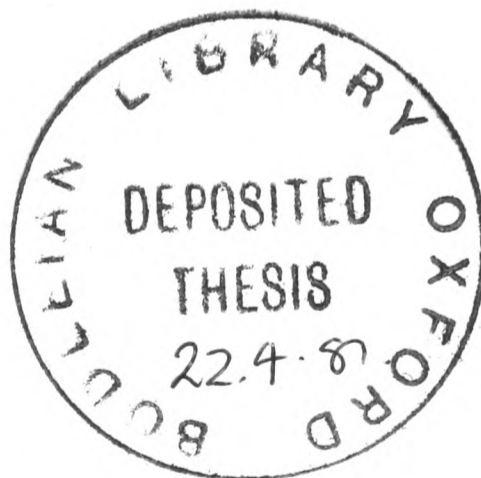


Thesis presented to the University of Oxford
for the degree of Doctor of Philosophy

PALAEOECOLOGY AND SEDIMENTOLOGY OF WAULSORTIAN 'REEFS'
(LOWER CARBONIFEROUS)

NINA MORGAN



Wolfson College

and

Department of Geology and Mineralogy

University of Oxford

Trinity, 1980

PALAEOECOLOGY AND SEDIMENTOLOGY OF WAULSORTIAN 'REEFS'
(LOWER CARBONIFEROUS)

BY

NINA MORGAN

Wolfson College and Department of Geology and Mineralogy, Oxford

Submitted for D.Phil., Trinity, 1980

ABSTRACT

Palaeoecological and sedimentological analysis has been applied in the study of Lower Carboniferous Waulsortian 'reefs' exposed in the Manifold Valley, North Staffordshire and in the Meuse Valley in southern Belgium. Because Waulsortian 'reefs' have similar faunal, lithological and palaeogeographical characteristics in all of their occurrences it is argued that conclusions drawn from the Manifold and Meuse Valleys are applicable to the facies as a whole.

Evidence is presented to show that lithological facies previously recognised within the Belgian Waulsortian can also be recognised elsewhere, and that changing sedimentation rates can explain many of their characteristic differences. Faunal and sedimentological evidence indicates that the rate of sedimentation increased as the mounds developed. It is argued that the mound sediment was produced in situ and faunal data suggests that the surface of the mounds was firm. Early submarine lithification is thought to have been an important process in producing firm substrates and in maintaining steep depositional slopes. Fabrics and lithological components suggestive of early lithification have been recognised.

A general model for Waulsortian development, based on conclusions drawn in this thesis, is presented.

LONG ABSTRACT

This thesis looks at Waulsortian mounds from a palaeoecological point of view. Palaeoecology is used here to mean the study of organisms present, their relation to each other and their relation to and effect upon the environment in which they lived. There are two main reasons for choosing a palaeoecological approach to this problem. Firstly, purely sedimentological studies have left many questions unanswered. Because most carbonate sediment is organically produced and because it is well known that organisms are very sensitive to their environment, it is logical to examine organisms, particularly their morphological adaptations and patterns of co-occurrence, in order to understand more about depositional environments. Secondly, although palaeoecology is potentially a very valuable aid in the study of depositional environments, there are many problems associated with the technique itself. During the course of this research, many methods have been tried in order to find the most effective ways of collecting, handling and objectively interpreting data. Nevertheless, sedimentology, carbonate petrography and field observation, both detailed and reconnaissance, have been very important elements of this study because they have provided a means of testing and evaluating hypothesis derived from faunal considerations.

Mapping and plotting of available stratigraphic information in the carbonate mound complex in the Manifold Valley has shown that mound development began in the Courceyan (Tn3c) and continued through the Arundian (V1b). The complex youngs towards the east. It is composed of at least five smaller mounds which have coalesced to form a large mass. The contact between the mounds and off-mound sediments is abrupt.

Fingers of off-mound sediment interdigitate with unbedded mound limestone and in some areas off-mound sediments are seen to envelope small carbonate mounds. The predominant lithology of the complex is medium to light grey biomicrite which is similar to that found in the Biomicrite Facies of the Belgian Waulsortian recognised by Lees et al. (1977). Occasionally there are small patches of a fenestrate bryozoa and spar-rich lithology similar to their Blue Vein Facies.

Similarities in age and lithology suggest that the Manifold Valley carbonate mounds represent examples of Waulsortian 'reefs'. Comparison with the model developed for the Belgian Waulsortian by Lees et al. (1977) indicates that only the upper part of the Waulsortian, the Biomicrite Facies, is exposed in the Manifold Valley. The Blue Vein Facies, which is characteristic of the lower parts of the Waulsortian is thought to be present below ground.

A comparison of the Manifold Valley faunas with those from other localities shows no significant difference between them. Thus, the faunal trends found in the Manifold Valley are likely to be applicable to Waulsortian faunas as a whole.

Morphological and structural analysis of the faunas in the Manifold Valley suggests that the substrate of the mounds was by and large a firm one because the majority of the organisms are adapted to life on firm, but not necessarily hard, substrates. The most significant components of faunal variation in the Manifold Valley are changes in diversity, density/maximum size (which are highly correlated) and amount of fenestrate bryozoa. Density increases significantly from the older to the younger mounds. Density measurements indicate a clumped spatial distribution of organisms. This may be caused by the faunal response to substrate heterogeneity.

The faunal diversity trends in the Irish and Belgian Waulsortian follow the trends predicted by the community succession model of Johnson (1972) and Walker and Alberstadt (1975). According to this model, the diversity trends in the Manifold Valley predict the existence of an earlier phase of community development which is not exposed. This gives further weight to the supposition based on lithological evidence that an earlier facies of the Waulsortian will be found below the surface.

Lees et al. (1977) predict that fenestrate bryozoa and crinoid debris will be relatively rare in the Biomicrite Facies. The paucity of the remains of these organisms in the Manifold Valley is compatible with the idea that it is the Biomicrite Facies which is exposed there.

Modern fenestrate bryozoa are limited in their distribution by high sedimentation rates and there is evidence that sedimentation affected Palaeozoic crinoids as well. These findings suggest that the decrease in amounts of bryozoa and crinoid debris in the Biomicrite Facies as compared with the Blue Vein Facies is indicative of an increase in the rate of sedimentation as the Waulsortian developed.

The lack of any organisms capable of trapping sediment and the common occurrence of the pure carbonate Waulsortian 'reefs' interbedded with shaley deposits leads to the conclusion that the sediment was produced in situ. Presumably mound growth stopped when sediment production ended. The identity of the producer is unknown.

Early submarine lithification, which has been reported from many marine environments, is a likely mechanism for providing the firm substrates for which a large percentage of the fauna was adapted. The development of a cohesive sediment surface due to lithification also provides a mechanism for the maintenance of steep depositional slopes.

The presence in the Manifold Valley of clotted micrite and radiaxial fibrous spar provides evidence that this process occurred. The degree of lithification may not have been uniform, in some areas the sediment remained soft while in others thin lithified crusts were formed. The development of thin crusts on depositional surfaces suggests a mechanism for the formation of the range of radiaxial fibrous spar-filled cavities commonly orientated parallel to depositional surfaces by removal of sediment below the crusts. Formation of crusts is thought to be restricted by high sedimentation rates and it follows that sparry cavities will be lacking in areas of high sediment production. There is a decrease in the amount of sparry cavities towards the younger parts of both the Manifold Valley mounds and the Belgian Waulsortian. This distribution, as well as the large amounts of void filling early radiaxial fibrous spar in the Blue Vein Facies and abundance of microspar in the Biomicrite Facies provides evidence that sediment production increased as the Waulsortian developed.

Based on conclusions drawn in earlier chapters a general model for Waulsortian development is presented. Early lithification combined with a trend towards upward increase in sedimentation are thought to explain many of the features observed in the Waulsortian.

ACKNOWLEDGEMENTS

I am grateful to the many people who provided friendship, support and advice during the course of this research. Special thanks are due to the geologists of the Institute of Geological Sciences, Leeds, who often provided working space, unpublished information and advice. In particular, Neil Aitkenhead and Dave Mundy suggested the Manifold Valley field area; members of the North Staffordshire Mapping Unit provided friendship and encouragement in the field; the members of the Palaeontology Department, especially M. Mitchell, W. Ramsbottom and M. Reynolds, identified fossils, helped with taxonomy and made the IGS reference collections available to me; and R. Thurrell and F. Cox of the Mineral Assessment Unit arranged permission for the examination of the Alstonefield and Kniveton Boreholes.

Geologists at other Universities have also been very generous with their time and knowledge, especially John Miller of Edinburgh University who introduced me to their Luminoscope, Robin Bathurst of Liverpool University whose discussion was immeasurably helpful, and Alan Lees of the University of Louvain-la-Neuve, who originally showed me the Belgian outcrops and provided a base from which to carry out the Belgian field work.

Useful critical reviews of parts of this thesis were made by Neil Aitkenhead (I.G.S., Leeds), Hugh Jenkyns (Oxford), Eric Mountjoy (McGill University), Tim Palmer (Oxford) and Tom Patterson (Hist. of Medicine Unit, Oxford). Thanks are due also to Phil Powell, who fought valiantly for correct spelling and grammar, and Dorothy Cooke typed the final copy.

Financial support for field work was provided by the Burdett-Coutts Fund at Oxford, The Committee for Graduate Studies at Oxford,

the Geological Society of America, The Royal Geographical Society (Henrietta Hutton Fund), The Society of Sigma Xi and Wolfson College Travel Fund.

Finally, I would like to thank my parents, who not only supported me in many ways, but spent their holiday cutting and pasting.

CONTENTS

	<u>Page</u>
<u>Chapter 1 INTRODUCTION</u>	1
1.1 General description of the Waulsortian	2
1.2 The term reef	2
1.2.1 Definition	2
1.2.2 Inapplicability to the Waulsortian	3
1.2.3 Alternative terminology	3
1.2.4 Terms used in this thesis	4
1.3 Distribution and palaeogeography of Waulsortian 'reefs'	4
1.4 Description of Waulsortian 'reefs'	6
1.5 Understanding the Waulsortian	6
1.5.1 Major problems	6
1.5.2 Relevance to other geological settings	7
1.6 Topics emphasized	7
1.7 Methods used in this study	8
1.7.1 Lower Carboniferous stratigraphy	8
1.7.2 Field work and sampling	9
1.8 Organisation of this thesis	9
<u>Chapter 2 KNOWLEDGE OF THE WAULSORTIAN DERIVED FROM PREVIOUS</u> <u>STUDIES</u>	11
2.1 The Belgian Waulsortian	12
2.1.1 Recognition of the Waulsortian and subsequent studies	12
2.1.2 Expanded definition of the Waulsortian	13
2.1.3 The findings of Lees, Noel and Bouw (1977)	15
2.2 The Irish Waulsortian	17
2.2.1 Principal studies	18
2.2.2 Extent of the Irish Waulsortian	18

	<u>Page</u>	
2.2.3	Geometry of the mound complex	19
2.2.4	Conclusions derived from studies of mound geometry	21
2.3	The British 'reef'-knolls	21
2.3.1	Comparison with the Belgian Waulsortian	23
2.3.2	Definition of the term 'reef'-knoll	23
2.3.3	Controversies over the origin of 'reef'-knolls	23
2.3.4	Recognition of shelf marginal and basinal 'reef'-knolls	24
2.3.5	Differences between shelf marginal and basinal 'reef'-knolls	25
2.3.6	Suggested restriction of Dixon's (1921) comparison	27
<u>Chapter 3 FIELD GEOLOGY OF THE MANIFOLD VALLEY</u>		28
3.1	Location	29
3.2	Previous research	29
3.3	General geology	32
3.3.1	Regional geology	32
3.3.2	Palaeogeography	33
3.3.3	Stratigraphy	36
3.4	Field observations	36
3.4.1	Age relationships	36
3.4.2	The Manifold Valley carbonate mounds	39
3.4.2.1	Contacts with off-mound sediments	39
3.4.2.2	Geometry of the mounds	43
3.4.3	Carbonate mound lithology	46
3.4.4	Borehole data	48
3.4.4.1	Alstonefield borehole	48
3.4.4.2	Kniveton borehole	49
3.4.4.3	Bioclasts	49
3.5	Conclusions	50

	<u>Page</u>
<u>Chapter 4 FAUNAL DATA</u>	52
4.1 Previous work	53
4.1.1 Faunal studies	53
4.1.2 Generalisations about Waulsortian faunas	54
4.2 Faunal investigations in this study	55
4.2.1 Aims	56
4.2.2 Sources of Data	56
4.2.3 Methods	57
4.2.3.1 Sampling Methods in the field	57
4.2.3.2 Faunal measurements	59
4.2.3.3 Statistical methods	62
4.2.4 Comparisons between Waulsortian faunas from ' different areas	61
4.2.5 Description of the Manifold Valley faunas	84
4.2.5.1 'Pocket' faunas	88
4.3 Results of principal components analysis	93
4.4 Discussion	99
4.4.1 Changes in faunal diversity	99
4.4.2 Changes in faunal density	101
4.4.3 Relative amounts of bryozoa	102
4.4.4 Implications of these trends	103
4.5 Conclusions	103
<u>Chapter 5 LITHOLOGICAL DATA</u>	106
5.1 Principal lithological components	107
5.2 Definition of terms	107
5.2.1 Cement (Spar)	107
5.2.2 Microspar	109
5.2.3 Micrite	109
5.2.4 Clotted Micrite	114
5.2.5 Bioclasts	114

	<u>Page</u>
5.3 Lithological trends in the Manifold Valley	114
5.3.1 Methods of determination	117
5.3.2 Description and discussion of trends	117
5.4 Submarine lithification	119
5.4.1 Significance in the Manifold Valley	119
5.4.2 Features recognised in recent sediments	119
5.4.3 Clotted micrite	120
5.4.3.1 Clotted micrite in the Manifold Valley	120
5.4.3.2 Origin of clotted micrites	122
5.4.4 Radiaxial fibrous spar	122
5.4.4.1 Radiaxial fibrous spar in the Manifold Valley	124
5.4.4.2 Origin of radiaxial fibrous spar	124
5.5 Lithological trends in the Belgian Waulsortian	125
5.5.1 Methods	125
5.5.2 Description and discussion of trends	126
5.6 Significance of early lithification in the Waulsortian	129
5.7 Origin of spar-filled cavities	130
5.7.1 Stromatactis cavities	133
5.7.2 Factors influencing cavity distribution	134
5.8 Depositional slopes	136
5.9 Origin of the micrite	137
5.9.1 Trapping of sediment	137
5.9.2 <u>In situ</u> production	138
5.10 Conclusions	138
<u>Chapter 6 MODERN ANALOGUES</u>	141
6.1 Partial analogues	142
6.2 Temperate water carbonates	142
6.3 Lithoherms	144
6.3.1 Description	144
6.3.2 Similarities to the Waulsortian	145

	<u>Page</u>
<u>Chapter 7 CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH</u>	148
7.1 Summary of conclusions	149
7.2 A model for the development of the Waulsortian	152
7.2.1 Sources of information	152
7.2.2 The model	152
7.3 Suggestions for further research	154
<u>Appendix 1 BOREHOLE LOGS</u>	156
Kniveton borehole	157
Alstonefield borehole	174
<u>Appendix 2 LOCALITY DETAILS</u>	194
English localities	195
Belgian localities	200
<u>Appendix 3 RAREFACTION AND DOCUMENTATION OF COMPUTER PROGRAMS</u>	206
A3.1 Rarefaction theory	207
A3.2 Rarefaction computer program	208
A3.3 SPSS programs	213
A3.4 STATUS program	213
A3.5 SPECIES program	214
<u>Appendix 4 Data</u>	229
A4.1 Faunal Data	230
A4.1.1 Faunal data lists and rarefaction coefficients	230
A4.1.2 Summary of faunal data	263
A4.1.3 Summary of means, variances and standard deviations of faunal data	264
A4.1.4. Analysis of variance tables for similarity coefficients	265
A4.1.5. Analysis of variance tables for faunal data	266
A4.1.6. Faunal lists from Shephard-Thorn (1963)	273
A4.1.7 Orientation analysis	277

	<u>Page</u>
A4.2 Lithological data	278
A4.2.1 Manifold Valley point count data	278
A4.2.2 Belgian point count data	283
A4.2.3 Analysis of variance tables for lithological data	285
<u>Appendix 5 CATHODOLUMINESCENCE PETROGRAPHY</u>	290
References	296

FIGURES

	<u>Page</u>
Fig 1.1 Carboniferous palaeolatitude map showing reported Waulsortian occurrences	5
Fig 1.2 Stratigraphic correlation chart	10
Fig 2.1 Distribution of the Belgian Waulsortian	14
Fig 2.2 Facies relationships in the Belgian Waulsortian	16
Fig 2.3 Growth forms in Waulsortian mounds	20
Fig 2.4 Trends in mound aggregation with increasing distance from shore in the Irish Waulsortian	22
Fig 2.5 Distribution of Lower Carboniferous 'reefs' in Britain	26
Fig 3.1 Locality map	30
Fig 3.2 Palaeogeography of the Derbyshire Dome in Chadian-Arundian (V1a) times	34
Fig 3.3 A. Palaeogeography in Asbian (V3b) times	35
B. Palaeogeography in Brigantian (V3c) times	35
Fig 3.4 A. Geological sketch map of the Manifold Valley	37
B. Two geological cross sections in the Manifold Valley	38
Fig 3.5 Age relationships in the Manifold Valley	40
Fig 3.6 A. Small carbonate mound draped by calcareous mudstones	42
B. Relationship between mound at Wettonmill Farm, Nan Tor and mound in layby	42
Fig 3.7 Sketch section along the River Manifold	45
Fig 3.8 Stacked mounds in outcrop and in borehole sections	45
Fig 3.9 Summary of geometrical relationships between mounds	47

	<u>Page</u>
Fig 4.1 Locations of sample sites	58
Fig 4.2 Examples of maximum dimension measurements of shells of various shapes	63
Fig 4.3 Manifold Valley sample localities arranged by geographic groups	66
Fig 4.4 Orientation of long axis directions of brachiopods and bivalves in fossil pockets	90
Fig 4.5 Comparison of a Pocket with a non-Pocket fauna	92
Fig 4.6 Summary of biostratigraphic differences in the Manifold Valley	97
Fig 4.7 Faunal composition of the Manifold Valley mounds	98
Fig 5.1 Radiaxial fibrous spar	108
Fig 5.2 Ostracode with sparry calcite fill	110
Fig 5.3 Bioclasts and intraclasts with sparry cement rims	110
Fig 5.4 Cross cutting veins	111
Fig 5.5 Mottled micrite	112
Fig 5.6 Micrite and microspar	113
Fig 5.7 Clots with cement rims	115
Fig 5.8 Micrite clots in microspar	116
Fig 5.9 Lithologic trends in the Manifold Valley	118
Fig 5.10 Intraclasts of clotted micrite in sparry cement	121
Fig 5.11 Main features of radiaxial fibrous spar	123
Fig 5.12 Lithologic trends in the Belgian Waulsortian	127
Fig 5.13 Breakdown of percentages of bryozoa and crinoid debris in Belgian point count data	128
Fig 5.14 Several varieties of radiaxial spar-filled cavities	131

	<u>Page</u>
Fig A5.1 Two stage cavity fill in plane and luminescent light	265
Fig A5.2 Late clear spar and cloudy granular spar under plane and luminescent light	266
Fig A5.3 Micrite and cloudy spar under plane and luminescent light	267

TABLES

Table 4.1 Morphological groups used for principal components analysis	65
Table 4.2 List of macrofauna reported from the Waulsortian in Britain, Eire and Belgium	68
Table 4.3 Matrix of Jaccard coefficients of association	85
Table 4.4 List of genera found in the Manifold Valley	86
Table 4.5 Summary of computer statistical and principal components runs	94
Table 4.6 Summary of principal components results	96
Table A3.1 List of cards for rarefaction computer program	209
Table A3.2 Sample of rarefaction output	212
Table A3.3 List of cards for STATUS	215
Table A3.4 Sample of output from STATUS	226
Table A3.5 List of cards for SPECIES	228

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 General description of the Waulsortian

The name Waulsortian was first used by E. Dupont in 1863 to describe a particular type of carbonate deposit in the Lower Carboniferous of southern Belgium which he distinguished by the presence of blue sparry veins. Since then the name has been applied to other micritic mounds of similar age which are thought to resemble the Belgian Waulsortian. As a result, Dupont's original definition (which is discussed in section 2.1) has become less specific. In general terms, the name Waulsortian is used to describe micritic mounds of late Tournaisian to early Visean age which lack any obvious framework-builders and are composed principally of micrite, including, but not restricted to, the 'blue vein' type. The mounds characteristically contain sparry masses, notably the flat-bottomed, digitate-topped Stromatactis cavities, (which are discussed more fully in section 5.7.1) although other sorts of cavities are present as well. The most frequently noted faunal elements are fenestellid bryozoa and crinoid debris. A diverse fauna of brachiopods, bivalves, gastropods, cephalopods and trilobites is also present (see section 4.1.1). However, because the faunal density is rather low and the distribution of the fossils often patchy (Lees et al., 1977) many workers have commented on the rarity of macrofauna (e.g. Parkinson, 1950; Prentice, 1951).

1.2 The term reef

1.2.1 Definition

The carbonate mounds which comprise the Waulsortian facies have frequently been referred to as reefs (e.g. Dixon, 1921; Demanet, 1923;

Parkinson, 1926; Lees et al., 1977). The meaning and use of this term has been much discussed in the geological literature (see for example Cummings, 1932; Ladd, 1944; Newell et al., 1953; Dunham, 1970 and many others). After a comprehensive review of the literature Heckel (1974) proposed that a reef should be defined as a circumscribed body which displays topographic relief above equivalent sediments, and differs from typically thinner equivalent deposits and surrounding and overlying rocks. It also displays evidence of potential wave resistance or, growth in turbulent water which implies wave resistance, and evidence of control over the surrounding environment.

1.2.2 Inapplicability to the Waulsortian

Lees (1961, 1964) and Lees et al. (1977) clearly point out the inapplicability of the term reef to the Waulsortian by showing that the Waulsortian, because of its lack of current-structures and typical occurrence in what is assumed to be deeper water sediments combined with its lack of organisms capable of building a rigid wave-resistant framework, shows no evidence of growth in turbulent water. Furthermore, although a relationship may exist between the mound and off-mound sediments, the Waulsortian appears to have had little or no direct influence on its immediate surroundings (see sections 2.1, 2.2, 2.3) and thus shows no evidence of control over the surrounding environment.

1.2.3 Alternative terminology

Occasionally new terminology has been introduced to describe the Waulsortian (e.g. Philcox, 1971), but for the purpose of this thesis it is felt that the use of unfamiliar and often cumbersome terminology (as suggested, for example, by Riding, 1977) may serve only to obscure the real problems concerning Waulsortian development.

1.2.4 Terms used in this thesis

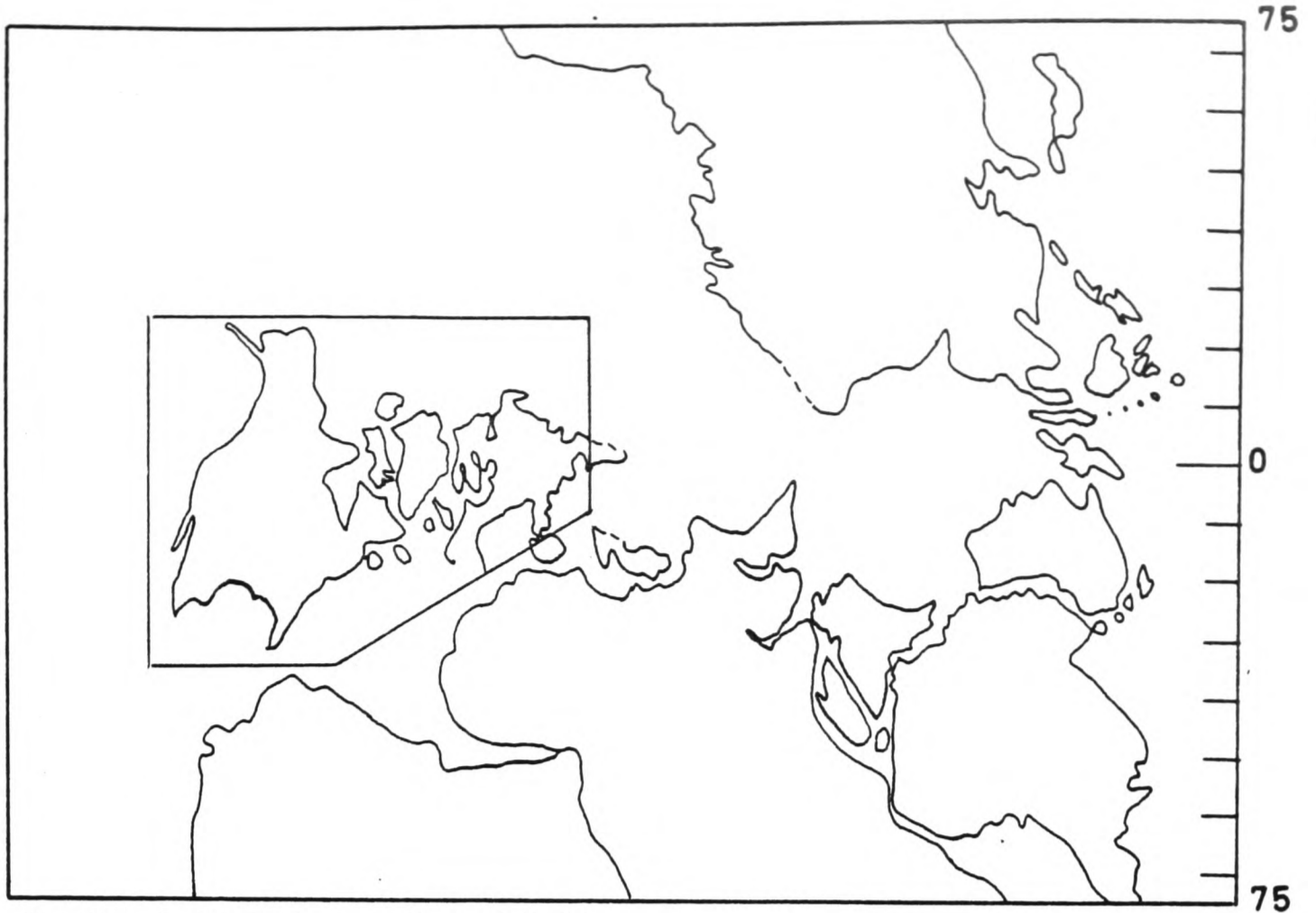
Therefore, in this thesis, the terms carbonate mound, and micritic mound, are used synonymously to describe the Waulsortian because it can be shown firstly (following the definition of Heckel, 1974) to differ in nature to some degree from equivalent deposits and surrounding and overlying rocks; secondly to be typically thicker than equivalent carbonates, and, thirdly, to have probably stood topographically higher than the surrounding sediment during some time in its depositional history (see Chapter 2). Occasionally, following the precedent set by Lees (1961, 1964), the term reef is used in inverted commas with the modifier Waulsortian (i.e. Waulsortian 'reef') to avoid confusion when references are made to the older literature where the term Waulsortian reef is commonly used.

1.3 Distribution and palaeogeography of Waulsortian 'reefs'

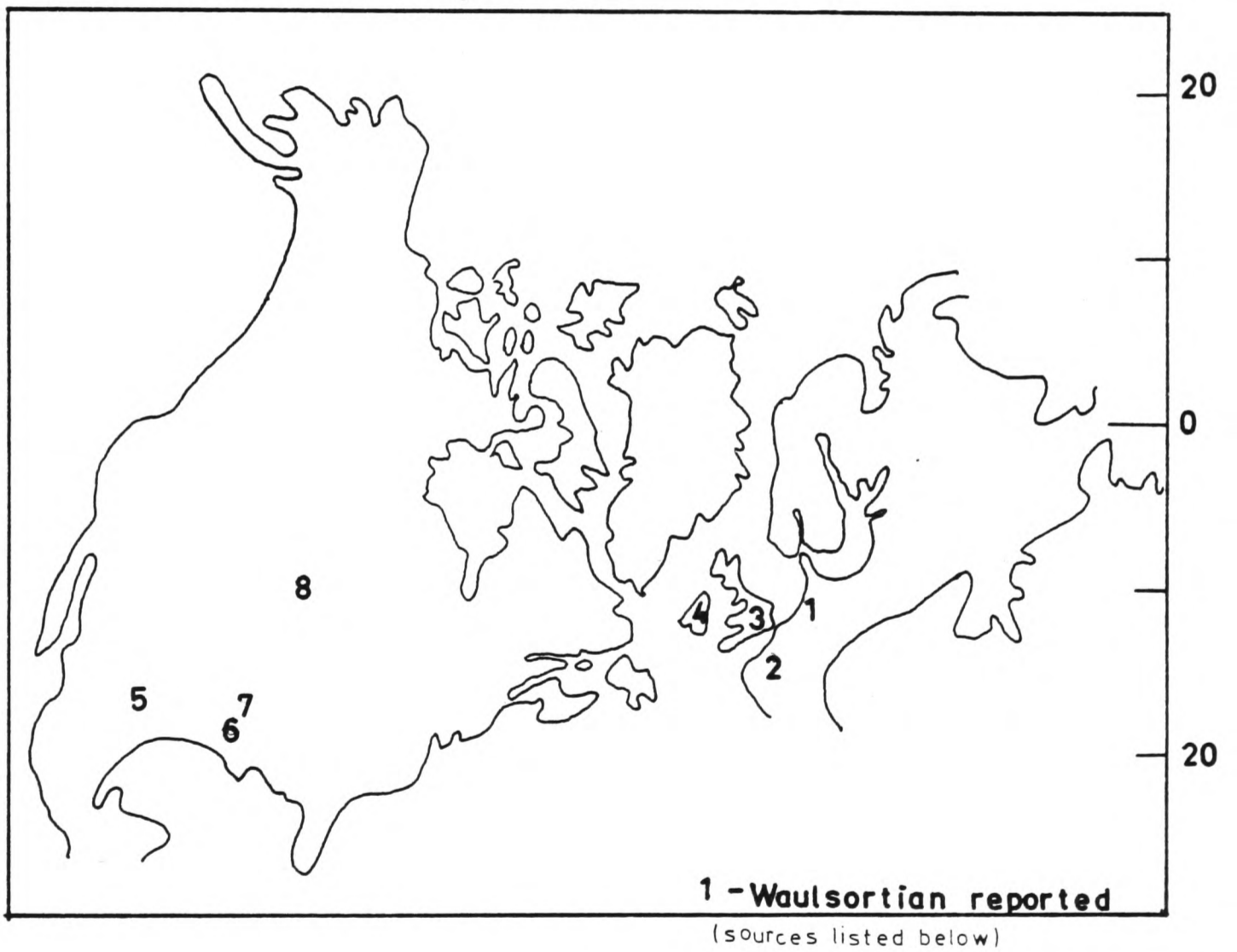
Waulsortian 'reefs' have been recognised in Belgium, France, England, Ireland and North America. Their distribution is shown in figure 1.1.

Palaeogeographically Waulsortian 'reefs' normally occur below the edges of shelves or in basins (Wilson, 1975) but not as a transitional facies between shelf and basin (see Chapter 2, especially section 2.3). Some evidence exists of structural control of the facies in that the upward growth of the mounds may have been partially controlled by subsiding blocks.

Recognisable algal remains are largely lacking from the mounds. The unsorted mixture of lime-mud and sand-sized bioclasts which comprises the mounds, along with the lack of observable current bedding and the absence of size-sorting and preferred orientation in fossil accumulations (see section 4.4.5) suggests a low energy depositional



Map after Smith, Briden and Drewry (1973)



- | | |
|--------------------------------------|------------------------------|
| 1. Belgium (Dupont, 1863) | 5. New Mexico (Pray, 1958) |
| 2. France (Delepine and Milon, 1923) | 6. Texas (Turner, 1957) |
| 3. England (Dixon, 1921) | 7. Oklahoma (Harbaugh, 1957) |
| 4. Ireland (Douglas, 1909) | 8. Montana (Cotter, 1965) |

Figure 1.1 L. Carboniferous palaeolatitude map showing reported Waulsortian occurrences.

environment. These features have led to the supposition that Waulsortian mounds developed in relatively deep water, possibly below the photic zone, but above the carbonate compensation depth (Wilson, 1975).

