock reefs are best exposed and previously most studied on Wenlock Edge (for reviews see Scoffin 1971, Riding 1981). Scoffin's (1971) work concentrated on the sedimentary setting of the reefs and the roles played by various organisms in reef building. He concluded that the reefs represent patch reefs, their abundance at Wenlock Edge reflecting a shelf edge position, but he failed to recognise any biotic zoning. Abbott (1976) also worked on the sedimentology of the reefs, arguing that they lacked a rigid framework and therefore resembled modern day mud mounds similar to those forming in Florida Bay. Abbott (1974) recognised a broad faunal zonation with Halvsites dominating the bases of reefs, passing upwards into faunas dominated by <u>Heliolites</u>, <u>Favosites</u> and ultimately stromatoporoids. Powell (1980) criticized Abbott's (1974) palaeoecological work, considering it to be oversimplified and weakly based taxonomically. After taxonomic revision, Powell recognised three coral/stromatoporoid associations in the reefs. The reef base association is characterised by a stabilizing fauna and the reef core and reef margin by colonization faunas (James 1983).

The general sedimentology and stratigraphy of the formation in the West Midlands were described by Butler (1939) and the stratigraphy

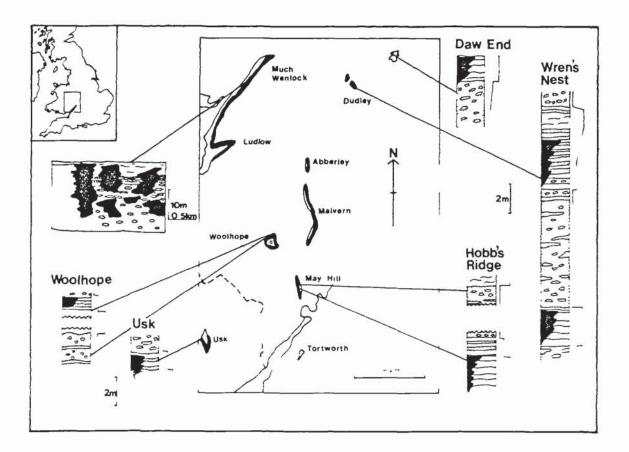


Figure 5.1 Locality map. The outcrop of the Wenlock Series is outlined and that of the Much Wenlock Limestone Formation highlighted in black. Top left inset shows the area covered on the central diagram. The sedimentary logs show the stratigraphical positions of reefs at each locality.

Limestone. The field appearance of the formation in the southern Welsh Borders and South Wales has been described by Lawson (1954), Lawson (1955), Walmsley (1959), Squirrell & Tucker (1960) and Phipps & Reeve (1967). Detailed microfacies, lithofacies and depositional environments of the Much Wenlock Limestone Formation are discussed in chapters 2 and 3.

environments of the Much Wenlock Limestone Formation are discussed in chapters 2 and 3.

The term reef is used here to refer to a product of the actively building and sediment-binding biotic constituents which have the capacity to erect wave resistant topographic features (Reijers & Hsu 1986).

5.3. REEF MICROFACIES

The sediments of the Wenlock reefs are divisible into 5 microfacies each characteristic of a different depositional environment. Wackestones, packstones, grainstones (Dunham 1964) and boundstones (Embry & Klovan 1972) all occur.

5.3.1 Wackestones, packstones and grainstones

MF. 1 Skeletal packstones (MF. 7 in chapter 2)

Skeletal packstones in the reefs are composed almost entirely of crinoid ossicles containing articulated stems up to 100mm long. This suggests little post-mortem transport, so that the skeletal packstones probably reflect the positions of crinoid thickets.

MF. 2 Coral/stromatoporoid packstones (MF. 9 in chapter 2)

Coral/stromatoporoid packstones contain both rolled and in situ colonial organisms which are surrounded by crinoid ossicles and occasional brachiopods. The rolled bioclasts often occur in close proximity to similar fossils which are in life position. Coupled with the lack of grain breakage and abrasion this suggests a local origin for the bioclasts. This microfacies formed in a low-energy environment, possibly with occasional turbulence to roll the fauna. Although some organisms are in life position they are too widely spaced to have formed a rigid framework.

MF.3 Skeletal grainstones (MF. 10 in chapter 2).

These are composed almost entirely of crinoid ossicles. The skeletal grainstones usually occur as pockets within the skeletal packstones, suggesting that they are the result of winnowing currents removing carbonate mud from the base of a crinoid thicket.

5.3.2 Boundstones

MF.4 Upright framestones (MF. 13 in chapter 2)

These framestones are composed of <u>in situ</u> coral colonies with an upright branching morphology. Such a growth morphology in colonial organisms is generally indicative of a low-energy environment (Abbott 1974, Powell 1980, James 1983).

MF. 4 Laminar framestones (MF. 14 in chapter 2)

These framestones are composed of colonial organisms with a laminar growth morphology, indicative of higher energy conditions than those in which upright branching morphologies occur (Abbott 1976, Powell 1980). Laminar tabular growth morphologies form in conditions of moderate turbulence and laminar encrusting growth morphologies in high-energy conditions (James 1983)

MF.5 Mottled micrite (MF. 12 in chapter 2)

Mottled micrites have a grumose texture (sensu Pettijohn 1975) with isolated tubules of Rothpletzella and Girvanella floating in the denser parts of the micrite. This suggests that they are of algal origin, a conclusion supported by the similarity of fine wavy lamination in this microfacies to cryptalgal lamination (Monty 1976). Similar micrites have been described from reefs on Wenlock Edge and from Gotland where they were attributed to algal activity (Hadding 1950, Scoffin 1971). In the reefs studied here the mottled micrites

may be pure or may contain <u>in situ</u> laminar colonies or skeletal debris.

5.4 REEF DESCRIPTIONS

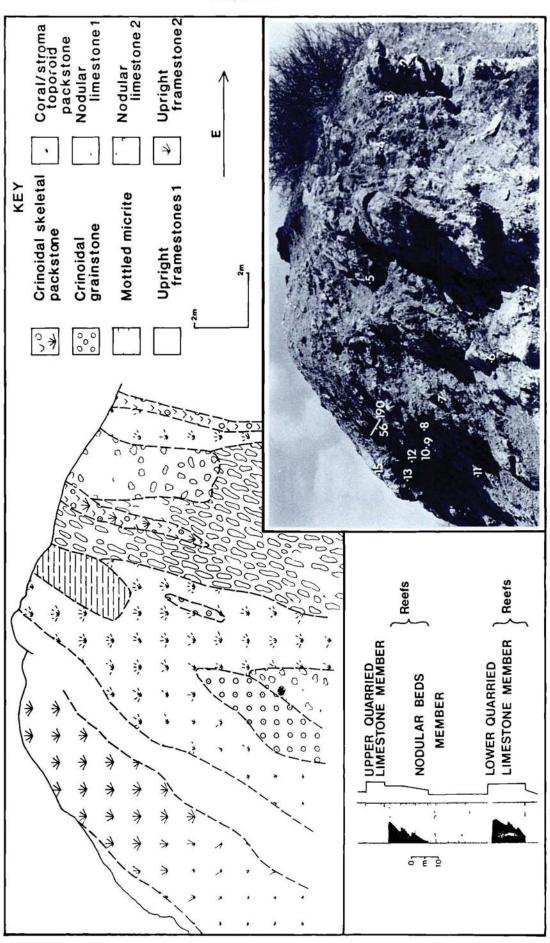
Three distinct types of reef occur. A possible fourth type which occurs at Usk is dominated by ramose bryozoans (Powell 1980). However, only the top surface of that reef is currently exposed making detailed work impossible.

5.4.1 Type A

Type A reefs were studied at Wren's Nest and Woolhope and also occur on Wenlock Edge (Scoffin 1971, Abbott 1976, Powell 1980) and in the Abberley Hills (Penn 1971). These reefs consist of limestone lenses up to 1m wide and 0.5m thick separated by silty mudstone partings. At Wren's Nest the reefs are exposed as upstanding mounds in the upper part of the Nodular Beds Member. Their contacts with the surrounding interbedded limestone and silty mudstone lithofacies are not seen, but reef margins described from Wenlock Edge (Scoffin 1971) are interdigitated with the surrounding sediment. Indentations in the reef margin correlate with thick silty mudstone beds in the surrounding sediments. The largest reef at Wren's Nest is at least 10m thick and 8m by 6m in the depositional horizontal. The microfacies and faunal variations of this large reef were mapped (Fig. 5.2). Other reefs at Wren's Nest appear similar but poor exposure prevents detailed mapping. These reefs show vertical variations in microfacies and fossil content. At Woolhope a reef is exposed in 2-dimensions in the nodular limestone lithofacies. Its apparent lateral extent and height are 2m and 4m respectively. This reef is composed of

Figure 5.2 Microfacies distribution in Type A reefs. Upper diagram shows the schematic distribution of microfacies in the largest reef at Wren's Nest, Dudley (SO 992 938). Nodular limestone 1 is composed of equidimensional nodules while nodular limestone 2 is composed of elongate nodules. Upright framestone 1 contains a less densely packed fauna than upright framestone 2. Photograph shows the field appearance of the reef with the positions of samples indicated by numbered dots. Scale of photograph is same as upper diagram. The lower left inset shows the distribution of reefs within the Much Wenlock Limestone Formation in the West Midlands.

FIGURE 5.2



coral/stromatoporoid packstones and its fauna was described by Powell (1980).

5.4.1.1 Sedimentology

The lowest part of the best exposed reef at Wren's Nest consists of skeletal packstones with small domal coral and stromatoporoid colonies. These are overlain by large lenses of coral/stromatoporoid packstones. There is then a thick zone composed of nodular limestones. The nodules consist of coral/stromatoporoid packstone and the surrounding silty mudstone contains abundant colonial organisms. The central part of the reef is dominated by large lenses of coral/stromatoporoid packstone with some patches of mottled micrite and crinoidal grainstone. The top of this unit is marked by a thick silty mudstone bed, above which the reef is composed of upright framestone. Top and base of this framestone zone contain a less densely packed fauna than the central part. The top of the reef is composed of crinoidal grainstone with pockets of laminar framestone.

5.4.1.2 Palaeontology

Crinoid ossicles are common throughout the reefs and are only mentioned where they are the dominant bioclasts. The coral/stromatoporoid packstone lenses and the nodular units toward the base of the reef are dominated by <u>Halysites thomasi</u>. Small domal colonies of <u>Stelliporella parvisitella</u>, <u>Heliolites interstinctus</u>, <u>H. megastoma</u> and <u>Thecia expatiata</u> are also present. The lenses of coral/stromatoporoid packstone in the reef centres are also dominated by <u>Halysites thomasi</u>, with common <u>H. catenularis</u>. Ramose trepostomes and <u>Coenites juniperinus</u> are commonly associated with the <u>Halysites</u> colonies. Domal colonies in the centre of the reef are composed of

Favosites multipora and Paleofavosites rugosus. The presence of crinoidal packstones and mottled micrites indicate that the reef was locally colonized by crinoids and algae. The upright framestones are dominated by Stelliporella parvisitella with common ramose trepostomes and Coenites juniperinus. Within the upright framestone microfacies large high-domed colonies of Densastroma are clustered together in pockets. The crinoidal grainstones at the tops of the reefs contain laminar encrusting colonies of Labechia conferta.

5.4.1.3 Sedimentology of surrounding lithofacies

The bases of Type A reefs are surrounded by mud-rich parts of the interbedded limestone and silty mudstone lithofacies. The reefs at Wren's Nest and Wenlock Edge extend upward into the mud-poor parts of this lithofacies but disappear before deposition of the wavy-bedded crinoidal grainstone lithofacies of the Upper Quarried Limestone Member (section 2.3). The interbedded limestone and silty mudstone lithofacies in the West Midlands forms an upward shoaling sequence (section 2.5.2). The mud-poor parts were deposited in a low-energy environment on the open shelf. As deposition continued the environment was affected progressively more often by high-energy storm events, the upper parts of the reefs growing in this environment. Shallowing continued until the environment was above normal wavebase and the depositional energy high (section 2.5.1). This zone of maximum wave energy migrated from E to W depositing the wavy-bedded crinoidal grainstone lithofacies (section 2.6). At Woolhope, four beds of skeletal packstone extend for approximately 5m from the reef edge into the the surrounding bedded lithofacies. The bioclasts in these beds are not in life position but show no signs of extensive reworking.

Despite the surrounding lithofacies being sparcely fossiliferous these beds contain common coral and stromatoporoid fragments suggesting that the debris is reef-derived. The beds therefore resemble the talus beds described from bedded lithofacies adjacent to reefs on Wenlock Edge (Scoffin 1971).

5.4.1.4 Relief

The exposure of Type A reefs at Wren's Nest does not allow estimation of relief but Scoffin (1971, p. 198) estimated that the maximum relief on Type A reefs at Wenlock Edge was 3m.

5.4.2 Type B reefs

Type B reefs occur in the Lower Quarried Limestone Member in the West Midlands where they are unbedded bodies composed dominantly of pale grey micrite. The reefs are only accessible at Walsall where 3 are exposed in the vertical face of Daw End railway cutting. Only the most westerly reef is seen in full, the others only having their bases exposed. The largest reef was mapped in detail (Fig. 5.3); it is 30m across and 5m thick. The bases of all the reefs at Daw End nucleate on a 300mm thick skeletal grainstone bed. Their lateral margins spread rapidly over the surrounding thick-bedded oncoid-rich lithofacies.

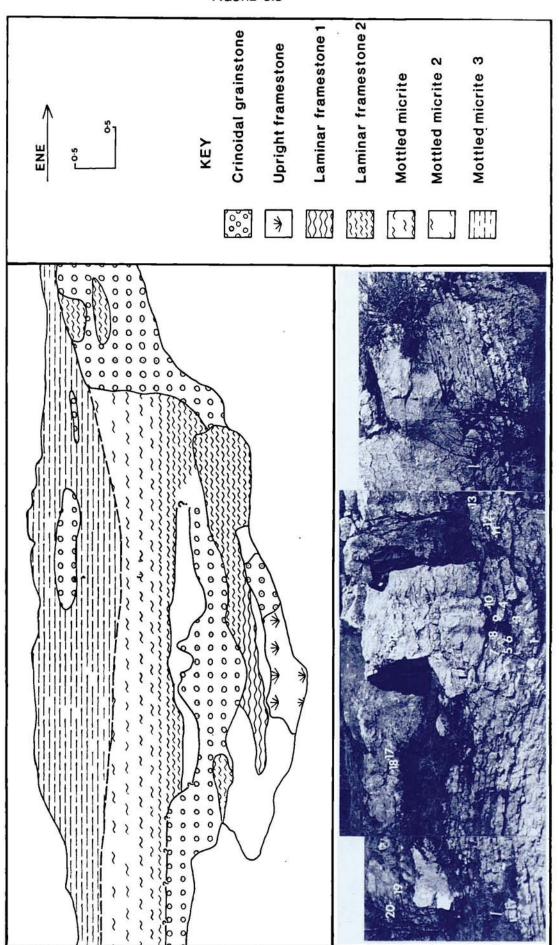
5.4.2.1 Sedimentology

The base of each reef is composed of upright framestone which is overlain by a thin zone of mottled micrite. The mottled micrite is succeeded by laminar framestones which initially contain no matrix between successive colonies, but which have skeletal packstones between laminar colonies higher in the reef. Crinoidal packstones dominate the reef directly above the laminar framestones. In the reef

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Figure 5.3 Microfacies distribution in Type B reefs. Upper diagram schematically shows the distribution of microfacies in the largest reef in the Lower Quarried Limestone Member at Daw End, Walsall (SP 03410030). Laminar framestone 1 is composed of colonies which lie on top of on another and laminar framestone 2 of colonies which grow on intervening sediment. Mottled micrite 2 contains scattered laminar colonies and mottled micrite 3 is almost clast-free. The photograph shows the field appearance and numbered dots mark the location of samples. Figure for scale. For stratigraphic position of reefs see lower left inset on Fig. 5.2.

FIGURE 5.3



core crinoidal packstones are followed by mottled micrites but on the E flank of the reefs the crinoidal packstones dominate until the close of reef growth. The mottled micrites in the reef core contain scattered coral and stromatoporoid colonies.

5.4.2.2 Palaeontology

The upright framestones at the bases of Type B reefs are composed of Halysites catenularis with a few high domal colonies of Heliolites megastoma and Paleofavosites asper. The overlying laminar framestones contain Thecia expatiata and Stelliporella parvisitella at the base and Paleofavosites asper and Favosites multipora towards the top. Crinoid thickets must then have developed over the whole reef and subsequently dominated the fauna on the E flank of the reef until reef growth ended. In the reef core the mottled micrites contain laminar colonies of Thecia expatiata, Stelliporella parvisitella and Labechia conferta. On the W flank of the reef the mottled micrites contain colonies of Syringopora bifurcata.

5.4.2.3 Sedimentology of the surrounding bedded sediments

Type B reefs occur in the thick-bedded oncoid-rich lithofacies. The abundance of algae indicates deposition within the photic zone (Swinchatt 1969, Riding 1975, Wray 1977, Riding 1984 and sections 2.5.3 & 3.6), and common oncoids suggest slow deposition in relatively low-energy conditions (Peryt 1977). Variations in oncoid morphology indicate that the Lower Quarried Limestone Member is a shoaling upwards sequence (section 3.6). Its base was deposited in low-energy conditions below wavebase, its middle parts above storm wavebase and its upper parts close to normal wavebase. High-energy deposits are rare, even towards the top of the member. This is due to

the mid-shelf position of the environment; wave energy was expended on the large flat shelf to the W (section 3.7).

5.4.2.4 Relief

In sections which contain Type B reefs the thickness of the Lower Quarried Limestone Member increases by 1-2m. Correlation of oncoid morphotypes from below and above reefs with those in non-reef sections suggests that 4-5m of reef corresponds to 2-3m of bedded lithofacies (section 3.7 and Fig. 3.9). These points suggest a relief of 1-2m, but preferential compaction of the argillaceous component of the bedded lithofacies needs to be considered. At present the combined thickness of silty mudstones beds in the parts of the lithofacies which are laterally equivalent to the reefs is only 0.3m. Prior to compaction this would have been approximately 0.5m, suggesting that the relief on Type B reefs was between 0.8m and 1.8m.

5.4.3 Type C reefs

Type C reefs only occur at May Hill where they are exposed in a vertical quarry face at Hobb's Ridge (Fig. 5.4). They are steep sided bodies 2-3m wide and up to 5m high, which are composed dominantly of pale grey carbonate mudstone. The true shape of the reefs cannot be established due to the 2 dimensional exposure. However, the widths of the reefs and their spacing are remarkably constant. Hence it is unlikely that the reefs were tall cylindrical bodies and more probable that they are elongate ridges.

5.4.3.1 Sedimentology and palaeontology

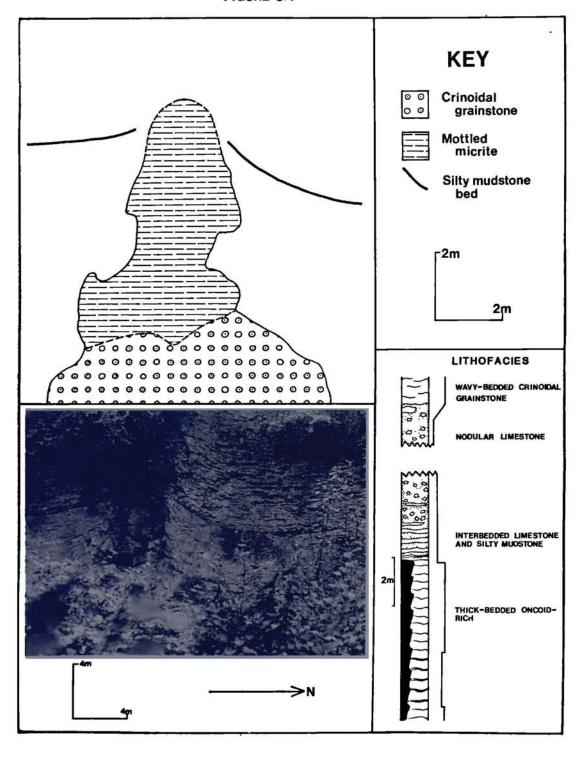
The bases of the reefs are not exposed. The lowest parts seen are composed of crinoidal grainstones. These rapidly grade up into

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Figure 5.4 Microfacies distribution in Type C reefs. Upper diagram shows the schematic distribution of microfacies within the largest reef at Hobb's Ridge, May Hill (SO 695 195). The field appearance of the reef and surrounding lithofacies are shown in the photograph and the stratigraphic setting of the reefs in the right hand inset.

FIGURE 5.4



mottled micrites which form most of the exposed reefs. The crinoidal grainstones at the base indicate the former presence of crinoid thickets. The mottled micrite in the overlying parts of the reefs indicate that they were formed dominantly by algae.

5.4.3.2 Sedimentology of surrounding lithofacies

The thick-bedded oncoid-rich lithofacies which surrounds these reefs contains abundant algae indicating deposition in the photic zone. Brachiopod assemblages suggest some turbulence in the environment but not very high-energy conditions (Section 4.5.2.4).

5.4.3.3 Relief

The silty mudstone bed which marks the top of many reefs at May Hill appears to be continuous over the reef tops, suggesting that relief was low, definitely no more than 0.5m. However, the critical parts of the section are obscured by vegetation.

5.5. REEF GROWTH

5.5.1 Type A reefs

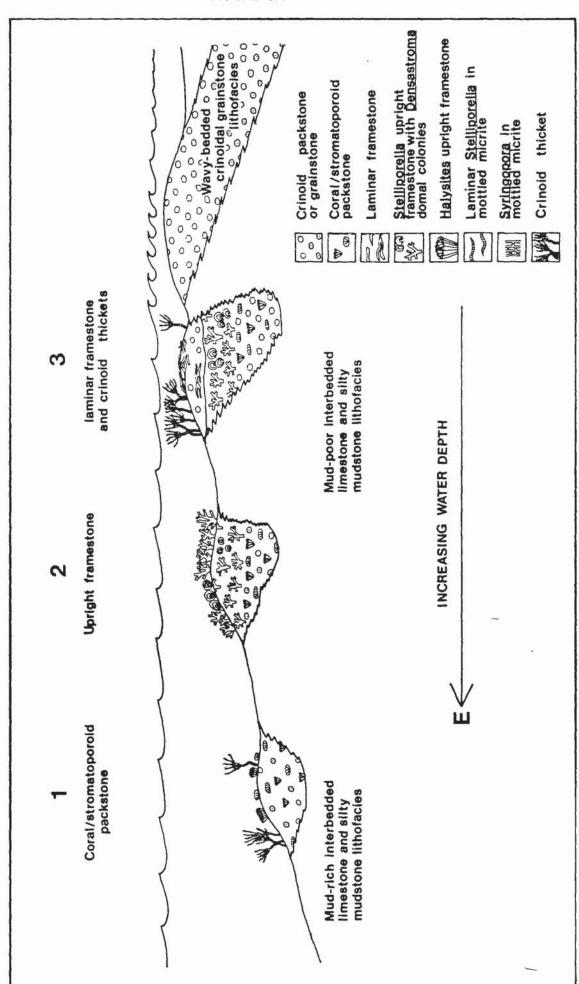
Type A reefs at Wren's Nest occur within the interbedded limestone and silty mudstone lithofacies which was deposited on the open shelf during a regression (section 2.6). The lowest parts of the mapped reef lack a framework and probably formed a low mound (Fig. 5.5). The dominance of <u>Halysites</u> at this level in the reef indicates low-energy conditions since its delicate pallisades were unable to withstand turbulence (Powell 1980). <u>Halysites</u> was able to withstand high sedimentation rates, however, as the sediment would have accumulated between the upright pallisades. Similarly <u>Heliolites</u> and <u>Stelliporella</u>, which are also abundant in this part of the reef, were

able to withstand relatively high sedimentation rates due to their coenenchymal colonies (Hubbard & Pocock 1972, Powell 1980). The base of the reef therefore grew in a low-energy environment with relatively high sedimentation rates. Halvsites also dominates the coral/stromatoporoid packstones in the middle of the reef, suggesting that conditions were still low-energy. Favosites and Paleofavosites, which are the common domal colonies in this part of the reef, had a cerioid skeleton which was less capable of coping with high sedimentation rates than corals with a coenenchymal morphology. This indicates that while there was little variation in the energy of the environment, sedimentation rates were decreasing. This is supported by the decrease in the amount of silty mudstone in the surrounding lithofacies (section 2.5.2). A similar decrease in silty mudstone content of the formation is seen on Wenlock Edge (Scoffin 1971), explaining the upward increase in abundance of Favosites described by Abbott (1976) within these reefs. At this growth stage the reefs were probably low mounds with small coral and stromatoporoid colonies on their surfaces together with crinoid thickets and patches of algae. The Stelliporella parvisitella colonies in the overlying framestones have a robust branching morphology which was suited to relatively lowenergy conditions but which could withstand some turbulence (James 1983) (Fig. 5.5). The laminar growth morphology of the stromatoporoids at the top of the mapped reef is indicative of high-energy conditions. The reefs during this period probably had their maximum relief of a few metres and were colonized by crinoids (Fig. 5.5). The crinoid thickets were occasionally destroyed and the resulting sands

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Figure 5.5 Growth of Type A reefs. Stage 1. Reefs begin growth in a low-energy environment in relatively deep water during deposition of the mud-rich parts of the interbedded limestone and silty mudstone lithofacies. The reefs were initially low mounds dominated by small coral and stromatoporoid colonies with small crinoid thickets. Stage 2. Shallowing of the environment led to the development of an upright framework dominated by digitate colonies of Stelliporella parvisitella. Stage 3. Further shallowing resulted in colonisation by crinoids with stabilization by laminar Labechia conferta. Shallowing also resulted in deposition of the mud-poor parts of the interbedded limestone and silty mudstone lithofacies. During stage 3 the reefs grew in front of an advancing carbonate sandbody.

FIGURE 5.5



stabilized by laminar encrusting colonies of <u>Labechia conferta</u>. This destruction may have resulted from storm events which are evidenced in the surrounding lithofacies. The reefs at this time occupied a position in front of an advancing sandbody and the palaeogeography therefore resembled Wilson's (1975) type 2 carbonate margin, bordering a low to moderate energy basin.

5.5.2 Type B reefs

The large <u>Halysites</u> colonies in these reefs developed directly on a 300mm thick continuous skeletal grainstone bed (Fig. 5.6). The cements in this bed suggest early lithification in a marine-phreatic diagenetic realm (section 6.4.1), indicating that it formed a hard, stable substrate. This explains the lack of a stabilization fauna at the bases of Type B reefs. The top of the skeletal grainstone bed is irregular and coral growth was probably initiated on slightly raised areas. Low-energy conditions at the start of reef growth are suggested by the dominance of <u>Halysites</u> at the reef-base. After a brief period of algal domination the reef surface was colonized by laminar colonies of Thecia expatiata and Stelliporella parvisitella. Upwards this fauna is replaced by one dominated by Favosites and Paleofavosites, a change reflecting the transition from reef stabilization to reef colonization (Powell 1980, James 1983). The reefs were now low mounds with tabular colonies living on their surfaces (Fig. 5.6). Crinoid thickets then developed on the upper surfaces of the reefs. At this time the reefs probably resembled the generalized model for Wenlock reefs proposed by Abbott (1976). Crinoid thickets continued to dominate the E flank of the mapped reef while the remainder of the structure was built by the

Figure 5.6 Growth of Type B reefs. Stage 1. Initial colonization of continuous grainstone bed by Halysites in a low energy environment. Stage 2. Reef surface now colonized by tabular colonies. Stage 3. Shallowing resulted in the reef surface being colonized by crinoid thickets. Stage 4. Reef built dominantly by algae wi i scattered colonies of Thecia expatiata Stelliporella parvisitella and Labechia conferta. The E flank was still dominated by crinoid thickets. For key see Fig.5.5

FIGURE 5.6

Mottled micrite with laminar Stelliporella and branching Syringopora 四 超 6000 3 Dense crinoid of thicket 2 Tabular colonies form laminar framestone Upright framestone sediment trapping and binding action of algae (Fig. 5.6). A similar asymmetry in Waulsortian reefs has been described and interpreted to reflect uniform current directions (Wilson 1975). By applying this model to the Type B reefs, an E to W offshore current direction is inferred. The middle and upper parts of the reef core were dominated by algae, but occasional laminar colonies of Thecia expatiata, Stelliporella parvisitella and Labechia conferta indicate that conditions were suited to the growth of opportunistic coral species locally.

The main restraints on coral growth which are likely to have affected the Wenlock shelf are water circulation and the sediment load of the water. The thick-bedded oncoid-rich lithofacies in the West Midlands was deposited in an environment where wave energy was reduced by the extensive area of shallow water to the W (section 3.7). In such an environment the water circulation would have been low, generally favouring algal growth. The mid-shelf was occasionally affected by storm events which temporarily increased water circulation. This may have been a controlling factor in allowing corals to occasionally colonize an otherwise alga-dominated environment. Water circulation may have also been a controlling factor in determining the distribution of algal and coral/stromatoporoid reefs (section 5.6).

5.5.3 Type C reefs

Growth of Type C reefs started when crinoid thickets trapped and stabilized sediment in similar manner to <u>Thallassia</u> in modern environments (Davies 1970) to form low mounds. At this stage the Type C reefs resembled the model proposed for all Wenlock reefs by Abbott

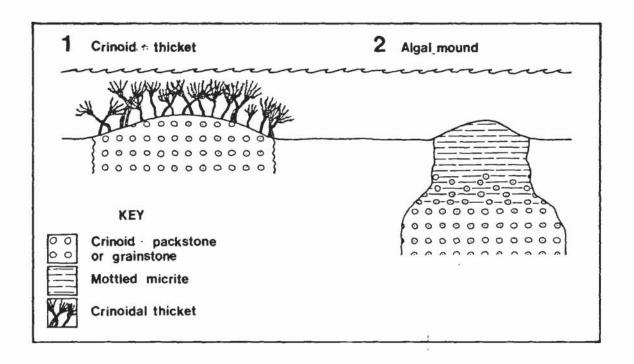


Figure 5.7 Growth of Type C reefs. Stage 1. Reef colonized by crinoid thickets. Stage 2. Reefs now built solely by algae.

(1974) (Fig. 5.7). As growth continued algae became the dominant reef builders. During this stage the reefs were probably ridge-like bodies with a relief of less than 50cm.

5.6 FACTORS CONTROLLING REEF DISTRIBUTION

English Wenlock reefs are only common in the thick-bedded oncoid-rich lithofacies and the interbedded limestone and silty mudstone lithofacies. Both these were deposited in relatively shallow water environments where stable substrates were locally available. The absence of reefs from other lithofacies is variously due to the lack of stable substrates (ferruginous crinoidal grainstone and wavy-bedded

crinoidal grainstone lithofacies) or poor water circulation and rapid sedimentation of silty mudstone (nodular limestone and silty micrite lithofacies). The latter is clearly seen to inhibit growth of Type A reefs on Wenlock Edge where reefs margins are strongly indented adjacent to thick silty mudstone beds (Scoffin 1971). Type A reefs grew on an open shelf in front of an advancing carbonate sandbody. In this environment water circulation would have been good and sedimentation rates relatively low, making conditions ideal for coral (James 1983) and stromatoporoid (Nestor 1981) growth. This explains the abundance of Type A reefs in the interbedded limestone and silty mudstone lithofacies of the West Midlands and Wenlock Edge. The bases of Type A reefs were not seen but on Wenlock Edge they frequently nucleate on lenses of skeletal grainstone. These grainstones were probably partly lithified in the marine environment. Type B and Type C reefs occur in the thick-bedded oncoid-rich lithofacies in which oncoids are common, reflecting the lack of stable substrates. The mottled micrites in the reefs occur above zones of crinoidal packstone and grainstone. The grainstones show evidence of early diagenesis in the marine phreatic environment (section 6.4.1), indicating that they were at least partly lithified and therefore provided a stable substrate for the algae to colonize. Although Type B and Type C reefs grew in similar sediments, were built by algae and nucleated on similar substrates, their cross sections are different. This variation in shape is probably due to the rate of reef growth compared with sedimentation rate. Type B reefs grew faster than the surrounding sediment accumulated and therefore spread rapidly outwards. The vertical sides of Type C reefs suggest that the rates of reef growth

and sedimentation were similar. This is supported by the lack of relief on these examples compared with Type B reefs. Algal reefs such as these tend to grow in restricted environments (Shaver 1974, Wilson 1975, Reading 1981), reflecting the tolerance of algae to adverse conditions (Wray 1977). Type B reefs grew on the mid-shelf, with a large expanse of shallow sea to the W (section 3.7) which damped the wave energy of the environment. In such an environment water circulation would probably have been poor tending to favour algal growth.

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CHAPTER 6

MARINE: SHALLOW-BURIAL: DEEP-BURIAL DIAGENESIS OF A SILURIAN LIMESTONE

ABSTRACT. Cements in the Much Wenlock Limestone Formation (United Kingdom) include micrites, turbid spars and clear spars. The clear spars are the most important volumetrically, and can be subdivided depending on their relationship with compaction fracture. Each cement type is fully described before its diagenetic environment is reconstructed.

Micritic cements in the formation morphologically resemble modern marine micrites composed of high Mg calcite. The turbid spars are all now low Mg calcite, but were probably derived from aragonite and high Mg calcite precursors; hence they are interpreted as stabilised marine cements. Stabilisation was accompanied by a period of dissolution which created secondary voids prior to precipitation of the clear cements. After dissolution, but prior to compactional fracture, first generation low Mg calcite cements were precipitated as syntaxial overgrowths and drusy void fills. The cathodoluminescence and petrographic features of these cements closely resemble examples which in the past have been interpreted as meteoric-phreatic cements. However when biostratigraphical, sedimentological and isotopic evidence is considered it becomes clear that meteoric water did not enter the formation. Isotopic data, and the spatial distribution of

secondary voids and ferroan calcite, indicate that the precompactional clear cements were precipitated at shallow burial depths, from fluids that were expelled from the surrounding organic-rich mudstones.

Following compactional fracture the remaining pore spaces were filled by coarse, equant and uniformly luminescent calcite. These burial cements were precipitated at depths of 1 to 1.5 km. The final diagenetic products were stylolites and strongly ferroan calcite veins.

6.2 INTRODUCTION

In many ways the Much Wenlock Limestone Formation of the Welsh Borders and the West Midlands is a typical shelf carbonate unit; predominantly comprising bedded and nodular limestones interbedded with fine siliciclastics. Small bioherms occur within these bedded sediments. The limestones are composed of a large variety of microfacies, ranging from low-energy carbonate mudstones and skeletal wackestones to high-energy well sorted grainstones (chapter 2). Microfacies distribution in most sections reflects an upward increase in depositional energy, which can be correlated with the local midlate Wenlock regressive event. Deposition of the formation began in the West Midlands, in a stable mid-shelf environment (chapter 2), and spread diachronously to the S and W (Bassett 1974). In the southern Welsh Borders the shelf was less stable. The shelf margin occurred around Wenlock Edge where most previous sedimentological and diagenetic work has been focussed (Abbott 1974, Oldershaw & Scoffin 1967, Scoffin 1971, Shergold & Bassett 1970). Consequently the work here has centred on little studied outcrops of the formation in the West Midlands, Abberley, the Malverns, May Hill and Usk (Fig. 6.1). In these areas the petrography and CL. of cements closely resemble the classic, marine cement/dissolution/freshwater cement/compaction/burial cement, cement stratigraphy (Carpenter & Ogelesby 1976, Frank et al. 1982, Grover & Read 1983, Meyers 1974). Isotope, biostratigraphical and sedimentological data, however, indicate that meteoric water did not enter the formation. Carbon and oxygen isotope data imply that the pore waters responsible for precipitation of the apparently meteoricphreatic pre-compactional clear spars were enriched in 13C relative to

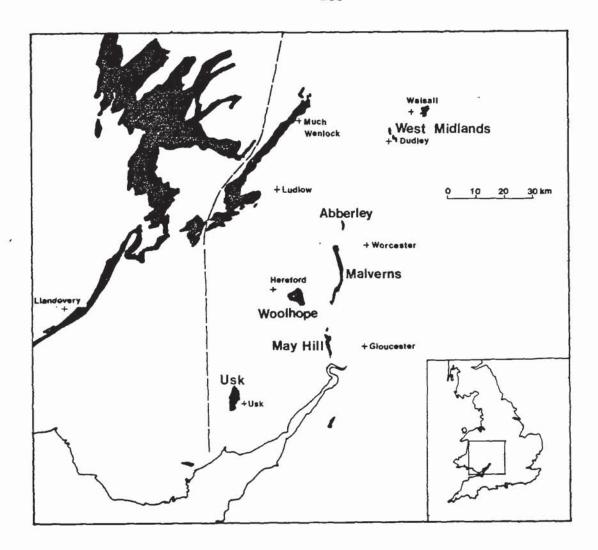


Figure 6.1. Locality map. Inset shows the area covered on the main map. Black areas represent outcrops of Wenlock rocks, the Much Wenlock Limestone Formation being confined to those areas east of the dashed line. The areas involved in this work are the West Midlands, Abberley, Malverns, Woolhope, May Hill and Usk.

sea water. This, together with the spatial distribution of secondary voids and ferroan calcite, suggests that the fluids responsible originated from the organic-rich mudstones which surround the Much Wenlock Limestone Formation. These fluids were forced into the limestone at shallow burial depths creating mixing zones within the limestone. Initial mixing at shallow burial depths produced undersaturation. Later fluids from the mudstones had chemically evolved and produced oversaturated waters on entering the limestones. This model explains both the isotopic and petrographic data. Since the Much Wenlock Limestone Formation is representative of many carbonate shelf deposits the processes described may be widely applicable. Without good sedimentological and biostratigraphical constraints the diagenetic data alone can be easily misunderstood. In this case it would have lead to an inaccurate estimation of the timing of secondary void formation, which is important when considering the pathways open to fluid migration during diagenesis.