1.4 Description of Waulsortian 'reefs'

Waulsortian 'reefs' are therefore considered to represent deep water carbonate mud mounds, often of large size and possessing depositional slopes which are commonly more than thirty degrees, and may be up to fifty degrees (Lees, 1961). They lack framework-building organisms and are rather sparsely populated. The carbonate sediment is assumed to have been produced locally because the surrounding sediments are often very different from the sediments which make up the mounds (see for example Lees et al., 1977).

1.5 Understanding the Waulsortian

1.5.1 Major problems

Some of the major unsolved problems in the Waulsortian include: the absence of framework-builders and doubts as to the ability of the organisms present to have provided baffles or sediment binders sufficient to explain the formation of mounds of such large size and with such steep depositional slopes; the source of the enormous quantities of very pure carbonate mud present; the origin of the various types of sparry masses; the absence of sedimentary reef breccias and the fact that Waulsortian 'reefs' have had little or no direct influence on their immediate surroundings (Wilson, 1975; Lees et al., 1977).

1.5.2 Relevance to other geological settings

Answers to the above problems are relevant in many geologic settings because build-ups composed chiefly of lime-mud and lacking framework-building organisms are common throughout the geologic record (Wilson, 1975). Small Cambrian micritic mounds occur in eastern California (Morgan, 1976). Large carbonate mounds with Stromatactis and other sparry masses occur in the Ordovician of Nevada (Ross et al., 1975); the Devonian of Alberta (Philcox, 1965), of the eastern United States (Heckel, 1973), of the Spanish Sahara (Dumestre and Illing, 1967) and of Southern Belgium (Lecompte, 1957); parts of the Silurian 'reefs' of the central United States (Lowenstam, 1950) and in the Upper Cretaceous of France (Kennedy and Juignet, 1974) to name but a few of many possible examples. Lime-mud build-ups have also been recognised in recent environments; for example in Florida Bay (Stockman et al., 1967; Neumann et al., 1977), British Honduras (Pusey, 1964) and Western Australia (Davies, 1970).

Whatever their age or exact faunal content the understanding of carbonate mounds faces several basic problems which are as yet unsolved. These include the source of the carbonate sediment, the mechanism of its accumulation and its preservation in a mound-shaped form, and the nature of the factors which influence their localisation. A better understanding of the Waulsortian 'reefs' which are among the most conspicuous of lime-mud build-ups (Heckel, 1974) should lead to a better understanding of carbonate mounds in general.

1.6 Topics emphasized

This thesis looks at Waulsortian mounds from a palaeoecological point of view. Palaeoecology is used here to mean the study of the organisms present, their relation to each other and their relation to

and effect upon the environment in which they lived. There are two main reasons for choosing a palaeoecological approach to this problem. Firstly, purely sedimentological studies have left many questions unanswered. Because most carbonate sediment is organically produced and because it is well known that organisms are very sensitive to their environment, it is logical to examine organisms, particularly their morphological adaptations and patterns of co-occurrence in order to understand more about depositional environments. Secondly, although palaeoecology is potentially a very valuable aid in the study of depositional environments, there are many problems associated with the technique itself. During the course of this research many methods have been tried in order to find the most effective ways of collecting, handling and objectively interpreting data.

The above paragraph notwithstanding, sedimentology, carbonate petrography and field observation, both detailed and reconnaissance, have been very important elements of this study. The problem lies not in obtaining field and lithologic data, but in finding an interpretational framework on which to organise them. Darwin's comment "How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service" has great relevance in this study. Most often hypotheses suggested by palaeoecological interpretation of the fauna have provided the basis for interpretation and gathering of mapping and sedimentological data.

1.7 Methods used in this study

1.7.1 Lower Carboniferous stratigraphy

Meaningful work on the Waulsortian must be based on studies of several different occurrences because the facies is incompletely

represented in any one area. In order to compare the various localities a knowledge of Lower Carboniferous stratigraphy is essential. Figure 1.2 shows the stratigraphic correlation chart used for the purposes of this study. At the present time the Belgian stratigraphic system is the most refined and is used whenever possible in this thesis. Where stratigraphic information in England and Ireland is not precise enough to permit the use of Belgian zonation, the British system of the original authors is used and figure 1.2 may be consulted to find approximate equivalence in Belgian zones.

1.7.2 Field work and sampling

Detailed field mapping and faunal and lithological collecting was done in the Manifold Valley, north Staffordshire. Further reconnaissance field work and sampling was done in the Meuse Valley in southern Belgium and field trips were made to Eire and to Derbyshire and Yorkshire in England in order to provide a broad basis for comparison of the similarities and differences of the Waulsortian in different geological settings.

1.8 Organisation of this thesis

This thesis begins with a description of the principal Waulsortian outcrops in Belgium, Eire and England and a presentation of the major models so far developed. The data derived from detailed mapping and faunal and lithological study in the Manifold Valley, as well as from more limited collecting and lithological studies in Belgium, are presented and analysed in the succeeding three chapters. A discussion of modern analogues for the Waulsortian follows. The thesis ends with a summary of conclusions derived from this study and suggestions for further research.

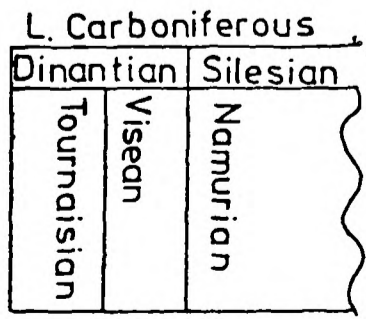
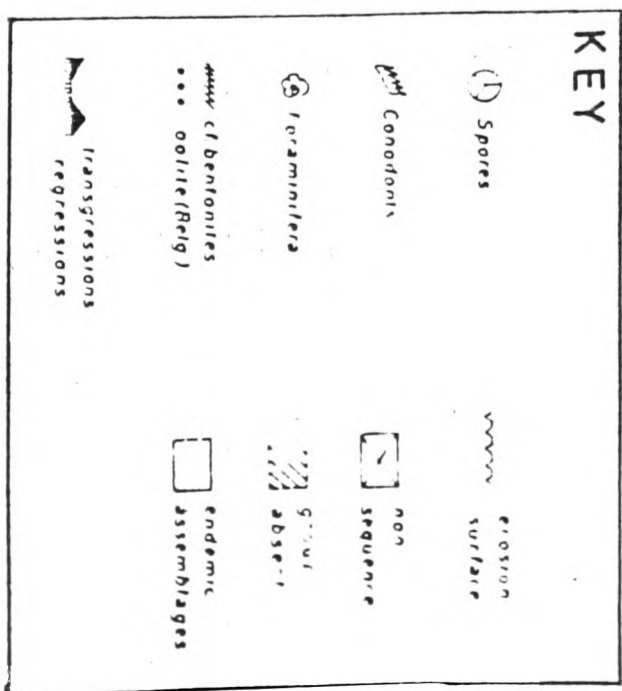
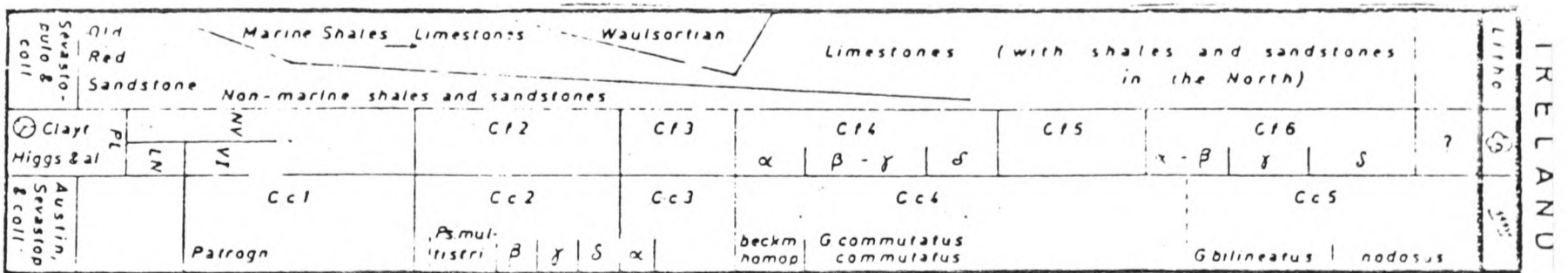
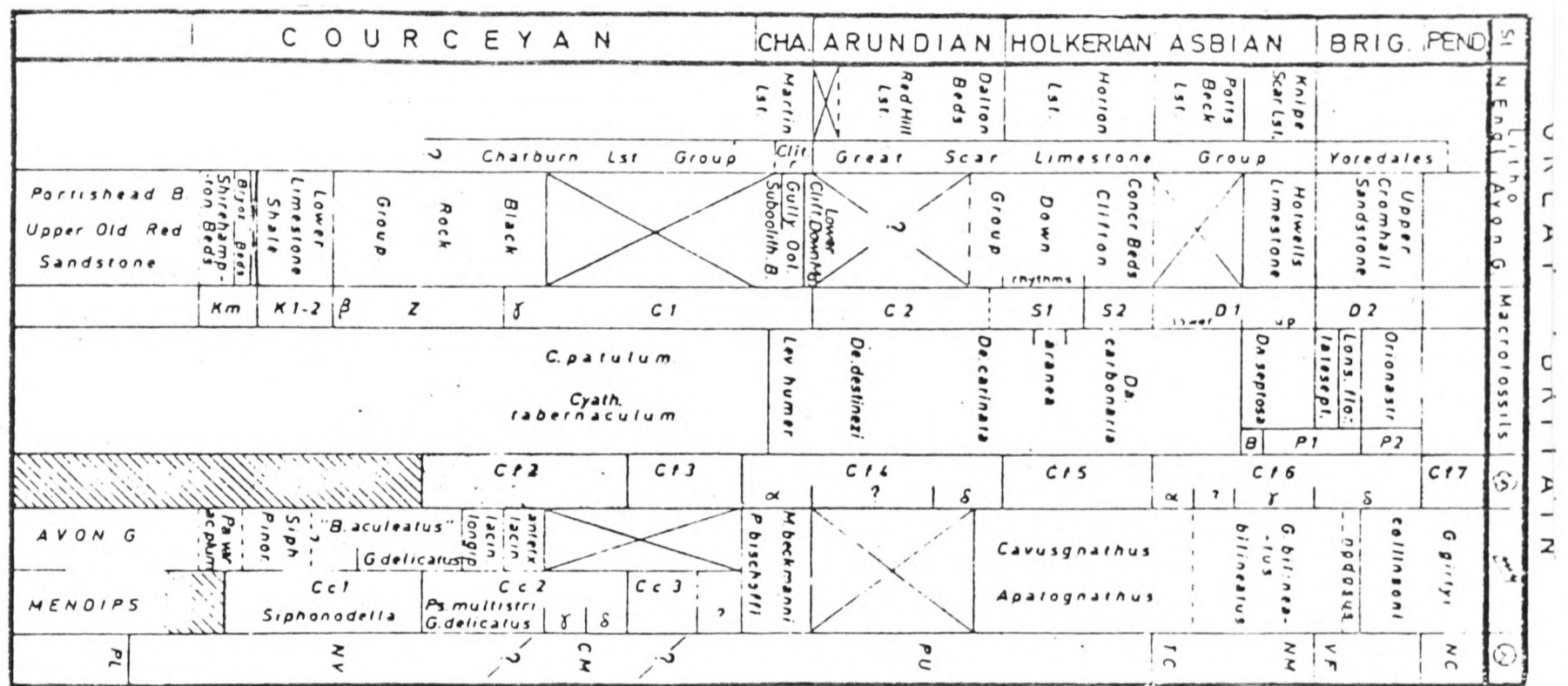
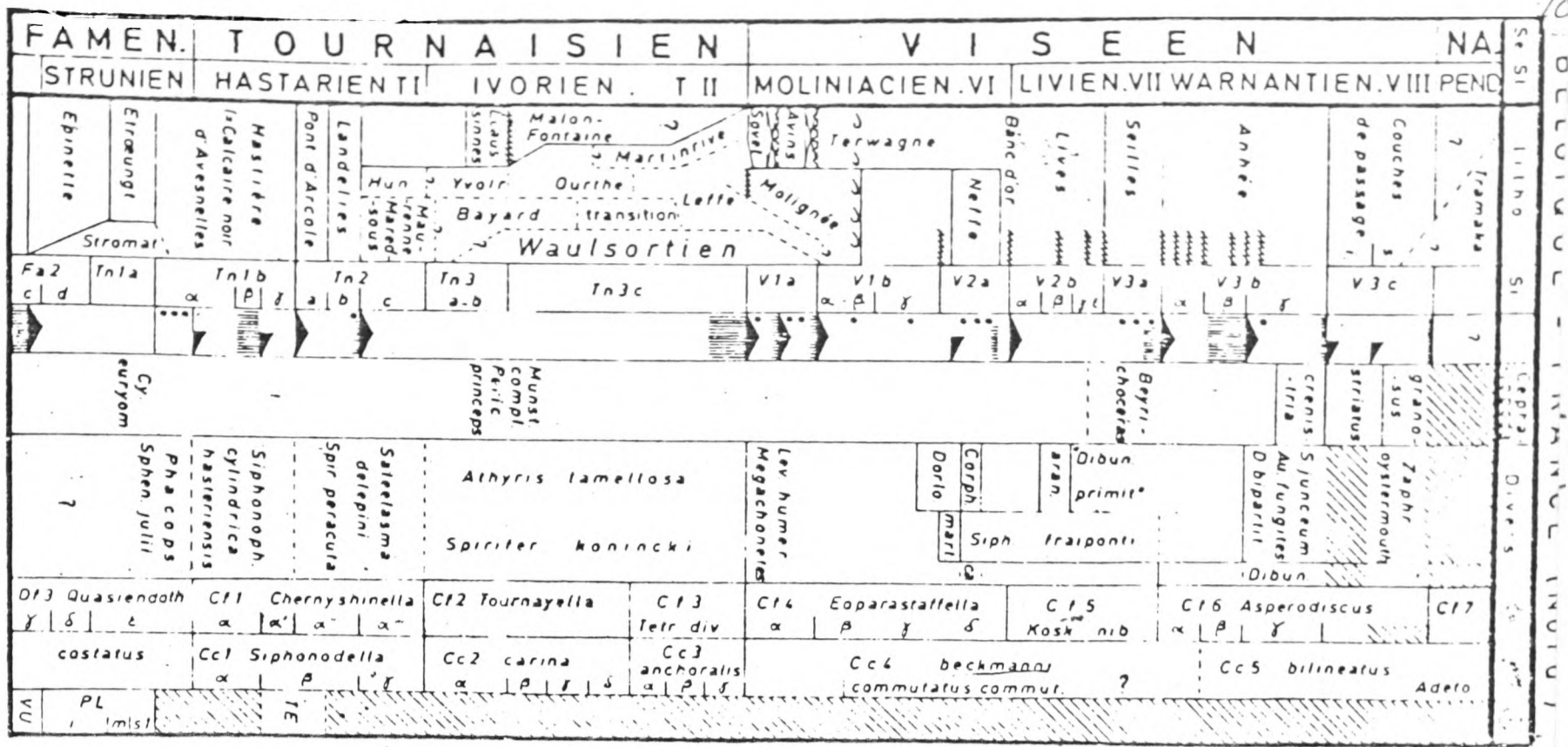


Figure 1-2
Stratigraphic correlation chart
 References:
 Confl, R., Austin, R., Bless, M., Dil, N., Groessens, E., Lees, A., Lögnerstae, D., Lys, M., Paproth, E., Pilet, H., Polty, E., Ramsbottom, W., Sevastopulo, G., 1976. International correlation of Dinantian Strata. Chart compiled at Louvain-la-Neuve.

CHAPTER 2

KNOWLEDGE OF THE WAULSORTIAN DERIVED FROM PREVIOUS STUDIES

2 KNOWLEDGE OF THE WAULSORTIAN DERIVED FROM PREVIOUS STUDIES

2.1 The Belgian Waulsortian

2.1.1 Recognition of the Waulsortian and subsequent studies

The Waulsortian facies was first described from the Meuse Valley in southern Belgium by E. Dupont (1863) in a paper which defined stratigraphic units in the Carboniferous Limestone of Belgium. He described a rock type which "se compose d'un calcaire grenu, à teinte ordinairement pâle. Son caractère pétrographique principal est de contenir des noyaux de spath radié entourés d'un bord bleu foncé." (is composed of a granular limestone, normally of pale colour. Its principal petrographic characteristic is that it contains centres of radiating spar, surrounded by a dark blue border). He believed that this unusual lithology had stratigraphic significance, and named the unit *Asisse de Waulsort*, after a nearby village. It was defined as level four in his six level stratigraphic scheme for the Lower Carboniferous.

Dupont's stratigraphic system was greatly debated in his own time. Eventually he modified his views and divided the Lower Carboniferous into three stages (*étages*); the *Tournaisien*, *Waulsortien* and *Viséen*. Dupont found many places where the *Tournaisian* and the *Visean* were in contact, but developed the idea of local unconformities (*lacunes*) to explain this.

In 1888 de la Vallée-Poussin contested this new scheme. He showed that the *Tournaisian* was immediately succeeded by the *Visean* without a break in sedimentation and that the *Waulsortian* 'stage' occurred sometimes in the *Tournaisian* and sometimes in the *Visean*; thus it could not be a time stratigraphic unit.

Since then the Belgian Waulsortian has been the subject of numerous studies, including further work by E. Dupont (1865, 1883) and papers by Dorlodot (1893), Demanet (1923, 1958), H. Dupont (1969), Bouw (1971), Noel (1973), Lees et al. (1977) and others.

2.1.2 Expanded definition of the Waulsortian

As a result of this work and of the recognition of similar facies in the Lower Carboniferous of Europe and North America, Dupont's initial definition of the facies has been greatly expanded.

It has been recognised that the Waulsortian is a carbonate mound facies which extends from Tn3 through Vla (Demanet, 1923, 1958; Conil and Dupont, 1965; Dupont, 1969; Bouw, 1971; Noel, 1973; Lees et al., 1977). However, individual mounds do not necessarily cover this whole range. The mounds vary greatly in size and have been reported up to more than 1 km across and 350 m thick (Wilson, 1975; Lees et al., 1977). In Belgium, Waulsortian rocks are mainly restricted to the Dinant synclorium (figure 2.1).

Dupont's original statement of the definitive characteristics of the Waulsortian (1863; see previous page) has proved very difficult to apply both in Belgium and elsewhere because rocks with blue sparry veins are often intimately associated with non-blue vein limestones which seem to be closely related in both time and space. Most subsequent authors seem to use a somewhat broader definition of the Waulsortian and include the closely related massive or crudely stratified non-blue vein limestones in the mound facies (for example see Demanet, 1923; Dupont, 1969). Until recently no clear statement of the nature and stratigraphic range of the Belgian Waulsortian, which is considered the type area for this sort of carbonate mound, has been attempted.

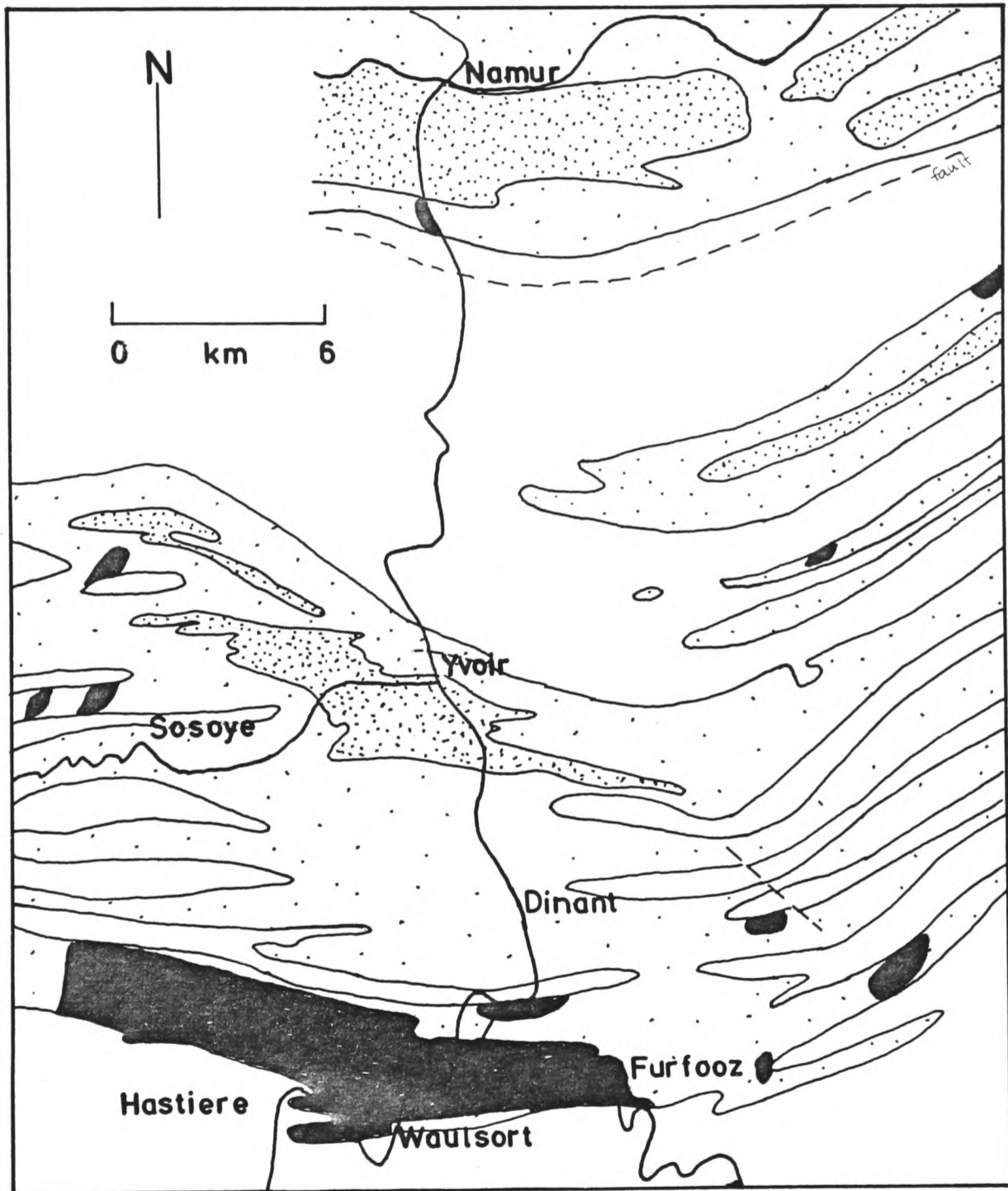
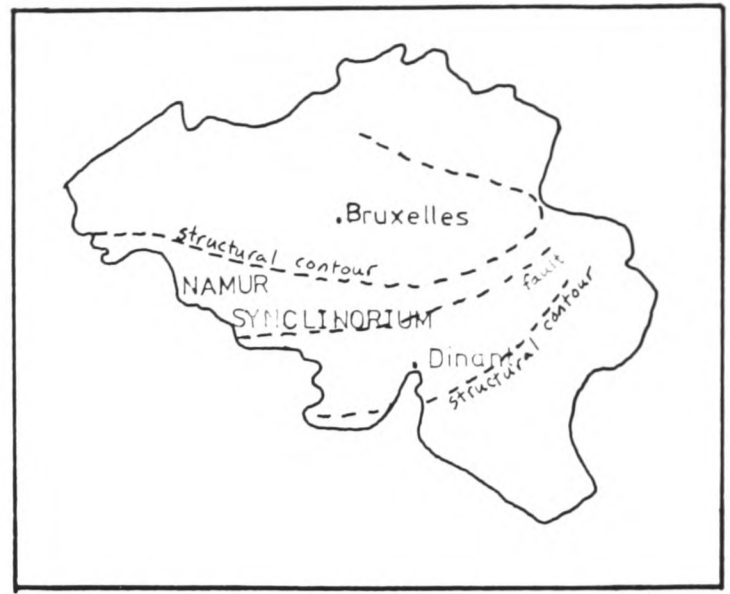
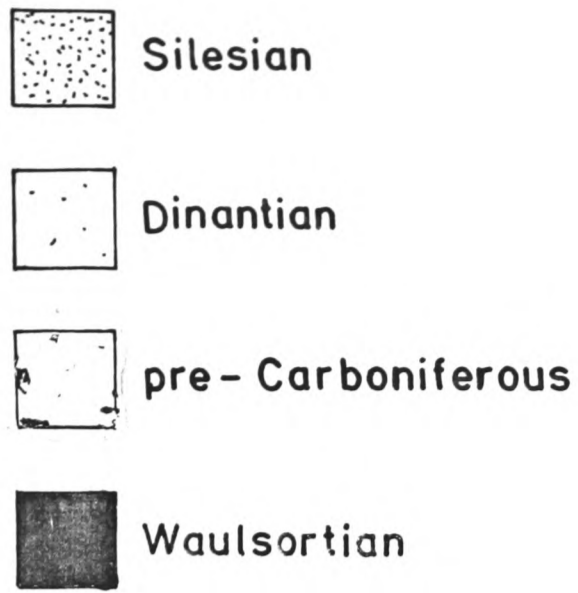


Figure 2-1 Distribution of the Belgian Waulsortian

2.1.3 The findings of Lees, Noel and Bouw (1977)

A recent study by Lees et al. (1977) describes in detail many features of the Belgian Waulsortian, presents a model of its lithological relationships and suggests some ideas to explain its development. The following discussion is based on their paper.

Figure 2.2, which is taken from figure 2 and figure 11 of their paper, summarises the relationships found by Lees et al. (1977). They divide Waulsortian development into three phases which they relate to three off-'reef' facies. The off-'reef' facies include: the Bayard (well-bedded, grey crinoidal and bryozoan biomicrites and biomicrudites, often cherty); the Leffe (well bedded micrites and biomicrites, which have a higher percentage of micrite and smaller-sized skeletal debris than the Bayard, as well as intraclasts and peloids at some levels); and the Leffe-Molignée (the normal Leffe facies with a lateral equivalent of black and grey, sometimes cherty limestones arranged in sequences of alternating platy and massive beds).

Lees et al. regard the Bayard Facies as the 'normal' facies in which the mounds grew. The contact between the Bayard and the Leffe is gradational rather than sharp. Although the converse is not necessarily true, the presence of the Leffe seems to be related to the presence of the Waulsortian, but the nature of the relationship is not understood. The Molignée contains allochems similar to those found in the Leffe and the contact between the two units is again gradational.

The off-'reef' facies are thought to correspond to phases in the development of the mounds themselves. The Bayard is associated with phase A (see fig 2.2) which is often thought of as being the typical Waulsortian lithology. It consists of the blue vein limestone and is largely composed of sparry calcite which fills cavities of various shapes and outlines fronds of fenestrate bryozoa. Often associated with this

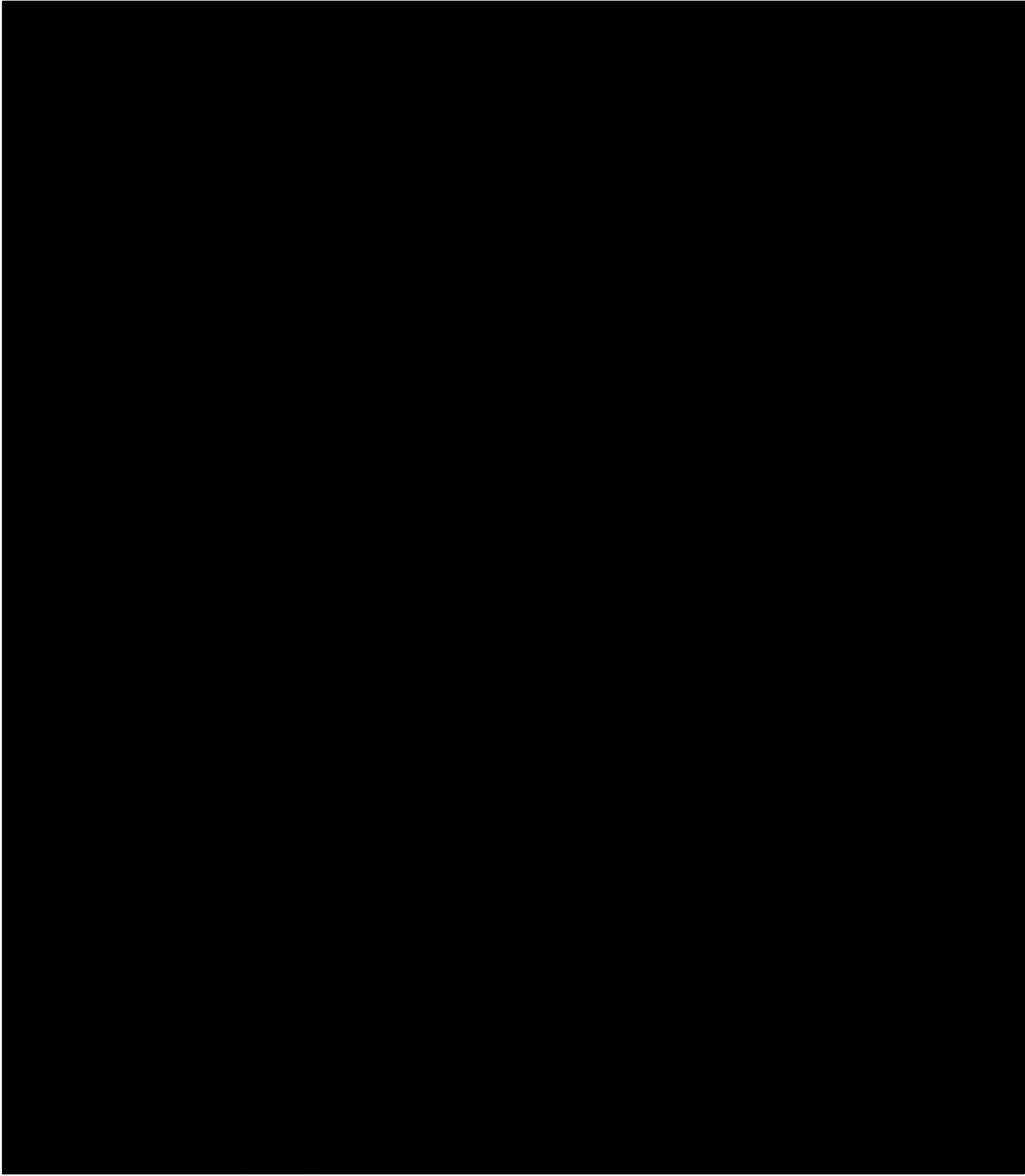


Figure 2.2 Facies relationships in the Belgian Waulsortian
(Lees et al. (1977) figs. 2 & 11)

facies are crinoid-rich biomicrites and biomicrudites which are sometimes grain supported. After allowing for compaction, there is a high mound to off-mound thickness ratio between the phase A Waulsortian and the Bayard (approximately 6:1) and depositional slopes are often 25 degrees or more.

In both phases B and C the mound to off-mound thickness ratio decreases, though it is always greater than 1:1.

There is a marked change of lithological facies within the Waulsortian at the beginning of phase B. The blue vein limestone greatly decreases and occurs only as pods in a mainly pale grey biomicrite. Crinoid debris, sparry masses and fenestellid fronds are much less common.

Higher in the mound the blue vein lithologies tend to die out. Phase C is made up almost entirely of the pale grey biomicrite similar to that found in phase B.

Using this lithologic model as a basis, Lees et al. make a number of suggestions concerning the mode of development of the Waulsortian. They believe that the mounds grew by local production of carbonate mud (as opposed to trapping sediment produced elsewhere) and that phase A represents the time of optimum mound growth. They feel that the rates of mud production were similar in each of the three phases, but that the mechanism for retaining mud was less effective in the later stages. This they relate to changes in effective energy levels, believing phase A to represent a time of low energy on the sea floor, and phases B and C to represent periods of increased energy levels. They conclude that Waulsortian mounds were soft surfaced mud mounds whose sediment was produced locally.