6.3 CEMENT DESCRIPTION

6.3.1 Micritic envelopes

Allochems grade from unmicritised grains to those which have been totally micritised and are recogniseable only by their shapes (Fig. 6.2a). Most common, however, are grains with a dark rind forming a micritic envelope. Frequently the original grain around which the envelope formed has been replaced by sparry calcite. In this case the envelope is represented by a series of dark inclusions within a sparry calcite mosaic, with crystal faces which cross the original micrite/skeletal boundary (Fig. 6.2c).

Micritisation is common in algal-rich wackestones (e.g. Lower

Figure 6.2. Micritic, ferroan and early marine cements. a). Micritised grains. br.— brachiopod shell with micritic envelope. tr.— completely micritised allochem, from its shape thought to have been a trilobite fragment. b). Micritic (Mc) cement on a crinoid ossicle (Cr). c). Line of inclusions representing micritic envelope (Me) on gastropod shell (Ga). d). Crinoid ossicle which has been replaced by clear spar (Ce). Iron exides (Fe) have preserved its outline and parts of the stereome system. e). Open meshwork of needles: low Mg calcite after aragonite. f). Inclusion—rich equant crystals (Ma) commonly form an isopachous rim around primary pores. Low Mg calcite after high Mg calcite.

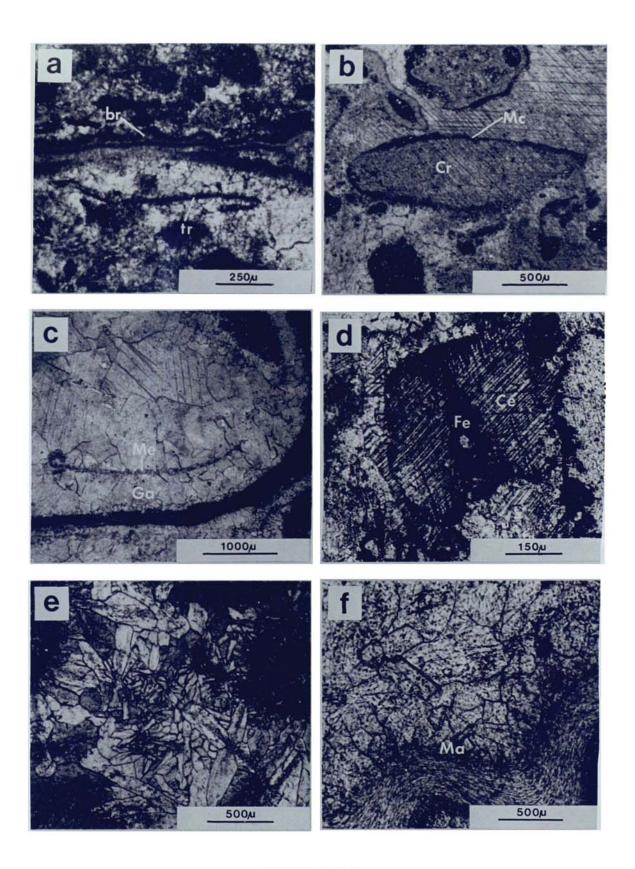


FIGURE 6.2

Quarried Limestone Member of the West Midlands) and peloidal grainstones (eg. Upper Quarried Limestone Member of the West Midlands). It is generally absent from nodular lithologies, but present in interbedded limestone and silty mudstone lithologies. 6.3.2 Micritic and iron oxide cements

Micrite cements are dense, often mottled and contain microdolomites. They resemble micritised rinds, but are additional to the grain surface rather than an incursion into it. They underlie turbid cements, but their distribution and abundance cannot be determined since they are difficult to distinguish from spongiostromate algal coats and sedimentary micrites.

Iron oxide cements occur most commonly in a crinoidal grainstone unit which marks the top of the Much Wenlock Limestone Formation at May Hill and in the southern Malverns. They pre-date turbid spars, generally being precipitated within crinoid stereome systems, so preserving their outline after dissolution. Iron oxide cements occasionally occur as thin cortices around allochems.

6.3.3 Turbid sparry cements

Inclusion-rich cements are present throughout the formation but are not abundant. They are most common and show the widest range of morphologies in the bedded sediments, particularly grainstone microfacies.

Turbid spars most commonly occur as uneven but continuous rims around primary pores. Staining of the cements indicates that they are generally non-ferroan, but that they become strongly ferroan in parts of the formation where the succeeding clear cements are iron-rich. In

Figure 6.3. Marine cement fabrics and their probable precursors. A). gastropod shell with micritised rim becomes a micrite-lined secondary void after dissolution. B). Gastropod shell with aragonite fan overgrowths. Shell is altered to neomorphic spar and the fans to large square ended blades (cf. Fig. 5e). C). Varying styles of aragonite fibres which retain their morphology subsequent to stabilisation. These cements most commonly form isopachous rims. D). Bundles of aragonite fibres orientated obliquely to the brachiopod shell substrate become square ended blades (cf. Fig. 5c-d). E). Fan-like mass of aragonite fibres retains its radiating appearance, but the fibres are replaced by small equant crystals (cf. Fig. 5f). F). Crinoid ossicle with micritic cement is converted to low Mg calcite with microdolomites. These microdolomites commonly occur in stereome cavities. G). Crinoid ossicle with bladed overgrowth is altered to an inclusion-rich syntaxial crystal. Under ppl. the inclusions outline a vague bladed pattern; under C.L. these blades are clearly seen as ghosts. Secondary voids are also created. H). Geopetal fill with oldest cements pre-dating the sediment. Above the fill the cements are converted to small equant crystals but below it they retain their bladed appearance (cf. Fig.4e-f). I). Bladed overgrowth is altered to a single crystal. Inclusion density and luminescence reveal its bladed precursor (cf. Fig. 4c-d). J). Radial fibrous calcite retaining its morphology subsequent to neomorphism (cf. Fig.4 a-b).

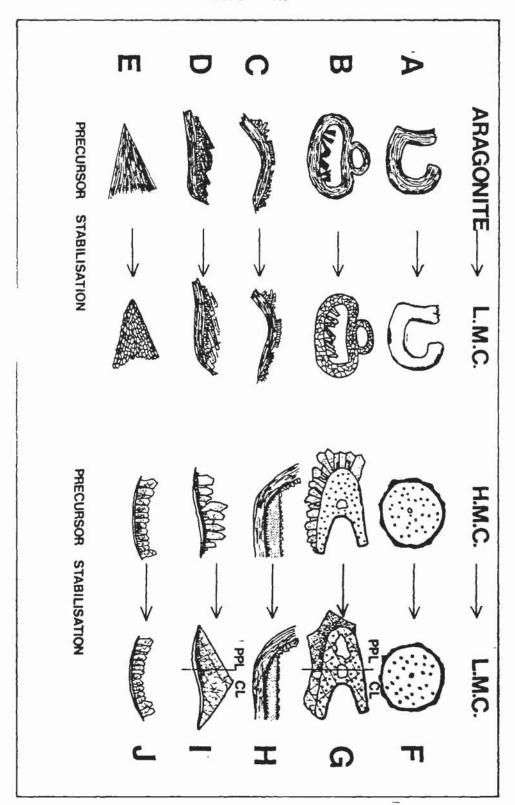


Figure 6.4. Sparry marine cements. a) & b). Bladed inclusion-rich cements with curved cleavages and undulose extinction which respectively closely resemble radial fibrous calcite and fascicular optic calcite. c). Two inclusion-rich single crystals in which the distribution of inclusions reveals a poorly defined bladed pattern (A). Original substrate now preserved as micrite (S). d). C.L. Inclusion-rich areas are resolved into distinct blades (A), that contain brightly luminescent microdolomites (D). Low Mg calcite after bladed high Mg calcite. e). Geopetal infill. Small inclusion-rich equant crystals above (Ma) the fill are marine cements (cf. Fig. 6.2b), which retain a bladed to fibrous morphology below the fill (Ma'). The marine cements are overlain by pre-compactional clear spars, which without C.L. are difficult to distinguish from overlying post-compactional burial cements (Bu). f). C.L. of geopetal structure. Marine cements are generally dull (Ma & Ma') but contain strongly luminescent patches (C). The pre-compactional clear cements, resolved into the non-luminescent/strongly luminescent couplet (A), are overlain by burial cements (Bu).

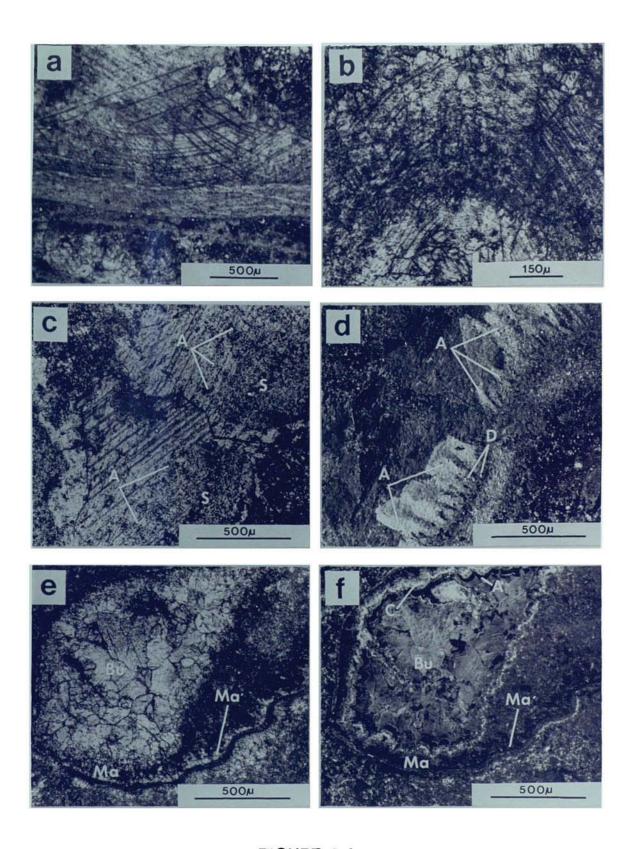


FIGURE 6.4

reefs the common textures are a meshwork of fine needles, small equant crystals, large single crystals and syntaxial overgrowths (Figs 6.3 & 6.4a-d). Except in the meshworks of fine needles the inclusions, many of which are recogniseable as microdolomites, form poorly defined bladed or fibrous patterns (Figs 6.3 & 6.4c). Within geopetal structures the oldest turbid cements underlie the sediment fill (Fig. 6.4e), where they have a bladed to fibrous morphology. Such cements grade into coeval equigranular spars above the fill which lack the bladed appearance (Figs 6.3 & 6.4e-f). In the bedded lithofacies additional textures include microdolomite-rich blades and aggregates composed of small equant crystals which retain an overall fan-like morphology (Figs 6.3 & 6.5f). Turbid blades have curved cleavages and undulose extinction (Fig. 6.5a-b), closely resembling radiaxial fibrous mosaic and fascicular optic calcite (Bathurst 1959, Kendall & Tucker 1973, Kendall 1977, Kendall 1985). Other blades are square ended, up to 1mm long with inclusion-rich cores and inclusion-free rims. These blades occur as an irregular open meshwork or a tightly packed mass. In the tight masses the blades are inclined obliquely to the substrate (Figs 6.3 & 6.5c-e).

Turbid cements generally display dull luminescence, though some have a blotchy appearance with irregular non-luminescent or strongly luminescent patches (Fig. 6.4e-f). The vague radial pattern suggested by inclusion density in the microdolomite-rich cements is resolved into distinct blades under luminescence (Figs 6.3 & 6.4c-d). Isotopically these cements have a d180 value (\S 0 = -5.1 - -5.8 PDB) similar to that of Silurian marine carbonates (Frykman 1986) but they are relatively enriched in heavy carbon (\S C = +4.7 - +5.2 PDB) (Fig.

Figure 6.5. Marine sparry cements. a). Square-ended blades orientated obliquely to the substrate. b). C.L. of area A in 6.5c. The blades have inclusion-rich cores and clear rims. c). Randomly orientated open meshwork of square-ended blades with inclusion-rich cores and clear rims. d). Radiating mass of calcite. Although retaining a fan-like morphology it is a mosaic of small low Mg calcite crystals. e). Bladed relics (Ca) within part of a silicified nodule f). Bladed relics (Ca) underlain by an isopachous silicified rim (Si) and surrounded by calcite ghosts

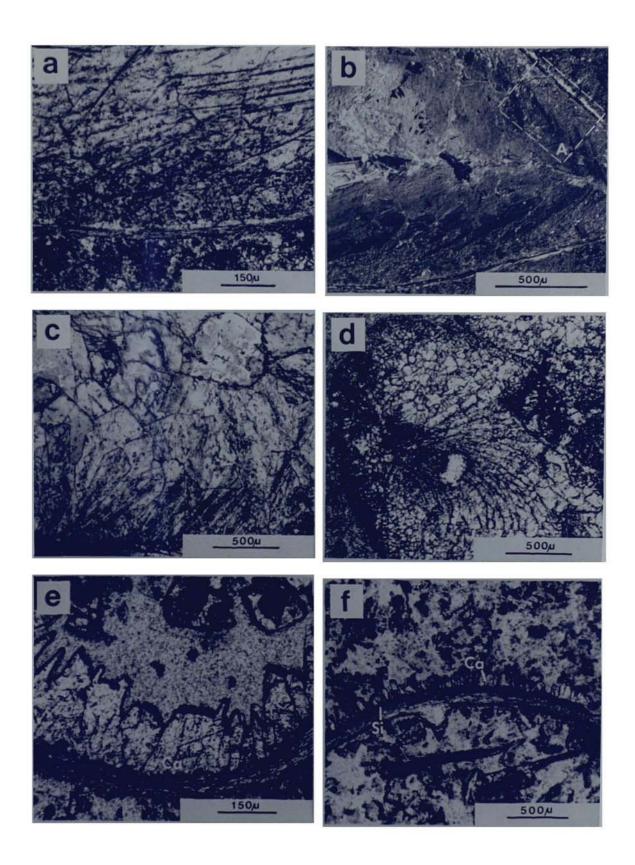


FIGURE 6.5

6.6).

6.3.4 Secondary voids and neomorphism

Commonly crinoid ossicles and gastropod shells were partly removed by dissolution. The resulting secondary voids were filled with clear spars (Fig. 6.7a-d). Gastropod shells were also commonly replaced by a coarse calcite mosaic of neomorphic spar (Bathurst 1975). Dissolutional features are most abundant at the top and base of the formation, and scattered through the bedded lithofacies.

6.3.5 Inclusion-free cements

The clear cements are subdivided into those which respectively pre- and post- date compactional fracture.

6.3.5.1 Pre-compactional clear cements

In primary pores pre-compactional clear cements have sharp contacts against the anhedral crystal terminations of the earlier turbid spars. The pre-compactional spars form bladed crystals with scalenohedral terminations, syntaxial overgrowths or have equant drusy fabrics. While these cements are morphologically similar throughout the formation, they vary both in iron content and luminescence characteristics. Staining shows that while these pre-compactional clear spars are dominantly non-ferroan they are strongly ferroan in those areas where secondary voids are most abundant (the top and base of the formation, and in occasional limestone beds of nodular lithofacies) (Fig. 6.8). In these same areas pyrite is often associated with the calcite cements.

Luminescence characteristics vary between bedded and reefal lithofacies. In the reefs a couplet comprising an older nonluminescent zone (with or without thin strongly-luminescent subzones)

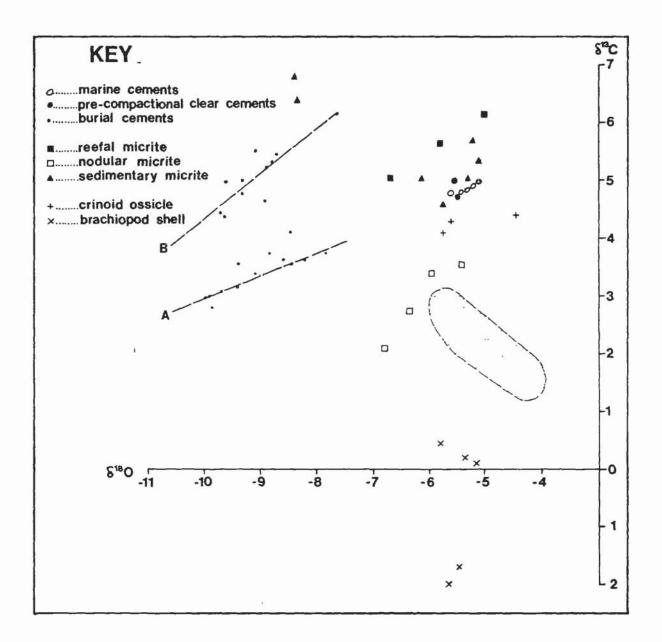


Figure 6.6. Carbon/oxygen isotope plot for spars, micrites and allochems. A and B are lines of best fit for the two clusters of burial cement data. Note the \S^nO axis has a first value of $\S^nO = -4$. The stippled area represents the field in which published isotopic values for Silurian marine carbonates plot.

Figure 6.7. Dissolutional features and pre-compactional cements. a). Crinoid ossicle (Cr) in which patches of clear spar (Ce) fill secondary voids. b). C.L. of 7a. Secondary voids lack the marine cements of primary voids. They are filled with nonluminescent/strongly luminescent pre-compactional spars (A) and burial cements (Bu). c) Gastropod shell filled with burial cement (Bu) and pre-compactional clear spars which are not easily seen without C.L. d). C.L. of gastropod shell. The non-luminescent/strongly luminescent spars (A) are overlain by burial cements (Bu). e). Crinoid ossicle from a reef showing complete luminescence stratigraphy. Marine cements (Ma), difficult to distinguish from the substrate, are overlain by non-luminescent/strongly luminescent pre-compactional cements (A) which are then succeeded by burial cements (Bu). f). Luminescence zonation in bedded lithofacies. Marine cements comprise a thin isopachous rim, overlain by dull pre-compactional cements, which in this example have strongly luminescent tips. The dull blades are time equivalents of the non-luminescent/strongly luminescent couplets in reefal cements.

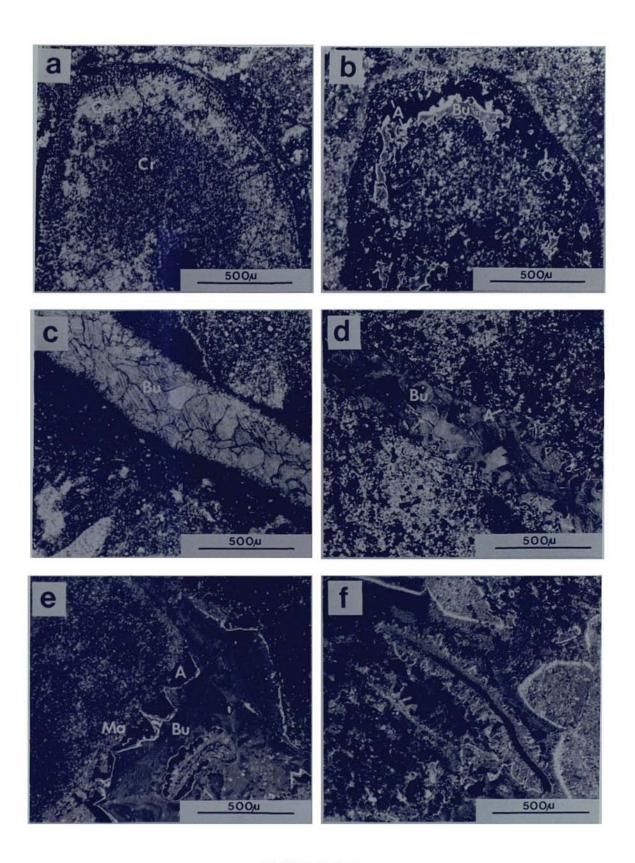
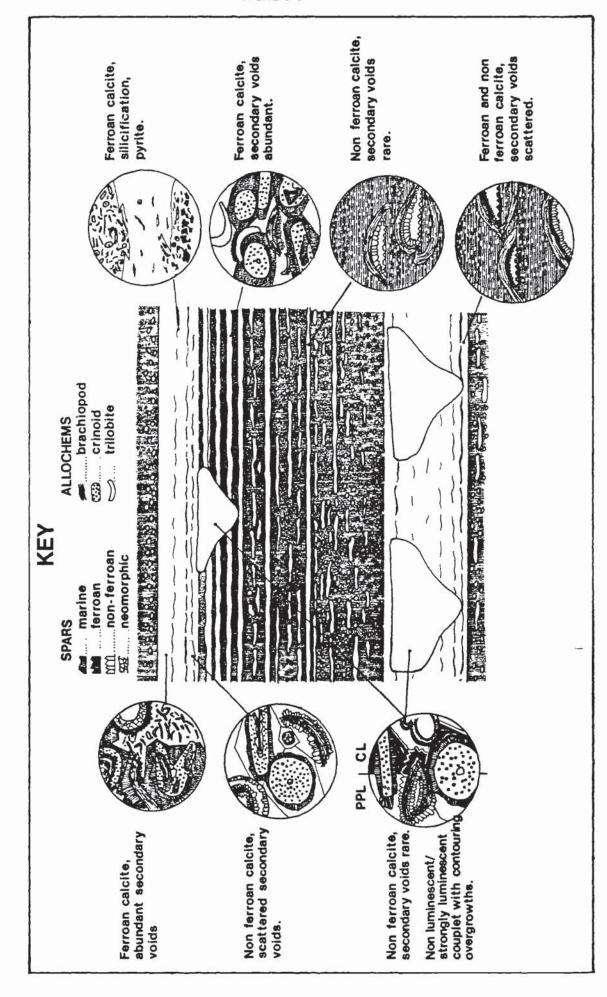


FIGURE 6.7

6 / 5 inter

Figure 6.8. Distribution of secondary voids and pre-compactional clear spars. Central section is a schematic illustration of the Much Wenlock Limestone in the West Midlands. The stippled areas are silty mudstones. The seven insets are diagramatic representations of thin sections in ppl and, in the case of reefal cements, under C.L. The field of view in each case is about 2.5mm. Secondary voids are most abundant at the top of the formation, at its base and in occasional limestone beds in muddy lithofacies. In the same areas the precompactional cements are ferroan.



is overlain by a bright yellow strongly luminescent zone (Figs 6.8 & 6.7c). The thin subzones reveal the positions of progressively younger crystal terminations, allowing changes in cement morphology to be followed. The oldest terminations are commonly spired or contouring (Walkden & Berry 1984). Younger terminations become successively less anhedral, a trend culminating at the outer surface of the euhedral, strongly luminescent zone (Fig. 6.8). The non-luminescent/strongly luminescent couplet occurs in all the reefs studied, but is absent from bedded lithofacies. Dull cements in bedded lithofacies sometimes have non-luminescent tips or, very rarely, a thin strongly luminescent outer zone (Fig. 6.4f).

The isotopic signature of the pre-compactional clear cements is similar to that of the turbid spars; \S^*O values ($\S^{15}O = -5.0 - -5.1$ PDB) lie within the range of Silurian marine carbonates, and $\S^{15}C$ values are relatively heavy ($\S^{15}C = +4.6 - +5.1$ PDB) (Fig. 6.6). 6.3.5.2 Post-compactional clear cements

Post-compactional clear cements are coarse, euhedral and dominantly equant. There is a tendency for the older spars to be slightly bladed and smaller than the younger spars. Despite their morphological uniformity staining shows that their iron content is variable. While the post-compactional spars are generally non-ferroan their youngest parts can be weakly ferroan. Variation is also dependent on lithology; post-compactional cements close to silty mudstones are strongly ferroan, but they are non-ferroan in mudstone-free units. Hence, ferroan cements occur at the top and base of the formation, and in limestone beds surrounded by silty mudstone.

Post-compactional clear cements nucleate either on older spars or directly on compactional fracture surfaces. Such fractures are generally small and localised, but longitudinal tensile fractures occasionally occur in mudstone-free lithologies. Such spar-filled fractures are generally cut by stylolites, though some veins filled by weakly ferroan calcite both cut, and are cut, by stylolites

The post-compactional cements all luminesce weakly and show little intensity variation (Figs 6.2f & 6.4d). Where zonation does occur it can be directly related to iron content; the areas which have the lowest intensity are the richest in iron.

Isotopically the post-compactional cements plot in a field which extends from $\S^{13}O = -7.8 - -10.1$ PDB and $\S^{15}C = +2.6 - +6.2$ PDB. Within this field the data plots into two distinct clusters. One cluster forms a linear trend (A on Fig. 6.6) which if extrapolated coincides with the line created by the isotopic values of the marine cements. The other data points plot around a line (B on Fig. 6.6) which is parallel to the trend formed by the isotopic values of the micrites. If these two linear trends are extrapolated they intersect at approximately $\S^{19}O=-12$ and $\S^{13}C=+2$.

6.3.6 Pressure solution and late-stage vein fill

Pressure solution, expressed as stylolites, affects all the above fabrics. The most common form of stylolite is digitate with a fill up to 5mm thick of clay, silica and organic matter. Smaller discontinuous microstylolites do occur at grain contacts but are relatively rare. Closely packed anastomosing stylolites, separated by clay, silica, organic matter and allochems with ragged edges, often form gently undulating seams up to 50mm thick. These seams occur in

less muddy limestone units such as the Lower Quarried Limestone of the West Midlands. They are evenly distributed and parallel to bedding, often giving the less muddy limestones a well bedded appearance in the field.

Strongly ferroan calcite veins are commonly closely associated with the stylolites. Veins occurring within stylolites consist of bladed ferroan calcite, the blades growing perpendicular to the vein walls. Zones of anastomosing veinlets up to 100mm wide in pure limestone lithofacies both cut and are cut by stylolites. The calcite in these veinlets is strongly ferroan but remains in optical continuity with any allochems that they cross.

6.3.7 Dolomitisation

Apart from the microdolomite inclusions within turbid spars described above, dolomite is rare in the Much Wenlock Limestone Formation. In only one instance coarse, euhedral dolomite occurs near the top of the formation at May Hill. There the crystals grow replacively in all calcite cements, and in allochems. Under CL. the dolomites are zoned bright and dull orange.

6.3.8 Silicification

Silicification is rare and confined to elongate nodules parallel to bedding in the Upper Quarried Limestone of the West Midlands.

Calcitic remnants are common within the nodules, as are silicified ghosts of allochems (Fig. 6.5 e & f). Some bladed cements are also preserved. These blades closely resemble the clear pre-compactional cements. The blades are usually separated from the substrate by an

isopachous rim of inclusion-rich silica which morphologically resembles the turbid cements of the unsilicified limestone.

6.4 DIAGENETIC ENVIRONMENTS

6.4.1 Diagenetic environments of micrite and turbid spar cements

Micritic envelopes form today in a variety of environments from repeated algal and fungal boring (Bathurst 1965). Recent micritic cements are precipitated in marine environments as cryptocrystalline high Mg calcite. The presence of microdolomites in the micritic cements of the Much Wenlock limestone Formation implies a high Mg calcite precursor. This, combined with the early nature of the micritic cements, suggests that they were precipitated in a marine environment soon after deposition.

All the turbid cements are now low Mg calcite, but evidence for unstable precursors is common. Inclusion-rich bladed spars and large equant crystals contain microdolomites that are similar in appearance and distribution to those described by Lohmann & Meyers (1978), suggesting a high Mg calcite precursor. The similarity of the radiating fibrous masses, the meshworks of fine needles and the square ended blades to modern aragonite cements (Fig. 6.2) (Illing 1954, Alexanderson 1969, Schroeder 1972, James & Ginsburg 1979, Longman 1980, Sandberg 1985), suggests that the original mineralogy of these spars was aragonite. The morphology of the original precipitate is sometimes preserved beneath geopetal fills (Figs 6.3 & 6.4e), where bladed to fibrous crystals are encased in geopetal sediment. A bladed precursor to the large single crystals and syntaxial overgrowths is

also suggested by the inclusion patterns and the bladed ghosts seem under luminescence (Figs 6.3 & 6.4c-d). Fibrous aragonite and bladed high Mg calcite are precipitated from sea water at present suggesting that the turbid spars are stabilised marine-phreatic cements. This interpretation is supported by their presence below geopetal infills, indicating precipitation soon after deposition. The lack of evidence for early compaction in the limestones indicates that cement precipitation took place within a few metres of the depositional surface. Despite their morphological uniformity the turbid cements could not have been precipitated synchronously throughout the formation. The spars in the lower parts of the formation must have been present while the upper parts were still being deposited.

Compared with other Silurian marine carbonates these cements are enriched in 5°C (Fig. 6.6). Since the original unstable cements were marine precipitates, their isotopic signature prior to stabilisation would have plotted in the field of Silurian marine carbonates. Their present values must therefore reflect the isotopic signature of the pore fluid in which stabilisation occurred. The source of this fluid is discussed in the next section.

6.4.2 Diagenetic environment of the pre-compactional clear cements

Pre-compactional clear cements lack evidence of unstable precursors and probably represent first generation low Mg calcite. Several of the petrographic fabrics described above (e.g. low Mg calcite overgrowths on crinoid ossicles, bladed to equant drusy void fills, neomorphism and abundant dissolution) appear identical to fabrics attributed to meteoric water diagenesis (Friedman 1964, Bricker 1971, Matthews 1968, Meyers 1978, Longman 1980, James & Klappa

1983, Harris et al. 1985, Loucks 1985). Luminescence characteristics similar to those of the pre-compactional cements of the Much Wenlock Limestone Formation, have been explained previously by diagenesis in a meteoric-phreatic environment. Carpenter & Ogelesby (1976), Frank et al. (1982), Grover & Read (1983), and Meyers (1978) have shown that in many cases luminescence intensity in calcite is controlled by Fe2 and Mn1 content, and is therefore related to the oxidation state of the precipitating fluid. This interpretation has led to the overgeneralisation in the literature that a non-luminescent/strongly luminescent couplet is the product of an influx of oxidising fluid which became stagnant. In this model, contouring overgrowths form from repeated influxes of oxidising fluids which corroded the underlying spar and then became stagnant (Walkden & Berry 1984). In view of the petrographic features described above, such an oxidising fluid could easily be interpreted as meteoric water. Despite these features it seems unlikely that meteoric water ever entered the Much Wenlock Limestone Formation during precipitation of the pre-compactional clear spars. Meteoric water may be introduced into a formation along a palaeoaquifer (Grover & Read 1983) or, more commonly, by subaerial exposure. There is no sedimentological evidence of subaerial exposure in the Much Wenlock Limestone Formation. Laterally extensive and contemporaneous luminescent zones are characteristic of palaeoaquifer systems, and although such luminescence zones are traceable for hundreds of kilometres in the Much Wenlock Limestone Formation, biostratigraphical evidence indicates that they are not contemporaneous. Biostratigraphy and sedimentology show that the formation is diachronous (Bassett 1974, chapter 2), being older to the

E., probably to the extent that the formation was buried beneath mudstones in the West Midlands at the same time as limestones were being deposited in the Welsh Borders (chapter 2). The isotopic data discussed below also suggest that meteoric water did not enter the Much Wenlock Limestone Formation during precipitation of the precompactional clear spars.

In any carbonate/water pore fluid system the solid is the major control on carbon isotopes, and the water the major reservoir of oxygen. Therefore, in order for a fluid to equilibrate with a carbonate body, but retain a relatively high "C value, as is the case here, the pore-fluid must have been very rich in heavy carbon and the system relatively open. The O of the precipitate in an open system is generally controlled by the composition of the fluid. The \S "O values of the pre-compactional clear cements (\S "O = -5 - -5.1 PDB) approximate to Silurian marine carbonates, further suggesting a non-meteoric diagenetic evironment. Variations in carbon isotope values of pore fluids result primarily from contact with decomposing organic matter, bacterial fermentation producing heavy carbon (Fig. 6.9) Organic-rich mudstones, examples of which occur above, below and within the Much Wenlock Limestone Formation, are a common host for bacterial fermentation. The mudstones surrounding and within the Much Wenlock Limestone Formation are therefore a likely source for the 13C enriched fluids. In order for the fluids to stabilise the marine cements and precipitate the clear spars, they had to migrate into the limestones. At the depths where bacterial fermentation occurs mudstones would be compacting and dewatering (Fig. 6.9), but the limestones would have been relatively rigid due to the marine cements.



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Figure 6.9. Organic matter degradation related to mudstone dewatering. The zones of organic matter decomposition, with the rate of diagenetic CO_2 production and the ^{13}C of the CO_2 produced in each zone, are shown on the left of the diagram (after Irwin et al. 1977). The sediment column is drawn to scale in the centre and related to the dewatering curve for mudstones on the right (after Burst 1989).

The limestones would therefore have resisted compaction, setting up a hydrostatic gradient. This would have forced water out of the mudstone into the limestone. The isotopic values of the pre-compactional clear spars are therefore explained by waters escaping from organic-rich mudstones at shallow burial depth. This model must also be capable of explaining the petrographic data.

Isotopic data indicate that the pore fluids present in the Much Wenlock Limestone Formation on deposition mixed with waters that were expelled from the surrounding mudstones. In such a mixing system the saturation state of the final solution depends on the ionic concentrations of Ca^{2^+} and $OO_5^{2^-}$, OO_2 partial pressures and ionic strengths in the parent fluids (Wigley & Plummer 1976). The composition of the pore fluids in the Much Wenlock Limestone Formation approximated to sea water. Fluids in the mudstones would have had a similar composition initially but would then have evolved rapidly, primarily due to organic matter decay.

After deposition bacterial oxidation followed by sulphate reduction produced OO_2 , increasing the POO_2 of pore fluids in the mudstones (Fig. 6.9). During this period the pH of the environment would have remained relatively constant. The ionic strength of fluids being expelled from the mudstones was relatively low, due to the filtering affect (White 1965), but this would have been a relatively minor control (Wigley & Plummer 1976). Mixing two fluids whose main difference is their POO_2 values produces an undersaturated solution (Wigley & Plummer 1976). Therefore secondary voids formed where fluids escaping from the mudstones first entered the limestones (Fig. 6.10a). As this undersaturated solution dissolved calcite its Ca^{2+} and OO_3^{2-}

concentrations rose, creating a new mixing system at the nose of the invading waters. Fluids with contrasting concentrations of Ca²⁺ and CO₃²⁻ mixed there, producing over-saturated solutions (Fig. 6.10b). This contrast therefore counteracted the undersaturation caused by the PCO₂ variation, ultimately causing calcite to be precipitated in front of the advancing undersaturated fluids. So as more fluid was forced into the limestones a zone of precipitation swept through the formation, followed immediately by carbonate-corrosive waters. Hence an area within the formation was affected by periodic precipitation and dissolution (Fig. 6.10c-d). The further the advancing fluids penetrated the formation the more distant became the source of CO₂, and consequently the dissolutional affects decreased away from the limestone/mudstone contact.