2.2 The Irish Waulsortian

2.2.1 Principal studies

The similarity between the Irish 'lower unstratified limestone' and the Waulsortian 'reefs' of Belgium was first noted by Douglas (1909), but the name Waulsortian does not seem to have been directly applied to these limestones until the work of Delepine (1940). Since the initial recognition by Douglas, the Irish Waulsortian has been the subject of numerous published studies including contributions by Turner, (1937, 1938a and b, 1962); Delepine (1940, 1949, 1951); Neville (1958); Schwarzacher (1961); Lees (1961, 1964); Shephard-Thorn (1963); Hudson et al. (1966) and Philcox (1963, 1971).

2.2.2 Extent of the Irish Waulsortian

The Waulsortian attains its greatest European development in central Ireland where it forms a continuous complex. Eastwards it passes into shelf facies bioclastic limestones, oolites and dolomites. Southwards it passes abruptly into an offshore clastic facies (Lees, 1964; MacDermot and Sevastopulo, 1972).

In Ireland the Waulsortian was deposited from Tn3 to V1b times (Delepine, 1949; Turner, 1962; Shephard-Thorn, 1963; Hudson et al., 1966). Both the base and the top of the complex are thought to be diachronous (George, 1958). The complex may have originally covered 18,000 km² (Lees, 1961), but the thickness developed was not uniform over this area. There are two centres of deposition where the Waulsortian is exceptionally thick: near Limerick, where an estimated 1200 m is present (Shephard-Thorn, 1963); and near Cork, where a similar thickness is thought to occur (Lees, 1961).

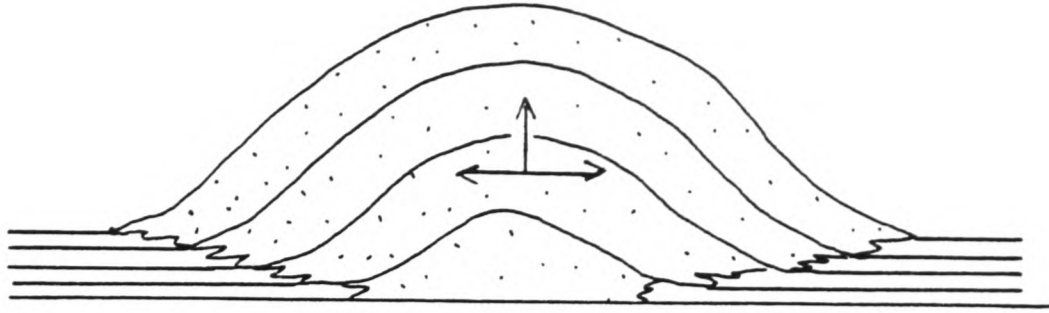
Faunal collections in the Limerick area reveal faunas of Tn3 age (Shephard-Thorn, 1963) and less complete information from the Cork area suggests that Waulsortian rocks of Tn3 age may also be present there

(Delepine, 1949). The presence of relatively old Waulsortian rocks in the two areas of maximum thickness gives rise to the supposition that these were the two areas where growth began (Lees, 1964).

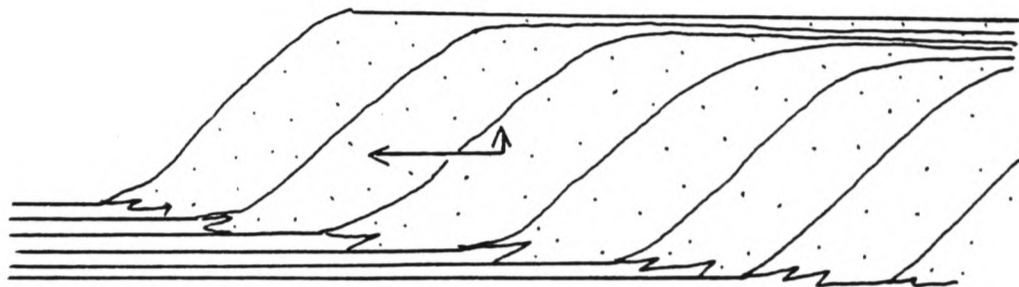
2.2.3 Geometry of the mound complex

Measurement of the attitude of sparry calcite masses and growth surfaces defined by shaley partings, layers of skeletal debris and other lithological changes, has allowed the elucidation of several growth forms within the complex. Lees (1961, 1964) distinguished a spectrum of variation in mound external morphology in the north-central part of the complex in which sheet-form and knoll-form mounds (see figure 2.3a) comprise the end members. In the southern part of the complex Whitbread (1963) recognised a different growth geometry which he termed blanket-form (see figure 2.3b). Similar blanket-form growth has been documented by Philcox (1971) in the south-central part of the complex. The controls on bank geometry are thought to have been 1) the shape of the surface on which growth started 2) the relative positions of the growth centres 3) the growth vectors associated with the various geometries 4) relative rates of bank and off-bank sedimentation (Lees, 1964; Philcox, 1971).

Lees (1964) believes that the complex grew by aggregation of banks, mainly of the knoll-form. Sheet-form banks apparently do not enter into the normal sequence of the complex development. They seem to have been dominant when conditions favoured rapid spread of the mudbanks into areas formerly the site of lagoonal sedimentation, and they are commonly found where the main complex is thin. Lees outlines a growth sequence which shows increasing aggregation of knoll-form mounds from the lagoonal areas, where isolated knolls are found, towards the centre of the complex, where knoll-form mounds are highly aggregated (see

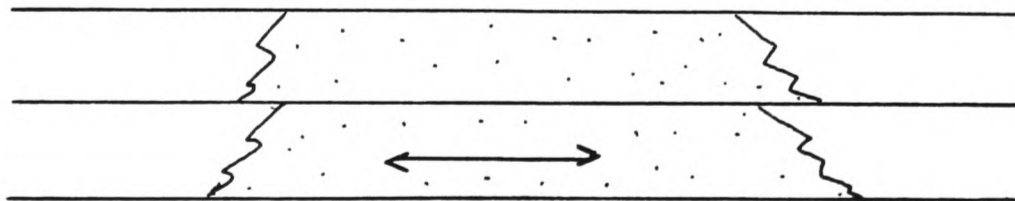


Knoll form



Sheet form

A.



Blanket form

B.

Figure 2-3 A & B. Growth forms in Waulsortian mounds. Arrows indicate relative rates and directions of growth. (compiled from Lees (1961) and Whitbread (1963))

figure 2.4). He relates this trend towards increasing aggregation to increasing distance from shore, increasing thickness of Waulsortian rocks and decreasing proportions of terrigenous sediment in the central part of the complex.

The presence in the southern part of the complex of blanket-form mounds which show very little topographic relief is not predicted by this model. The difference between these forms and the knoll-forms is thought to be a higher rate of micrite deposition in the off-mound sediments associated with them (Philcox, 1971). Whether this higher rate of off-mound sedimentation is due to increased erosion of the mounds or to some other source is not clear, but the end result is a high ratio of off-mound sediments to mound thickness. Decrease of the proportion of terrigenous sediment in Lees' model would seem to imply decreasing proportions of off-mound or intermound bedded sediments. Therefore, Lees' model predicts how growth forms will develop under conditions of relatively low off-mound sedimentation, but does not explain how high off-mound sedimentation rates might affect mound geometry.

2.2.4 Conclusions derived from studies of mound geometry

In general, studies of mound geometries in the Irish Waulsortian have led to the conclusion that external mechanical factors, such as sedimentation rates and distance from shore are the main controls on bank geometry and that further study of bank geometries and off-mound sediments will lead to a better understanding of Waulsortian development (Lees, 1961, 1964; Whitbread, 1963; Philcox, 1971).

2.3 The British 'reef'-knolls



Figure 2-4. Trends in mound aggregation with increasing distance from shore in the Irish Waulsortian (compiled from Lees(1964) and MacDermot and Sevastopulo (1972))

2.3.1 Comparison with the Belgian Waulsortian

The British 'reef'-knolls were first compared with the Belgian Waulsortian by Dixon (1921) who likened the petrographic characteristics of the 'reef'-dolomite in the Lower Carboniferous of Pembrokeshire, Wales with the 'reef'-knolls of Clitheroe, Lancashire and with the Belgian Waulsortian. Because of the many controversies over various aspects of the 'reef'-knolls, Dixon's comparison has often been misunderstood.

2.3.2 Definition of the term 'reef'-knoll

The term 'reef'-knoll was introduced by Tiddeman (1889, 1890, 1892, 1900) in his description and interpretation of the limestone hills which form prominent topographic features in NW Yorkshire and NE Lancashire. Features such as the rapid change in thickness in the knoll limestone, the lack of well defined stratification, and the fact that beds dip away from the knolls on all sides, a feature which he interpreted as representing original dips, led him to suggest that the knolls represented reefs growing up on a sinking sea bottom from the life and death of the animals of whose remains they are composed' (Tiddeman, 1889, p.602).

2.3.3 Controversies over the origin of 'reef'-knolls

This interpretation led to two long running controversies: whether the knolls represented original depositional features, and if so, did they represent reefs.

Many workers believed that the knolls were of secondary origin; either tectonic (Marr, 1899; Wilmore, 1907), erosional (Hudson, 1930, 1932) or formed by a combination of the two processes (Bond, 1950 a).

Support for Tiddeman's belief of a primary depositional origin

came from, among others, Vaughan (1916); Dixon (1921); Garwood and Goodyear (1924); Parkinson (1926, 1935, 1936, 1944, 1950) and Black (1950, 1954). Tiddeman's hypothesis is now the generally accepted one (Parkinson, 1957).

Tiddeman was of the opinion that the knolls represented reefs and several later authors including Bond (1950 b, c) and Parkinson (1957, 1964) agreed with this view. However, dissenting ideas were expressed by Geikie (1903) who noted that the 'reef'-knolls appeared to be due to the irregular aggregation of submarine debris in situ, but that true reef structure could not be detected. This view was supported by Dixon (1921) and Black (1954). In more recent literature some of the 'reef'-knolls are referred to as reefs (for example the Castleton apron-reefs referred to by Wolfenden, 1958; Simpson and Broadhurst, 1969; Broadhurst and Simpson, 1973; Timms, 1978 and the Craven reef belt referred to by Mundy, 1978). Others, such as the knolls at Clitheroe (Miller and Grayson, 1972) and the Lower Visean carbonate buildups in N. Staffordshire and S. Derbyshire (Thach, 1965) are not considered to represent reefs. The inapplicability of the term to the carbonate buildups examined in this thesis has been discussed in section 1.2.2.

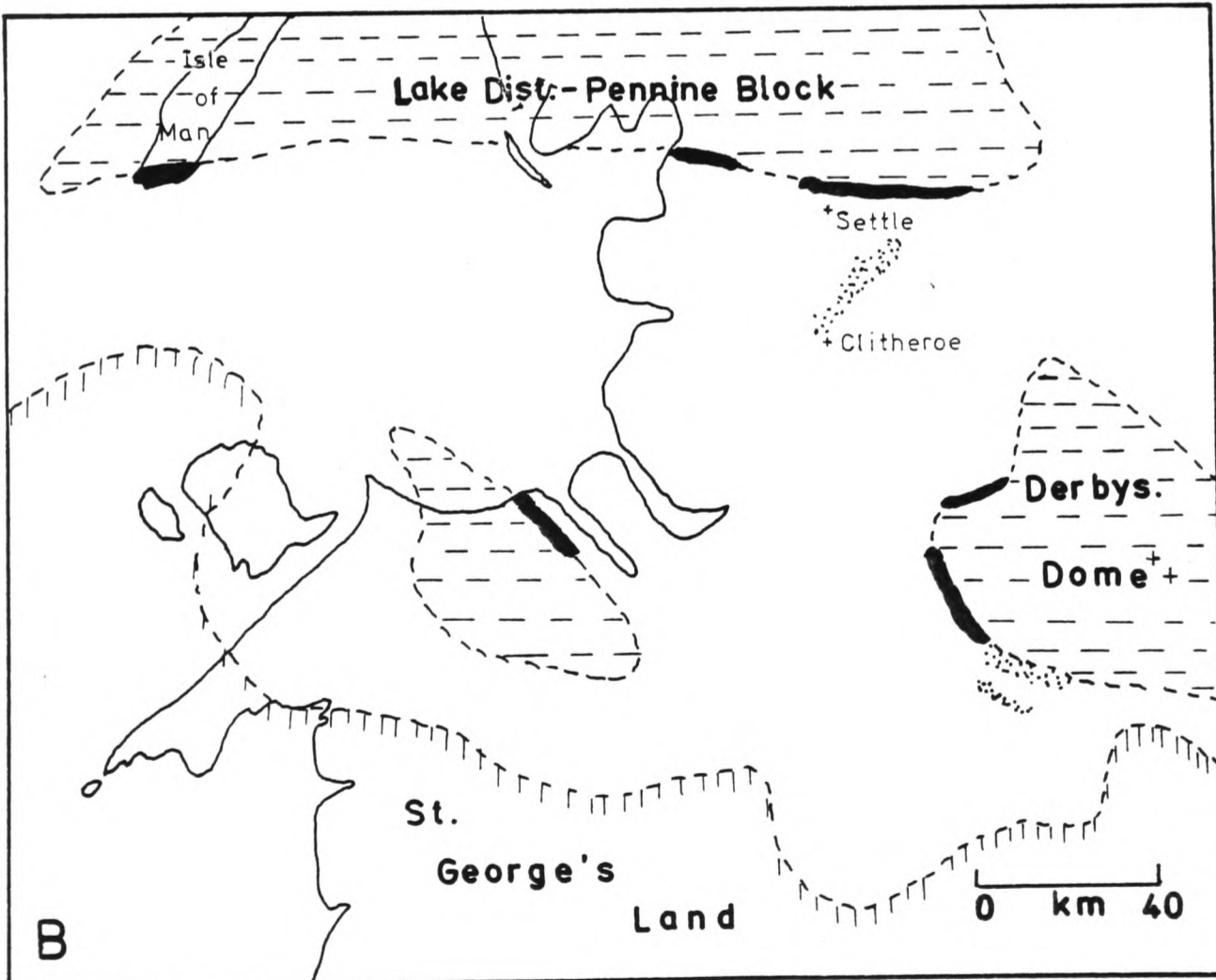
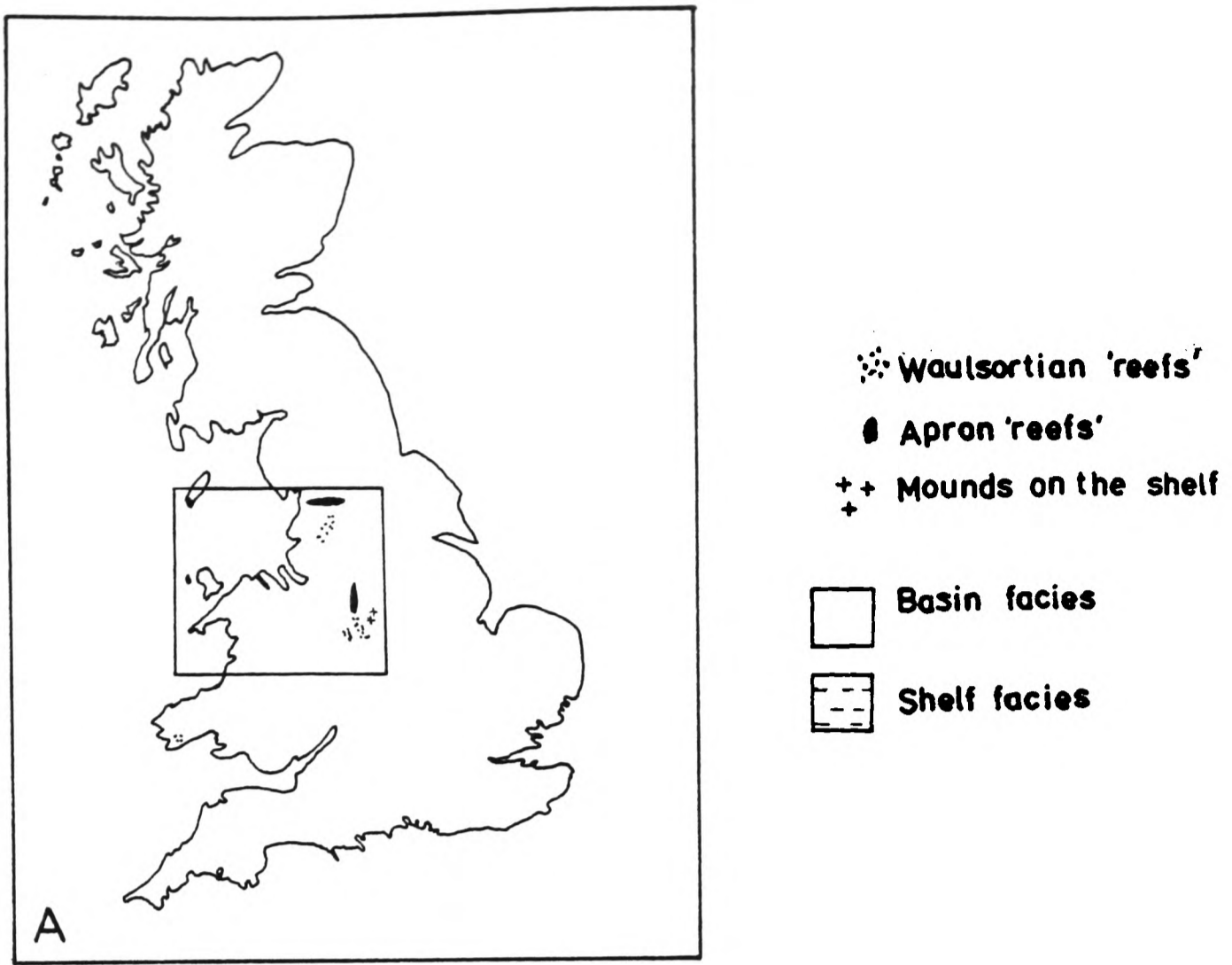
2.3.4 Recognition of shelf marginal and basinal 'reef'-knolls

Hudson (in Parkinson, 1950, p.291) and Bond (1950) recognised two main occurrences of 'reef'-knolls: marginal to shelf edges, and in the basins (there are in fact 3 main occurrences. See section 3.3.2). This distribution was commented on by Black (1954) who noted that the basinal knolls were generally the older of the two; and Parkinson (1957) supports this view (although he previously implied this in his 1950 paper). Comments were made concerning the different shape of the 'reef'-knolls from the different settings (for example

Black, 1954), but the idea that these differences might reflect different modes of origin was generally ignored. This has resulted in comparisons between essentially unrelated phenomena and led to great confusion among those not greatly familiar with British stratigraphy. A recent essay by Wilson (1975) makes it clear that the existence in Britain of separate L. Carboniferous carbonate mound developments of dissimilar origin is not well known. The distribution of the shelf marginal and basinal mounds is shown in figure 2.5.

2.3.5 Differences between shelf marginal and basinal 'reef'-knolls

As indicated by Black (1954) the shelf edge buildups are somewhat younger; roughly D1 to D2 age as opposed to approximately C1 to C2S1 age of the basinal mounds. However, a few of the basinal mounds may extend into the D zone (see section 3.4.1). It is the shelf edge buildups which are most often referred to as reefs (see the last paragraph but one) and this reflects some of the important differences between the two types. These differences include the presence in the shelf edge buildups of a recognisable framework community including an algal framework in some instances (Mundy, 1978), seemingly higher faunal density and greater faunal diversity as compared with the basinal mounds; a bathymetric range of at least one hundred metres which supported contemporaneous faunal communities of very different character (Broadhurst and Simpson, 1973; Timms, 1978); and possible subjection to freshwater diagenesis soon after formation (Adams and Evans, 1979). In contrast, framework communities or the presence of significant amounts of algae cannot be recognised in the basinal mounds. Their faunal densities and diversities are relatively low; the effect of bathymetry on community development cannot be recognised, nor is there evidence of early freshwater diagenesis.



(modified from Bond (1950b), Parkinson (1957) and Wilson (1975))

Figure 2-5 A. Distribution of Lower Carboniferous 'reefs' in Britain (surface exposures only)
B. Distribution of facies in the L. Carboniferous of Northern England and Wales

2.3.6 Suggested restriction of Dixon's (1921) comparison

In making the comparison between the 'knoll-reefs' of Britain and the Belgian Waulsortian Dixon (1921) compared a 'reef'-knoll in the Lower Carboniferous of Pembrokeshire with the knolls at Clitheroe and the Belgian Waulsortian. The Clitheroe knolls are examples of the basinal type (see figure 2.5) and in light of the differences which exist between shelf edge and basinal 'reef'-knolls, it seems best to restrict the label Waulsortian to the basinal mounds.

CHAPTER 3

FIELD GEOLOGY OF THE MANIFOLD VALLEY

3 FIELD GEOLOGY OF THE MANIFOLD VALLEY

3.1 Location

The principal area mapped and sampled for this study is in the southern Pennines bounded by grid references SK 0900 5800 and SK 1200 5800 on the north and SK 0900 5400 and SK 1200 5400 on the south. It is located in the extreme north-east corner of Staffordshire and generally known by the regional name Manifold Valley. The Manifold Valley, as referred to in this thesis extends from Ecton in the north to Beeston Tor in the south. The nearest village is Wetton and other landmarks in the area include Wettonmill, Sugarloaf, Manor House and Thor's Cave. The Manifold Valley is drained principally by the River Manifold, although two smaller streams, Hoo Brook, and an un-named stream that runs south from Manor House to Redhurst Halt are also important. A locality map is shown in figure 3.1.

3.2 Previous research

The first studies of the area were done as part of the Geological Survey mapping of sheets 81 NE, 81 SE, 72 NE and adjoining areas. This work was discussed in a Memoir of the Geological Survey of England and Wales by Green and others which was published in 1869. In this memoir three divisions in the Carboniferous were recognised; the limestones, divided into three units by the volcanically derived 'toadstones', the Yoredale series consisting of sandstones and shales with some limestones, and the Millstone Grit. In 1901 Wheelton Hind and J. Howe correlated the Manifold Valley succession with the Pendleside series of the Clitheroe area in Lancashire based on faunal similarities, but it was not until 1905 that Vaughan's zonal scheme for the Lower Carboniferous was introduced. In 1906 Wain and Stobbs published a report of an excursion into the

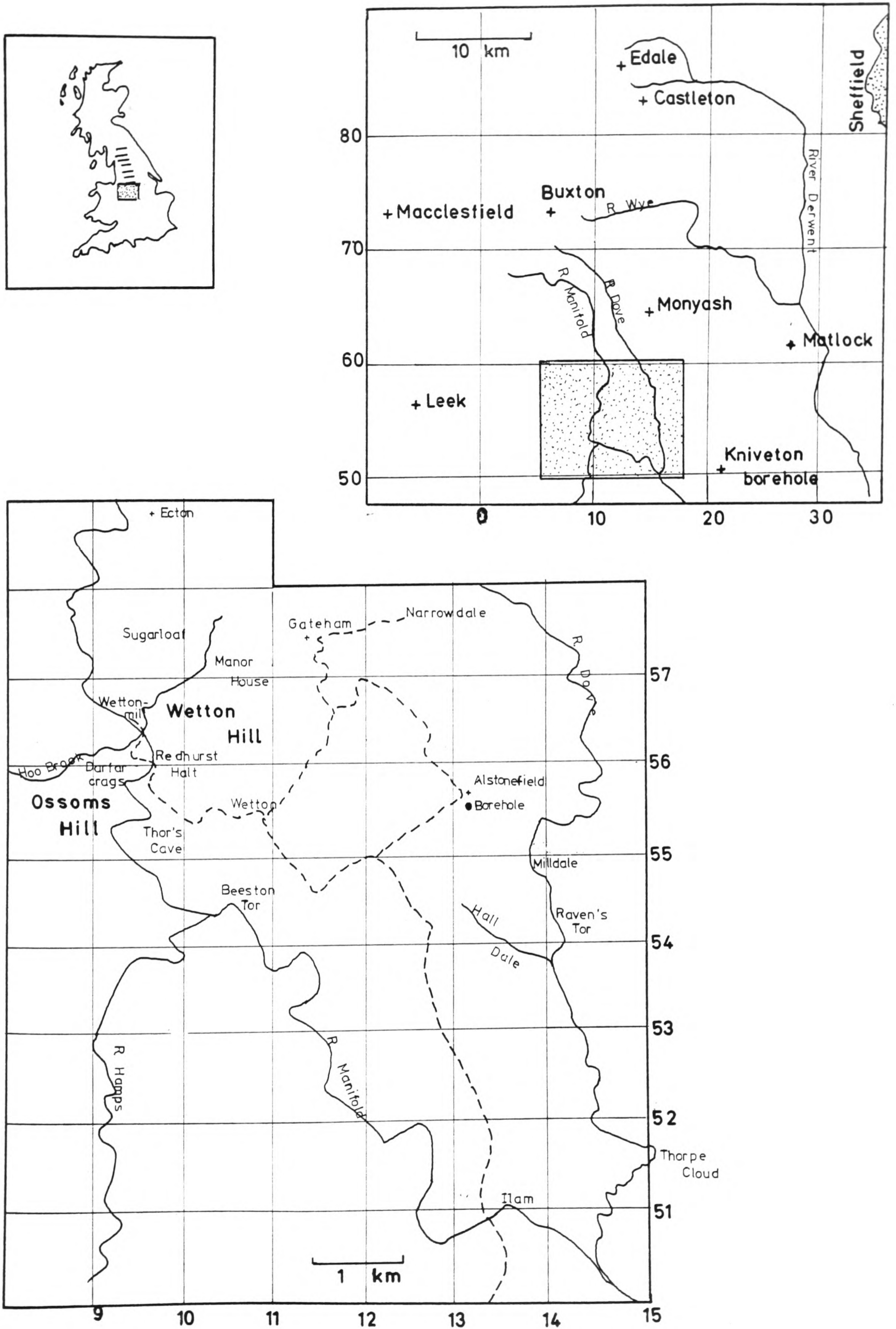


Figure 3-1. Locality Map

Manifold Valley region in which they recognised Vaughan's D zone in the beds exposed at Waterhouses. A more comprehensive attempt to apply these faunal zonations was made by Sibley in 1908, who published a study of the faunal succession in the Midlands, in which he included the Manifold Valley area. He concluded that the base of the Carboniferous was not exposed in the region and that the rocks could be assigned to Vaughan's zones D1, D2 and D3. In doing this he recognised the abnormal facies presented by the mound limestones, which he referred to as the Brachiopod Beds, and on faunal evidence concluded that they could all be placed in the D2 zone. Further attempts to understand the geology in Southern Derbyshire and North Staffordshire seem to have been lacking until the 1930's when the successful application of Bisat's (1924) goniatite zonation scheme in the North of England encouraged Yorkshire geologists to attempt to employ it farther south.

G. B. Alexander made extensive collections and published some of the correlations based on them in a 1940 report on a field excursion in the Buxton area. In 1942, R. G. S. Hudson attempted a general synthesis of the area to provide background information for the study of borehole sections. In that study he recognised the existence of Carboniferous rocks older than D age and coined some local formation names, some of which are still in use in a redefined form. In 1950, Parkinson mapped and studied Dovedale, the adjacent region to the east, and concluded that three major facies, the massif, reef and basin could be recognised in each of the three faunal zones, C2, S1 and D1, represented there. This was followed in 1951 by a paper by J. E. Prentice on the Carboniferous Limestone of the Manifold Valley. In this work, he recognised a succession from Tournaisian to Namurian rocks, which he divided into a lower and an upper series. The lower series consisted of 'cementstones' and massive limestones of C1 age overlain by black cherty limestones of

C2S1 age. The upper series contained massive limestones of D1 age overlain by shelly limestones and shales of D2 to P2 age. He thus recognised that there were two phases of mound formation and placed the major mound development in the C1 zone. He considered the area to represent a marginal facies between the Derbyshire block and the Cheshire basin consisting of bedded limestones, reef limestones and black cherty limestones.

The next major research in the area was done by Tran Kim Thach in a PhD thesis completed in 1965, but never published. In this work he elaborated Parkinson's idea of three main lithofacies through time and concluded that a lagoon, bank and gulf facies could be well defined throughout the Lower Viséan, but were less clear in the Upper Viséan. He mapped a large area, bounded by grid references SK 130 615, SK 180 470, SK 075 566 and SK 275 533. He provided lithological descriptions of the rocks, as well as presenting interpretations concerning the sedimentology. Thach, like Prentice, recognised that all the mound limestones were not of the same age, but he took this differentiation of the carbonate mound masses further by noting that several different shapes and growth forms could be seen within them.

The area has recently been mapped on the 1:50,000 scale by the Institute of Geological Sciences and a memoir to accompany the map is in preparation.

3.3 General geology

3.3.1 Regional geology

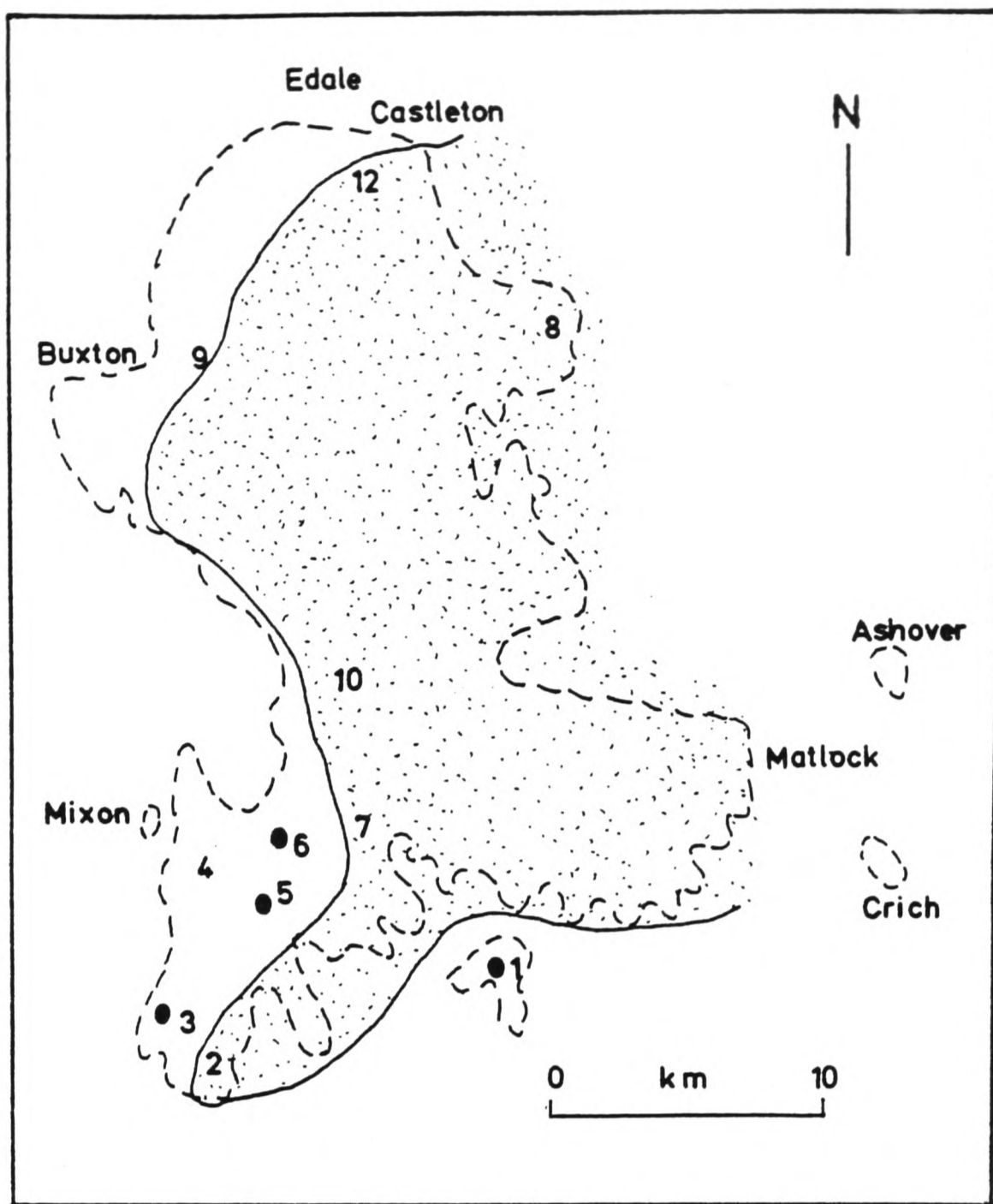
The Manifold Valley lies on the SW edge of the Derbyshire Dome (Ford, 1977), which was positioned near the northern edge of the Mercian Highlands in Carboniferous times (George, 1958). The Dome is often

thought of as a limestone massif bordered by outward dipping reef limestones and deeper water basinal deposits of the Widmerpool gulf, with a partial cover of Millstone Grit (Ford, 1977; Falcon and Kent, 1960). However, the structure is not so simple. There is a broad flat axial region near the western margin of the Derbyshire Dome which trends N-S, but the axis is broken by numerous faults. The simple dome structure is complicated by the interaction of folds of three general trends; E-W, N-S, and NW-SE. Folding seems to have been contemporaneous with sedimentation, sometimes resulting in local unconformities (Ford, 1977).