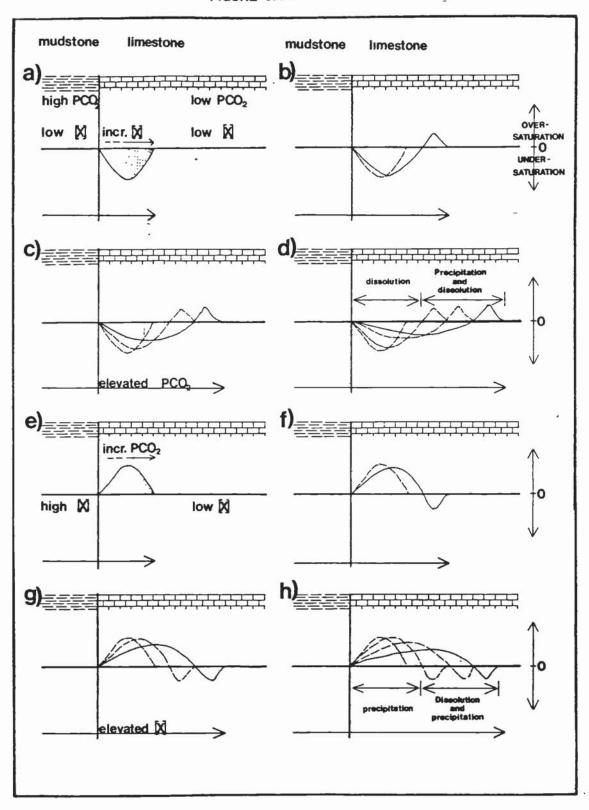
The pore waters in the mudstones became acidic and reducing when bacterial fermentation of organic matter began (Baas Becking et al. 1960, Kraupskopf 1979). Such fluids dissolve carbonates, which leads to an increase in their Ca²⁺ and CO₃²⁻ concentrations. Oversaturation resulted when these fluids entered the limestone and mixed with waters of relatively low Ca²⁺ and CO₃² concentrations (Fig. 6.10e) (Wigley & Plummer 1976). As the resulting zone of precipitation pushed further into the limestone a secondary mixing system was created at its head (Fig. 6.10e-f), where contrasting PCO₂ values resulted from calcite precipitation. This system produced under-saturation. As more fluids were forced into the limestone the over-saturated waters were therefore preceded through the formation by a zone of dissolution (Fig. 6.10g-h).

The reducing nature of the fluids escaping from the mudstones

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Figure 6.10. Mixing systems in the Much Wenlock Limestone Formation created during shallow burial. a-d). The initial input of waters from the mudstones. These fluids had elevated POO_2 creating under-saturation on entering the limestone (a). As these fluids dissolved calcite their Ca^{2+} and CO_3^{2-} concentrations were increased, creating a new mixing system at the front of the advancing fluids (a & b). c & d show the situation developing as the fluids penetrated the formation further. e-f). Later fluids had elevated Ca^{2-} and CO_3^{2-} concentrations. This led to over-saturation on mixing with the limestone pore fluids (e). The secondary mixing zone created in this situation produced under-saturation (f-h).

FIGURE 6.10



means they would have initially precipitated strongly ferroan calcite. Fluids in the limestone were alkaline and oxidising at this time. As the acidic reducing fluids from the mudstones mixed with the alkaline and oxidising waters already present in the limestones, the eh of the fluid was increased and non-ferroan calcite was precipitated. Therefore away from mudstone units the pre-compactional clear spars are non-ferroan. As the fluid evolved within the limestone it passed through the stability field of pyrite, explaining the association of pyrite with ferroan cements. The abundance of secondary voids and strongly ferroan calcite at the top and base of the Much Wenlock Limestone Formation is therefore explained. The variability of precompactional cements in limestone beds within muddy lithologies is controlled by the original nature of the surrounding mudstones. The rhythmic precipitation and dissolution in this model accounts for the presence of contouring overgrowths, without having to invoke repeated pulses of carbonate-corrosive waters. The only feature not fully explained by this model is the luminescence variation. Without geochemical data it is impossible to determine the activators and quenchers of luminescence. It seems unlikely that iron and manganese are solely responsible for the luminescence variation in the Much Wenlock Limestone Formation, since both non-ferroan and ferroan cements exhibit the same luminescence colours.

Silicification post-dates these shallow burial cements, as evidenced by the preserved calcite blades within the silica nodules. The nodules are replacive leaving many poorly defined skeletal relics. The rarity of silica nodules in the Much Wenlock Limestone Formation makes further interpretation impossible.

6.4.3 Diagenetic environment of post-compactional spars

The oements which post-date compactional fracture formed after sufficient overburden had accumulated to induce fracturing. Combined with their coarse equant nature and uniform luminescence this suggests that these spars are burial cements. The relative rarity of compactional fractures in the Much Wenlock Limestone Formation suggests it was not deeply buried. This is supported by the maturation colours of conodonts and organic walled microfossils, which indicate a maximum burial depth of 1-1.5 km (Epstein et al. 1976).

The depth of burial can also be estimated from the oxygen isotope values. By substituting the maximum and minimum dO18 values of the burial cements into the equation used by O'Neil et al. (1969) a temperature increase of approximately 300° during precipitation is suggested. This implies a depth increase of approximately 1km. The equation is only valid if temperature was the major control on dol8 variation. The two separate linear trends seen within the burial cements represent two suites of samples prepared and run on separate occasions. Sample preparation for each set was identical and analytical error has been ruled out (Fallick pers.comm.). suggesting the variation is of primary origin. The two sets of samples came from approximately two metres apart in a homogeneous microfacies. A possible explaination of the separate trends is the mixing of two fluids with a composition converging on $\delta^{18}O = -12 \delta^{19}C = +2$. However, the coexistence of two compositionally different fluids 2 metres apart in a relatively deep burial diagenetic environment, generally considered to be uniform, is improbable. It could also be that the data represent two periods of cement precipitation; a later one

stabilising a younger one. It is statistically unlikely however that the two phases would have been completely separated by random sampling of void fills. The distribution of data is still unexplained and further samples are being analysed to try and resolve the problem.

The relative timing of cement precipitation, stylolite formation and veining is not easy to demonstrate due to the lack of examples with cross-cutting relationships. Figure 6.11 shows the probable ranges during which the various burial fabrics formed.

6.5 DIAGENETIC HISTORY OF THE MUCH WENLOCK LIMESTONE FORMATION

During its lithification the Much Wenlock Limestone Formation passed through three broad diagenetic regimes; marine-phreatic, shallow burial and deep burial. Within each regime distinctive fabrics were formed (Fig. 6.12).

Micritisation was the first process to affect the formation. It was followed by precipitation of micrite cements, and in a few examples, iron-oxide precipitation. The first spars to be precipitated, mainly bladed high Mg calcite and fibrous aragonite, formed in the marine-phreatic diagenetic environment. Active cementation in this environment only extended a few tens of millimetres into the sediment column, where water fluxes were high. The limestone was therefore well cemented soon after deposition.

As sedimentation continued siliciclastic mudstones both within and surrounding the formation began to de-water. These waters migrated into the limestones, thereby mixing with fluids present in the Much Wenlock Limestone since deposition. Due to varying organic decay

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Figure 6.11. Timing of deep burial diagenetic products. The relative timing of each feature is shown by a solid line. Dashed lines represent limits of uncertainty.

Figure 6.12. Diagenetic history of the Much Wenlock Limestone

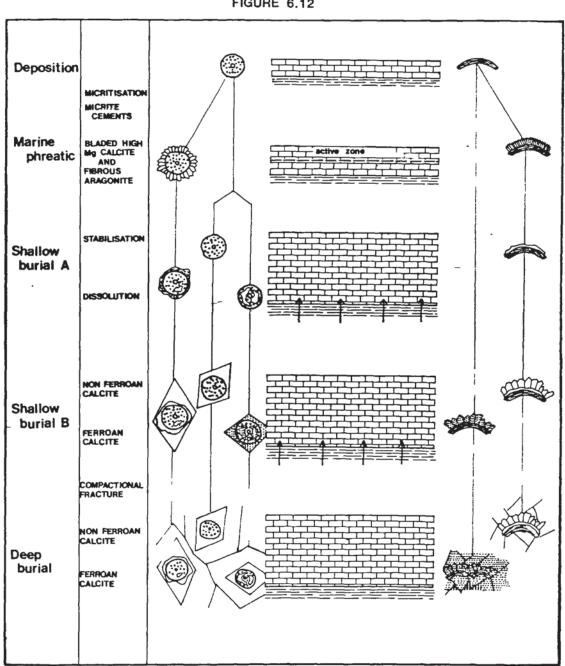
Formation. The environments in which the formation was lithified, and
the processes within those environments, are listed on the left. The
right hand flow chart traces the evolution of a stable allochem with
and without an unstable overgrowth. On the right the evolution of an
unstable allochem with an unstable overgrowth is followed.

FIGURE 6.11

	T
	INCR. DEPTH
NON FERROAN 'EARLY' BURIAL CEMENTS	
WEAKLY FERROAN LATE BURIAL CEMENTS	
TENSILE FRACTURE	
STYLOLITES	
STRONGLY FERROAN CALCITE VEINS IN STYLOLITES	
STRONGLY FERROAN VEINLETS	

FIGURE 6.12

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processes in the mudstones the composition of their pore fluids evolved with time. The initial fluids from the mudstones mixed with those in the limestones to produce under-saturation. As these under-saturated fluids moved through the limestones secondary voids were created where the fluids were most active. As the waters swept through the limestone a zone of calcite precipitation was pushed in front of them, resulting in parts of the formation being affected by rhythmic precipitation and dissolution. With continued burial anaerobic fermentation began in the mudstones. Waters forced from the mudstones at this depth combined with the limestone pore fluids to cause oversaturation. Although these waters pushed a secondary zone of dissolution before them, their main product was clear pre-compactional cement. Further burial resulted in compactional fracture, onset of stylolitisation and precipitation of burial cements at a maximum depth of 1-1.5 km.

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CHAPTER 7

CONCLUSIONS

Based on field appearance 7 lithofacies are recognised within the Much Wenlock Limestone Formation. They were deposited on a shallow shelf that was divided into a stable northern and an unstable southern part. The distribution of lithofacies on the southern section of the shelf was controlled by local subsidence, making correlation with the stable northern area difficult. The oldest part of the formation in the north, the Lower Quarried Limestone Member, is an alga-rich limestone seen only in the West Midlands. The algae in this limestone commonly encrust allochems to form oncoids of which three morphotypes are recognised: Type I were constantly rolled during formation, Type II sporadically rolled and Type III remained stationary during growth. The sequential variation of these morphotypes in the Lower Quarried Limestone Member indicates that deposition began below wavebase and that shallowing resulted in the upper part of the member being constantly, but gently, reworked during deposition. Although these upper parts of the member were deposited close to normal wavebase, high-energy microfacies do not occur. This is probably because wave energy was dissipated over the large expanse of shallow shelf which existed to the W. Following deposition of the Lower Quarried Limestone Member the whole of the northern shelf received deep water, low-energy calcareous silty mudstone deposits. From this time onwards the formation on the northern shelf was deposited in a gradually shallowing environment on an open shelf, culminating with the

deposition of a carbonate sandbody above wavebase. The sequence of lithofacies produced by this shallowing migrated to the W, so that relatively low-energy deeper water deposits were forming on Wenlock Edge while a high-energy sandbody was being deposited in the English Midlands. Behind the advancing carbonate sandbody which marks the top of the formation, low-energy silty mudstones were deposited to form the lowest part of the Elton Beds in the West Midlands.

The faunas in the bedded lithofacies of the Much Wenlock
Limestone Formation are dominated by brachiopods and bryozoans, based
on which 14 faunal assemblages are described. Eleven of these consist
of in situ faunas and 3 of reworked fossils. In order to distinguish
in situ assemblages from sedimentary faunal assemblages it is
necessary to study microfacies in conjunction with the palaeoecology.
The distribution of in situ faunas is controlled by:
a) Turbulence. Thick—shelled, heavily ribbed pedunculate brachiopods
and robust ramose trepostome bryozoans generally occur in turbulent
environments. Lower—energy environments contained thin, smoother—
shelled brachiopods and articulated rhabdomesine cryptostomes.
Turbulence is depth—related.

b). Substrate-type. Soft and hard bottom faunas were identified in the formation. Hard bottom faunas are dominated by pedunculate brachiopods and bryozoans. Soft bottom faunas generally lack bryozoans and contain quasi-infaunal or ambitopic brachiopods. <u>Isorthis</u> is an exception, being pedunculate but common in soft substrates. It may be that <u>Isorthis</u> had a rhizopedunculate pedicle making it suited to this life style. Soft substrates are common in deeper, lower-energy

environments, but also occur in shallower high-energy lithofacies, indicating that this parameter is not directly depth-controlled.

- c). Ease of feeding. Difficult feeding for brachiopods results from low concentration of organic matter in the water, or its effective dilution by fine sediment in suspension. Low concentrations occur in deeper water and dilution in shallow, sediment—laden water. Both these environments were only colonized by brachiopods with efficient lophophores. Since difficult feeding can occur in both shallow and deep water, this parameter is not depth—controlled.
- d). Other organisms in the environment. In alga-rich lithofacies a distinctive brachiopod assemblage occurs in which the common brachiopods all maintained a life position with their commisures raised off the sediment surface. This probably helped in preventing the animals being colonized by algae. Alga-rich sediments will only occur in the the photic zone, but within this restriction they are not depth controlled.

While some of these parameters are loosely depth-related, it is an overgeneralisation to suggest that that faunas in the Much Wenlock Limestone Formation are depth-controlled.

Two of the lithofacies in the formation contain reefs; the others lack reefs due variously to poor water circulation, high sedimentation rates and excessive turbulence preventing the formation of stable substrates. Three reef types are recognised;

Type A. Type A reefs were built by corals and stromatoporoids and grew dominantly on the open northern part of the shelf. Reef growth began on skeletal grainstones which were stabilised by early marine cements. The reefs were initially low mounds colonized by scattered corals, but shallowing of the environment led to the formation of upright frameworks overlain by laminar frameworks. The final growth-stage of these reefs took place in front of the E to W migrating sandbody.

Type B. Type B reefs were built mainly by algae but crinoid thickets developed locally. Initial colonization of a skeletal grainstone bed was by corals. Poor water circulation, however, prevented corals and stromatoporoids from flourishing and allowed algae to dominate. Type B reefs spread laterally over the surrounding lithofacies, indicating that reef growth was more rapid than sedimentation rate and giving the reefs a lensoid shape.

Type C. Type C reefs were built dominantly by algae, reflecting growth in an area of poor water circulation. They have vertical sides suggesting that reef growth was matched by sedimentation rate.

Cements in the formation reflect marine-phreatic, shallow burial and deep burial diagenetic environments. The marine-phreatic cements were dominantly bladed and needle-like high Mg calcite or aragonite, which were later stabilised to turbid low Mg calcite. Prior to precipitation of the overlying clear spars a dissolution event partially dissolved unstable marine carbonates. The fluids responsible for this dissolution had similar isotopic compositions to those which precipitated the overlying pre-compactional clear spars. All were

enriched in heavy carbon relative to sea water. These fluids originated from the organic-rich mudstones which surround the formation, being forced into the limestone by compaction at shallow burial depths. Initially the fluids had high carbon dioxide partial pressures, which produced a zone of undersaturation on entering the formation and created secondary voids. This zone of undersaturation was gradually pushed further into the formation by additional fluids from the mudstones. Later fluids entering the formation were enriched in [Ca] and [CO], which mixed with fluids already present in the formation to produce an oversaturated zone. As this zone moved further into the formation cements were precipitated which resemble the products of meteoric water diagenesis. However, sedimentological and biostratigraphical data indicate that meteoric water did not enter the formation at this time. Deeper burial of the formation led to compactional fracture, stylolitisation and precipitation of burial cements in the remaining voids.

APPENDIX II

Palaeoecological data. The numbers of individuals of each species are given for all collections processed. The collections are deposited with the National Museum of Wales on accession number $87.50~\rm G$

DEA

Resserella	22	Anrhynchonella	
Isorthis	17	Rhynchotreta	
Dalejina	6	Microsphaeridiorhynchus	
Skenidioides		Sphaerirhynchia	
Leptaena	3	Ramose trepostome	11
Scamnomena		Encrusting trepostome	
Amphistrophia	4	Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	44
Coolinia		Ptilodictine cryptostome	6
Strophonella		Trilobite	2
Pholidostrophia	2	Gastropod	1
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	5	Massive coral	
Protochonetes	20	Solitary coral	
Pentlandina		Inarticulate brachiopod	1
Ribbed atrypid		Tentaculites	
"Glassia"			
Nucleospira			
Whitfieldella			
Atrypa	1Ĭ		
Eospirifer	2		
Howellella	21		
Kozlowskiellina			
Striispirifer			
Spinella			
Homeospira			
Meristina			
Gypidula	9		

DEB

Resserella	5	Anrhynchonella	
Isorthis	11	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	
Skenidioides	È	Sphaerirhynchia	
Leptaena	2	Ramose trepostome	5
Scamnomena		Encrusting trepostome	
Amphistrophia	2	Fenestella	
Leptostrophia	6	Rhabdomesine cryptostome	22
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	4
Pholidostrophia		Gastropod	2
Katastrophomena	i	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	
Protochonetes	11	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	29	Tentaculites	
"Glassia"	12		
Nucleospira			
Whitfieldella			
Atrypa	82		
Eospirifer			
Howellella	16		
Kozlowskiellina			
Striispirifer			
Spinella		x .	
Homeospira			
Meristina		*	
Gypidula	14		

DED

Resserella	15	Anrhynchonella	
Isorthis	2	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	
Skenidioides		Sphaerirhynchia	
Leptaena	3	Ramose trepostome	7
Scamnomena	2	Encrusting trepostome	
Amphistrophia	5	Fenestella	
Leptostrophia	5	Rhabdomesine cryptostome	5
Coolinia	7	Ptilodictine cryptostome	3
Strophonella		Trilobite	1
Pholidostrophia		Gastropod	
Katastrophomena	p.	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	10	Massive coral	
Protochonetes	20	Solitary coral	
Pentlandina		Inarticulate brachiopod	4
Ribbed atrypid	1	Tentaculites	
"Glassia"	35		
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	2		
Howellella	16		
Kozlowskiellina			
Striispirifer			
Spinella		*	
Homeospira			
Meristina			:
Gypidula	11		

DEE

Resserella	24	Anrhynchonella	5
Isorthis	4	Rhynchotreta	
Dalejina	3	Microsphaeridiorhynchus	
Skenidioides		Sphaerirhynchia	
Leptaena	1	Ramose trepostome	5
Scamnomena		Encrusting trepostome	1
Amphistrophia	1	Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	2
Coolinia	Ь	Ptilodictine cryptostome	4
Strophonella		Trilobite	3
Pholidostrophia	1	Gastropod	1
Katastrophomena	("Stick" coral	
Leangella		Branching coral	
Eoplectodonta	15	Massive coral	
Protochonetes	5	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid		Tentaculites	
"Glassia"	4	Fistuliporids	3
Nucleospira			
Whitfieldella			
Atrypa	٦ .		
Eospirifer	1		
Howellella	15		
Kozlowskiellina			
Striispirifer			
Spinella		•	
Homeospira	1		
Meristina			
Gypidula	12		

DEF

Resserella		Anrhynchonella	12
Isorthis	2	Rhynchotreta	6
Dalejina		Microsphaeridiorhynchus	13
Skenidioides		Sphaerirhynchia	9
Leptaena	1	Ramose trepostome	١
Scamnomena	1	Encrusting trepostome	١
Amphistrophia	4	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	2
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	١
Pholidostrophia		Gastropod	
Katastrophomena		"Stick" coral	2
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid		Tentaculites	
"Glassia"	12		
Nucleospira			
Whitfieldella			
Atrypa	/8		
Eospirifer Cyrtia Howellella	6 3 11		
Kozlowskiellina			
Striispirifer	2		
Spinella	٩		
Homeospira			
Meristina			
Gypidula	10		

Resserella		Anrhynchonella	!3
Isorthis		Rhynchotreta	9
Dalejina		Microsphaeridiorhynchus	23
Skenidioides		Sphaerirhynchia	5
Leptaena		Ramose trepostome	
Scamnomena	1	Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia		Rhabdomesine cryptostome	
Coolinia	3	Ptilodictine cryptostome	
Stropnonella		Trilobite	2
Pholidostrophia		Gastropod	2
Katastrophomena	a e	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	1	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	37	Tentaculites	4
"Glassia"	8		
Nucleospira			
Whitfieldella			
Atrypa	2		
Eospirifer	11		
Cyrtia Howellella	15		
Kozlowskiellina			
Striispirifer	1		
Spinella	Ĩ.		
Homeospira			
Meristina			
Gypidula	17		

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R'es serella		Anrhynchonella	9
Isorthis	1	Rhynchotreta	14
Dalejina		Microsphaeridiorhynchus	21
Skenidioides		Sphaerirhynchia	5
Leptaena	Y	Ramose trepostome	2
Scamnomena	2	Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	1
Coolinia	3	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostropnia		Gastropod	11
Katastrophomena	a	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	3	Massive coral	
Protochonetes	3	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	36		3
"Glassia"	8	Fishuliporid	3
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	7 2		
(yrtia Howellella	9		
Kozlowskiellina			
Striispirifer	3		
Spinella	5		
Homeospira			
Meristina			,
Gypidula	11		

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R 'es serella	5	Anrhynchonella	2
Isorthis	3	Rhynchotreta	6
Dalejina	2	Microsphaeridiorhynchus	46
Skenidioides		Sphaerirhynchia	4
Leptaena	<i>y</i> -	Ramose trepostome	53
Scamnomena	15	Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia	2	Rhabdomesine cryptostome	31
Coolinia		Ptilodictine cryptostome	4
Strophonella		Trilobite	
Pholidostrophia	Î	Gastropod	4
Katastrophomena	i	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	2	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid		Tentaculites	1
"Glassia"	12	Fistuliporid	2
Nucleospira			
Whitfieldella		ŧ.	
Atrypa	1		
Eospirifer	2		
(yrtia Howellella	2		
Kozlowskiellina			
Striispirifer			
Spinella		•	
Homeospira			
Meristina			-
Gypidula	2		

	Anrhynchonella	6
	Rhynchotreta	6
1	Microsphaeridiorhynchus	62
	Sphaerirhynchia	34
Ī	Ramose trepostome	54
8	Encrusting trepostome	6
	Fenestella	4
3	Rhabdomesine cryptostome	13
	Ptilodictine cryptostome	
	Trilobite	6
	Gastropod	8
	"Stick" coral	
	Branching coral	
	Massive coral	
	Solitary coral	
	Inarticulate brachiopod	
,	Tentaculites	4
5	Futuliporid	12
4		
9 8		
1	oā 	
4	Ň()	
2		
	3 4 9 8	Rhynchotreta Microsphaeridiorhynchus Sphaerirhynchia Ramose trepostome Encrusting trepostome Fenestella Rhabdomesine cryptostome Ptilodictine cryptostome Trilobite Gastropod "Stick" coral Branching coral Massive coral Solitary coral Inarticulate brachiopod Tentaculites Futuliporiol

	1,5 0		
Resserella	7	Anrhynchonella	
Isorthis	3	Rhynchotreta	
Dalejina	5	Microsphaeridiorhynchus	1
Skenidioides		Sphaerirhynchia	1
Leptaena	1	Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia	2	Rhabdomesine cryptostome	2
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	1
Pholidostrophia	3	Gastropod	1
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	10	Solitary coral	
Pentlandina		Inarticulate brachiopod	2
Ribbed atrypid	14	Tentaculites	
"Glassia"	15		
Nucleospira			
Whitfieldella			
Atrypa	96		
Eospirifer	3		
Howellella	1		
Kozlowskiellina			
Striispirifer			
Spinella		•	
Homeospira			
Meristina			
Gypidula	4		

R'esserella		Anrhynchoneila	14
Isorthis		Rhynchotreta	54
Dalejina		Microsphaeridiorhynchus	8
Skenidioides		Sphaerirhynchia	6
Leptaena		Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia		Rhabdomesine cryptostome	
Coolinia	2	Ptilodictine cryptostome	
Strophonella		Trilobite	1
Pholidostrophia		Gastropod	5
Katastrophomena		"Stick" coral	
Leangella	ž.	Branching coral	
Eoplectodonta	Ī	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	14	Tentaculites	3
"Glassia"	35		
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	1		
Howellella	21		
Kozlowskiellina	6		
Striispirifer			
Spinella		•	
Homeospira			
Meristina			×
Gypidula	6		

R'esserella		Anrhynchonella	9
Isorthis		Rhynchotreta	21
Dalejina		Microsphaeridiorhynchus	27
Skenidioides		Sphaerirhynchia	8
Leptaena		Ramose trepostome	2
Scamnomena		Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia		Rhabdomesine cryptostome	١ :
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostrophia		Gastropod	2
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	
Protochonetes	5	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	27	Tentaculites	4
"Glassia"	8		
Nucleospira			
Whitfieldella		-	
Atrypa			
Eospirifer			
Howellella	12		
(yrHa Kozlowskiellina	2		
Striispirifer			
Spinella	22	•	
Homeospira			
Meristina			280
Gypidula	6		

R'esserella		Anrhynchonella	6
Isorthis		Rhynchotreta	15
Dalejina		Microsphaeridiorhynchus	28
Skenidioides		Sphaerirhynchia	3
Leptaena		Ramose trepostome	2
Scamnomena	1	Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia		Rhabdomesine cryptostome	4
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	2
Pholidostrophia		Gastropod	1
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	21	Tentaculites	1
"Glassia"	38		
Nucleospira	: (1)		
Whitfieldella			
Atrypa			
Eospirifer			
Howellella	18		
Cyrtia Kozlowskiellina	8		
Striispirifer			
Spinella	4		
Homeospira			
Meristina			99
Gypidula	5		

Resserella	10	Anrhynchonella	2
Isorthis	3	Rhynchotreta	
Dalejina	5	Microsphaeridiorhynchus	1
Skenidioides		Sphaerirhynchia	6
Leptaena	3	Ramose trepostome	8
Scamnomena	1	Encrusting trepostome	
Amphistrophia	4	Fenestella	1
Leptostrophia	1	Rhabdomesine cryptostome	1
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	1
Pholidostropnia	5	Gastropod	6
Katastrophomena	1	"Stick" coral	1
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	5	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	12	Tentaculites	
"Glassia"			
Nucleospira			
Whitfieldella		•	
Atrypa	36		
Eospirifer Cyrtia	12		
Howellella	4		
Kozlowskiellina			
Striispirifer			
Spinella	4	•	
Homeospira			
Meristina			;
Gypidula	5		

Resserella	7	Anrhynchonella	
Isorthis	7	Rhynchotreta	
Dalejina	3	Microsphaeridiorhynchus	
Skenidioides		Sphaerirhynchia	
Leptaena		Ramose trepostome	9
Scamnomena		Encrusting trepostome	1
Amphistrophia	5	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	6
Coolinia	1	Ptilodictine cryptostome	
Stropnonella		Trilobite	
Pholiaostropnia	1	Gastropod	2
Katastrophomena	į.	"Stick" coral	2
Leangella		Branching coral	
Eoplectodonta	1	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	١
Ribbed atrypid	5	Tentaculites	١
"Glassia"			
Nucleospira			
Whitfieldella			
Atrypa	6		¥
Eospirifer	3		
(yrtia Howellella	2		
Kozlowskiellina			
Striispirifer			
Spinella			
Homeospira			
Meristina			
Gypidula			

Resserella	5	Anrhynchonella	2
Isorthis	Ψ .	Rhynchotreta	2
Dalejina	2	Microsphaeridiorhynchus	2
Skenidioides		Sphaerirhynchia	1
Leptaena	3	Ramose trepostome	19
Scamnomena		Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia	4	Rhabdomesine cryptostome	31
Coolinia	4	Ptilodictine cryptostome	4
Strophonella		Trilobite	
Pholidostrophia		Gastropod	8
Katastrophomena	ı	"Stick" coral	7
Leangella		Branching coral	
Eoplectodonta	3	Massive coral	2
Protochonetes	2	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	8	Tentaculites	
"Glassia"	16	Fisheliponic	2
Nucleospira			
Whitfieldella			
Atrypa	4		
Eospirifer	4		
Cyrtia Howellella	9		
Kozlowskiellina	3		
Striispirifer	1		
Spinella	à		
Homeospira			
Meristina			•
Gypidula	2		

Resserella	5	Anrhynchonella	
Isorthis	2	Rhynchotreta	2
Dalejina		Microsphaeridiorhynchus	3
Skenidioides		Sphaerirhynchia	16
Leptaena	7	Ramose trepostome	3
Scamnomena	40	Encrusting trepostome	
Amphistrophia	5	Fenestella	1
Leptostrophia	8	Rhabdomesine cryptostome	5
Coolinia	9	Ptilodictine cryptostome	3
Strophonella		Trilobite	
Pholidostrophia		Gastropod	13
Katastrophomena		"Stick" coral	4
Leangella		Branching coral	
Eoplectodonta	1	Massive coral	
Protochonetes	10	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	5
"Glassia"	19	Fishuliporid	1
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	1 2		
Cyrria Howellella	ิ้น		
Kozlowskiellina	1		
Striispirifer			
Spinella	,	•	
Homeospira			
Meristina			
Gypidula			

R tes serella	l	Anrhynchonella	
Isorthis		Rhynchotreta	15
Dalejina		Microsphaeridiorhynchus	52
Skenidioides		Sphaerirhynchia	4
Leptaena	2	Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	4	Fenestella	
Leptostrophia	2	Rhabdomesine cryptostome	ļ
Coolinia	4	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostrophia		Gastropod	4
Katastrophomena		"Stick" coral	4
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid		Tentaculites	6
"Glassia"	12		
Nucleospira			
Whitfieldella			
Atrypa	2		
Eospirifer	6		
(yetha Howellella	2		
Kozlowskiellina			
Striispirifer	2		
Spinella			
Homeospira			
Meristina			
Gypidula			

R es serella	2	Anrhynchonella	
Isorthis		Rhynchotreta	11
Dalejina		Microsphaeridiorhynchus	39
Skenidioides		Sphaerirhynchia	10
Leptaena	ſ	Ramose trepostome	20
Scamnomena	5	Encrusting trepostome	
Amphistrophia	1	Fenestella	2
Leptostrophia	1	Rhabdomesine cryptostome	Į.
Coolinia	2	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostropnia		Gastropod	6
Katastrophomena	1	"Stick" coral	2
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	2
"Glassia"	38	Fisheliporial	1
Nucleospira			
W hitfieldella		-	
Atrypa	2		
Eospirifer	1		
Howellella	14		
Kozlowskiellina			
Striispirifer	1	-	
Spinella		•	
Homeospira			
Meristina			
Gypidula			

R'esserella		Anrhynchonella	
Isorthis	•	Rhynchotreta	37
Dalejina		Microsphaeridiorhynchus	15
Skenidioides		Sphaerirhynchia	34
Leptaena		Ramose trepostome	8
Scamnomena	8	Encrusting trepostome	1
Amphistrophia		Fenestella	5
Leptostrophia	2	Rhabdomesine cryptostome	1
Coolinia	7	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostropnia	1	Gastropod	7
Katastrophomena		"Stick" coral	3
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	2	Tentaculites	3
"Glassia"	31		
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	2		
Howellella	5		
Kozlowskiellina			
Striispirifer	7		
Spinella	•		
Homeospira			
Meristina			ją.
Gypidula			

Resserella	ĺ	Anrhynchonella	
Isorthis		Rhynchotreta	39
Dalejina	4	Microsphaeridiorhynchus	8
Skenidioides		Sphaerirhynchia	29
Leptaena		Ramose trepostome	18
Scamnomena	2	Encrusting trepostome	
Amphistrophia	2	Fenestella	4
Leptostrophia	2	Rhabdomesine cryptostome	12
Coolinia	1.	Ptilodictine cryptostome	1
Strophonella		Trilobite	2
Pholidostrophia		Gastropod	7
Katastrophomena	3	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	1	Massive coral	
Protochonetes	1	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid		Tentaculites	1
"Glassia"	13		
Nucleospira			
Whitfieldella			
Atrypa	1		
Eospirifer	2		
Howellella	2		
Kozlowskiellina -			
Striispirifer			
Spinella	,		
Homeospira			
Meristina			96
Gypidula	1		

R'esserella		Anrhynchonella	
Isorthis		Rhynchotreta	19
Dalejina		Microsphaeridiorhynchus	14
Skenidioides		Sphaerirhynchia	18
Leptaena		Ramose trepostome	6
Scamnomena	6	Encrusting trepostome	
Amphistrophia	۷.	Fenestella	6
Leptostrophia		Rhabdomesine cryptostome	4
Coolinia	3	Ptilodictine cryptostome	1
Strophonella		Trilobite	1
Pholidostrophia	1	Gastropod	4
Katastrophomena	į.	"Stick" coral	1
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid		Tentaculites	4
"Glassia"	23		
Nucleospira			
Whitfieldella			
Atrypa	2	*	
Eospirifer	4		
Howellella	5		
Kozlowskiellina			
Striispirifer			
Spinella	į.	•	
Homeospira			
Meristina		ă	
Gypidula			

Resserella	9	Anrhynchonella	1
Isorthis	7	Rhynchotreta	7
Dalejina	2	Microsphaeridiorhynchus	2
Skenidioides		Sphaerirhynchia	5
Leptaena	12	Ramose trepostome	13
Scamnomena	3	Encrusting trepostome	
Amphistrophia	9	Fenestella	5
Leptostrophia	8	Rhandomesine cryptostome	7
Coolinia	9	Ptilodictine cryptostome	2
Stropnonella		Trilopite	3
Pholidostropnia		Gastropec	4
Katastrophomena	.	"Stick" cora.	2
Leangella		Branching coral	
Eoplectodonta	I	Massive coral	
Protochonetes	4	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	
"Glassia"	7	Fistuliporical	2
Nucleospira			
Whitfieldella			
Atrypa	5	*	
Eospirifer	2		
Howellella	15		
Kozlowskiellina	1		
Striispirifer	I .		
Spinella	,	L a	
Homeospira			
Meristina			
Gypidula	2		

Resserella	9	Anrhynchonella	
Isorthis	16	Rhynchotreta	2
Dalejina	T	Microsphaeridiorhynchus	18
Skenidioides		Sphaerirhynchia	8
Leptaena	3	Ramose trepostome	9
Scamnomena	5	Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia	3	Rhabdomesine cryptostome	9
Coolinia	6	Ptilodictine cryptostome	1
Stropnonella		Trilobite	đ
Pholidostropnia		Gastropod	
Katastropnomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	6	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	13	Tentaculites	
"Glassia"	3	Fishuliporid	2
Nucleospira			
Whitfieldella			
Atrypa	2		.*
Eospirifer	3		
Cyrtia Howellella	30		
Kozlowskiellina			
Striispirifer			
Spinella	,		
Homeospira			
Meristina			
Gypidula	1		

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Resserella	1	Anrhynchonella	
Isorthis	3	Rhynchotreta	1
Dalejina		Microsphaeridiorhynchus	3
Skenidioides		Sphaerirhynchia	5
Leptaena		Ramose trepostome	14
Scamnomena	Ĩ	Encrusting trepostome	1
Amphistrophia		Fenestella	
Leptostrophia		Rhabdomesine cryptostome	8
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostropnia	I	Gastropod	5
Katastrophomena		"Stick" coral	3
Leangella		Branching coral	P
Eoplectodonta	1	Massive coral	1
Protochonetes	3	Solitary coral	1
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	11	Tentaculites	
"Glassia"	5		
Nucleospira	2		
Whitfieldella			
Atrypa			
Eospirifer			
Howellella	5		
Kozlowskiellina	2		
Striispirifer			
Spinella			
Homeospira			
Meristina			
Gypidula		ù.	