3.3.2 Palaeogeography

During the Lower Carboniferous a basinal and shallow shelf facies were being deposited in the Derbyshire Dome. The basinal sediments include thin-bedded cherty limestones, calcareous mudstones and shales, while the shelf sediments consist of lighter coloured, thicker-bedded bioclastic limestones. The configuration of the shelf edge changes quite a bit over Chadian-Arundian, Holkerian-Asbian and Brigantian times. A palaeogeographic map of the Derbyshire Dome region in Chadian-Arundian times is shown in figure 3.2. In Chadian and Arundian times carbonate mounds developed in the SW edges of the basin. By Asbian times, the edges of the shelf had migrated somewhat and a second type of carbonate mound development occurred, with mounds growing along the steep edges of the shelves. In Brigantian times the position of the shelf edge did not change greatly, but a third type of carbonate mound development began; mounds developed on the shelf. Palaeogeographic maps of the region in Asbian and Brigantian times are shown in figure 3.3.

The Manifold Valley is located in the basinal rocks of the SW edge of the main massif. Structurally it is in the axis of the Ecton



Key to Reference Points

- 1 Kniveton Borehole
- 2 Weaver Hills (Ludford, 1951, 1970)
- 3 Weaver Hills (Ludford, 1951, 1970)
- 4 Manifold Valley (Prentice, 1951)
- 5 Manifold Valley (Prentice, 1951)
- 6 Dovedale (Parkinson, 1950)
- 7 Dovedale (Parkinson, 1950)
- 8 Eyam Borehole (Dunham, 1973)
- 9 Woo Dale Borehole (Cope, 1973)
- 10 Hartington (Sadler & Wyatt, 1966)
- 11 Edale (Hudson & Cotton, 1945)
- 12 Castleton (Shirley & Horsfield, 1940; Parkinson, 1947)

KEY

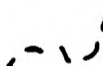





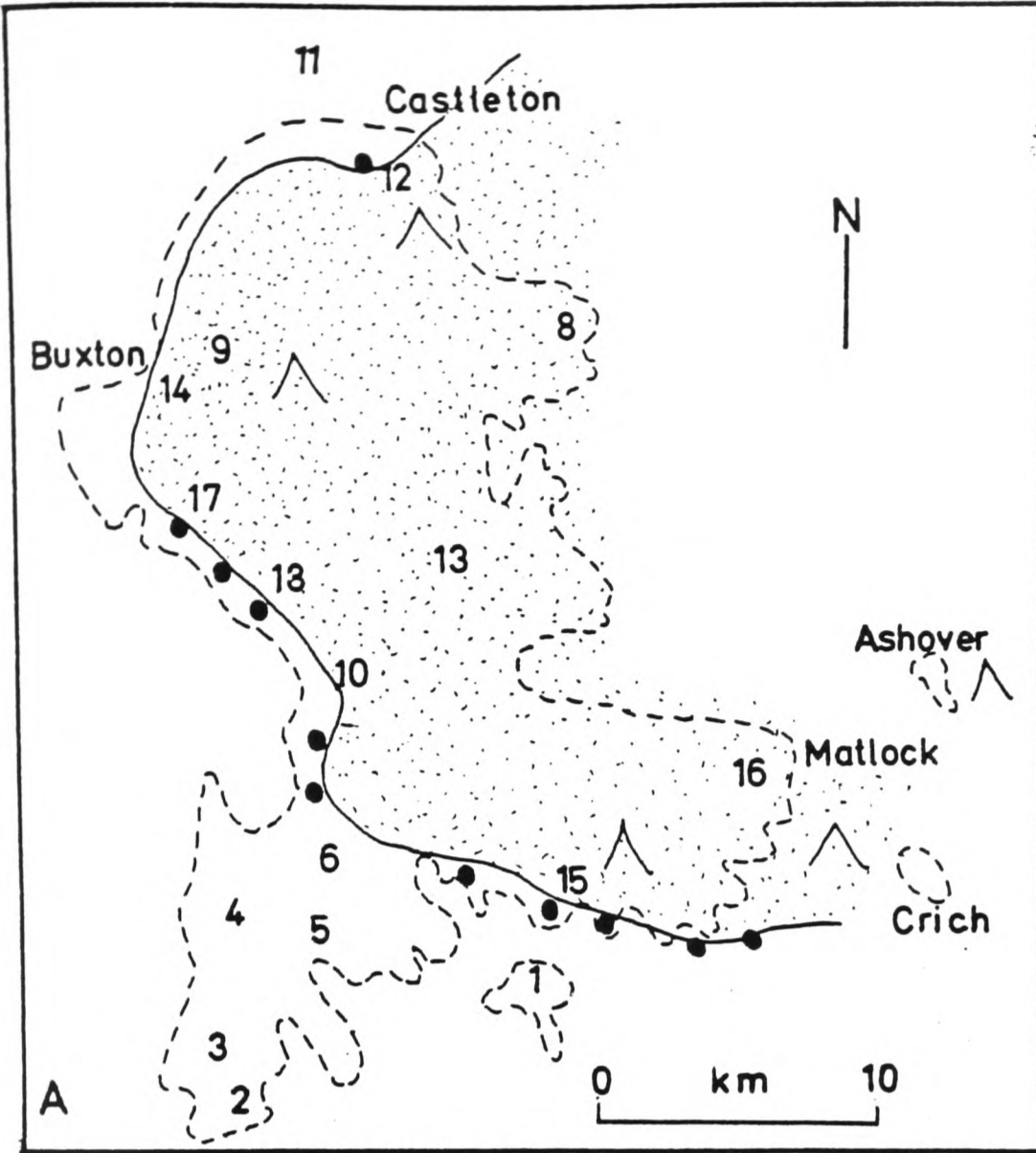
-  outline of present day Carb. 1st. outcrop
-  position of shelf edge
-  shelf
-  basin
-  carbonate mounds
-  volcanoes
- 9** specific reference points

Figure 3-2. Palaeogeography of the Derbyshire Dome in Chadian-Arundian (V1a) Times



Reference Points

- 1-12 as in fig. 3-2
- 13 Monyash (Shirley, 1958)
- 14 E. Peak Dist. (Fearnside et al., 1932)
- 15 S. Derbyshire (Thach, 1965)
- 16 Matlock-Wirksworth (Shirley, 1958)
- 17 Earl Sterndale (Wolfendon, 1958)
- 18 Hartington - Matlock (Cox & Bridge, 1977)
- 19 Chapel en le Frith (Stevenson & Gaunt, 1971)

Key as in figure 3-2

General References for figs. 3-2 & 3-3

- George et al., 1976
- Falcon & Kent, 1960
- Ford, 1977
- Sadler & Wyatt, 1966
- Sylvester-Bradley & Ford, 1968

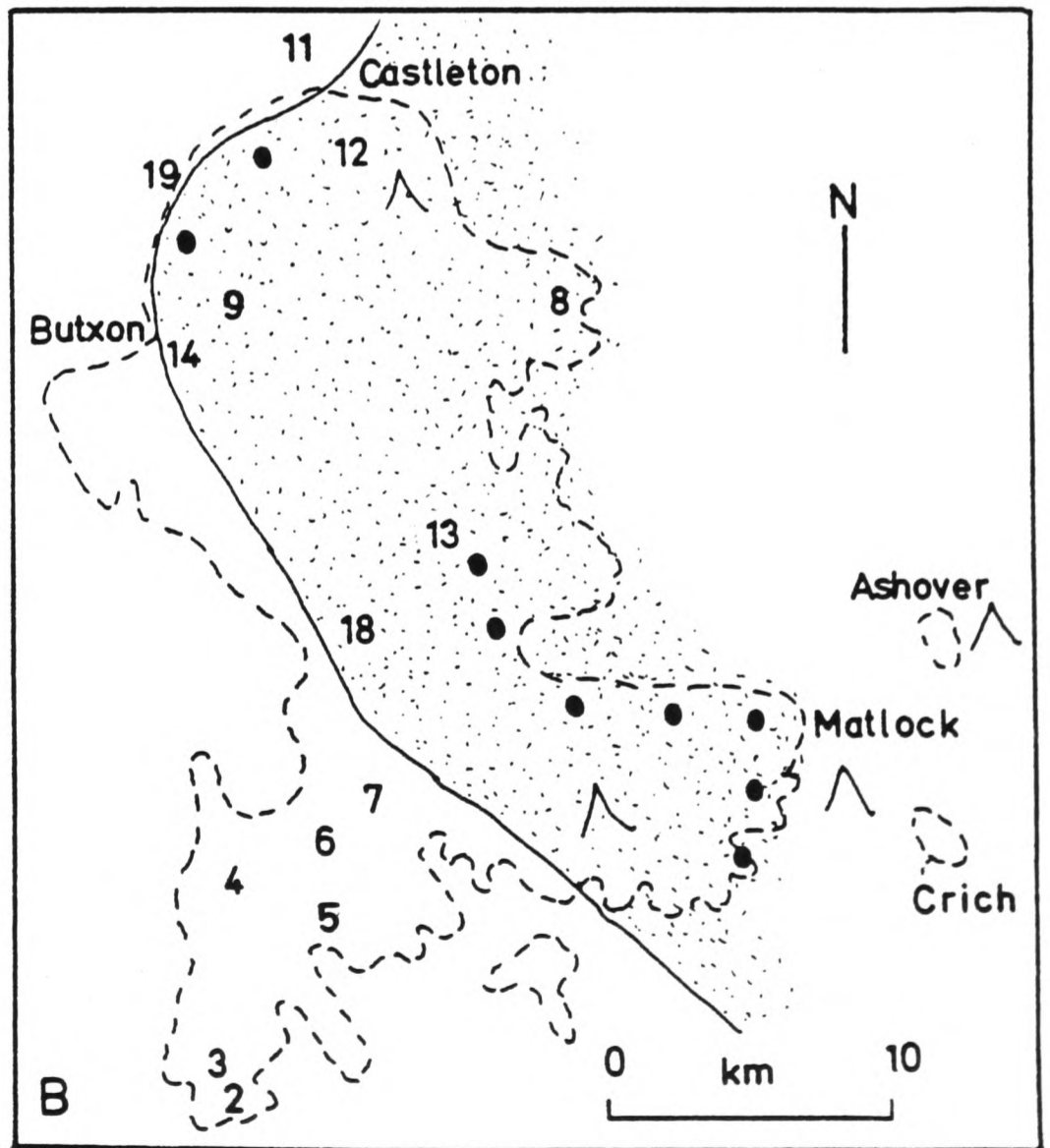


Figure 3-3. A. Palaeogeography in Asbian (V3b) times B. Palaeogeography in Brigantian (V3c) times

Anticline, which, along with the Mixon, Dovedale and Kniveton Anticlines form the major N-S trending anticlines of the Dome. A geological sketch map of the Manifold Valley and two cross sections are shown in figures 3.4a and b.

3.3.3 Stratigraphy

The Institute of Geological Sciences recognise three formations within this area. These are the Milldale Limestones, the Ecton-Hopedale Limestones and the Mixon-Limestone Shales. The Milldale Limestones consist of two facies; a light one made up of light coloured crinoid-rich bioclastic limestones, and a dark one which is muddy, cherty and poorly fossiliferous. The Ecton Limestones are mid to dark grey mainly thinly bedded and may have been laid down by turbidites. Their lateral equivalents, the Hopedale Limestones are also mainly medium to dark grey, but are thickly bedded and can be very fossiliferous. The Mixon Limestone-Shales are a turbidite deposit and consist of dark shale and dark grey limestones (N. Aitkenhead, pers. com.).

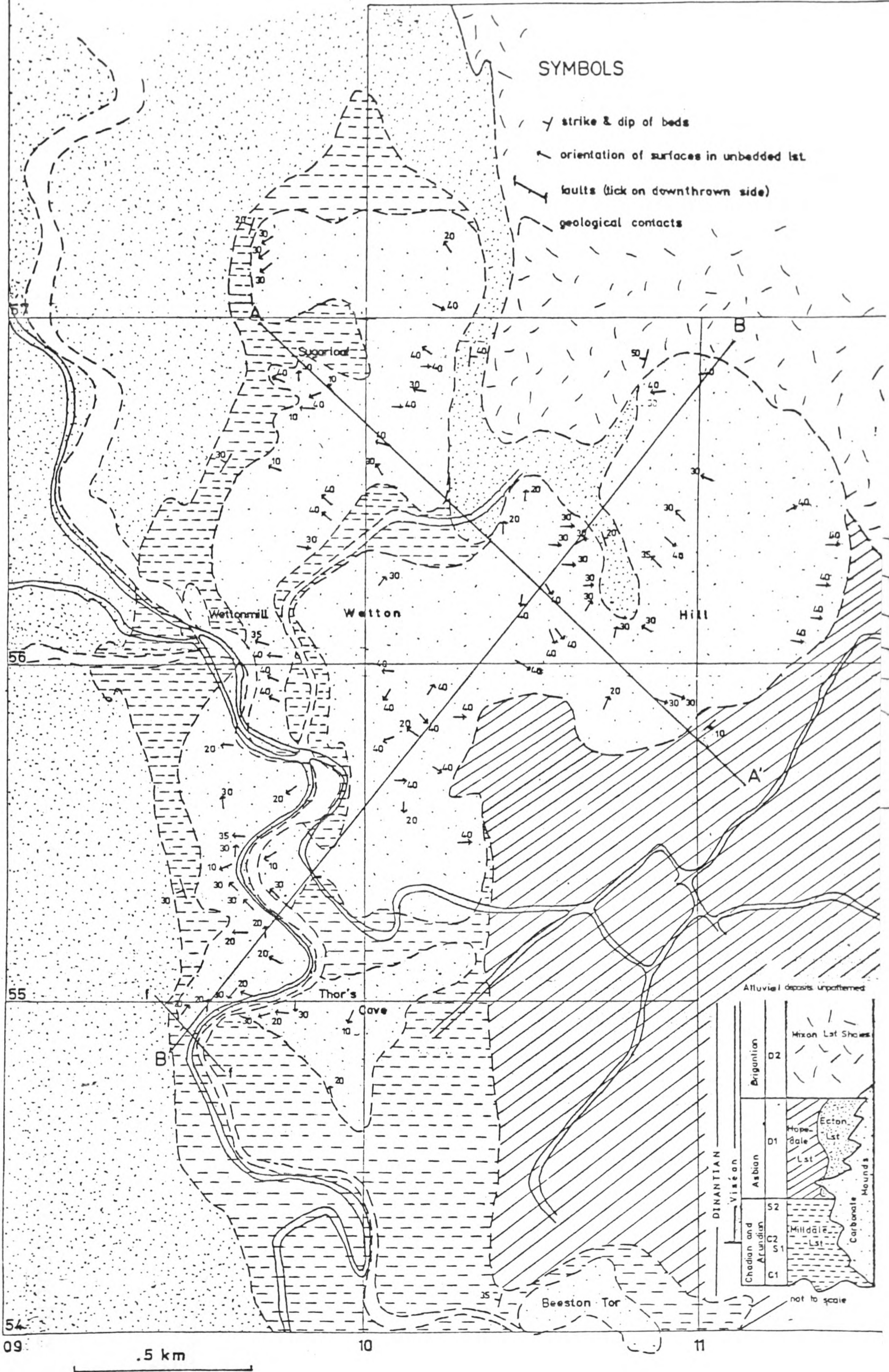
The rock units just described were mapped on lithological grounds and although they do not necessarily correspond with faunal zones, their approximate position within the Dinantian correlation scheme of George et al. (1976) is shown in the generalised stratigraphic section in figure 3.4a. The correlation between this Dinantian stratigraphic scheme and those used in Belgium and Ireland has been shown in figure 1.2.

3.4 Field observations

3.4.1 Age relationships

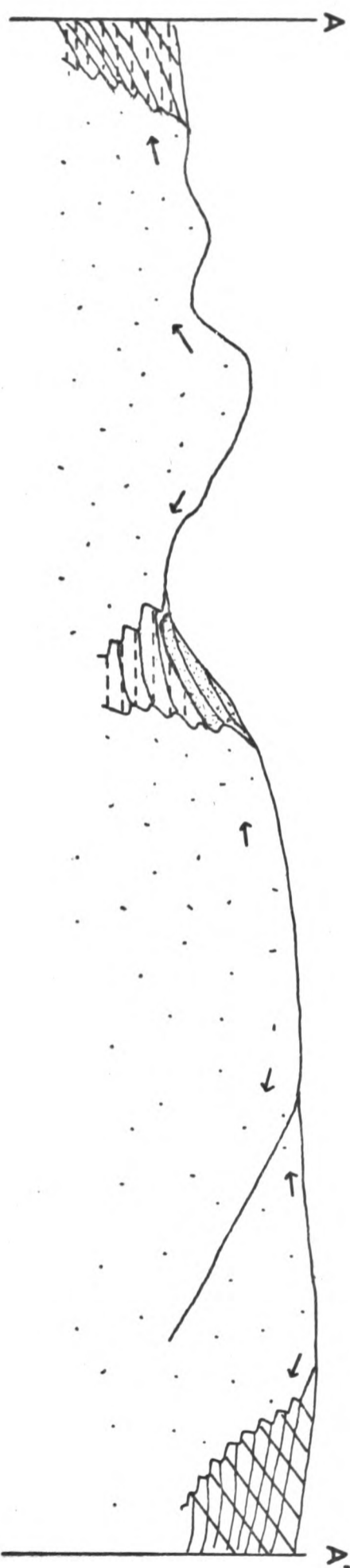
Information on the distribution of faunal zones within the mounds was derived from brachiopod, conodont and foram samples which were

Figure 3-4a Geological sketch map of the Manifold Valley (based on mapping done for this study, Geol. Survey sheets SK 15NW & 05NE & Thach (1965))



SK 0972 5690

SK 1120 5564



SK 0945 5487

SK 1110 5700

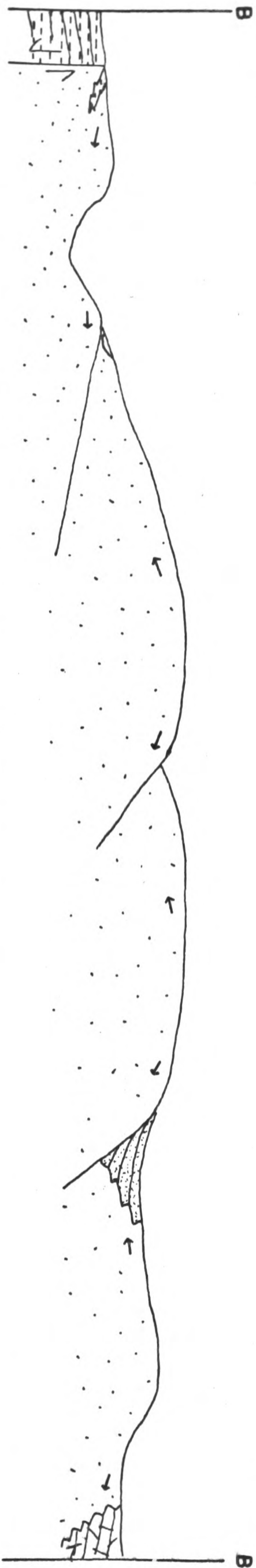


Figure 3-4b. Two geological cross sections in the Manitold Valley. Symbols & stratigraphic units as in figure 3-4a (horizontal scale = 1:10,560 vertical scale x2)

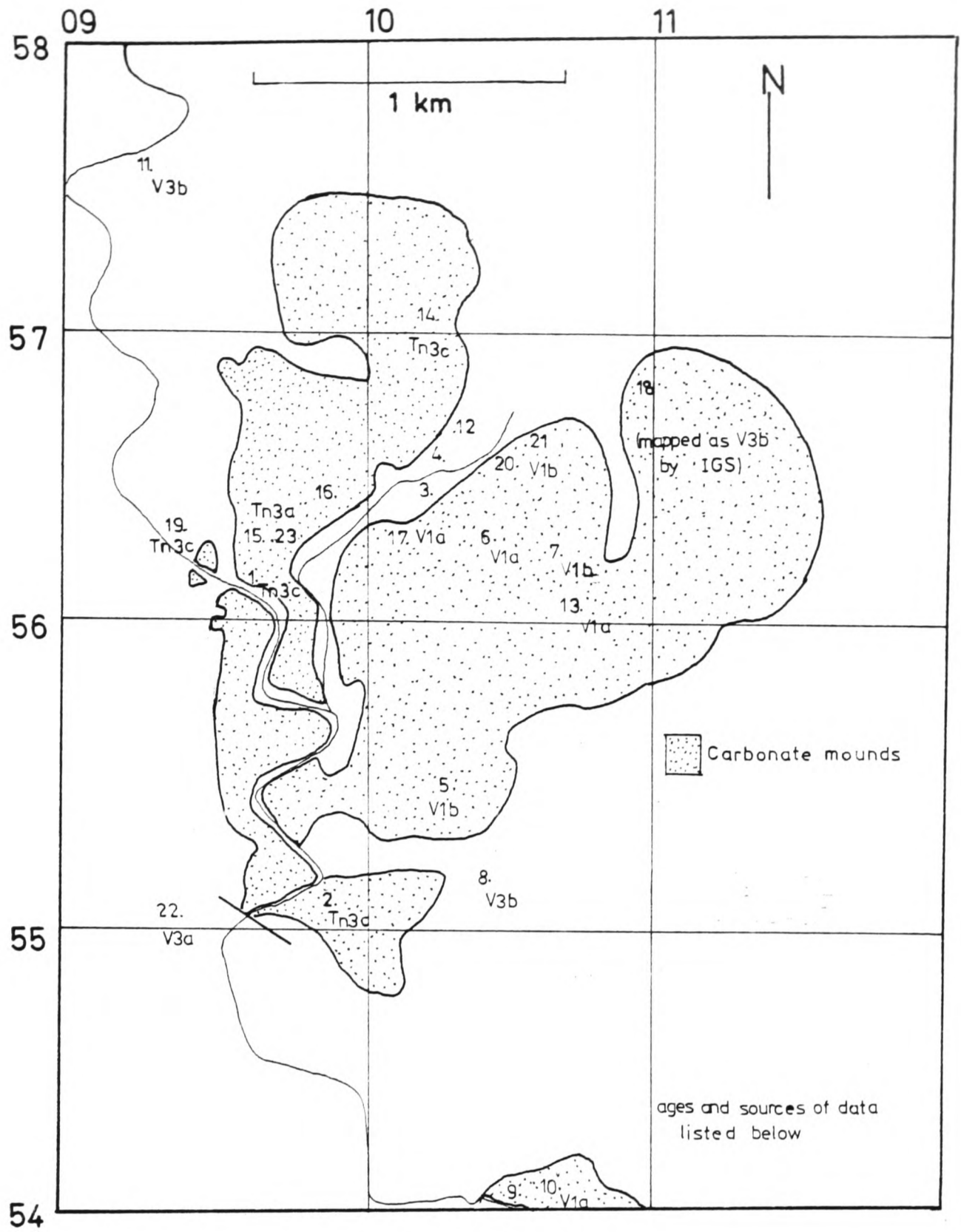
collected in connection with this study and with the I.G.S. mapping of the area (figure 3.5). Faunal samples from within the mounds show that the mounds young towards the east and towards the north-east. From west to east, each of the three mounds shown in the geological cross section A to A' (figure 3.4b) contain faunas of successively younger age zones. Similarly, the mounds shown in cross section B to B' (figure 3.4b) young progressively towards the north-east. Thor's Cave mound seems to have been formed relatively early and Beeston Tor mound in the middle of a period of mound development which began in the Courceyan and continued throughout the Chadian and Arundian and into the Asbian (sediments of Holkerian age have not been recognised in this region (Aitkenhead et al., 1979)).

3.4.2 The Manifold Valley carbonate mounds

3.4.2.1 Contacts with off-mound sediments

Localised folding along N-NW to S-SE axes in the Manifold Valley area has caused intense crumpling in the less resistant basinal thin bedded sediments, while the more resistant unbedded limestones of the carbonate mound mass have remained undeformed. As a result, basinal sediments are often tightly folded in the proximity of the carbonate mounds, or faulted up against them. This has the effect of obscuring the depositional relationships between the two in many areas.

The contacts between the mound and off-mound sediments in the Manifold Valley are always abrupt; bedded off-mound limestones do not gradually become more like the mound sediments as they approach the mounds. Indications of the type of boundary which exists between off-mound limestone and the carbonate mounds is well shown in only a few exposures. Two types of boundaries seem to occur between the mound



- 1. SK0958 5612 IGS conodonts (Tn3c)
- 2. SK0988 5509 IGS forams (Tn3c)
- 3. SK1017 5645 IGS conodonts (V1b)
- 4. SK1024 5648 IGS goniatites (V1b)
- 5. SK1029 5551 IGS goniatites (V1b)
- 6. SK1043 5627 IGS brachiopods (V1a)
- 7. SK1064 5622 IGS brachiopods (V1a)
- 8. SK1041 5520 IGS corals (V3b)
- 9. SK1059 5410 IGS brachiopods (V1a)
- 10. SK1066 5402 IGS brachiopods (V1a)
- 11. SK1025 5664 IGS conodonts (V3b)
- 12. SK1025 5664 IGS brachiopods (V3b)
- 13. SK1079 5604 This study forams* (V1a)
- 14. SK1024 5710 This study forams* (Tn3c)

- 15. SK0971 5623 This study forams* (Tn3a)
- 16. SK0988 5647 This study forams* (?V2a)
- 17. SK1066 5637 This study conodonts+ (V1a)
- 18. SK1087 5683 This study conodonts+ (?V1b)
- 19. SK0936 5619 IGS conodonts (Tn3c)
- 20. SK1048 5657 IGS conodonts (V1b)
- 21. SK1050 5658 IGS conodonts (V1b)
- 22. SK0935 5504 IGS conodonts (V3a)
- 23. SK0973 5620 This study forams* (Tn3a)

* identified by Tim Marchant, Trinity College, Dublin
 + identified by Mike Reynolds, IGS, Leeds

Figure 3-5 Age relationships in the Manifold Valley

and off-mound sediments in this area. The first consists of small carbonate mounds contained within the basinal sediments. Good examples of this can be seen at Wettonmill Farm (grid reference SK 0986 5610). The most spectacular is behind the farm house where blasting has exposed a small mound with thin-bedded dark cherty calcareous mudstones draping it. This is shown in figure 3.6a. The small mound exposed in the layby across the river from Wettonmill Farm is probably another example of this sort of relationship, though it is not so clearly shown. There the cherty mudstones are seen below the mound in the river bed and similar beds dipping off the mound are exposed in the road cut opposite. The same sort of relationship may also occur at Beeston Tor, but as the exposure is inferior and the mound is much larger in size than those at Wettonmill, the relationship is correspondingly difficult to substantiate. In the bed of the River Manifold (grid reference SK 1065 5405) unbedded mound limestone can be seen to rest on bedded dark limestones and shales. The boundary between the two is apparently sharp. Along the footpath between the River Manifold and Larkstone Lane (SK 1040 5410) there is continuous exposure for approximately sixty metres which shows unbedded light coloured biomicrite of the flank of the mound. There follows less than forty metres of non-exposure then bedded dark calcareous shales are seen to dip at 35 degrees away from the mound. These two exposures suggest that Beeston Tor may also be an example of a mound enveloped in bedded basinal sediments.

The second type of contact between mound and adjacent sediments which is found in this region is one of interdigitation. The most convincing example of this is found on the footpath between Redhurst Halt and Beeston Tor, where the relationship between Thor's Cave and the adjacent basinal rocks is seen (approximate grid reference SK 095 549). Unfortunately exposure in this locality is no longer

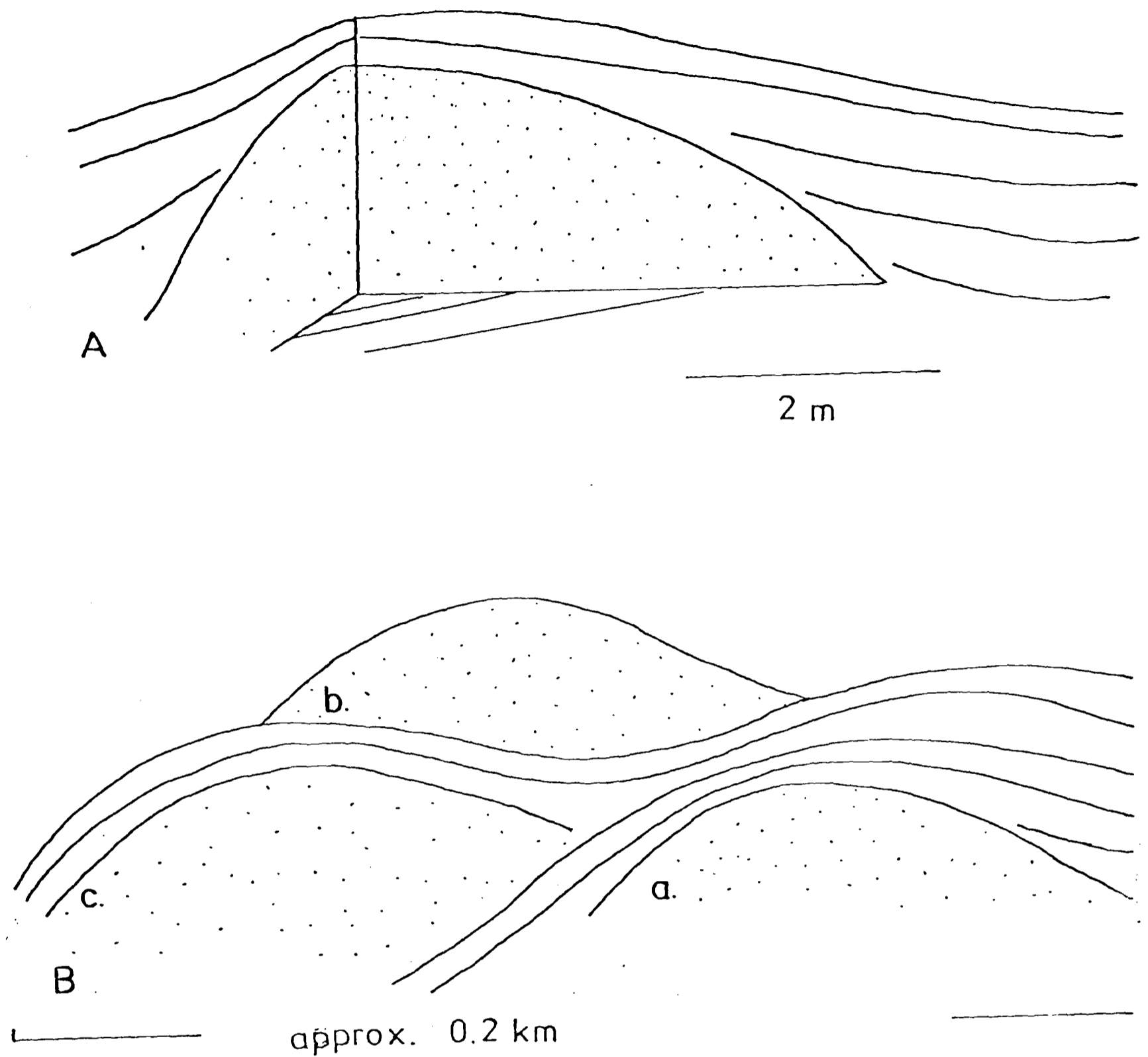


Figure 3.6 A Diagram of small carbonate mound draped by calcareous mudstones behind the farmhouse at Wettonmill

B Schematic diagram of relationship between mound at Wettonmill farm (a), Nan Tor (b), and small mound in layby (c)

good, but outcrops along the footpath, never separated by more than a few metres of non-exposure, show a succession of light coloured unbedded mound limestone; dark thinly-bedded calcareous mudstones and then mound limestone again. Rapid alternation of rock types such as this is suggestive of an interdigitating boundary between the mound and basinal sediments. This exposure was apparently much cleaner in the past because Prentice (1950) cites it, noting the rapid alternation of facies at the edge of the mound.