BHR 3

Resserella	1	Anrhynchonella	4
Isorthis	+	Rhynchotreta	2
Dalejina		Microsphaeridiorhynchus	3
Skenidioides		Sphaerirhynchia	15
Leptaena		Ramose trepostome	17
Scamnomena	1.	Encrusting trepostome	1
Amphistrophia	Ĭ	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	16
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostrophia		Gastropod	
Katastrophomena		"Stick" coral	2
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	4
Protochonetes	1	Solitary coral	3
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	7	Tentaculites	
"Glassia"	2		
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	2		
Howellella	6		
Kozlowskiellina	2		
Striispirifer			
Spinella	•		
Homeospira			
Meristina			2
Gypidula	1		

BHR 4

	2	Anrhynchonella	5
Isorthis	6	Rhynchotreta	١
Dalejina	1	Microsphaeridiorhynchus	4
Skenidioides	2	Sphaerirhynchia	
Dicoelosia Leptaena	~	Ramose trepostome	11
Scamnomena		Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia		Rhabdomesine cryptostome	11
Coolinia	3	Ptilodictine cryptostome	1
Strophonella		Trilobite	4
Pholidostrophia		Gastropod	
Katastrophomena		"Stick" coral	
Leangella		Branching coral	9
Eoplectodonta		Massive coral	
Protochonetes	4	Solitary coral	3
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	9	Tentaculites	2
"Glassia"	3		
Nucleospira			
Whitfieldella		-	
Atrypa			
Eospirifer	1		
Howellella	4		
Kozlowskiellina	5		_
Striispirifer			
Spinella	,		
Homeospira			
Meristina			
(iici istiiid			

R'esserella	4	Anrhynchonella	2
Isorthis	\$	Rhynchotreta	1
Dalejina	2	Microsphaeridiorhynchus	4
Skenidioides		Sphaerirhynchia	6
Leptaena	ì	Ramose trepostome	7
Scamnomena	2	Encrusting trepostome	
Amphistrophia	2	Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	8
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	1
Pholidostrophia	Ĭ	Gastropod	8
Katastrophomena		"Stick" coral	
Leangella		Branching coral	4
Eoplectodonta		Massive coral	5
Protochonetes	3	Solitary coral	7
Pentlandina	1	Inarticulate brachiopod	
Ribbed atrypid	13	Tentaculites	
"Glassia"	2		
Nucleospira			
Whitfieldella	Ĭ		
Atrypa			
Eospirifer	2		
Cyctia Howellella	13		
Kozlowskiellina	1		
Striispirifer			
Spinella		× ·	
Homeospira			
Meristina			*0
Gypidula			

		12411 6		_
Resserella	11		Anrhynchoneila	2
Isorthis	5		Rhynchotreta	
Dalejina	1		Microsphaeridiorhynchus	
Okenidioides	1		Sphaerirhynchia	7
Leptaena	1		Ramose trepostome	28
Scamnomena	1		Encrusting trepostome	3
Amphistrophia	2		Fenestella	2
Leptostrophia			Rhabdomesine cryptostome	25
Coolinia	1		Ptilodictine cryptostome	
Strophonella			Trilobite	
Pholidostrophia	2		Gastropod	14
Katastrophomena	1		"Stick" coral	
Leangella			Branching coral	4
Eoplectodonta			Massive coral	
Protochonetes	3		,	10
Pentlandina			Stromaloponid Inarticulate brachiopod	t
Ribbed atrypid	30		Tentaculites	
"Glassia"	2			
Nucleospira	2_			
Whitfieldella	2			
Atrypa	1			
Eospirifer				
Howellella	8			
Kozlowskiellina	1			
Striispirifer				
Spinella		•		
Homeospira				
Meristina				
Gypidula				

BHQ 7

Resserella	6	Anrhynchonella	
Isorthis	6	Rhynchotreta	
Dalejina	2	Microsphaeridiorhynchus	
Orcoelosia Skenidioides	1	Sphaerirhynchia	5
Leptaena	ſ	Ramose trepostome	7
Scamnomena		Encrusting trepostome	1
Amphistrophia		Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	2
Coolinia	I	Ptilodictine cryptostome	2
Strophonella		Trilobite	
Pholidostrophia	2	Gastropod	8
Katastrophomena		"Stick" corai	Ţ
Leangella		Branching coral	4
Eoplectodonta		Massive coral	3
Protochonetes	6	Solitary coral	15
Pentlandina	1	Inarticulate brachiopod	
Ribbed atrypid	18	Tentaculites	
"Glassia"	5		
Nucleospira	f		
Whitfieldella	1		
Atrypa	6		
Eospirifer	1		
Cyttia Howellella	3 6		
Kozlowskiellina	4		
Striispirifer		-	
Spinella		•	
Homeospira			
Meristina			
Gypidula			

Resserella	6	Anrhynchonella	1
Isorthis	10	Rhynchotreta	
Dalejina	1	Microsphaeridiorhynchus	9
Skenidioides		Sphaerirhynchia	8
Leptaena	4	Ramose trepostome	6
Scamnomena	2	Encrusting trepostome	
Amphistrophia	1	Fenestella	2
Leptostrophia	1	Rhabdomesine cryptostome	13
Coolinia	2	Ptilodictine cryptostome	
Strophonella		Trilobite	2
Pholidostrophia	3	Gastropod	6
Katastrophomena	í	"Stick" coral	2
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	5	Solitary coral	4
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	27	Tentaculites	2
"Glassia"		Fistuliporid	1
Nucleospira	1		
Whitfieldella	2	-	
Atrypa	<u>į</u>		
Eospirifer (yrtia	1		
Howellella	10 .		
Kozlowskiellina	5		
Striispirifer			
Spinella		•	
Homeospira			
Meristina			13
Gypidula			

4 1 Anrhynchonella Resserella ١ Rhynchotreta Isorthis Microsphaeridiorhynchus Dalejina 5 Sphaerirhynchia Skenidioides Ramose trepostome Leptaena Encrusting trepostome Scamnomena Fenestella Amphistrophia Rhabdomesine cryptostome Leptostrophia Ptilodictine cryptostome `Coolinia Trilobite Strophonella Gastropod Pholidostrophia "Stick" coral Katastrophomena Branching coral Leangella Eoplectodonta Massive coral Solitary coral Protochonetes Inarticulate brachiopod Pentlandina 2 Tentaculites Ribbed atrypid "Glassia" Nucleospira Whitfieldella 64 Atrypa Eospirifer Howellella Kozlowskiellina Striispirifer Spinella Homeospira

Meristina

Gypidula

13

Anrhynchonella 1 8 Resserella 4 Rhynchotreta Isorthis 1 Microsphaeridiorhynchus Dalejina 9 Sphaerirhynchia Skenidioides Ramose trepostome Leptaena Encrusting trepostome Scamnomena Fenestella Amphistrophia Rhabdomesine cryptostome Leptostrophia Ptilodictine cryptostome Coolinia Trilobite Strophoneila Gastropod Pholidostrophia "Stick" coral Katastrophomena Branching coral Leangella Massive coral Eoplectodonta Solitary coral Protochonetes Inarticulate brachiopod Pentlandina 3 Tentaculites Ribbed atrypid "Glassia" Nucleospira Whitfieldella 76 Atrypa Eospirifer Howellella Kozlowskiellina Striispirifer Spinella Homeospira Meristina

Gypidula

6

Resserella	3	Anrhynchonella	
Isorthis	9	Rhynchotreta	
Dalejina	1	Microsphaeridiorhynchus	16
Skenidioides		Sphaerirhynchia	17
Leptaena	3	Ramose trepostome	10
Scamnomena		Encrusting trepostome	
Amphistrophia		Fenestella	1
Leptostrophia		Rhabdomesine cryptostome	5
Coolinia	2	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostrophia		Gastropod	I
Katastrophomena		"Stick" coral	4
Leangella		Branching coral	1
Eoplectodonta		Massive coral	1
Protochonetes	3	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	
"Glassia"	9		
Nucleospira			
Whitfieldella			
Atrypa	2		
Eospirifer			
Howellella	14		
Kozlowskiellina			
Striispirifer	11		
Spinella	•		
Homeospira	1		
Meristina			
Gypidula			

Resserella		Anrhynchonella	
Isorthis	11	Rhynchotreta	
Dalejina	3	Microsphaeridiorhynchus	6
Skenidioides		Sphaerirhynchia	4
Leptaena		Ramose trepostome	9
Scamnomena		Encrusting trepostome	
Amphistrophia	ι	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	3
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilopite	
Pholidostrophia		Gastropod	
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes		Solitary coral	2
Pentlandina		Inarticulate brachiopod	3
Ribbed atrypid		Tentaculites	
"Glassia"	Í	Fishuliporid	3
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer			
Howellella	12		
Kozlowskiellina			
Striispirifer	1		
Spinella			
Homeospira	2		
Meristina			
Gypidula			

Resserella	3	Anrhynchonella	
Isorthis	9	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	42
Skenidioides		Sphaerirhynchia	20
Leptaena	5	Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	1	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	3
Pholidostrophia		Gastropod	2
Katastrophomena	i.	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	١
Protochonetes	2	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	
"Glassia"			
Nucleospira			
Whitfieldella			
Atrypa	3		
Eospirifer	1		
Howellella	25		
Kozlowskiellina			
Striispirifer	8		
Spinella			
Homeospira	1		
Meristina			
Gypidula			

-270-BE 5

R'esserella	1	Anrhynchonella	
Isorthis	13	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	16
Skenidioides		Sphaerirhynchia	5
Leptaena	2	Ramose trepostome	3
Scamnomena		Encrusting trepostome	
Amphistrophia	1	Fenestella	1
Leptostrophia		Rhabdomesine cryptostome	
Coolinia		Ptilodictine cryptostome	
Stropnonella		Trilobite	1
Pholidostrophia		Gastropod	
Katastrophomena	i	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	١
Protochonetes	Ĭ.	Solitary coral	2
Pentlandina		Inarticulate brachiopod	5
Ribbed atrypid	1	Tentaculites	
"Glassia"	2		
Nucleospira			
Whitfieldella			
Atrypa	2		
Eospirifer Cyceia Howellella	2		
Kozlowskiellina			
Striispirifer	6		
Spinella			
Homeospira			
Meristina			
Gypidula			

R'esserella	5	Anrhynchonella	
Isorthis	17	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	22
Skenidioides		Sphaerirhynchia	12
Leptaena	5	Ramose trepostome	2
Scamnomena		Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia	6	Rhabdomesine cryptostome	
Coolinia	3	Ptilodictine cryptostome	0
Strophonella		Trilobite	~
Pholidostrophia	2	Gastropod	
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	4	Tentaculites	
"Glassia"	8		
Nucleospira			
Whitfieldella	l		
Atrypa	1		
Eospirifer (yrtia Howellella	1		
Kozlowskiellina			
Striispirifer	12	-	
Spinella	9		
Homeospira			
Meristina			
Gypidula			

R esserella	1	Anrhynchonella	
Isorthis	21	Rhynchotreta	
Dalejina	3	Microsphaeridiorhynchus	13
Skenidioides		Sphaerirhynchia	13
Leptaena	1	Ramose trepostome	8
Scamnomena		Encrusting trepostome	1
Amphistrophia	2	Fenestella	3
Leptostrophia	1	Rhabdomesine cryptostome	3
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilopite	2
Pholidostrophia		Gastropod	l
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta	Ĭ	Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	
"Glassia"	2		
Nucleospira			
Whitfieldella		*	
Atrypa	3		
Eospirifer			
Howellella	6		
Kozlowskiellina			
Striispirifer	15		
Spinella		•	
Homeospira			
Meristina			٠
Gypidula			

Resserella		Anrhynchonella	
Isorthis	7	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	30
Skenidioides		Sphaerirhynchia	31
Leptaena	1	Ramose trepostome	2
Scamnomena		Encrusting trepostome	2
Amphistrophia	4	Fenestella	
Leptostrophia	2	Rhabdomesine cryptostome	1
Coolinia	4	Ptilodictine cryptostome	
Strophonella		Trilopite	4
Pholidostropnia	Ţ	Gastropod	1
Katastrophomena	à	"Stick" coral	1
Leangella		Branching coral	1
Eoplectodonta		Massive coral	
Protochonetes	6	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	<u>ہ</u>	Tentaculites	
"Glassia"	14		
Nucleospira	2		
Whitfieldella	1		
Atrypa			
Eospirifer (yrtia	6		
(grtia Howellella	9		
Kozlowskiellina			
Striispirifer	14		
Spinella		x	
Homeospira			
Meristina			87
Gypidula			

Resserella	2	Anrhynchonella	
Isorthis	20	Rhynchotreta	
Dalejina	3	Microsphaeridiorhynchus	13
Skenidioides		Sphaerirhynchia	4
Leptaena	3	Ramose trepostome	2
Scamnomena		Encrusting trepostome	1
Amphistrophia	2	Fenestella	
Leptostrophia	*	Rhabdomesine cryptostome	4
Coolinia	1	Ptilodictine cryptostome	
Strophonella		TriloDite	
Pholidostropnia		Gastropod	
Katastrophomena		"Stick" corai	
Leangella		Branching coral	1
Eoplectodonta		Massive coral	
Protochonetes	l	Solitary coral	
Pentlandina		Inarticulate brachiopod	l
Ribbed atrypid		Tentaculites	I
"Glassia"	3	Fishiliporid	6
Nucleospira	1		
Whitfieldella	xe.		
Atrypa	5		
Eospirifer			
Howellella	8		
Kozlowskiellina		_	
Striispirifer	3		
Spinella	,		
Homeospira			
Meristina			
Gypidula			

Resserella	16	Anrhynchonella	
Isorthis	41	Rhynchotreta	
Dalejina	5	Microsphaeridiorhynchus	6
Skenidioides		Sphaerirhynchia	4
Leptaena		Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	6
Pholidostrophia	1	Gastropod	
Katastrophomena		"Stick" coral	ł
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	2	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	3	Tentaculites	
"Glassia"	t		
Nucleospira			
Whitfieldella			
Atrypa	12		
Eospirifer (yrtia Howellella	1		
Kozlowskiellina			
Striispirifer	2		
Spinella	,		
Homeospira			
Meristina			

Gypidula

Resserella	16	Anrhynchonella	
Isorthis	36	Rhynchotreta	1
Dalejina	4	Microsphaeridiorhynchus	1
Skenidioides		Sphaerirhynchia	14
Leptaena		Ramose trepostome	ı
Scamnomena		Encrusting trepostome	
Amphistrophia	2	Fenestella	
Leptostrophia	4	Rhabdomesine cryptostome	
Coolinia	ť.	Ptilodictine cryptostome	
Stropnonella		Trilopite	8
Pholidostropnia	4	Gastropod	١
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	2	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	7	Tentaculites	
"Glassia"			
Nucleospira			
Whitfieldella			
Atrypa	35		
Eospirifer (574:a Howellella			
Kozlowskiellina			
Striispirifer		-	
Spinella	1	· ·	
Homeospira			
Meristina			¥
Gypidula	2		

Resserella	3	Anrhynchonella	
Isorthis	9	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	29
Skenidioides		Sphaerirhynchia	16
Leptaena	2	Ramose trepostome	ı
Scamnomena		Encrusting trepostome	
Amphistrophia	8	Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostrophia		Gastropod	3
Katastrophomena	i	"Stick" coral	1
Leangella		Branching coral	
Eoplectodonta		Massive coral	1
Protochonetes	7	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	4	Tentaculites	
"Glassia"	17		
Nucleospira	2		
Whitfieldella	1	· ·	
Atrypa	1,8		
Eospirifer	2		
Howellella	II		
Kozlowskiellina			
Striispirifer	2		
Spinella			
Homeospira		G _E	
Meristina			(4)
Gypidula			

Resserella	3	Anrhynchonella	
Isorthis	9	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	26
Skenidioides		Sphaerirhynchia	13
Leptaena	2	Ramose trepostome	1
Scamnomena	1	Encrusting trepostome	
Amphistrophia	8	Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	
Coolinia	6	Ptilodictine cryptostome	1
Strophonella	I	Trilopite	1
Pholidostrophia		Gastropod	
Katastrophomena	i	"Stick" coral	
Leangella		Branching coral	2
Eoplectodonta		Massive coral	
Protochonetes	14	Solitary coral	
Pentlandina		Inarticulate brachiopod	I
Ribbed atrypid	2	Tentaculites	
"Glassia"	12		
Nucleospira			
Whitfieldella			
Atrypa			
Eospirifer	1		
Howellella	10		
Kozlowskiellina			
Striispirifer	4		
Spinella			
Homeospira			
Meristina			•
Gypidula			

DE 16

R'esserella	2	Anrhynchonella	
Isorthis	12	Rhynchotreta	3
Dalejina		Microsphaeridiorhynchus	26
Skenidioides		Sphaerirhynchia	7
Leptaena		Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	4	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	
Coolinia	4	Ptilodictine cryptostome	
Stropnonella		Trilobite	2
Pholioostrophia		Gastropod	l
Katastrophomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	18	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	8	Tentaculites	
"Glassia"	8		
Nucleospira		*0	
Whitfieldella	1		
Atrypa	1		
Eospirifer			
Howellella	/6		
Kozlowskiellina			
Striispirifer]		
Spinella		•	
Homeospira	1		
Meristina			÷
Gypidula			

Décession	1	Anrhynchonella	4
Resserella	, ,		1
Isorthis	,	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	7
Skenidioides		Sphaerirhynchia	8
Leptaena	8	Ramose trepostome	8
Scamnomena		Encrusting trepostome	I
Amphistrophia	5	Fenestella	
Leptostrophia	1	Rhabdomesine cryptostome	2
Coolinia	2	Ptilodictine cryptostome	1
Strophoneila		Trilobite	8
Pholidostrophia	1	Gastropod	
Katastrophomena	1	"Stick" coral	P
Leangella		Branching coral	
Eoplectodonta	2	Massive coral	
Protochonetes	2	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	13	Tentaculites	
"Glassia"	10	Fistuliporid	1
Nucleospira			
Whitfieldella	1		
Atrypa	7		
Eospirifer	4		
Howellella	6		
Kozlowskiellina			
Striispirifer			
Spinella		•	
Homeospira			
Meristina			š
Gypidula			

BWA 2

Resserella	1	Anrhynchonella	
Isorthis	3	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	33
Skenidioides		Sphaerirhynchia	12
Leptaena	1	Ramose trepostome	1
Scamnomena		Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia	2	Rhabdomesine cryptostome	
Cociinia		Ptilodictine cryptostome	
Stropnonelia		Trilopite	1
Pholicostropnia	2	Gastropoc	
Katastropnomena	1	"Stick" cora.	
Leangelia		Branching cora.	
Eoplectodonta		Massive coral	
Protochonetes	14	Solitary coral	
Pentlandina		Inarticulate brachiopod	1
Ribbed atrypid	12	Tentaculites	
"Glassia"	14		
Nucleospira			
Whitfieldella	3		
Atrypa	2		
Eospirifer	5		
Howellella	16		
Kozlowskiellina			
Striispirifer			
Spinella		•	
Homeospira		a .	
Meristina			
Gypidula			

BWA 3

Anrhynchonella Resserella 1 Rhynchotreta Isorthis 1 Dalejina Microsphaeridiorhynchus 9 3 Sphaerirhynchia Skenidioides Ramose trepostome Leptaena Encrusting trepostome Scamnomena Fenestella Amphistrophia Leptostrophia Rhabdomesine cryptostome Coolinia Ptilodictine cryptostome Strophonella Trilobite Pholidostrophia Gastropod "Stick" coral Katastrophomena Leangella Branching coral Massive coral Eoplectodonta Protochonetes 5 Solitary coral Inarticulate brachiopod Pentlandina Ribbed atrypid Tentaculites 14 "Glassia" 4 Nucleospira Whitfieldella Atrypa 7 Eospirifer 4 5 Howellella Kozlowskiellina Striispirifer Spinella Homeospira Meristina

Gypidula

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R'esserella		Anrhynchonella	9
Isorthis	12	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	16
Skenidioides		Sphaerirhynchia	12
Leptaena		Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	8	Fenestella	
Leptostrophia	3	Rhabdomesine cryptostome	1
Coolinia	5	Ptilodictine cryptostome	_
Strophoneila		Trilobite	5
Pholidostrophia	10	Gastropod	6
Katastropnomena		"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	25	Solitary coral	
Pentlandina		Inarticulate brachiopod	1
Ribbed atrypid	5	Tentaculites	
"Glassia"	4		
Nucleospira	1		
Whitfieldella	Ť		
Atrypa	3		
Eospirifer	3		
Howellella	W		
Kozlowskiellina			
Striispirifer			
Spinella	,	x	
Homeospira			
Meristina			
Gypidula	1		

BW0 7

Resserella	5	Anrhynchonella	2
Isorthis	6	Rhynchotreta	10
Dalejina	Ĭ	Microsphaeridiorhynchus	4
O scoelosia Skenidioides	(Sphaerirhynchia	1
Leptaena	2	Ramose trepostome	6
Scamnomena	2	Encrusting trepostome	ı
Amphistrophia	L	Fenestella	١
Leptostrophia		Rhabdomesine cryptostome	4
Coolinia		Ptilodictine cryptostome	
Stropnonella		Trilobite	
Pholidostrophia		Gastropod	
Katastrophomena	1	"Stick" coral	1
Leangella		Branching coral	7
Eoplectodonta		Massive coral	2
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	٩	Tentaculites	
"Glassia"	1		
Nucleospira			
Whitfieldella			
Atrypa	1		
Eospirifer			
Howellella	4		
Kozlowskiellina	2	_	
Striispirifer	ì		
Spinella			
Homeospira			
Meristina			g*
Gypidula			

BW0 6

Resserella	1	Anrhynchonella	3
Isorthis	8	Rhynchotreta	2
Dalejina		Microsphaeridiorhynchus	4
Skenidioides		Sphaerirhynchia	1
Leptaena	q	Ramose trepostome	3
Scamnomena	1	Encrusting trepostome	
Amphistrophia	3	Fenestella	3
Leptostrophia		Rhabdomesine cryptostome	4
Coolinia	1	Ptilodictine cryptostome	
Strophonella		Trilobite	2
Pholidostrophia		Gastropod	
Katastrophomena	i	"Stick" coral	3
Leangella		Branching coral	9
Eoplectodonta	2	Massive coral	1
Protochonetes	3	Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	4	Tentaculites	
"Glassia"	5	Fistuli porid	1
Nucleospira			
Whitfieldella			
Atrypa	3		
Eospirifer (yrtia	3		
Howellella	15		
Kozlowskiellina	<u>~</u>		
Striispirifer			
Spinella			
Homeospira			
Meristina			
Gypidula	1		

BWO 9

		*	
Resserella	2	Anrhynchonella	5
Isorthis	1	Rhynchotreta	4
Dalejina		Microsphaeridiorhynchus	6
Skenidioides		Sphaerirhynchia	22
Leptaena	1	Ramose trepostome	2
Scamnomena	Ţ	Encrusting trepostome	
Amphistrophia		Fenestella	
Leptostrophia	5	Rhabdomesine cryptostome	1
Coolinia		Ptilodictine cryptostome	
Strophonella		Trilobite	
Pholidostropnia		Gastropod	1
Katastrophomena		"Stick" coral	3
Leangella		Branching coral	5
Eoplectodonta		Massive coral	3
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	17	Tentaculites	
"Glassia"	٩		
Nucleospira			
Whitfieldella	4		177.
Atrypa	7		
Eospirifer	1		
(yrtia Howellella	6		
Kozlowskiellina	2		
Striispirifer			
Spinella		•	
Homeospira			
Meristina			
Gypidula	4		

BW0 12

Resserella		Anrhynchonella	
Isorthis	8	Rhynchotreta	2
Dalejina		Microsphaeridiorhynchus	q
Skenidioides		Sphaerirhynchia	3
Leptaena	4	Ramose trepostome	10
Scamnomena	1	Encrusting trepostome	
Amphistrophia	3	Fenestella	9
Leptostrophia		Rhabdomesine cryptostome	٩
Coolinia	1	Ptilodictine cryptostome	1
Strophonella		Trilobite	1
Pholidostrophia	Ţ	Gastropod	1
Katastrophomena		"Stick" coral	4
Leangella		Branching coral	6
Eoplectodonta		Massive coral	4
Protochonetes	3	Solitary coral	
Pentlandina	t	Inarticulate brachiopod	2
Ribbed atrypid	16	Tentaculites	
"Glassia"	5		
Nucleospira			
Whitfieldella	I		
Atrypa	4		
Eospirifer	2		
Howellella	17		
Kozlowskiellina	4		
Striispirifer	2		
Spinella	,		
Homeospira			
Meristina			٠
Gypidula			

BTF 1

Rés serella	3	Anrhynchonella	
Isorthis	8	Rhynchotreta	
Dalejina		Microsphaeridiorhynchus	7
Skenidioides		Sphaerirhynchia	14
Leptaena		Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	3	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	1
Coolinia	2	Ptilodictine cryptostome	
Strophonella	Ī	Triiobite	2
Pholidostrophia	7	Gastropod	
Katastrophomena		"Stick" coral	1
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	16	Solitary coral	
Pentlandina		Inarticulate brachiopod	١
Ribbed atrypid	1	Tentaculites	
"Glassia"	3		
Nucleospira	1		
Whitfieldella	2	•	
Atrypa	30		
Eospirifer	3		
Howellella	38		
Kozlowskiellina			
Striispirifer			
Spinella			
Homeospira			
Meristina			×
Gypidula			

BTF 2

Resserella	21	Anrhynchonella	
Isorthis	23	Rhynchotreta	
Dalejina	5	Microsphaeridiorhynchus	2
Skenidioides		Sphaerirhynchia	7
Leptaena	2	Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	2	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	2
Coolinia		Ptilodictine cryptostome	
Stropnoneila		Trilopite	1
Pholidostrophia	1	Gastropod	١
Katastrophomena	i.	"Stick" coral	
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	2	Solitary coral	1
Pentlandina		Inarticulate brachiopod	5
Ribbed atrypid	5	Tentaculites	
"Glassia"		Fistuliporid	1
Nucleospira			
Whitfieldella			
Atrypa	16		
Eospirifer			
Howellella	5		
Kozlowskiellina			
Striispirifer			
Spinella	52	X	
Homeospira			
Meristina			
Gypidula			

BTF 3

Resserella	2	Anrhynchonella	
Isorthis	27	Rhynchotreta	1
Dalejina	2	Microsphaeridiorhynchus	7
Skenidioides		Sphaerirhynchia	20
Leptaena	2	Ramose trepostome	
Scamnomena		Encrusting trepostome	
Amphistrophia	6	Fenestella	
Leptostrophia		Rhabdomesine cryptostome	
Coolinia	3	Ptilodictine cryptostome	
Strophonella		Trilobite	t
Pholidostrophia	2	Gastropod	1
Katastrophomena	a	"Stick" coral	1
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes	11	Solitary coral	
Pentlandina		Inarticulate brachiopod	1
Ribbed atrypid	2	Tentaculites	
"Glassia"	7		
Nucleospira			
Whitfieldella	3		
Atrypa	3		
Eospirifer	5		
Howellella	14		
Kozlowskiellina			
Striispirifer	1		
Spinella			
Homeospira			
Meristina			ŧ
Gypidula			

BCMD 1

R'esserella	2	Anrhynchonella	
Isorthis	9	Rhynchotreta	1
Dalejina		Microsphaeridiorhynchus	25
Skenidioides		Sphaerirhynchia	8
Leptaena	ľ	Ramose trepostome	7
Scamnomena		Encrusting trepostome	
Amphistrophia		Fenestella	2
Leptostrophia		Rhabdomesine cryptostome	2
Coolinia	2	Ptilodictine cryptostome	1
Strophonella		Trilobite	
Photidostrophia		Gastropod	1
Katastrophomena	a	"Stick" coral	4
Leangella		Branching coral	
Eoplectodonta		Massive coral	
Protochonetes		Solitary coral	
Pentlandina		Inarticulate brachiopod	
Ribbed atrypid	24	Tentaculites	
"Glassia"	13		
Nucleospira			
Whitfieldella			12
Atrypa		*	
Eospirifer			
Howellella	12		
Kozlowskiellina			
Striispirifer			
Spinella		•	
Homeospira			
Meristina			(*)
Gypidula			

BCMO 2

R'esserella	3	Anrhynchonella
Isorthis	23	Rhynchotreta
Dalejina		Microsphaeridiorhynchus
Skenidioides		Sphaerirhynchia
Leptaena	2	Ramose trepostome
Scamnomena		Encrusting trepostome
Amphistrophia	3	Fenestella
Leptostrophia		Rhabdomesine cryptostome 2
Coolinia	4	Ptilodictine cryptostome
Strophoneila	4	Trilobite 5
Pholidostrophia		Gastropod
Katastrophomena	a .	"Stick" corai
Leangella		Branching coral
Eoplectodonta		Massive coral
Protochonetes	8	Solitary coral
Pentlandina		Inarticulate brachiopod
Ribbed atrypid	3	Tentaculites
"Glassia"	5	
Nucleospira	1	
Whitfieldella	4	
Atrypa	7	
Eospirifer	1	
Howellella	8	
Kozlowskiellina		_
Striispirifer	Ĭ	
Spinella		•
Homeospira		
Meristina		
Gypidula		

APPENDIX III

Sedimentary logs of core material examined. The key to all the logs is given on page $\,$. All the core material is deposited with the National Museum of Wales on accession number

KEY

Limestone nodule with sharp boundary

" " diffuse "

Limestone bed

Silty mudstone

Reef

✓ Skeletal fragment

O Crinoid Ossicle

/# Bryozoan fragment

Coral and/or Stromatoporoid

Peloid

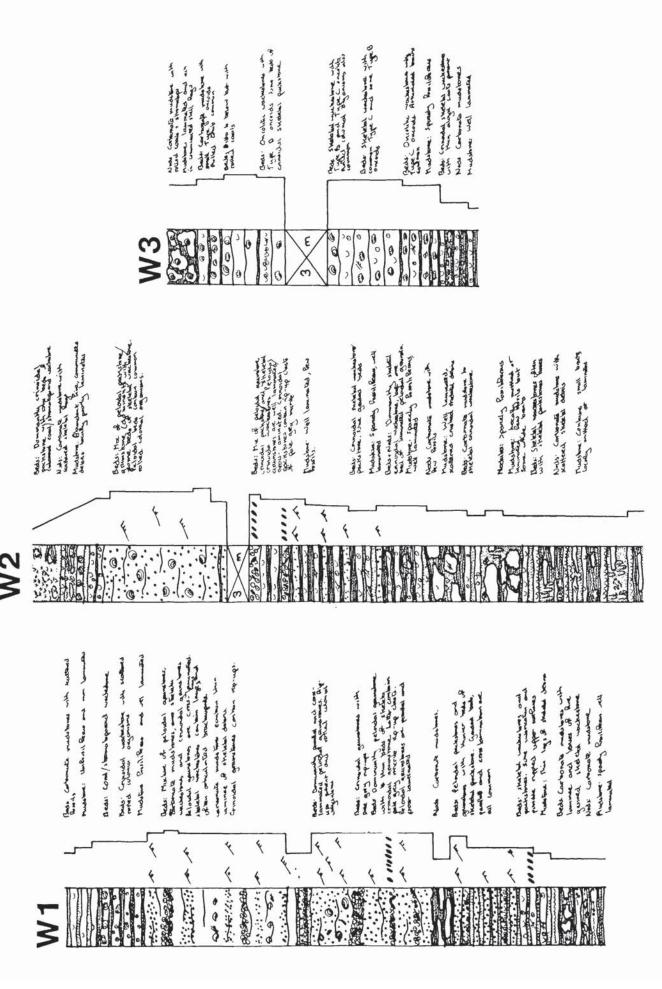
● Rip-up clast

3 Oncoid

N Bioturbation

Cross-lamination

Imbricated clasts



ख 00 000 000 000 a Pap 00 5400 0 % 40 000 200 0 . 67 more. 00 0# 3 00 S 0 OA 8 (C 0 0 0 . 0 00 0 4 6 6 000 00 6 . . ***** 00 0 000 00 000 5000 900 SVE 057 ⇒ ¢3 ক্তি

Node fine & elebel newbestone to coone training podred shelded weches force Anthrology brocks

Mudstone spanely Resulterne but pochet if colonial organisms and

Nochs wenerally carbonate mudatione some was backuped hughents

Much tome Highly Cossiliferns including articulated buchapads

Node Corbonate mudebone, with scattered elected debots

Mudstone sponedy Poss liberous with occasional while broken Some bominae of Rive students deforts

Nods: Carbonate muditiones with scattered whole bruchs. scuttered whole

Mudatore soundly Possilikens and lauly poorly laninated

Node. Carbonate mudelones with scattered shaketh debru and accumonal thin alays coass

Mustbene: Conerally sparely highly bout the saw but with one highly gacked lenses.

Beds oncolific Arelabil machastones with trype of oncoids Usually hightly ported machanas to protesting high the colored origination prosent and oncoids carbonate machana with machana with acutand Cosile

Mudshine: hammaled and

Beds humaly partial wartestone with Type B oncids, sheletal detars musty boken.

Beds: Fine, looky garred worked with creasured Yough Paymorts and Type G and E oncolds

Beds. Appropriate Consolituses and the second secon

Bods Oncolitic, stretch washesbre Type C oncods dominate whole brichiopode common. Them tooks of shelding padatone also common

Decks Centre lossely packed skeletal waterlooms brone Pangs hive thin algol contingo

Abochules. Shelelah washesbones and peolstones when with lange Burguants and attendated bankungants Smaller noclules U.S. Corbonals smallpones

Muse tone: & peach fourlishing with some orthodox boards boards boards

sendiform standard of

Mudetone Spendy Hess House

Page 297

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(学) Abds carbonate mustere with consistent enall brightens and a few articulated bruche EC# 5 Mushow generally spacely fossilifens but the horas of sollers and languages 9 0 5 THE

Nods corbonol. midetunes with when scattered his debre and very occusional logger logge

Mudatore: Spaning Asselifences

Noch carbonate madebases with some largely pocked wasterbours and scattered articulated bracknopods

Muchatoria. Sporcely Bossiliberous birth with some posters of Rice andated details. Some brokeroution

Nocts. A Kine strikelist backspare mitted

Nods: Fyzish mestorad ones are achamate mudalands thougade nodules are skeldal consider puchehones

Muchalore remeasily poorly Possilibenus but palats and tamine of Ana stellabil John a Locally well laminated

Nods. Fine 111-12 1 steeled wachesburgs

Mudstone Present as the black gettings

ander to have but pelandal

Backs: Lasely packed stretchal waches home with small Type workerhone with small Type A and Type of concods Occasional bed of collect of

Beds: hoosely packed skeletal waschestones: H Tipe B and Tipe C oncress Some beds contain rolled (contain

Base (nee) he indestone with type (no do hauge steller Rouge 1 med articulated Huns 1000m

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Mudelme yearly mandalos

Node: Carbonste mudde scattered skalabe Prog

Mudshowe: Speeding Bourlines
with occasional economical
actividated bounds

Bads skeddal articulates bashs and large singly values

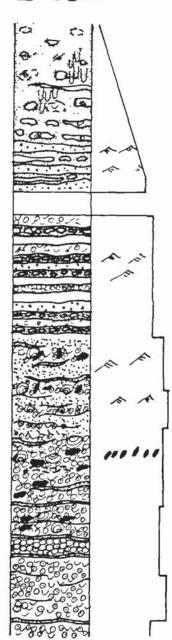
Muditore speaky Rossille orly accional strudows books nother

wees: hoosely gailed skided waterbruss with large and orticated their bushingeds. Thing alread Conts are common to the control of the control

Node Carbonale muddone with suttend Sugments, to shelpful wacherbones

Page 298

D102



Nachules. Dominathy see carbonate smudshave with scuttered Brayments and white books

Mudstone: Sparedy BossiliPenus with scattered while busine Brohumburae

Beds Februa assumptione which s cross aminated

Nodules: Duminanten corbonole

13 eds 13 elocala) grandones, conocido) packstones and appendic mudaline coox-commonen os common

Nodules Conference muchane with eccentered Welder debara

Interteded consider shelder packstone and personal according to work of the source of

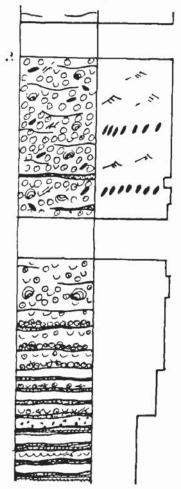
Heavily stylvherd bed of

Beds: Crumoidal statebal
packstones with solled coods
and bujorooms. Elongate
rip-up class of pale any
microle are also common.
Elongate Roymont can be
Indoncate

candy emphiline line tone -

Beds: Tightly padred crimovolal packstone with rolled count whomas some porallel lummation

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ermedal packebone to againstone commonly miche commonly now-tweet commonly now-twent to and imporcation some poled only

Well serted crowidal posteriore to assume to the common of the colonial comments

Bads: shoteled commonded tookles breed with bases of convoided pechalome and generating

Beds, Cortonale mudelone uffer with a lease of sketelly vachestore

Beds Atlanda a runs bree and commonate mustobers be bed not leave stall not leave and

Muleine: Sporedy Porlibor