3.4.2.2 Geometry of the mounds

The mounds mapped probably represent a composite mass of five or more. An analysis of bank geometry was done using the methods described by Lees (1964 p.490, 512, 514). Briefly, these include measuring probable growth surface attitudes by noting the orientation of sparry calcite masses, layers of skeletal debris and of fenestellid fronds. These measurements give an indication of the shape of individual mounds within the complex. The final shape of the complex is influenced both by the geometry of individual mounds which comprise it and by later erosion when mound growth has ceased either temporarily or permanently.

Individual mounds can be most convincingly seen when they are separated from each other by even a small thickness of basinal sediments. In figure 3.4b, the cross section from A to A' (grid references SK 0969 5688 to SK 1120 5560) shows an example of this; the westernmost mound lies structurally beneath the central mound and is separated from it by several metres of Milldale Limestone. Support for this hypothesis can be found in an examination of the faunal age data available for this area (see figure 3.5) which indicate that the central mound is younger than the western mound. Further evidence for this sort of mound geometry can be found in the previously described exposures at

Wettonmill Farm and at the layby across the river from the farm, as well as at the nearby Nan Tor mound (grid reference SK 0983 5627).

In these cases it is clear that small carbonate mounds have developed individually in close proximity to each other, both in space and probably in time, and are separated by a thickness of inter-mound sediment. A sketch of this relationship is shown in figure 3.6b.

When individual mounds are not separated by intermound sediment it is necessary to rely entirely on the measured attitudes of growth surfaces, as any physical evidence of erosion surfaces between two mounds, such as boulder beds or abrupt termination of sparry masses is difficult to prove in these exposures. Such things have been noted elsewhere and the relationship between such structures and the attitude of growth surfaces has been shown (for example Lees, 1964; Simpson and Broadhurst, 1969).

The changes in attitude of the growth surfaces shown in figure 3.4a suggest that the two lobes of Wetton Hill are composed of two separate mounds and biostratigraphic evidence (see figure 3.5) suggests that the eastern mound is the younger of the two. Examination of dipping surfaces further suggests the possibility of at least two mounds south of the central mound (see figure 3.4b cross section B to B'). Dips measured along the footpath between Redhurst Halt and Beeston Tor indicate that there too several mounds may be represented. As shown in figure 3.7, it is clear that changes in direction and magnitude of dips of growth surfaces in the mounds occur, although because of the nature of the exposures true dips are not shown. If a series of mounds stacked in various attitudes with respect to each other is considered as shown in figure 3.8, it would be possible to derive the pattern of dips actually seen in the field.

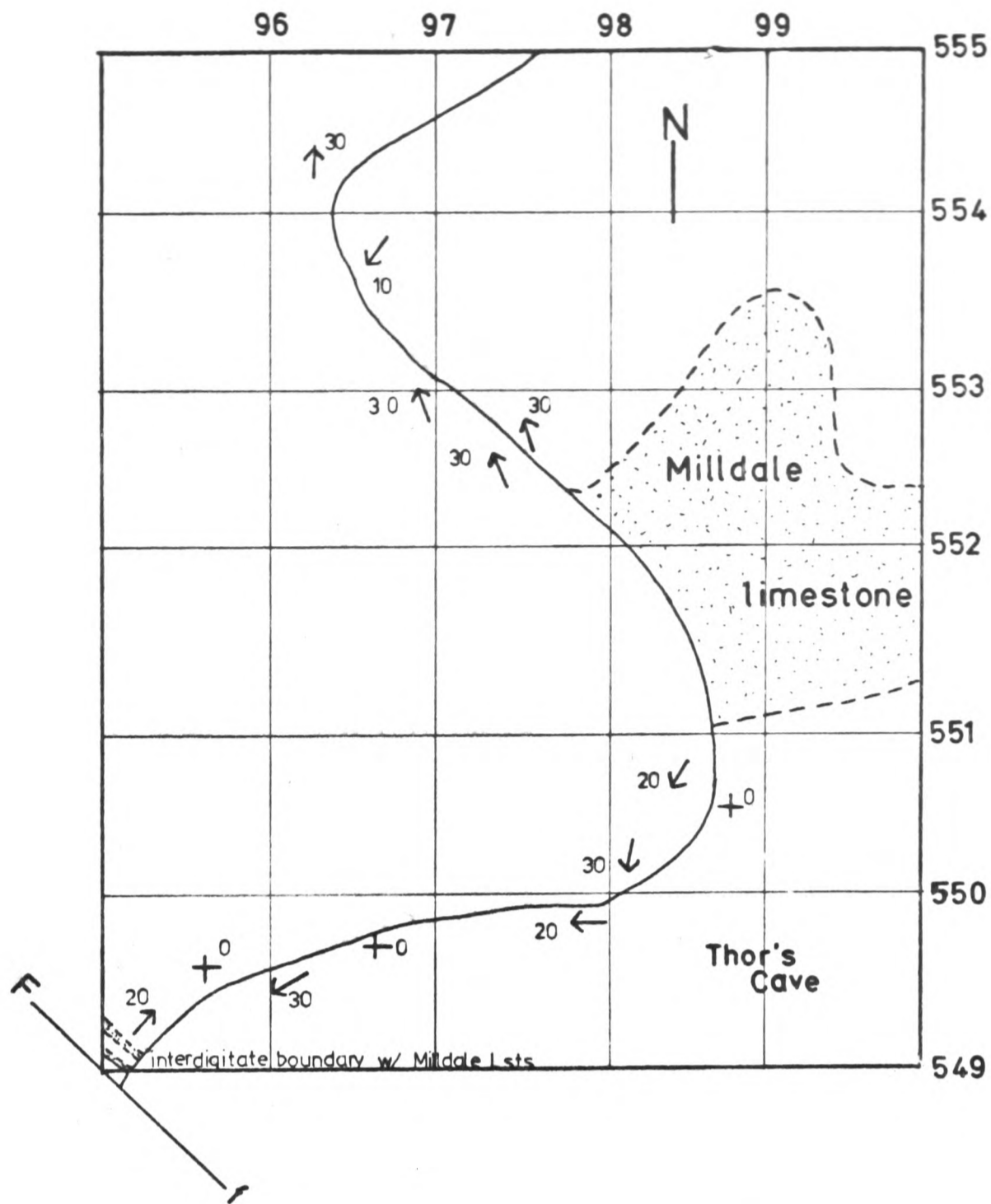


Figure 3-7. Sketch section along the River Manifold. Rocks exposed are carbonate mounds, except where indicated.

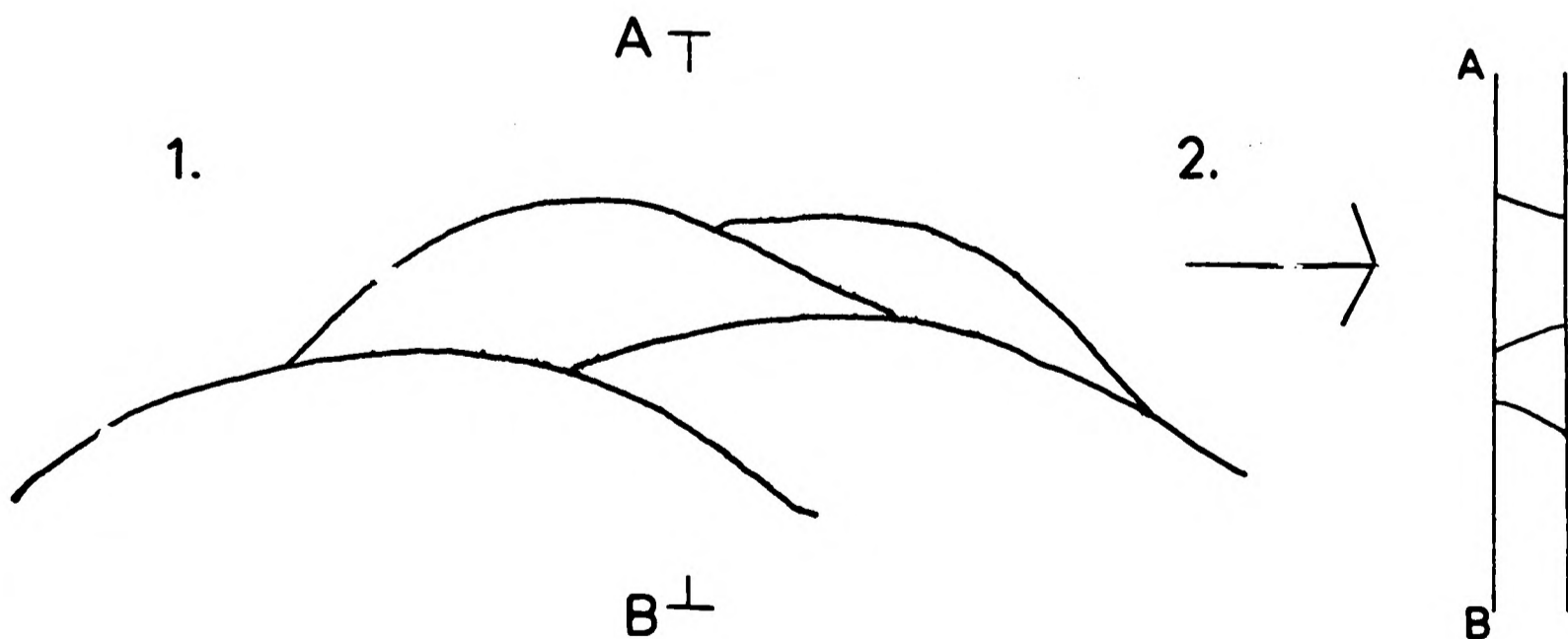


Figure 3-8.
1. Diagram showing stacked mounds

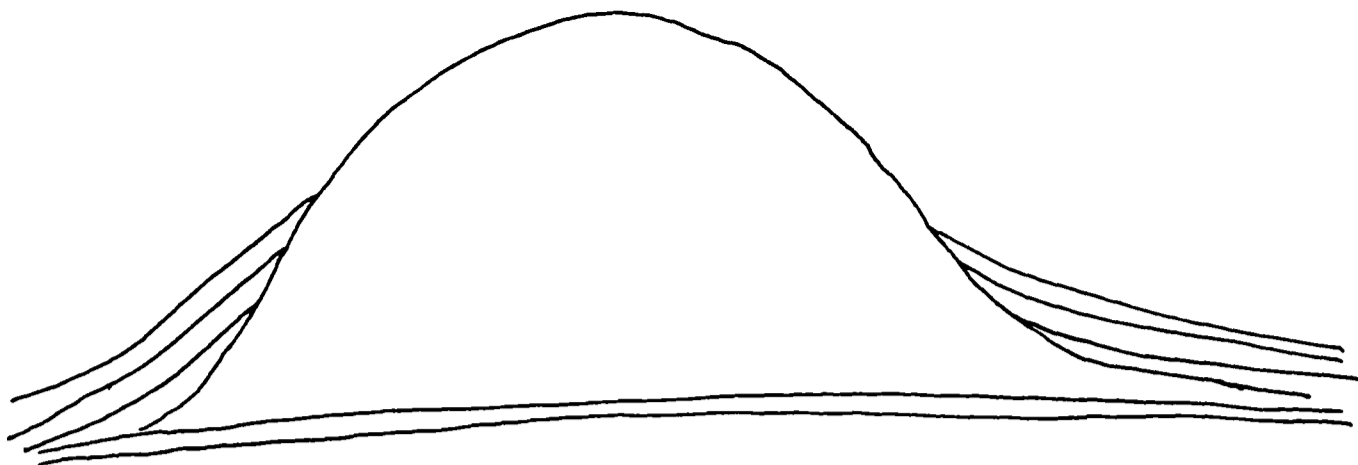
2. Likely appearance of dipping growth surfaces in a core drilled from A to B

A third type of mound geometry found in the area is that of a solitary mound separated by basinal sediments. This is most clearly shown at Beeston Tor, where there is no evidence of changing directions or magnitudes of growth-surface dips which would indicate the presence of more than one mound. Figure 3.9 summarises these geometrical relationships.

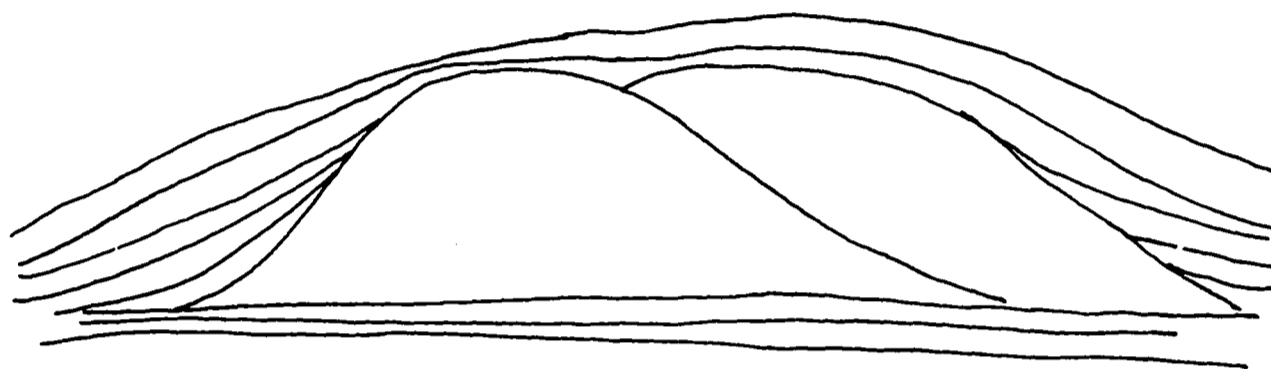
3.4.3 Carbonate mound lithology

In the carbonate mounds exposed in the Manifold Valley only one general lithological type is recognisable in field exposures. This is a medium to light grey biomicrite which is unbedded, although as previously noted, growth surfaces can sometimes be defined by the attitude of bioclastic debris or sparry veins and masses. Locally, crinoid debris is an important component, but very crinoid-rich rocks, where crinoids compose more than 20% of the rock are extremely rare. Very occasionally fenestellid bryozoa are seen encrusted by dark coloured spar which makes them look like dark veins in the lighter coloured micrite. This lithology resembles the Blue Vein Facies of Lees et al. (1977).

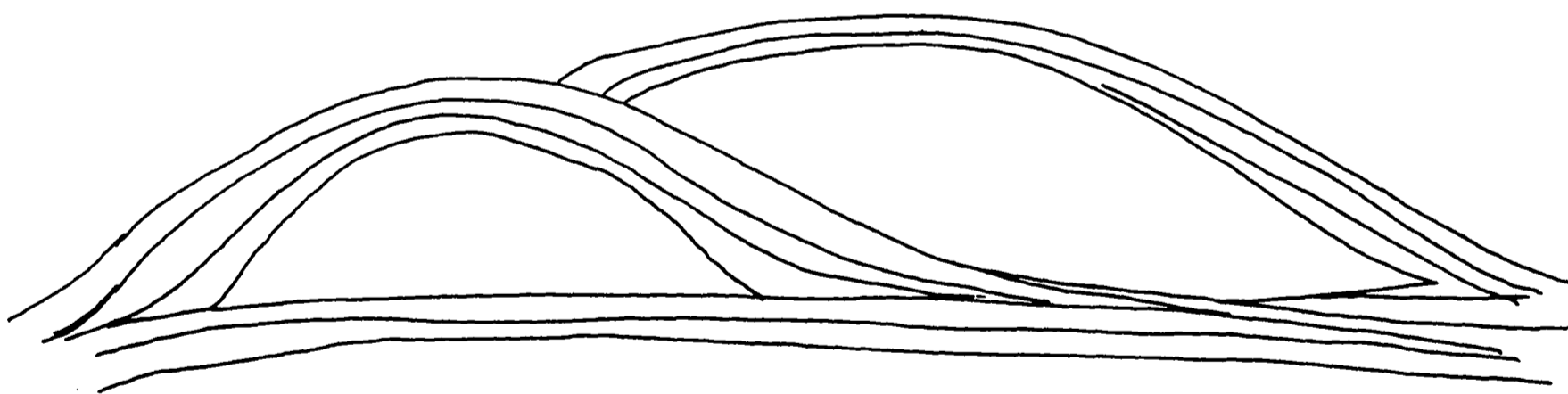
A variety of micrite types can be recognised in polished blocks or thin sections. These include "mottled" micrites, which are mixtures of light and darker coloured fine grained limestones, pellety micrites, and microspar. These will be defined, more fully described and analysed in Chapter 5. In general terms the lithologies seen within the mounds are comparable to those described by Lees et al. (1977) in the Biomicrite Facies of the Waulsortian 'reefs' of Belgium. The occasional presence of Blue Vein lithologies suggests that their Transitional Facies may be present as well.



1. Large solitary mound



2. Stacked mounds in contact with each other



3. Stacked mounds separated by intermound sediment

Figure 3-9 Summary of geometrical relationships between mounds

The principal bioclasts, other than crinoid debris and bryozoa are brachiopods, bivalves, trilobites, cephalopods and gastropods. Sponge spicules, calcispheres, encrusting bryozoa and forams are often seen in thin section. A detailed analysis of the fauna will be given in Chapter 4.

3.4.4 Borehole data

Additional data concerning the lithologies and internal structure of the Manifold Valley carbonate mounds was obtained by examination of two borehole cores provided by the Institute of Geological Sciences, which were drilled at two localities within a 12 kilometre radius of the Manifold Valley. Both cores penetrate carbonate mounds for 100 metres and in one the underlying sediments are not reached. The carbonate mounds are probably of a similar age and facies to those exposed in the Manifold Valley. One core is from Kniveton (grid reference SK 2122 5087, see figure 3.1) which is located in the Bradbourne Carboniferous inlier, approximately 12 kilometres from the Manifold Valley. The mound which was drilled is exposed on the surface in Standlow Lane and is enclosed in dark calcareous mudstones of ?C2S1 age. The second core is from Lode Lane in Alstonefield (SK 1371 5563, see figure 3.1). It drills into a carbonate mound which is not actually exposed on the surface.

3.4.4.1 Alstonefield borehole

The Alstonefield core exposes lithologies that are very similar to those exposed on the surface in the Manifold Valley. Because the core has been cut and etched many of the variations in the biomicrite are easily seen. Mottled micrites are very common throughout and pelley micrites are quite important at some levels. At 60 metres

the dark spar-encrusted fenestellid-rich lithology, which is rarely found in the Manifold Valley outcrop is present for 7 metres. It briefly occurs at a few other levels and four more metres of it are exposed at the bottom of the core. This lithology resembles the Blue Vein Facies of Lees et al.. Throughout the core, aligned sparry masses and veins and bioclastic debris outline growth surfaces. In cores it is impossible to take directions of orientation, but the magnitude of dip can be easily measured. The dips vary from horizontal to 30 degrees and these changes in dip are thought to represent mounds stacked on each other as at Thor's Cave (see figure 3.8).

3.4.4.2 Kniveton borehole

The Kniveton borehole core shows similar changes in dips and is also thought to represent several stacked mounds. The predominant lithology in this core, however, is rather different. Most of the core consists of fenestellid bryozoa surrounded by dark coloured spar in a matrix of light coloured spar and biomicrite. This lithology is similar to the Blue Vein Facies of Lees et al. (1977). At some levels the amount of spar decreases and biomicrite becomes the dominant lithology.

3.4.4.3 Bioclasts

Bioclasts in both cores include brachiopods and crinoid debris. Gastropods, cephalopods and rare corals are less often seen. The micro-fauna includes forams, ostracodes, calcareous sponge spicules and ?calcispheres. Detailed logs of both cores are included in Appendix 1.

3.5 Conclusions

The period of deposition of the carbonate mound complex in the Manifold Valley began in the Courceyan (Tn3c) and ended in the Asbian (V3b). Plotting of the available stratigraphic information derived from brachiopod, conodont and foram collections shows that the complex youngs towards the east. Their basinal palaeogeographic position, geometry and lithologic and faunal characteristics distinguish the Manifold Valley carbonate mounds from nearby shelf edge mounds of similar age.

The Manifold Valley carbonate mound complex consists of a minimum of five smaller mounds which have coalesced to form a large mass. The geometric relationships between mounds are similar to those recognised by Lees (1964) in the Irish Waulsortian. Some of the individual mounds are separated by deposition of bedded intermound sediments. Others grew on top of each other with no intervening deposition of basinal material. These configurations are inferred from measurements of growth surface attitudes defined by the orientation of sparry veins and masses, aligned bioclastic debris and rare geopetal sediments in cavities. At the edges of the carbonate mound complex the contact with the off-mound sediments is never gradational. Small mounds are found enveloped in the off-mound sediments, or interdigitation between the mound and off-mound sediments occurs.

The predominant lithology within the mound complex is medium to light grey biomicrite. This is similar to the Biomicrite Facies in the Belgian Waulsortian recognised by Lees et al. (1977). Rarely small patches of a fenestrate bryozoan and spar-rich lithology similar to the Blue Vein Facies (Lees et al., 1977) are found.

Two boreholes drilled within a 12 kilometre radius of the Manifold Valley into rocks of similar ages each go through 100 metres of mound

limestone. In one of the cores the principal lithology is biomicrite, similar to that exposed in the Manifold Valley. In the other, lithologies similar to those in the Blue Vein Facies of the Belgian Waulsortian are dominant.

This similarity of lithologies and age suggests that the Manifold Valley carbonate mounds represent examples of Waulsortian 'reefs'. Comparison with the model of Lees et al. (1977) for the Belgian Waulsortian may therefore be useful.

The information on the distribution of lithologies exposed in the Manifold Valley suggests that only the Transitional and Biomicrite Facies of Lees et al. (1977) are present above ground in the Manifold Valley. Therefore, the presence underground of a stratigraphically lower facies, similar to the Blue Vein, is predicted. The information derived from boreholes shows that the Blue Vein Facies is present underground nearby, but it is difficult to say if all the limestones of the Waulsortian Facies in the southern Pennines region are part of the same development.

CHAPTER 4

FAUNAL DATA

4 FAUNAL DATA

4.1 Previous work

4.1.1 Faunal studies

Faunal lists for the Waulsortian of Belgium were presented by E. Dupont (1863) in his paper defining the Waulsortian facies. He noted that the facies was fairly rich in macrofossils, including brachiopods, bivalves, cephalopods, gastropods and a few corals (mainly Amplexus). He noted that species composition was similar throughout the Waulsortian but that species occur in different relative proportions. A more comprehensive faunal study of the Belgian Waulsortian was made by F. Demanet (1923). He examined faunas from two exposures which he believed to represent different stratigraphic levels. He showed that macrofaunas vary according to their stratigraphic position, and his faunal lists indicate that this mainly reflects an increase in diversity at the higher levels. Other macrofaunal lists for the Belgian Waulsortian have been presented by Demanet (1958). H. Dupont (1969) provides a list of the microfauna.

The similarity between the faunas and lithologies of the Belgian Waulsortian and the 'Lower unstratified limestone' of Eire was first noted by Douglas (1909). Faunal lists for various parts of the Irish Waulsortian have since been published: Turner (1937) listed Waulsortian faunas in the Little Island region near Cork. Neville (1958) listed faunas from Waulsortian mounds near Ballymore, Co. Westmeath and Carrickboy in Co. Longford; he places the Ballymore mounds in a lower stratigraphic position than those at Carrickboy, and his faunal lists suggest an increase in diversity at the higher stratigraphic levels. Shephard-Thorn (1963) studied the faunas from the Shannon Estuary region

in Co. Limerick. He divided his collections by relative stratigraphic position, and observed that variations in the average size of individuals and in overall species diversity took place over time. Hudson et al. (1966) provided the only published quantitative faunal data for the Waulsortian in their study of the faunas at Feltrim Hill, Co. Dublin. Their results show a largely brachiopod-dominated assemblage within the Waulsortian and various changes in the bulk composition of the faunas between the mound and intermound deposits.

Faunal lists for the English Waulsortian are rare. Parkinson (1926) published a faunal list for the 'reef'-knolls in the Clitheroe area of Lancashire. Jackson (1919) provided the most complete account of the fauna of the mounds at Dovedale, Derbyshire, although the fauna of this area is briefly mentioned elsewhere, for example in Jackson (1941) and Parkinson (1950). The faunas in the Manifold Valley mounds in North Staffordshire are mentioned by Prentice (1951) and those in the Weaver Hills mounds, also in Staffordshire, by Ludford (1951, 1970).

4.1.2 Generalisations about Waulsortian faunas

A number of generalisations have been made about Waulsortian faunas. In some cases the preservation of fossils has been exceptionally good, and fossils from Waulsortian mounds have been figured in the classic monographs by Davidson (1858-63) on brachiopods, by Hind (1896-1905) on bivalves, and by Foord (1897-1903) on cephalopods, as well as being used in taxonomic studies, as for example in Parkinson's (1954 and 1969) work on Orthid and Rhynchonellid Brachiopods. However, owing to post-depositional processes such as dolomitisation, compaction and tectonic folding this sort of preservation is by no means the general rule.

The macrofauna is usually described as diverse (Lees et al., 1977; Hudson et al., 1966 and many others). It is dominated by brachiopods

and, to a lesser extent, by bivalve molluscs, with associated gastropods, crinoids, cephalopods, trilobites and bryozoans. The microfauna contains occasional filaments of the blue green alga Girvanella, some examples of the microproblematica *Kamaena*, as well as ostracodes, microtrilobites, forams and conodonts (Dupont, 1969; Lees et al., 1977).

An often-cited feature of Waulsortian mounds is the patchy distribution of their faunas. The shelly faunas are said to be mainly associated with the bryozoa-rich Blue Vein Facies where they are not homogeneously distributed, but tend to occur in localised patches or 'pockets' (Dupont, 1863; Lees et al., 1977). In exposures of primarily Biomicrite Facies, fossils have been described as scarce or present only in localised patches (Parkinson, 1950; Prentice, 1951).

The presence of abundant fenestellid bryozoa has been considered characteristic of Waulsortian mounds as a whole (Dupont, 1863; Douglas, 1909; and others) but in fact fenestrate bryozoa are quite sparse in some parts of the Waulsortian, such as the Biomicrite Facies of Lees et al. (1977) and the Manifold Valley mounds. The only characteristic coral is the solitary Amplexus coralloides, which is sometimes quite abundant (Ludford, 1951; Douglas, 1909). Other corals have been reported (see for example Demanet, 1923), but these are rather rare and in some cases may not have come from actual Waulsortian rocks, but from beds above (Lees et al., 1977).

The Waulsortian faunas are usually considered to be distinctive when compared with those from surrounding rocks (see for example Dupont, 1863; Prentice, 1951; Hudson et al., 1966) and this can probably be straight-forwardly demonstrated in most areas.

4.2 Faunal investigations in this study

4.2.1 Aims

While previous studies provide a good general view of Waulsortian faunas, with the exception of the study by Hudson et al. (1966) no quantitative data are given. In many cases even the stratigraphic level sampled is in doubt. Previously, no attempt has been made to sample systematically a Waulsortian development with the aim of determining, in at least a semi-quantitative way, the population characteristics, such as density and diversity of faunas, and changes in faunal composition in order to gain insight into factors of the physical environment which influenced them. This is one of the principal aims of the present study.

4.2.2 Sources of data

Most of the material for this study was obtained from the Manifold Valley in northern Staffordshire. Additional collections for comparative purposes were made in the Waulsortian outcrops in the Meuse Valley in southern Belgium. Further field observations of Waulsortian mounds were made in Eire; Clitheroe, Lancashire; Dovedale, Derbyshire; and the Weaver Hills, Staffordshire. Further collections of macrofossils from Waulsortian mounds in England and Eire were examined at the Institute of Geological Sciences, Leeds and the University Museum, Oxford.

In sampling the Waulsortian an attempt was made to include as much of the full spectrum of variation within the facies as possible. For example, in Belgium, the Waulsortian facies extends through several stratigraphic zones, and clear lithological variation is present as evidenced by the occurrence of the Blue Vein and the Biomicrite Facies (Lees et al., 1977). Samples were collected where feasible from all lithofacies and at all stratigraphic levels. In the Manifold Valley

mappable lithological variation is not present. However, the mound complex is composed of at least five separate mounds which developed over the time represented by several Belgian stratigraphic zones (see figure 3.5). In this area crinoid debris is locally important. In a few localities there are very dense accumulations of fossils, comparable to the pockets of fossils of Dupont (1863). Samples were collected from several mounds which together span the complete age range of the Waulsortian development. An effort was made to collect from the 'pockets' as well as from the crinoidal, non-crinoidal, biomicrite and bryozoa-rich areas.

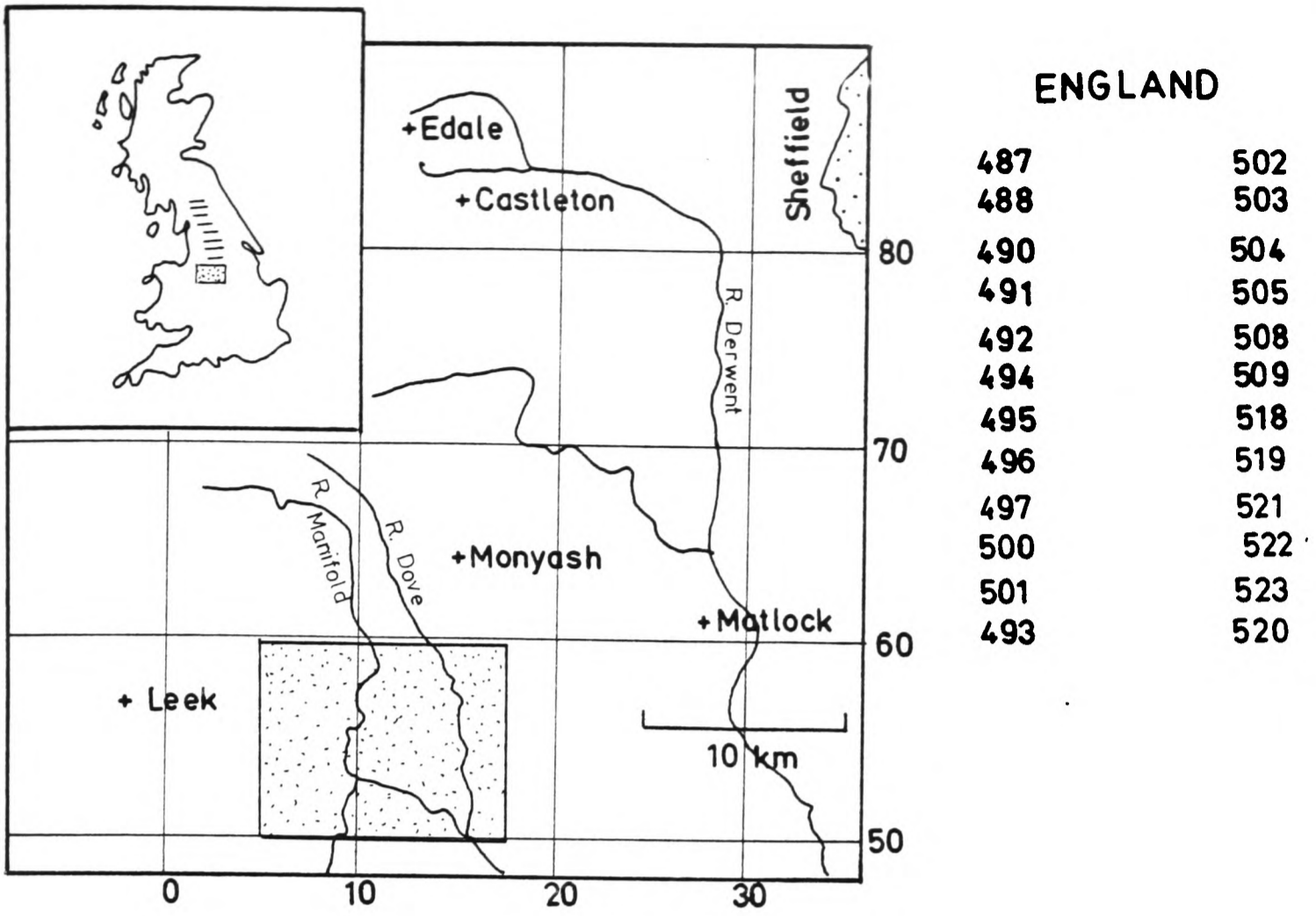
In all, seven usable faunal samples were collected in Belgium and twenty-four from the Manifold Valley. Locality maps and lists of sample sites for both areas are given in figure 4.1. Detailed locality information including grid references for the English localities and locality maps for the Belgian sites is given in Appendix 2.

4.2.3 Methods

4.2.3.1 Sampling methods in the field

The basic sampling method was to gather large quantities of Waulsortian limestone which were taken to the laboratory where they were carefully broken into small pieces by means of a rock splitter, and the macrofossils were extracted. This method is preferable to the breaking out of fossils in the field because it ensures that a more complete collection of macrofossils is obtained.

Exposure in both Belgium and the Manifold Valley is not complete and a sample site was arbitrarily defined by the physical extent of the outcrop. Thus the actual surface area sampled at each site varies somewhat. This difference is not considered to be of great significance



BELGIUM

Furfooz

- 550
- 551
- 552
- 553

Route Gendron - Celles

- 554
- 557

Moniat

- 556
- 558

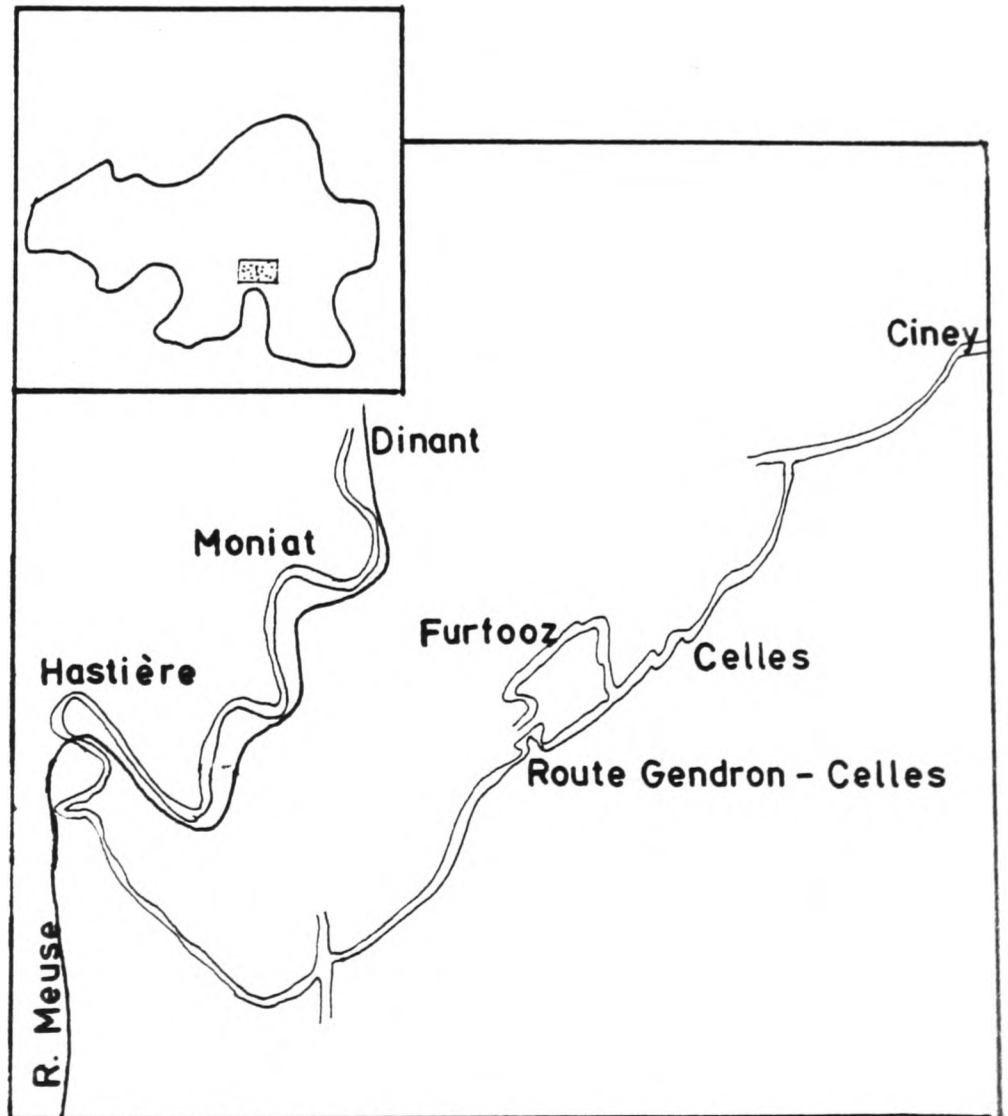


Figure 4-1 Locations of sample sites (Full locality details in appendix 2)

because the faunal characteristics measured for this study are not dependent on the size of the area sampled.

At each sample site two separate faunal samples were taken. The first sample was a faunal density sample and its purpose was to determine relative faunal densities between the various sites. The limestone for this sample was collected as uniformly as possible over the entire outcrop area. No preference was given to areas which seemed more fossiliferous. Each faunal density sample weighed between two and four kilogrammes. The method of calculation of relative faunal densities based on these samples is discussed in section 4.2.3.2. The second sample was the main faunal sample and its object was to obtain a relatively complete representation of the fauna present by collecting as many fossils as possible. In order to facilitate this, rock surfaces which showed accumulations of fossils were preferentially collected. Entire blocks rather than single fossils were collected in order to eliminate the bias imposed by the variable preservation of different fossil groups which makes some easier to see in the field than others.

4.2.3.2 Faunal measurements

The relative faunal density between sample sites was calculated by dividing the number of macrofossils found in a carefully broken up faunal density sample by the weight of the sample. Thus relative faunal densities are defined in this study as number of organisms/kgs. of rock broken.

It was necessary to exclude fenestrate bryozoa from this calculation because individual bryozoa cannot be counted in the same way as other macrofossils. Therefore, a separate measurement of the relative amounts of bryozoa was made by measuring the surface area in cm^2 covered by fenestrate bryozoa and dividing this by the weight (in kgs.) of rock

broken. Thus relative amounts of bryozoa are expressed as cm^2/kg . The trends documented in this way were subsequently confirmed by point counts of thin sections (see figure 5.9).

It must be emphasised that these measures are useful only in determining changes in faunal density between sample sites and do not necessarily represent true faunal density or amount of bryozoa present in any given area. Changes in sedimentation rates may also affect faunal density measurements. The relationship between faunal density and changing sedimentation rates in the Manifold Valley is discussed in section 4.3.

After faunal density measurements had been made the faunal density samples were combined with the main faunal sample. In order to calculate the completeness of the collection thus obtained, rarefaction coefficients were calculated and plotted. Rarefaction coefficients were developed originally as a type of diversity measure for biological communities (Sanders, 1968). Although their use for that purpose is somewhat controversial (Simberloff, 1972; Fager, 1972) they do give an indication of how many more new groups are likely to be found; thus constituting a measure of sufficient sample size (Heck et al., 1975). Rarefaction coefficients can be calculated at all taxonomic levels, so long as only similar taxonomic levels are compared (Raup, 1975). The main faunal sample was broken and the fossils combined with the density sample until the rarefaction coefficients indicated that a reasonably complete sample of all groups present was likely to have been found. Rarefaction coefficients were used only as a measure of sufficient sample size in this study. Details of the calculation and use of rarefaction coefficients are given in Appendix 3.

In this study fossils were identified to the generic level only. This was done for several reasons. The generally poor preservation

of the fossils in this area made specific identification of a large number of specimens impossible. Meaningful comparisons can only be made between similar taxonomic levels and it was decided that identification at the generic level, which was possible in most cases, provided sufficient detail. The use of generic rather than specific identification also helps to overcome the problems presented by the confused state of taxonomy of many Lower Carboniferous fossils. In the past many species have been given several names and because many papers giving faunal lists do not figure representative individuals, it is very difficult to compare faunal lists at this level. By grouping species names according to their modern generic names the effect of much of this oversplitting is compensated for. At the same time an indication of the relative diversity of the fauna is maintained.

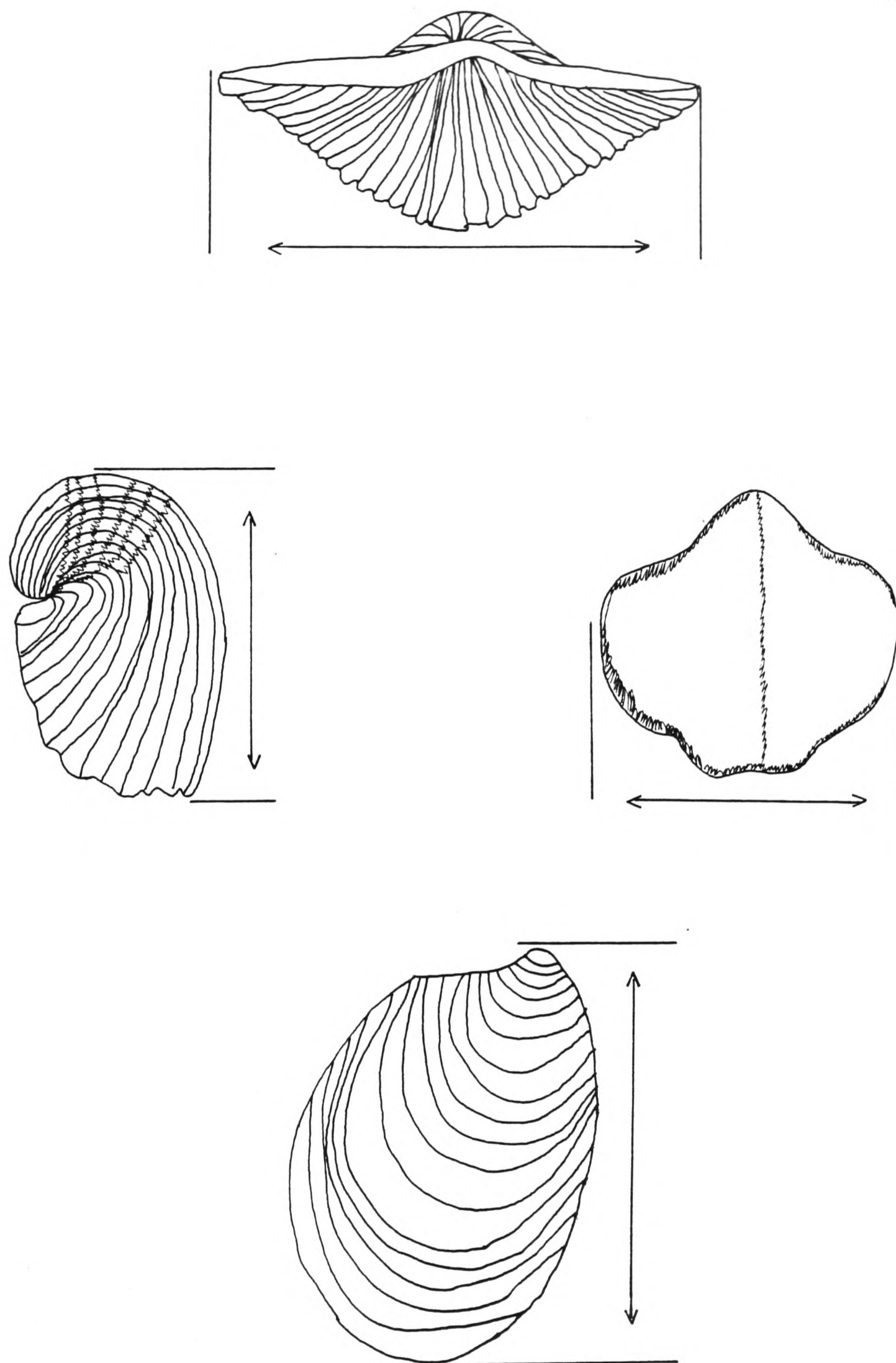
Diversity was calculated using a simple index of relative faunal diversity; counting the number of genera present in a collection. Many other diversity measurements have been suggested and there has been much discussion about the usefulness and accuracy of these measures (for example see Sanders, 1968). It becomes clear that it is very difficult to obtain reliable diversity measurements of modern faunas, let alone fossil ones. In any case, it is extremely difficult to devise any one measure which takes into account all the various factors included in diversity such as species richness and species dominance. For the purposes of this study, changes in the number of genera is considered to be the most significant information to be gained from a diversity measure, and it is probably most suited to the quality of the data available from fossil collections. If rarefaction coefficients suggest that most genera likely to be present in each locality have been found, then comparison of the number of genera found in various collections provides a reasonable relative diversity index.

In order to monitor relative changes in biovolume of the fauna as a whole the maximum dimension in cms of all brachiopods and bivalves was measured as shown in figure 4.2. Only brachiopods and bivalves were used because the other phyla present occur in statistically insignificant numbers.

In summary, the measurements made from collections at each sample site include relative faunal density, relative faunal diversity, relative amount of bryozoa, average maximum size, and a list of number of individuals present for each genus found. Lists showing this information, as well as plots of the rarefaction coefficients for each sample locality are given in Appendix 4.

4.2.3.3 Statistical methods

The organisms, expressed as a percentage of each total collection were grouped according to their morphological adaptations. The shape of shells can be a useful indicator of life habits of an organism (Rudwick, 1964; Stanley, 1970) and shell shape was the principal criterion used in morphological analysis. Among the brachiopods and bivalves the major morphological adaptations seem to be related to firmness of substrate. Indications of adaptation for life on soft substrates include the development of large flat shells (Walker and Alberstadt, 1975); the development of large flat interareas or extended hinge lines (Rudwick, 1970) and the development of a strongly concavo-convex or geniculate shell (Rudwick, 1970). Adaptations for life on firm substrates include a pedically or bysally attached life habit (Rudwick, 1970; Stanley, 1970). In the case of non-pedically attached shells the lack of flat surface areas, wide hinge lines or strong concavo-convexity argues that the organisms required firm substrates. Brachiopods and bivalves grouped according to their substrate preferences are



y

Figure 4-2 Examples of maximum dimension measurements of shells of various shapes

shown in Table 4.1. The assignment of substrate preferences is based on the above criteria and also on the life habits suggested by Mundy (1978) for the brachiopods, and Stanley (1972) and Watkins (1975) for the bivalves.

Substrate preferences for the other organisms have not been determined.

The collections from the Manifold Valley were grouped according to geographic areas, called for convenience East, Centre and West which roughly coincide with biostratigraphic zones (see figure 3.5). The sites in West are roughly of Tn3c level, those in Centre of V1b level and those in East of V3b level. It is tempting to assign palaeogeographic significance to this geographic distribution. However, it is important to remember that the distance across these geographic divisions is only 2.5 kms and that the general setting of this area during the growth of the mounds is basinal (see figure 3.2). The mounds are not far from a shelf edge, but any effects of this were probably masked by the gradual transgression which appears to have been taking place concurrently (figure 3.3a). Therefore, it is most likely that the primary significance of these divisions is stratigraphic; and the three areas represent progressively later stages of development of the mounds in a relatively unchanging environment.

Using data as described above, various descriptive statistics were calculated in order to represent the distribution of the various faunal elements. However, this type of statistical treatment did not immediately suggest further lines of research. In order to get an idea of which components of the data might be useful for further study, the data were used for principal components analysis. This form of factor analysis is useful for defining the principal components of variation, thus aiding the comparison of many collections which seem to vary in a complex manner. It is especially suitable for geological data because it involves purely mathematical manipulations and makes no assumptions

ADAPTED FOR FIRM SUBSTRATES

Smooth Spirifers

Actinochonchus
 Athyrids
 Brachythyrids
 Crurithyris
 Hustedfa
 Martinia
 Phricodothyris
 Reticularia

Non-Trail Productids

Avonia
 Chonetipustula
 Eomarginifera
 Krotovia
 Linoprotonia
 Overtonia
 Productina
 Pustula
 Quasiavonia

Other Brachiopods

Dielasma
 Orthids
 Pleuropugnoides
 Pugnax
 Rhipidomella
 Rhynchonellids
 Schizophoria
 Terebratulids

Bivalves

Parallelodon
 Posidoniella
 Streblochondria
 Strebloteria
 Smooth pectinids

ADAPTED FOR SOFT SUBSTRATES

Spirifers

Spirifer
 Tylothyris

Trail Productids

Antiquatonia
 Buxtonia
 Echinochoncus
 Plicatifera
 Productus

Other Brachiopods

Brochocarina
 Leptaenids
 Orthotetes
 Schellwienella
 Strophomenids

SUBSTRATE PREFERENCE NOT DETERMINED

Other organisms

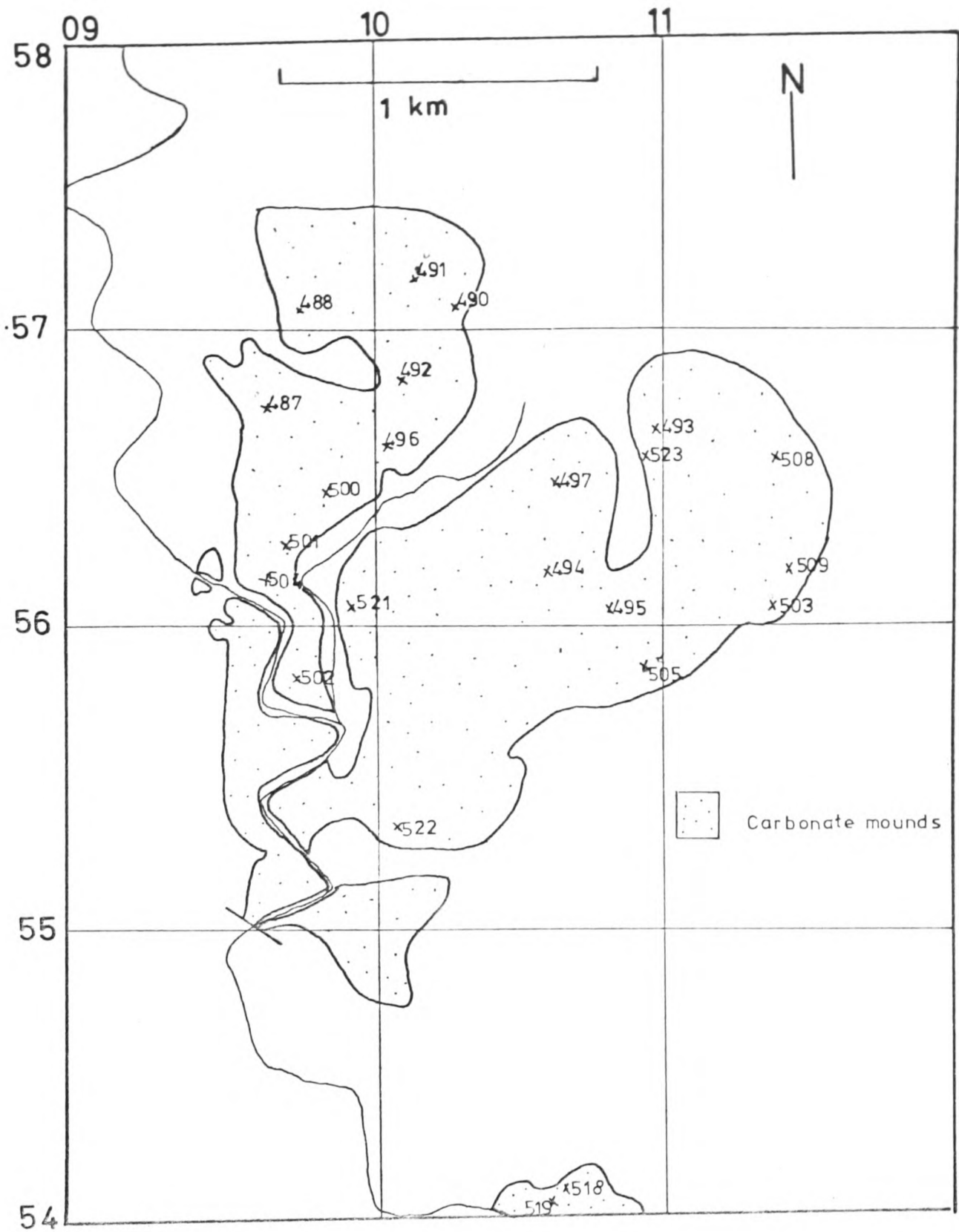
Cephalopods
 Corals
 Gastropods
 Others
 Trilobites

Bivalves

Pernopectem

Table 4-1. Morphological Groups used for Principal Components Analysis.

Names correspond to those used in faunal lists in Appendix 4.



West (Tn3c)

- 504
- 502
- 501
- 500
- 496
- 492
- 491
- 490
- 488
- 487

Centre (V1a-b)

- 494
- 495
- 497
- 521
- 522
- South
- 518
- 519

East (V3b)

- 509
- 508
- 505
- 503
- 523
- Pocket
- 493
- 520 (located in Dovedale, E. of area shown)

(grid references in appendix 2)

Figure 4-3 Manifold Valley sample localities arranged by geographic groups

about relationships which may or may not exist within the data (Davis, 1973).

All the statistical work with the exception of the rarefaction coefficients was done on the ICL 2980 computer at Oxford University. The descriptive statistics and principal components analysis for all of the faunal data was done using the Statistical Package for the Social Sciences (SPSS) programs. The data on maximum size could not be handled by these programs, so a separate program, called STATUS, was written to calculate these statistics. A program called SPECIES was written for the 2980 computer to compile uniform lists of SPSS input data. The rarefaction coefficients were computed using a program called DIV on the 1906 computer. Full documentation on the use of these programs is given in Appendix 3.

4.2.4 Comparisons between Waulsortian faunas from different areas

Comparisons between the Waulsortian in other areas and the Belgian Waulsortian have in the past been based principally on gross lithological characteristics (Douglas, 1909; Dixon, 1921). It is therefore of some interest to compare the collections made for this study with some of the published faunal lists from the Waulsortian of England, Eire and Belgium in order to see if the faunas are similar. If faunas are similar, environments are likely to be similar and there would then be some justification for comparing geographically widely separated Waulsortian developments. Table 4.2 presents a complete listing of all macrofauna reported from these regions and shows which genera have been found by the various authors.

Lithologically, the Belgian collections with the exception of those made for this study were probably mainly of the Blue Vein Facies of Lees et al. (1977). Those made specifically for this study were

Table 4.2 List of Macrofauna reported from the Waulsortian in
Britain, Eire and Belgium.

	L. U.		Belgium	Dupont (1863)	This Study	L. M. U.		L. U.	Eire	Hudson et al. (1966)	Jackson (1919) Dovedale	England	L. U.		This Study
BIVALVES															
<u>Aviculopecten forbesi</u> (M'Coy), <u>plicatus</u> (Sow.)	X	X	X	X						X		X	X		
<u>Cardiomorpha corrugata</u> (M'Coy), <u>inflatum</u> (M'Coy), <u>oblonga</u> (J. de C. Sow.), <u>orbicularis</u> (M'Coy)	X	X		X		X		X	X	X	X		X	X	
¹ <u>Conocardium aliforme</u> Sow., <u>hiburnicum</u> (Sow.), <u>konincki</u> Bally	X	X	X	X		X		X	X	X			X	X	
<u>Edmondia unioniformis</u> de Kon.)	X		X												
<u>Girtypecten tessellatus</u> (Phillips))												X			
<u>Leiopteria hirundo</u> de kon., <u>laminosa</u> Phillips, <u>lunulata</u> Phillips)		X	X			X	X					X	X		
<u>Limipecten</u> (sp.)										X					
<u>"Lithodomus"</u> (sp.)		X											X		
<u>"Mytilus"</u> (dactyloides M'Coy)	X			X											
<u>Parallelodon bistratus</u> (Portlock), <u>cingulatus</u> (M'Coy))		X			X					X			X	X	
<u>Pernopecten sowerbyi</u> (M'Coy))				X		X				X				X	
<u>Posidonella</u> (sp.)														X	
<u>Pteropecten</u> (sp.)	X	X												X	X
<u>Pteropectinella bosquentiana</u> (de Kon.), <u>eximus</u> (de Kon.), <u>granosa</u> (J. de C. Sow.), <u>radiata</u> (Phillips))											X				

	L. U.		Demanet (1958)	Dupont (1863)	This Study	L. M. U.		L. U.	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L. U.		This Study
	Demanet (1923)					Shephard-Thorn (1963)						Parkinson (1926) Clitheroe		
BIVALVES cont.														
<u>Sanguinolites</u> (<u>interruptus</u> Hind, sp.)		X		X		X	X		X					
<u>Schizodus</u> (<u>fragilis</u> (M'Coy), sp.)						X			X					
<u>Streblochondria</u> (<u>concentrico-lineatum</u> (Hind))									X					X
<u>Streblopteria</u> (<u>laevigata</u> (M'Coy))	X		X			X								X

¹Conocardium is sometimes placed in the suprafamily Rostroconchida (Moore, 1969).

	L.	U.	Demanet (1923)	Demanet (1958)	Dupont (1863)	This Study	L.	M.	U.	L.	U.	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L.	U.	This Study	
BRACHIOPODS																		
Inarticulates																		
<u>Crania</u> (<u>quadrata</u> McCoy)												X		X				X
<u>Lingula</u> (sp.)															X			
Articulates																		
ORTHIDS																		
<u>Rhipidomella</u> (<u>micchelini</u> (Leveille))	X		X			X								X				X
<u>Schizophoria</u> (<u>connivens</u> (Phillips), <u>palliat</u> a (Delepine); <u>resupinata</u> (Martin))	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
RHYNCRON ELLIDS																		
<u>Pleuropugnoides</u> (<u>carringtoniana</u> (Davidson), <u>flexistra</u> (Phillips), <u>pleurodon</u> (Phillips))				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<u>Pugnax</u> (<u>accuminatus</u> (Sow.), <u>platylobus</u> (J. de C. Sow.), <u>plicatus</u> (J. de C. Sow.), <u>pugnus</u> (Martin), <u>reniformis</u> (J. de C. Sow.))	X		X			X	X	X	X	X	X	X	X	X	X	X	X	X
<u>Stenoschisma</u> <u>crumena</u> (Martin), <u>pentangulata</u> (Demanet))												X		X				X
<u>Streptorhyn</u> (<u>senilis</u> (Phillips))														X		X		X

PRODUCTIDS cont.	L. U.				L. M. U.				L. U.				This Study
	Demamet (1923)	Demamet (1958)	Dupont (1863)	This Study	Shephard-Thorn (1963)	Neville (1958)	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	Parkinson (1926) Clitheroe			
<u>Dictyoclostus</u> (<u>multispiniferus</u> (Muir-Wood), <u>semireticulatus</u> (Sow.))	X	X	X		X	X	X	X	X	X			
<u>Echinochonus</u> (<u>punctatus</u> (Sow.), <u>venustus</u> (Thomas))				X					X				X
<u>Emarginifera</u> (<u>derbiensis</u> (Muir-Wood), <u>feltrimensis</u> (nom. nud. Ramsbottom), sp.)					X	X	X		X			X	X
<u>Fluctuaria</u> (<u>undata</u> (DeFrance))									X			X	X
<u>Institifera</u> (<u>tesselatus</u> (de Kon.))	X												X
<u>Institina</u> (<u>marginalis</u> (de Kon.))	X												
<u>Krotovia</u> (<u>spinulosa</u> (Sow.))		X	X		X	X	X		X			X	X
<u>Levitusia</u> (<u>humerosa</u> (J. de C. Sow.), <u>sublaevis</u> (de Kon.))		X			X								X
<u>Linoprotonia</u> (<u>cora</u> (d'Orbigny), <u>corrugatus</u> (McCoy))		X	X	X	X	X	X	X	X		X	X	X
<u>Overtonia</u> (<u>fimbriata</u> (J. de C. Sow.))		X		X		X	X	X					X
<u>Plicatifera</u> (<u>plicatus</u> (J. de C. Sow.), <u>pseudoplicatus</u> (Muir-Wood), sp.)	X	X	X	X	X	X	X		X			X	X
<u>Productina</u> (<u>margaritaceus</u> (Phillips), <u>pectinoides</u> (de Kon.))		X		X		X	X		X			X	X
<u>Productus</u> (<u>concinus</u> Sow., <u>deshayesianus</u> de Kon., <u>flemingi</u> Sow., <u>fourneri</u> Demanet, <u>garwoodia</u> Muir-Wood, <u>leuchtenburgensis</u> de Kon., <u>newberryi</u> Hall, <u>saleei</u> Demanet, <u>sorellii</u> Demanet))		X		X					X			X	X
<u>Pugilis</u> (<u>vaughani</u> (Muir-Wood))	X	X	X		X	X	X		X			X	

PRODUCTIDS cont.	L. U.		Demaret (1958)	Dupont (1863)	This Study	L. M. U.			L. U.	Neville (1958)	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L. U.		This Study
	Demaret (1923)					Shephard-Thorn (1963)										
<u>Pustula</u> (<u>interrupta</u> Thomas, <u>nodopustula</u> , Parkinson, <u>vilosa</u> Thomas, <u>pustulosa</u> (Phillips), <u>pyxidiformis</u> (de Kon.), <u>ruguta</u> (Phillips), <u>tenuipustula</u> (Thomas))	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
<u>Quasiavonia</u> (<u>acculeata</u> (Martin))				X	X							X			X	X
<u>Thomasella</u> (sp.)													X			X
SPIRIFERIDS																
<u>Actinochonchus</u> (<u>llamellosus</u> (Leveille), <u>paradoxus</u> (M'Coy))						X					X			X		X
<u>Athyris</u> (<u>expansus</u> Phillips, <u>planosulcata</u> (Phillips), <u>rotundata</u> (Martin), <u>waagoni</u> de Kon.)	X	X	X	X	X				X	X		X		X	X	X
<u>Brachythyris</u> (<u>hemisphericus</u> (M'Coy), <u>integricosta</u> (Phillips), <u>lingulifera</u> (Phillips), <u>ovalis</u> (Phillips), <u>pinguis</u> (Sow.), <u>planata</u> (Phillips), <u>rotundata</u> (Sow.), <u>sextadialis</u> (Phillips), <u>subrotundus</u> (M'Coy), <u>triradialis</u> (Phillips))	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<u>Cleiothyridinia</u> (<u>roissyi</u> (Leveille), <u>glabistra</u> (Phillips), <u>ingens</u> (de Kon.))						X	X	X			X					
<u>Composita</u> (<u>ambigua</u> (Sow.))													X			
<u>Crurithyris</u> (<u>urei</u> (Fleming))					X											X
<u>Davidsonina</u> (<u>septosa</u> (Phillips), <u>subcinctus</u> (de Kon.))														X		
<u>"Fusella"</u> (<u>convolutus</u> (Phillips), <u>trigonalis</u> (Martin), <u>rhomboides</u> (Phillips))	X												X		X	X

		L.	U.					L.	M.	U.	L.	U.					L.	U.		
				Demanet (1923)	Demanet (1958)	Dupont (1863)	This Study				Neville (1958)		Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold					
SPIRIFERIDS cont.																				
<u>Hustedia</u> (<u> davidsoni</u> de Kon., <u> radialis</u> (Phillips))		X											X		X					X
<u>Martinia</u> (<u> glabra</u> (Sow.), <u> planata</u> (Phillips), <u> rhomboidalis</u> (M'Coy))		X	X				X			X	X		X	X				X	X	X
<u>Martiniothyris</u> (<u> lineata</u> Sow.)																		X		
<u>Phricodothyris</u> (<u> insolita</u> George)						X	X						X							X
<u>Pseudosyrinx</u> (<u> sp.</u>)									X											
<u>Reticularia</u> (<u> elliptica</u> (Phillips), <u> imbricata</u> (Sow.), <u> lobata</u> (Muir-Wood), <u> obtusa</u> (Sow.), <u> reticulata</u> M'Coy, sp.)		X	X	X			X			X	X	X	X						X	X
<u>Spiriferellina</u> (<u> insculpta</u> (Phillips), <u> octoplicata</u> (Sow.), <u> peracuta</u> de Kon.)				X						X			X					X		
<u>Spirifer</u> (<u> acutus</u> de Kon., <u> attenuatus</u> J. de C. Sow., <u> bisulcatus</u> J. de C. Sow., <u> bollandensis</u> Muir-Wood, <u> coplowensis</u> Parkinson, <u> duplicicostus</u> (Phillips), <u> eximus</u> de Kon., <u> grandicostatus</u> M'Coy, <u> konincki</u> Dewalque, <u> neglectus</u> de Kon., <u> plicatosulcatus</u> North, <u> pentagonus</u> de Kon., <u> princeps</u> M'Coy, <u> striatus</u> (Martin))		X	X	X			X			X	X	X	X	X				X	X	X
<u>Syringothyris</u> (<u> cuspidata</u> Sow., <u> elongata</u> Sow., <u> exoleta</u> North)		X	X	X		X		X	X	X	X	X	X							
<u>Tylothyris</u> (<u> subconica</u> North)								X	X	X					X					X

CEPHALOPODS	L. U.		Demamet (1958).	Dupont (1863)	This Study	L. M. U.		L. U.	Neville (1958)	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L. U.		This Study
	Demamet (1923)					Shephard-Thorn (1963)							Parkinson (1926) Clitheroe		
<u>Actinoceras (insulare Foord)</u>												X			
<u>Apheloceras (hiburnicum Foord and Crick, lyriostomus de Kon., mutabile (M'Coy))</u>										X					
<u>Asymptoceras (foordi Hyatt, sp.)</u>										X				X	
<u>Beyrichocerotoides (sp.)</u>								X					X		
<u>Beyrichoceras (allei (Winchell), implicatum (Phillips), sp.)</u>							X						X	X	
<u>Cyrtoceras (apicale Foord)</u>										X					
<u>Discitoceras (leveillianum (de Kon.))</u>										X					
<u>Eusthenoceras (baillyi (de Kon.))</u>										X					
<u>Fascipericyclus (fasiculatus (M'Coy))</u>							X	X							
<u>Goniatites (belvalianus (de Kon.), crenistra (Phillips))</u>				X									X		
<u>Merocanites (compressus (Sow.))</u>								X							
<u>Munslerocheras (companatum (de Kon.), crassum Foord, pseudoganides George and Ponsford, rolella (de Kon.))</u>						X	X	X		X					
<u>Nautillopsites (hibernicus d'Orbigny)</u>							X	X							
<u>Nautilus (cariniferus J. de C. Sow.)</u>					X										
<u>Orthocone (sp.)</u>										X					X

CEPHALOPODS cont.	L. U.	Demanet (1923)		Demanet (1958)		Dupont (1863)		This Study	L. M. U.	Shephard-Thorn (1963)	L. U.	Neville (1958)		Hudson et al. (1966)		Jackson (1919) Dovedale		Prentice (1951) Manifold	L. U.	Parkinson (1926) Clitheroe		This Study
<u>Orthoceras</u> (<u>sollasi</u> Foord, <u>sancti-doulagh</u> Foord, <u>munsterianum</u> (de Kon.), sp.)	X				X													X	X	X		
<u>Planctoceras</u> (<u>globatum</u> J. de C. Sow.)													X	X								
<u>Solenochelilus</u> (<u>clausus</u> Foord, <u>hibernicus</u> Foord)									X	X				X								
<u>Vestinautilus</u> (<u>cariniferus</u> Sow., <u>crateriformis</u> Sow., <u>paucicarinatus</u> (Foord), sp.)			X	X					X	X							X					

CORALS	L. U.		Demamet (1958)	Dupont (1863)	This Study	L. M. U.		L. U.	Neville (1958)	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L. U.		This Study
	Demamet (1923)					Shephard-Thorn (1963)							Parkinson (1926)	Clitheroe	
<u>Amplexus</u> (<u>coralloides</u> Sow., sp.)			X	X	X	X	X	X	X	X	X	X	X	X	X
<u>Beaumontia</u> (<u>laxa</u> (M'Coy))														X	
<u>Carruthersella</u> (<u>compacta</u> Garwood)		X										X			
<u>Chaetetes</u> (sp.)												X			
<u>Clisophyllum</u> (sp.)														X	
<u>Cyathoxonia</u> (sp.)								X							X
<u>"Emonsia"</u> (<u>parasitica</u> (Phillips))														X	
<u>Koninkophyllum</u> (<u>clitheroense</u> Parkinson)														X	
<u>Michelinia</u> (<u>megastoma</u> (Phillips)), <u>tenuisepta</u> (Phillips), sp.)							X					X		X	
<u>Rotiphyllum</u> (sp.)	X	X								X	X				
<u>Siphonophyllia</u> (<u>cylindrica</u> (Vaughan))						X	X	X		X				X	X
<u>Syringopora</u> (<u>distans</u> Fischer, <u>ramulosa</u> Goldfuss, <u>reticularia</u> Goldfuss)												X		X	
<u>"Zaphrentis"</u> (<u>omalisusi</u> (Edwards and Halme), <u>amblyum</u> (Carruthers), <u>densum</u> (Carruthers), <u>junctosepta</u> (Smyth))							X					X		X	X

GASTROPODS		L.	U.	Demanet (1923)	Demanet (1958)	Dupont (1863)	This Study	L.	M.	U.	L.	U.	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L.	U.	This Study
<u>Baylea (communis de Kon.)</u>					X													
<u>Bellerophon (hiucius J. de C. Sow., tanentialis Phillips, tenuifascia Sow., sp.)</u>		X		X		X	X						X	X			X	X
<u>Bucania (textilus Hall)</u>				X														
<u>Chemnitzia (lefebrevi Leveille)</u>						X												
<u>Conularia (sp.)</u>																	X	
<u>Dispotea (prisca N'CoY)</u>						X							X					
<u>Lepetopsis (umbrellum (de Kon.))</u>		X		X	X								X					
<u>Ianthinopsis (imbricata (Phillips))</u>																	X	X
<u>Macrochilina (retilinea (Phillips), sp.)</u>					X								X				X	
<u>Mourlonia (laevis (Archiac and Verneuil))</u>				X														
<u>Naticopsis (ampliata (Phillips), elliptica (Phillips), planispira (Phillips), plicistria (Phillips), variata (Phillips), sp.)</u>				X														
<u>Phanerotinus (intermedium (de Kon.))</u>		X			X	X				X			X				X	X
<u>Platyceras (neritoides (Phillips), trilobus (Phillips), vetustus (J. de C. Sow.), sp.)</u>						X												
<u>Platyschisma (hellicoides Sow.)</u>						X				X			X				X	X

TRILOBITES	L. U.		Demamet (1958)	Dupont (1863)	This Study	L. M. U.		L. U.	Hudson et al. (1966)	Jackson (1919) Dovedale	Prentice (1951) Manifold	L. U.		This Study
<u>Bollandia</u> (sp.)														X
<u>Brachymetopus</u> (<u>maccoyi</u> (Portlock), <u>ouralicus</u> (de Verneuil))			X		X				X				X	X
<u>Cummingella</u> (<u>carringtonensis</u> Woodward, sp.)														X
<u>Griffithides</u> (<u>globiceps</u> (Phillips))		X	X										X	
<u>Phillipsia</u> (<u>gemmullifera</u> (Phillips), sp.)		X	X						X				X	X
Ostracodes								X			X		X	X

collected from both the Blue Vein and Biomicrite Facies. The localities collected by Shephard-Thorn are probably largely of the Biomicrite Facies. Those reported by Neville seem to have come from both facies. The fauna from Feltrim Hill is from rocks of predominately Blue Vein Facies. Waulsortian rocks of the Blue Vein Facies are normally rather rare in England and all of the English fossil localities are likely to have come from the Biomicrite Facies.

Inspection of Table 4.2 shows that in general terms the faunas from the three areas appear to be rather similar. The greatest similarities appear to be in brachiopod and bivalve genera. The faunal variation which does occur can be largely explained by the relative abundance of cephalopod genera in the Irish Waulsortian, the greater number of coral genera reported from England and the greater number of gastropod genera reported from Belgium.

These observations can be tested in a semi quantitative way by similarity coefficients. A great variety of similarity coefficients have been suggested but one of their common failings is that there is no means of determining the significance of the results. Ideally, a coefficient or curve which represents the amount of variation to be expected between different collections made from the same statistical population could be generated and this could be used to determine the significance of the calculated coefficients.

This method can be approximated by computing a matrix of an appropriate similarity coefficient and comparing the "within country" variation, which is taken to represent the expected similarity between two samples drawn from the same population, with "between countries" variation.

For this study a matrix of coefficients of similarity, which evaluate the similarity of faunal lists based on presence/absence data, was calculated. The formula used is $S=p/p+m$; where p = the number of instances when the same genera is present in both of the collections being compared (positive matches) and m = the number of instances where a genera occurs in one collection, but not in the other (mis-matches). The mutual absence of a species in collec-

tions being compared is ignored. The coefficients were then grouped according to whether they represented "within country" or "between countries" variation and significant differences between these groups were sought using analysis of variance.

The matrix of similarity coefficients calculated from the faunal lists in Table 4.2. is shown in Table 4.3. The groupings used in analysis of variance are shown in bold outlines. Triangular shaped groups represent the "within country" variation and rectangular shaped groups represent "between countries" variation. The analysis of variance table is shown in Appendix 4, section A4.1.4.

Analysis of variance indicates that there is no significant variation between the groups of similarity coefficients. This suggests that the faunas reported from the various Waulsortian developments are comparable. Thus, there is justification for the idea that environments in the various Waulsortian developments are similar and that no major faunal change occurs in conjunction with the lithological change from Blue Vein to Biomicrite Facies. It also suggests that the collections made for this study are as representative as any of the published lists of faunas likely to be found in the Waulsortian. It is therefore reasonable to suppose that deductions based on these collections will be applicable to Waulsortian environments as a whole.

4.2.5 Description of the Manifold Valley faunas

A list of genera collected in the Manifold Valley is shown in Table 4.4. The bulk composition of the fauna is 79% brachiopods, 17% bivalves and 4% others. This is similar to the bulk composition of the faunas reported by Hudson et al. (1966) from Feltrim Hill. Within the Manifold Valley faunas the most prevalent morphological groups are other brachiopods (21.7%), non-trail productids (17.7%), bivalves (17.0%) and smooth spirifers (16.5%). Within the group other brachiopods, those which shown adaptations for life on firm substrates make up 14.3% of the total.

	Demanet (1923)	Demanet (1958)	Dupont (1863)	This Study	Shephard-Thorn (1963)	Neville (1958)	Hudson et al. (1966)	Jackson (1919)	Prentice (1951)	Parkinson (1926)	This Study
Demanet (1923)	X										
Demanet (1958)	.42	X									
Dupont (1863)	.38	.33	X								
This study	.31	.31	.29	X							
Shephard-Thorn(1963)	.38	.29	.33	.24	X						
Neville (1958)	.35	.31	.43	.29	.34	X					
Hudson et al.(1966)	.31	.32	.30	.25	.40	.25	X				
Jackson (1919)	.27	.24	.39	.42	.25	.33	.20	X			
Prentice (1951)	.29	.21	.23	.25	.33	.26	.26	.21	X		
Parkinson (1926)	.42	.34	.29	.29	.43	.29	.36	.28	.33	X	
This Study	.35	.29	.30	.45	.34	.23	.38	.31	.31	.31	X

Table 4.3. Matrix of Similarity Coefficients

Table 4.4. List of Genera Found in the Manifold Valley

CORALS	BIVALVES (cont.)
Amplexus	Streblochondria
Cyathaxonia	Strebloteria
"Zaphrentis"	
	BRACHIOPODS
TRILOBITES	<u>Inarticulates</u>
Bollandia	
Brachmetopus	Crania
Cummingella	
Phillipsia	<u>Articulates</u>
CEPHALOPODS	ORTHIDS
Orthocone	Rhipidomella
Nautiloid	Schizophoria
GASTROPODS	RHYNCHONELLIDS
Bellerophon	Pleuropugnoides
Ianthinopsis	Pugnax
Naticopsis	Streptorhynchus
Platyceras	
Straparollus Euomphalus	STROPHOMENIDS
Straparollus Straparollus	Brochocarina
Sublites	Leptagonia
	Orthotetes
	Schellwienella
BIVALVES	
Parallelodon	TEREBRATULIDS
Pernopectin	Dielasma
Smooth Pectinids	Girtyella
Posidoniella	

PRODUCTIDS

Antiquatonia

Avonia

Buxtonia

Chonetipustula

Dictyoclostus

Echinochoncus

Eomarginifera

Krotovia

Linoprotonia

Overtonia

Plicatifera

Productina

Productus

Pustula

Quasiavonia

Thomasella

SPIRIFERIDS

Actinochoncus

Athyris

Brachythyris

Crurythyris

"Fusella"

Hustedea

Martinia

Phricodothyris

Reticularia

Spirifer

SPIRIFERIDS (cont.)

Smooth Spiriferids

Tylothyris

BRYOZOA

Fenestella

Fistulipora

OTHERS

Cyclus (crustacean)

Crinoid ossicles

Ostracodes

Those which are adapted for life on soft substrates make up 7.4% of the total. The non-trail productids, bivalves and smooth spirifers are all adapted to firm substrates. The groups spirifers (5.8%) and trail productids (5.5%) are adapted for life on softer substrates (see section 4.2.3.3). It is difficult to generalise about the substrate preferences of the juvenile brachiopods (11.6%) and the other organisms (4.2%).

In summary, of the faunas collected in the Manifold Valley 66% of the organisms are adapted for life on firm substrates, 19% are adapted for softer substrates and the substrate preferences for the remaining 16% cannot be determined.

4.2.5.1 "Pocket" faunas

In the Manifold Valley there are sporadic occurrences of seemingly anomalously high faunal density. One example of this type of dense fossil accumulation occurs in the Manifold Valley (collection 493; grid ref. SK 1097 5658). The well known brachiopod bed at the top of Thorpe Cloud in nearby Dovedale (collection 520; grid ref. SK 1535 5100) provides a second example. This marked patchiness of distribution of organisms and the occurrence of so-called "pockets" of fossils is well documented in other Waulsortian mounds (Dupont, 1863; Parkinson, 1950; Prentice, 1951; Shephard-Thorn, 1963; and others).

Several lines of evidence suggest that the pockets were original features of the mounds rather than later accumulations as is sometimes suggested (for example by Dupont, 1969). In order to test for obvious signs of current alignment, the orientation of the long axis of brachiopods and bivalves was measured on six slabs taken from the Manifold Valley example. Additionally, 76 measurements of long axis orientation were made on exposed horizontal surfaces of the Thorpe Cloud brachiopod bed. Circular diagrams of the measurements were plotted and the uniformity of the distribution was tested by means of Chi Square tests. (The method is described in Appendix 4, section 4.1.7). These calculations

indicate that shells in the Manifold Valley samples have random orientations. Those measured from Thorpe Cloud do not appear to have a random distribution. However, their distribution is not obviously bi- or unimodal as would be characteristic of current transported accumulations (Menard and Boucot, 1951; Schwarzacher, 1963). It must also be pointed out that the Thorpe Cloud measurements are the less reliable, because in some cases apparent long axis directions may have been measured. The orientation diagrams are shown in Figure 4.4. Another obvious indicator of transport is size sorting. This also does not seem to occur, as a wide size range is represented. The maximum dimensions measured in the Manifold Valley range from 0.1 to 5.8 cms and those from Thorpe Cloud range from 0.3 to 5.1 cms.

The diversity of the fauna in the Manifold Valley pocket is close to the mean diversity found in the Manifold Valley as a whole. However, the density, average maximum size and biovolume of the pocket fauna are well above the means of these characteristics in the complex as a whole (see section A4.1.2). Also, within the pockets there is a tendency towards domination of the fauna by a relatively few genera. In the Manifold Valley pocket 23 genera are represented. Of these 2 genera of Orthids make up 32.5% of the total. The remaining 67.5% is divided among the other 21 genera. Dominant groups also seem to be present in the Thorpe Cloud brachiopod bed. There 6 genera (Pleuropugnoides, Brachythyris, Crurithyris, smooth pectenids, Brochocarina and Spirifer) account for 67% of the total population. The other 15 genera make up the remaining 33% (see section A4.1.1, collections 520 and 493 and section A4.1.2).

High faunal densities, large average size and biovolume and tendency towards domination of the population by a few genera characterise the pocket faunas, but are not unique to them. Other collections from the Manifold Valley (for example collections 509, 508 and 496) exhibit densities as high or higher than those found in the pockets. Similarly there are other collections where the average size and biovolume are comp-

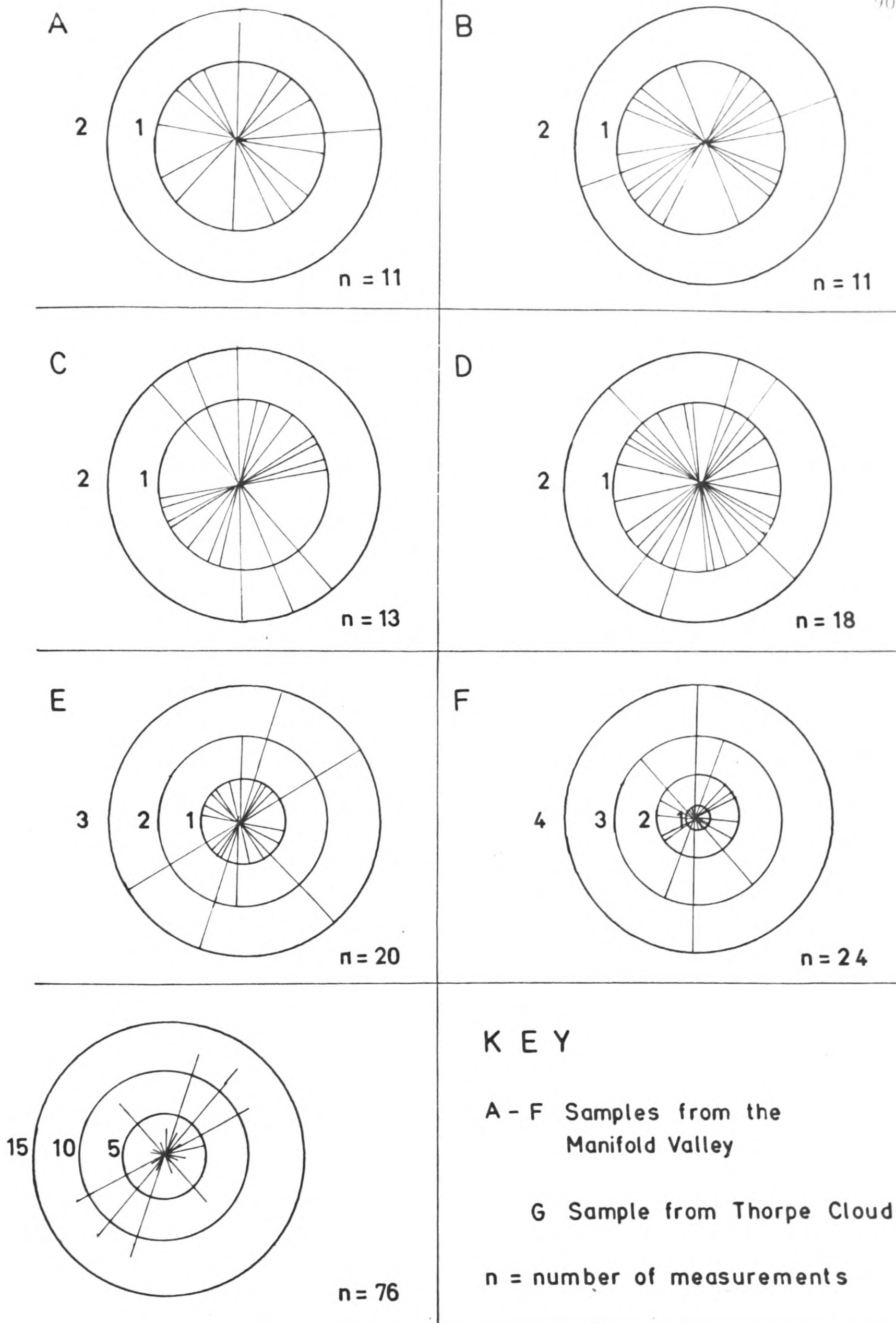


Figure 4.4. Orientation of long axis directions of brachiopods & bivalves in fossil 'pockets'

are likely to be. When there are conflicting results among the biostratigraphic groups, the results from Total and West have been preferred because they contain the largest number of cases. (Results shown in Table 4.6)

Runs 1 and 2 indicate that the variation among collections can be best explained by examining differences in diversity, density or the combined effects of density and average maximum size, which are highly correlated; amount of bryozoa and absence of bivalves in some collections, in that order.

These four factors account for only about 70% of the total variation among collections. In an attempt to understand the remaining percentage of variation, the first three of these measurements were excluded from run three. The results of this run are much more ambiguous. The presence of other organisms figures predominantly in factor 1. Factor 2 points towards bivalves; factor 3 seems to indicate the importance of comparisons between soft sediment adapted morphotypes and those more adapted for life on firm surfaces. Factor 4 is too vague to attempt an interpretation.

The significant changes in diversity, density/average maximum size and amount of bryozoa over biostratigraphic zones suggested by factor analysis do in fact occur and these trends are outlined in figure 4.4. The variations in faunal composition suggested by run 3 are much less clear (see figure 4.5).

The histograms in figure 4.4 show that there is a tendency for diversity to decrease for the older rocks (those in the Western mound) to the younger rocks (those in the Eastern mound). The trends in density are not as clear, but suggest an increase in density towards the younger parts of the complex.

In fossil communities density trends can sometimes be more apparent than real. Changing sedimentation rates may result in apparent changes in faunal density even if the density of the fauna does not change. If the density remains constant but the sedimentation rate increases, the density may appear to decrease because there will be proportionately more sediment

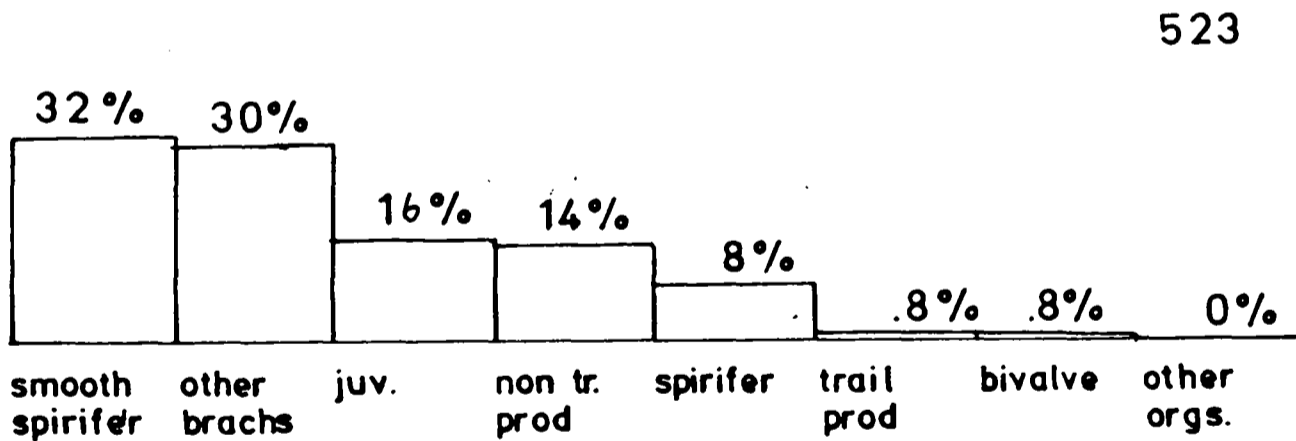
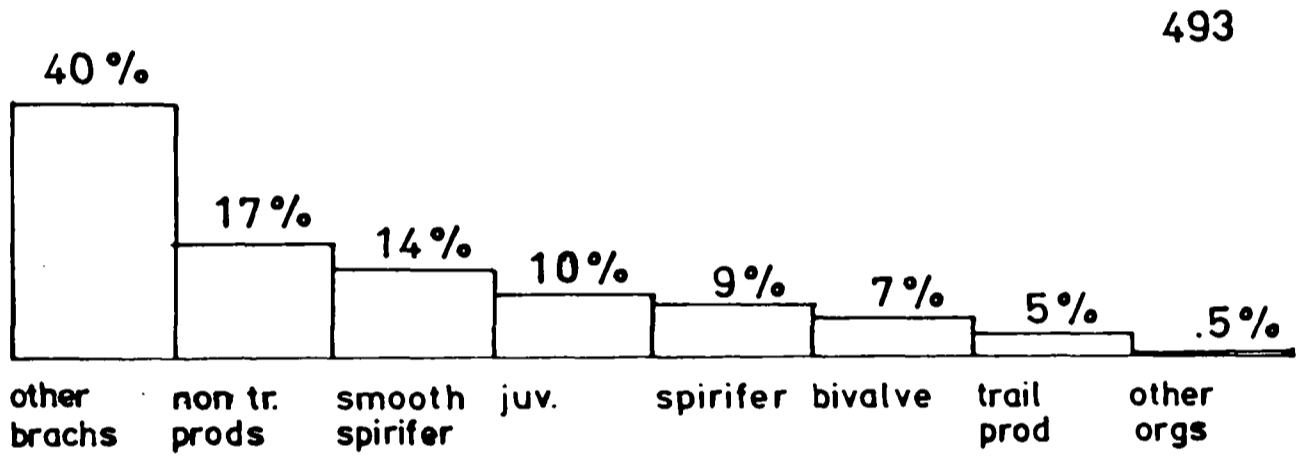
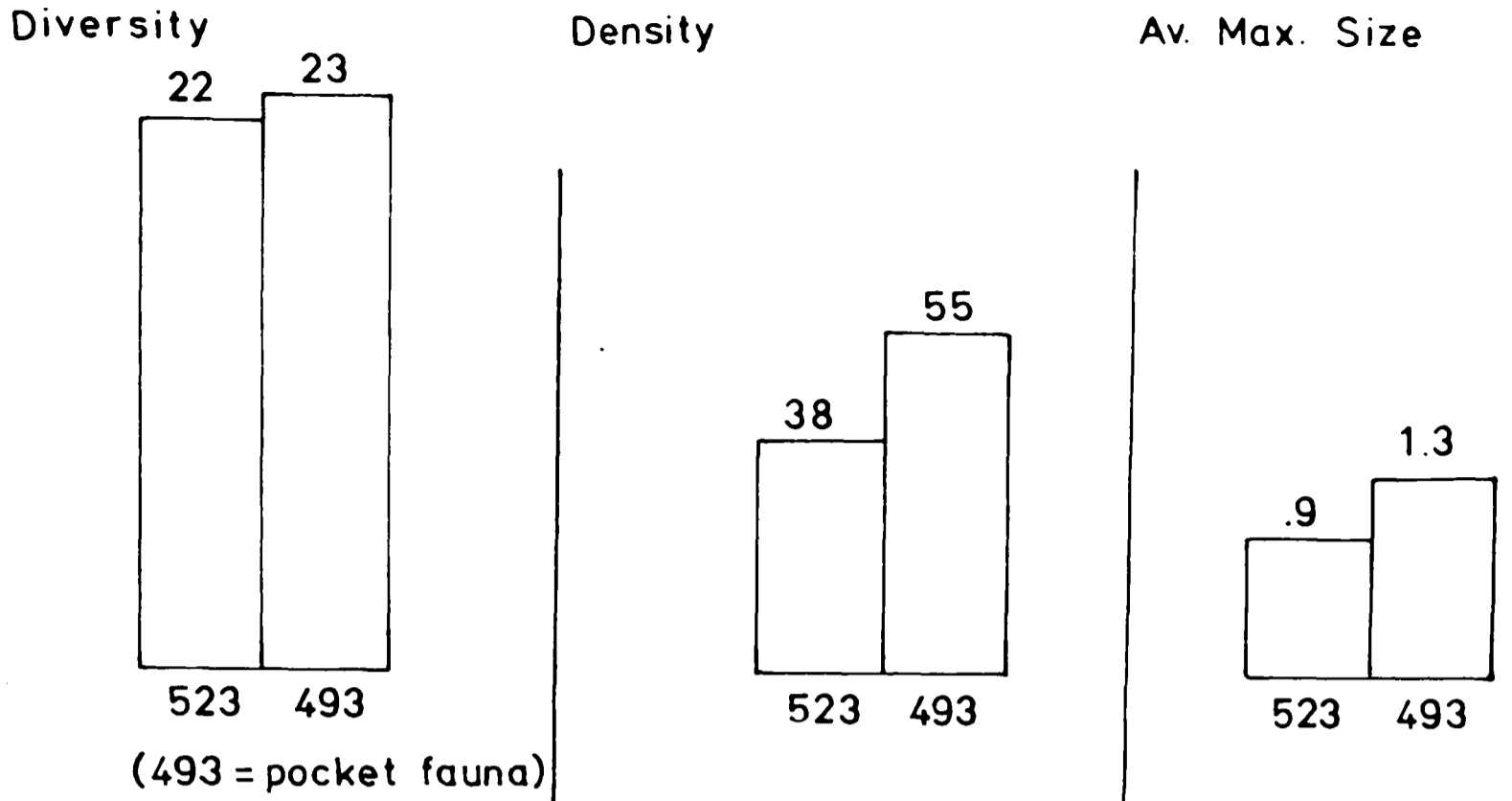


Figure 4.5. Comparison of a pocket (493) with a nearby non-pocket fauna (523).
(data in Appendix 4, section A4.1.2)

be recognised when the variance of the density measurements greatly exceeds their mean. This clearly occurs in the Manifold Valley (see section A4.1.3) where the variance of the density measurements exceeds the mean density in each geographic area and in the complex as a whole.

The occurrence of clumped distributions is thought to be regulated by such factors as local habitat differences and by reproductive processes (Odum, 1971). Both of these reasons seem logical in the context of the Waulsortian, although it is difficult to demonstrate the aggregation which may have been necessary for efficient reproduction. Some evidence of habitat differences can be deduced from the available data, particularly changes in the nature of the substrate. Although most of the fauna show adaptations for life on firm substrates, a significant percentage are clearly adapted for life on firm substrates and this points towards spatial heterogeneity of substrate type. This sort of variation in substrate could be responsible for the variation in dominance patterns and spatial distribution of organisms which seems to occur throughout the Manifold Valley, but which is made particularly noticeable by the occurrence of the pockets.

4.3 Results of principal components analysis

Principal components analysis was applied to the Manifold Valley faunal lists compiled for this study and the associated measurements of density, diversity, amount of bryozoa and average maximum size. The lists were grouped biostratigraphically as described earlier. A summary of the runs made is shown in Table 4.5. The purpose of the analysis was to suggest which variables could best explain the variation between collections.

In principal components analysis like variables are grouped and therefore this procedure can be useful in the understanding of relationships between variables. However, the factor in which a variable appears is governed by the nature and the number of the other variables. Thus, the variables, or groups of variables, which show the highest internal variation tend to appear in the first few factors (ie. those factors which account for

	Total Collection cases = 24	East cases = 5	Centre cases = 5	West cases = 10
<u>Descriptive statistics</u> : includes mean, standard deviation, variance, kurtosis, skewness, range, minimum value, maximum value	X	X	X	X
<u>Principal components analysis</u>				
Variables = other organisms, other brachiopods, spirifer, smooth spirifer, non-trail productids, trail productids, juveniles, bivalves, Density, Diversity, Amount Bryozoa, maximum size	X			
Variables = other organisms, other brachiopods, spirifer, smooth spirifer, non-trail productids, trail productids, juveniles, bivalves, Density, Diversity, Amount Bryozoa	X			
Variables = other organisms, other brachiopods, spirifer, smooth spirifer, non-trail productids, trail productids, juveniles, bivalves	X			

Table 4.5 Summary of Computer Statistical and Principal Components Runs.

the greatest percentage of the variation). Conversely, if a variable is constant throughout all collections it will appear in the last factors. It should also be noted that principal components analysis is basically a tool for clarifying patterns of variation in the data. Therefore, in hindsight, the results of principal components analysis may seem rather obvious. However, because "obvious" trends are frequently not clear in the untreated data, principal components analysis can be very helpful.

In principal components analysis, the larger the number of cases used, the more reliable the results are likely to be. Therefore, principal components analysis was run only for the total collection, because this contains the maximum number of cases. Results are shown in table 4.6

Runs 1 and 2 indicate that the variation among collections can be best explained by examining differences in diversity, density or the combined effects of density and average maximum size, which are highly correlated ($r=.76$); amount of bryozoa and absence of bivalves in some collections in that order.

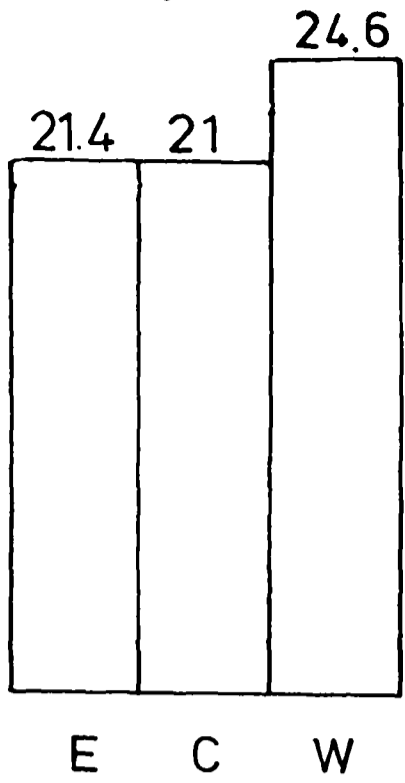
These four factors account for only about 66% of the total variation among collections. In an attempt to understand the remaining percentage of variation, the first three of these measurements were excluded from run 3. The results of this run are much more ambiguous. The presence of other organisms figures predominantly in factor 1. Factor 2 points towards bivalves; factor 3 seems to indicate the importance of comparisons between soft sediment adapted morphotypes and those more adapted for life on firm surfaces. Factor 4 is too vague to attempt interpretation.

The fact that only 66% of the variation is explained by the first 4 factors indicates that the relationships within the data are complex and not easily explained by only a few variables. Never-the-less, when changes in mean diversity, density/maximum size and amount of bryozoa over biostratigraphic zones are examined, the results are interesting (Figure 4.6). The variations in faunal composition suggested by run 3 are much less clear (Figure 4.7).

	Total collection cases = 24
1. variables = other organisms, other brachiopods, spirifers, smooth spirifers, non-trail productids, trail productids, juveniles, bivalves, Density, Diversity, Amount Bryozoa, Maximum size.	F_1 = Diversity F_2 = Density/size F_3 = Amount bryozoa and lack of smooth spirifers F_4 = lack of bivalves
2. variables = other organisms, other brachiopods, spirifers, smooth spirifers, non-trail productids, trail productids, juveniles, bivalves, Density, Diversity, Amount Bryozoa.	F_1 = Diversity F_2 = Density F_3 = Amount bryozoa and lack of smooth spirifers F_4 = lack of bivalves
3. variables = other organisms, other brachiopods, spirifers, smooth spirifers, non-trail productids, trail productids, juveniles, bivalves.	F_1 = + other organisms, non-trail, vs. - other brachiopods F_2 = - bivalves F_3 = + trail vs. - other brachiopods, smooth spirifers F_4 = + spirifers vs. - juveniles

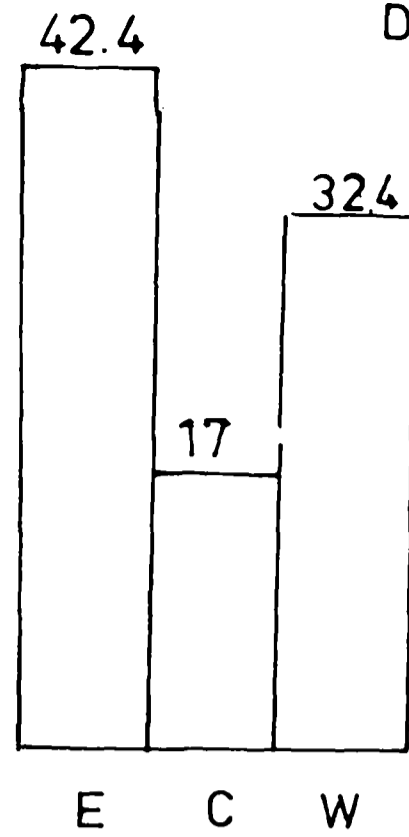
Table 4.6 Summary of Principal Components Results.

Diversity



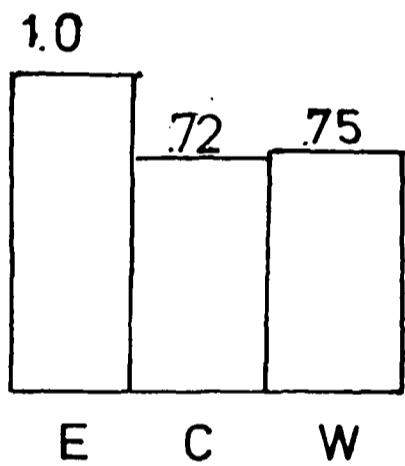
	E	C	W
E	X		
C	10	X	
W	90	90	X

Density



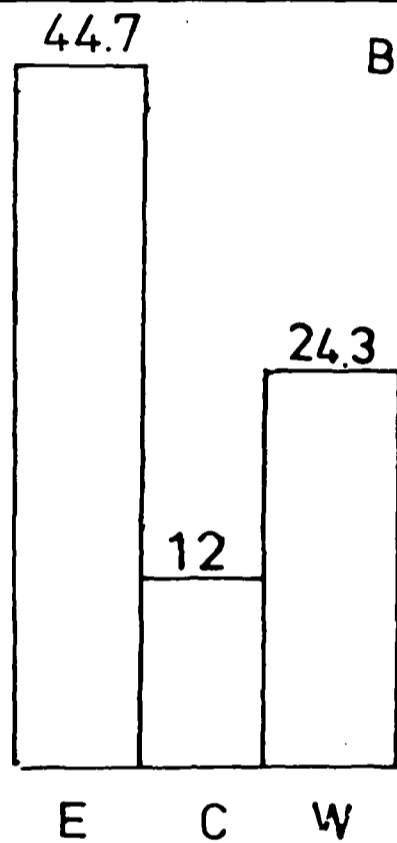
	E	C	W
E	X		
C	99	X	
W	80	97	X

Average maximum size (cm)



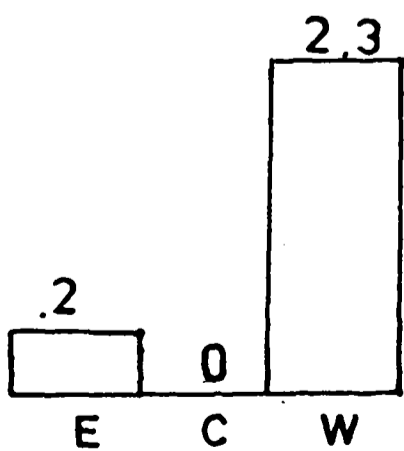
	E	C	W
E	X		
C	95	X	
W	99	30	X

Biovolume



	E	C	W
E	X		
C	99	X	
W	95	70	X

Amt. bryozoa (cm²/kg)



	E	C	W
E	X		
C	10	X	
W	80	80	X

KEY

E=Eastern (youngest) mound
 C=Central mound
 W=Western (oldest) mound

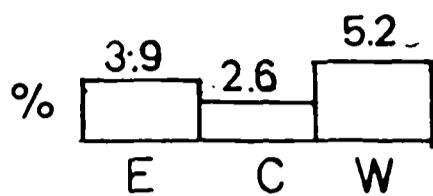
The matrices next to histograms show at what % confidence level the differences indicated are significant as shown by Analysis of variance

Measurements made as described in text. Data & calculations are shown in Appendix 4.

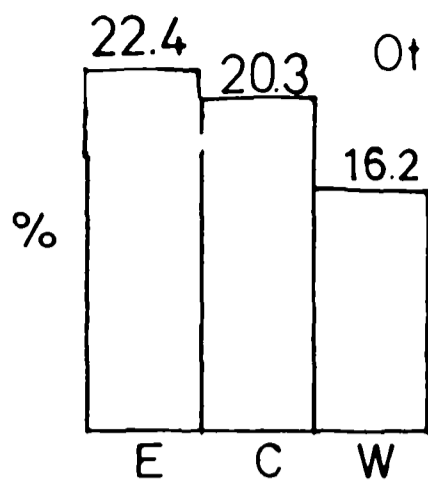
(see sections A4.1.2, A4.1.3, and A4.1.5)

Figure 4.6. Summary of biostratigraphic differences in the Manifold Valley

Other organisms

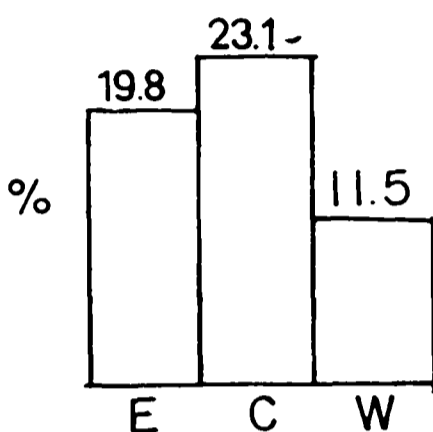


E C W
 E X
 C 30 X
 W 40 70 X



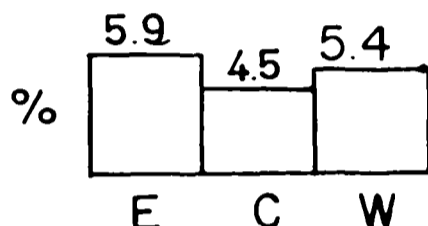
Other brachiopods
 E C W
 E X
 C 30 X
 W 80 60 X

Smooth spirifers



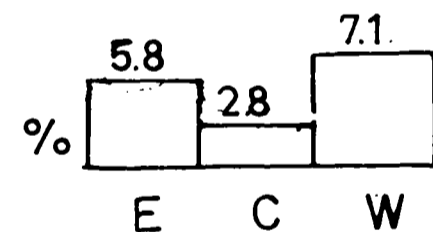
E C W
 E X
 C 50 X
 W 95 99 X

Spirifers



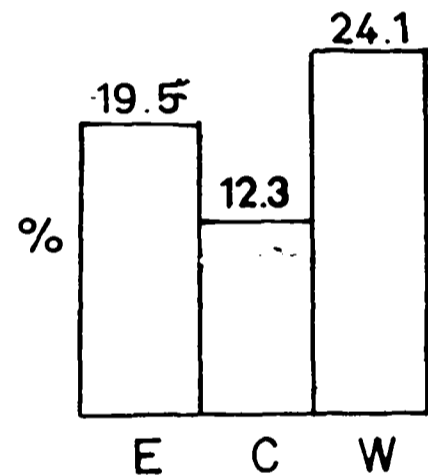
E C W
 E X
 C 50 X
 W 20 40 X

Trail productids



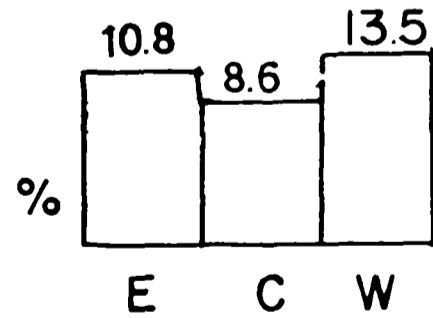
E C W
 E X
 C 80 X
 W 60 98 X

Non-trail productids



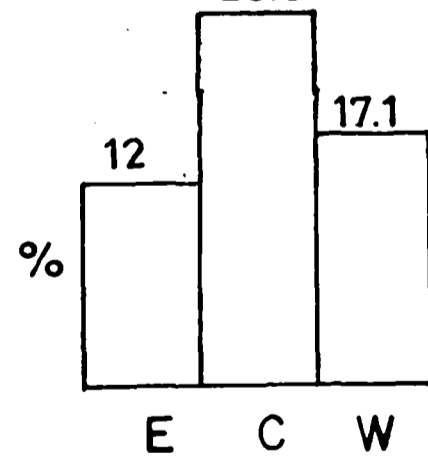
E C W
 E X
 C 70 X
 W 50 90 X

Juveniles



E C W
 E X
 C 30 X
 W 40 70 X

Bivalves



E C W
 E X
 C 90 X
 W 60 80 X

Figure 4.7. Faunal composition of the Manifold Valley mounds expressed as % of total fauna. Key as Fig. 4.6.

With regard to density trends it is important to remember that density changes in fossil communities can sometimes be more apparent than real. Changing sedimentation rates may result in apparent changes in faunal density, even if the density does not change. If density remains constant, but sedimentation rate increases, the density may appear to decrease because there will be proportionately more sediment surrounding each organism. In the Manifold Valley it will be shown that there are indications that the sedimentation rate increased towards the younger parts of the mounds (see section 4.4.4 and Chapter 5). Density also seems to increase as the mounds developed (section 4.4.2). This argues that the density trends are probably real.

4.4 Discussion

4.4.1 Changes in faunal diversity

A comparison of mean diversities by analysis of variance shows no significant changes over the mounds at the 95% confidence level.

This constancy of diversity could be interpreted to mean that the community had reached an equilibrium state and that no significant events had occurred to upset this equilibrium. This explanation is unsatisfying because it suggests no insights into the development of this stable environment and thus lends no insight into the development of the mounds.

A consideration of the theories of ecological succession may be useful. By and large succession seems to be a characteristic of the community itself and results from the fact that the action of the community on the habitat tends to make the areas less favourable for itself and more favourable for other sets of organisms until the climax state is reached. Uninterrupted succession can occur only in stable environments (Odum, 1971) and environmental disturbances will cause the community to be downgraded to a lower successional level (Johnson, 1972). Diversity trends resulting from succession sometimes show an initial increase followed by a decline in species numbers in the later successional stages (Pielou,

1966). In other cases, diversity appears to increase with succession, then level off (Odum, 1971).

Johnson (1972) discussed the relevance of these theories to the fossil record. Walker and Alberstadt (1975) and Bretsky and Bretsky (1975) present models of community succession based on geological examples. Their models predict an initial colonisation zone, followed by a zone of diversification and closing with a zone of dominance. In terms of diversity, the colonisation zone would have relatively low diversities; diversity would be highest in the diversification zone and would decrease in the dominance zone.

Where suitable data from the Waulsortian have been published, as for example that provided by Shephard-Thorn (1963) for the lower, middle and upper stratigraphic levels of the Waulsortian of northwest Co. Limerick, this same diversity pattern is also found. His faunal lists, which are reproduced in Appendix 4 section A4.1.6, show 38 species for the lower level, rising to 71 species in the middle levels and dropping to 51 species in the upper levels (22, 43 and 38 genera respectively). Collections made in Belgium during the course of this study point towards a similar diversity pattern. Although based on small collections, stratigraphic patterns in diversity emerge which are like those predicted by Walker and Alberstadt (1975) and Bretsky and Bretsky (1975). In faunas collected from Tn3a levels, 27 genera were found, in collections from Tn3c levels, 32 genera were found and in collections from Vla levels, 11 genera were found (see section A4.1.1). Because rarefaction coefficients calculated for these collections indicate that some were not complete representations of all genera present, these diversity measurements are somewhat imprecise. However, they are suggestive of a similar diversity pattern to that documented by Shephard-Thorn (1963). These examples indicate that diversity patterns predicted as a result of community succession may be relevant in the analysis of Waulsortian mounds.

According to this theory of community succession, the diversity trends

According to this theory of community succession, the fact that there is no significant increase in diversity from the older to the younger parts of the Manifold Valley mound complex suggests that only the final dominance stage of succession is present. The earlier stages of succession which would show an increase in faunal diversity over time do not seem to be exposed there.

Interestingly, this suggestion is in good agreement with the geological data for the Manifold Valley presented in Chapter 3. There it is argued that only the Biomicrite Facies, which occupies the upper parts of the Waulsortian in the model of Lees et al. (1977), is seen in the Manifold Valley. Thus, on geological, as well as ecological grounds, the lower part of the Waulsortian is reckoned to be missing in surface exposures.

4.4.2 Changes in faunal density

The parameter density, as defined in this thesis (number of organisms/kg. of rock broken) refers mainly to changes in the numbers of organisms present. However, in studies of mixed populations, where sizes of organisms are likely to vary, biomass/unit area is probably a more satisfactory measure of density (Odum, 1971). The parameter biovolume (numbers of individuals x average size of individuals/unit weight) approximates a biomass measure and examination of the trends in biovolume are likely to be more representative of density changes than examination of trends in the parameter density alone.

In the Manifold Valley biovolume increases significantly in the younger parts of the mounds. This could be interpreted to mean that the community has not yet reached the carrying capacity of the environment and therefore density increases because population growth is not limited by environmental factors.

However, density trends have also been related to diversity trends. Theoretical considerations of the roles of r-selected populations (characterised by high reproductive rates and short generation times) and k-

selected populations (selected for narrow functional range) in stable and unstable environments suggest that high faunal densities would be expected in conjunction with low faunal diversities and vice versa (Slobodkin and Sanders, 1969; Valentine, 1971).

In the Manifold Valley there is a suggestion of a trend towards decrease in diversity in the younger mounds. If diversity and density do follow opposite trends in this case, then the evidence of increasing density in the younger mounds lends weight to the suggestion that diversity is decreasing towards the younger mounds. The implications of this in terms of the community succession model are worth considering. A drop in diversity in the younger mounds would suggest that some of the intermediate stages of succession are exposed in the older mounds in the Manifold Valley, and that the younger mounds represent the drop in diversity associated with the dominance stage in the models of Johnson (1972) and Walker and Alberstadt (1975). However, it should be kept in mind that the diversity data presented here are not sufficient to confirm this possibility.

4.4.3 Relative amounts of bryozoa

The model of Lees et al (1977) suggests that the upper part of the Waulsortian contains relatively few fenestrate bryozoa. Collections made in Belgium for this study support this prediction. A mean of $7.25 \text{ cm}^2/\text{kg}$ of bryozoa was found in collections from Tn3a levels, and means of 0 were found in Tn3c and Vla levels.

Bryozoa are not common in the Manifold Valley (see section A4.2.1) and this paucity of bryozoa is compatible with the suggestion that it is the Biomicrite Facies which is exposed in the Manifold Valley (section 3.5). The Lees et al. model also predicts that there are two subfacies within the Biomicrite Facies (section 2.1.3). The lower is somewhat transitional in that it contains pods of the fenestrate bryozoa-rich Blue Vein Facies,

which become rare or non-existent in the upper subfacies. Data on the distribution of bryozoa within the Manifold Valley are not sufficient to show whether these two subfacies are present in the Manifold Valley. However, it is interesting to note that in the Manifold Valley, the only patches of Blue Vein-like lithologies which have been observed occur in the older parts of the mounds. This suggests that the two subfacies of the Biomicrite Facies may be present there and in the same stratigraphic order predicted by the model.

The palaeoecology of bryozoa is not well known. Most workers assume that fenestrate bryozoa have ecological requirements comparable with those of living reteporid cheilostomes which possess a similar fenestrated zoarium (P.D. Taylor, pers. com.). The controls on bryozoan distribution are not fully understood, but the work of Schopf (1969) on bryozoans off the New England coast of North America and of Lagaij and Gautier (1965) in the Rhone Delta in France indicates that high sedimentation rates restrict the occurrence of bryozoa.

4.4.4 Implications of these trends

These interpretations provide a basis for the suggestion that the lesser amount of bryozoa present in the Biomicrite Facies may be due to increasing rates of sedimentation in the younger parts of the Waulsortian. Further support for this idea may be found in a consideration of the distribution of crinoid debris within the Waulsortian. Lees et al. (1977) note that crinoid debris greatly decreases in the Biomicrite Facies, and crinoid debris is on the whole unimportant in the Manifold Valley. Lane and Burk (1976) suggest that Palaeozoic crinoids were capable of only limited arm movement. This may mean that crinoids, like bryozoa, were sensitive to high sedimentation rates and their decrease in the upper parts of the Waulsortian may be due to an increase in sedimentation. Thus, an important difference between the Blue Vein and the Biomicrite Facies may have been sedimentation rates.

The evidence of uninterrupted community evolution found in the faunal diversity trends in the Manifold Valley carbonate mounds implies that the composite nature of the complex (see Chapter 3) does not indicate major environmental unconformities. If this were the case, separate sequences of community evolution, or evidence of regression to earlier stages, would be expected in each of the small mounds which coalesced to form the mound complex and this has not been found.

4.5 Conclusions

Morphological and structural analysis of the fauna found in the Manifold Valley carbonate mounds suggests that the substrate was by and large a firm one. The majority of organisms (66%) are adapted to life on firm, but not necessarily hard, substrates. There is however, evidence of spatial heterogeneity of substrate types because 19% of the organisms show adaptations for life on soft substrates. The remaining 16% have indeterminate preferences. A comparison of the Manifold Valley faunas with published lists of Waulsortian faunas from other areas shows no significant differences between them. Thus, the trends shown by the Manifold Valley faunas are likely to be applicable to Waulsortian faunas as a whole.

Factor analysis indicates that changes in diversity, density/maximum size and amount of bryozoa are the most significant components of variation in the Manifold Valley mounds.

The data on faunal density indicates a clumped spatial distribution throughout the mounds. Occasionally, very dense 'pockets' of fossils are found. Evidence is presented to show that these 'pockets' represent non-transported material. The fauna in the pockets shows similar characteristics to the fauna elsewhere in the mounds and it is suggested that the pockets are notable simply because they are examples of a relatively dense aggregation of organisms in close proximity to a less dense clumping. Local habitat differences have been suggested as one cause of clumped spatial distributions. The demonstrable spatial heterogeneity in substrate types ~~within this area~~ provides further support for this hypothesis.

Density increases in the younger mounds while diversity appears to remain constant (although there is a suggestion of a trend towards decrease in diversity in the younger mounds).

Models put forward by Johnson (1972) and Walker and Alberstadt (1975) concerning trends in community succession are relevant. Data from published lists of Waulsortian faunas, especially that of Shephard-Thorn (1963) for NW Co. Limerick in Eire and data from faunal collections made in Belgium for this study reflect the diversity trends predicted by these models. With these ideas as a basis, it follows that the diversity trends discovered in the Manifold Valley imply the non-exposure of the earlier phases of community development.

This is in good agreement with the geological evidence presented in Chapter 3, which indicates that only the upper part of the Waulsortian, the Biomicrite Facies of the Lees et al. (1977) model, is present here. The paucity of bryozoa and crinoid debris found in the Manifold Valley is also compatible with this suggestion.

Studies of modern bryozoa show that sedimentation rates are an important limiting factor in bryozoan distribution. Palaeozoic crinoids may also have been sensitive to sedimentation. These findings suggest that the decrease in the amount of bryozoa found in the Biomicrite Facies, as compared with the Blue Vein Facies is indicative of an increase in the rate of sedimentation as the mounds developed.

CHAPTER 5

LITHOLOGICAL DATA

5 LITHOLOGICAL DATA

5.1 Principal lithological components

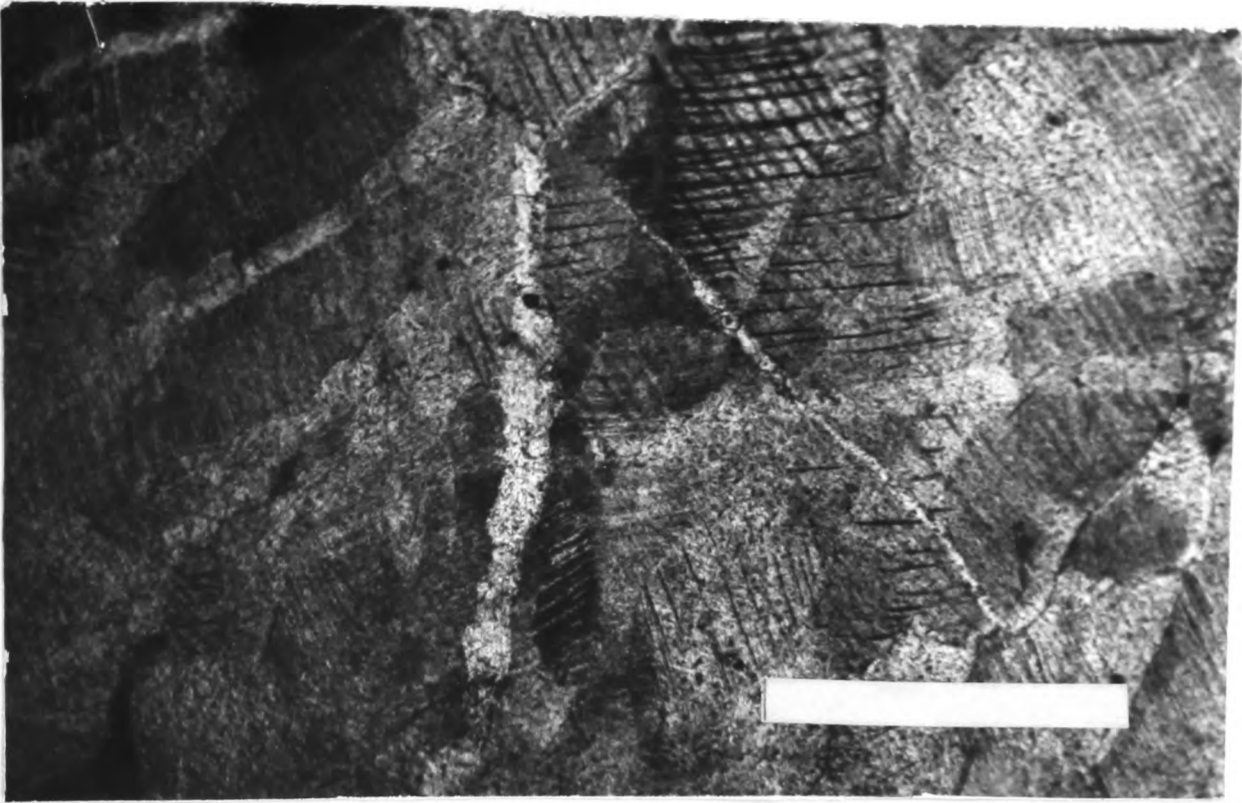
The lithological fabrics found in the Manifold Valley carbonate mounds, although seemingly homogeneous, are extremely variable on a small scale (cm range) and for this reason it is not possible to map lithological trends across the mounds (see Chapter 3).

The principal rock-type is a very fine-grained limestone which is light to medium grey in colour and appears smooth to porcellaneous on broken surfaces. Some dolomitisation has taken place, but this is not extensive. In polished blocks the limestone commonly has a mottled appearance caused by the alternation of light and darker grey areas. The polished blocks also reveal many elongated sparry masses which range in thickness from several centimetres to less than a millimetre. The spar crystals are often orientated with the long axes parallel to each other and to indications of depositional surfaces, such as geopetal fills of shells and thin layers of bioclasts.

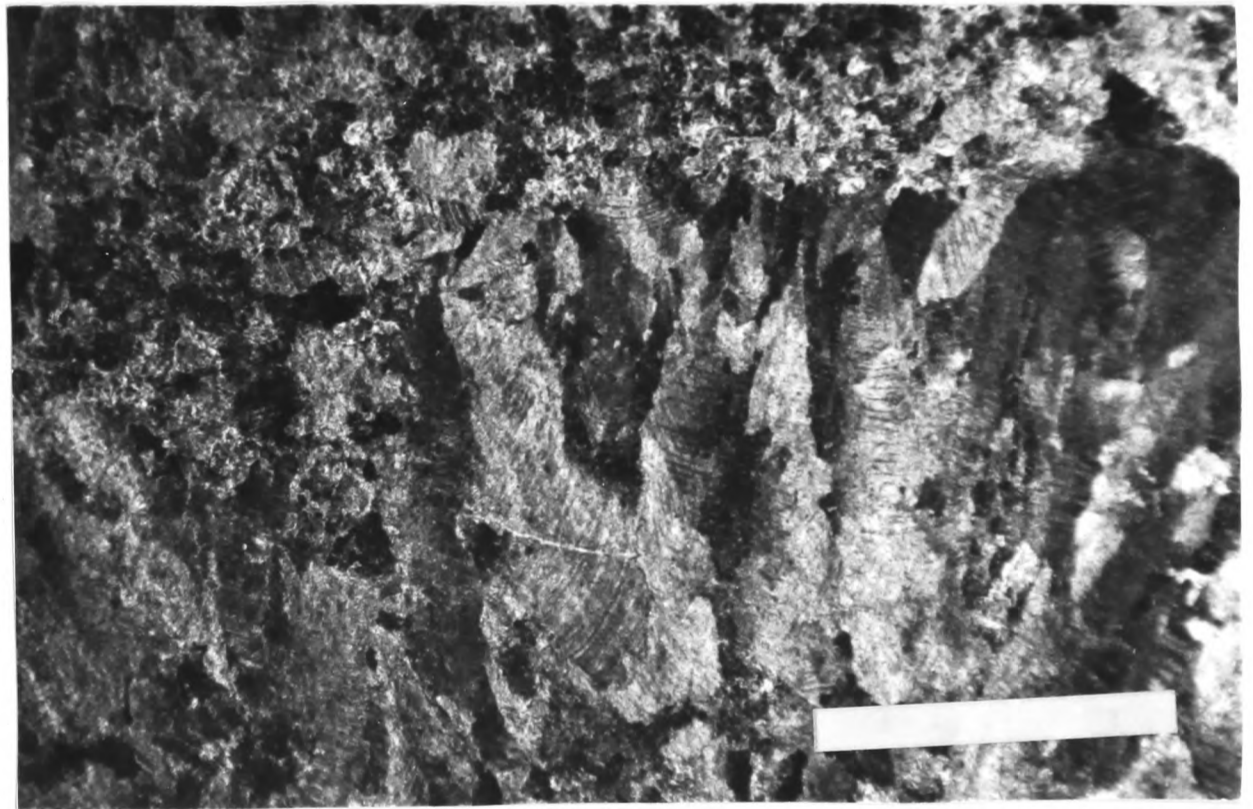
5.2 Definition of terms

5.2.1 Cement (Spar)

Cement includes all passively precipitated, space filling carbonate crystals which grow attached to a free surface (Bathurst, 1975). It appears clear to cloudy in thin section. Usually the size of the crystals increases away from the initial substrate, and there is a preferred orientation of optic axes and of long axes of the crystal shapes normal to it. In the Manifold Valley, cement is found in several habits; as the radiaxial fibrous spar defined by Bathurst (1959) (see figure 5.1); as blocky void-filling spar in cavities which are formed, for example,



A



B

Fig 5.1 Radiaxial fibrous spar.

- A Dull radiaxial fibrous spar, with curved cleavages, contrasts with brighter later cement-filled veins.
(scale = 1 mm, plane light).
- B Granular spar (top of photograph) contrasts with elongate radiaxial fibrous spar with curved cleavages.
(scale = 1 mm, crossed polars).

Both from Manifold Valley loc. 458.

by shells (figure 5.2); as a granular cement (defined by Bathurst (1958)) between fossil fragments (figure 5.3) and as a filling in cross-cutting veins (figure 5.4). The cross-cutting vein fills are generally clear, while the other types of cement commonly appear cloudy to brownish in thin section. The various types of cements can also be recognised by their luminescent properties. These characteristics are discussed in Appendix 5.

5.2.2 Microspar

Microspar (figure 5.6) is recognised in thin section by the presence of equidimensional calcite crystals with a relatively uniform size range of 5 to 10 microns which extends occasionally up to 50 microns (this follows the work of Folk, 1959; 1962; 1965). In thin section it appears relatively light coloured and translucent when compared with micrite, which is described in the next paragraph. It has, on average, much smaller crystals than does spar, and their size range is more uniform. The microspar crystals are not noticeably orientated with either long axes or optic axes normal to the edge of an initial substrate. Microspar often occurs as patches in micrite, and this patchiness of distribution may be responsible for the light and medium grey mottle pattern which is commonly seen on polished blocks (see figure 5.5).

5.2.3 Micrite

Micrite is recognised by its extremely small crystal size, which causes it to appear smooth to porcellaneous in broken rock surfaces. In thin section it is subtranslucent and thus appears darker coloured than either spar or microspar (figure 5.6). It could be argued that the fine-grained limestone in the Manifold Valley is not a true micrite, because it has been recognised by its distinctive appearance in thin

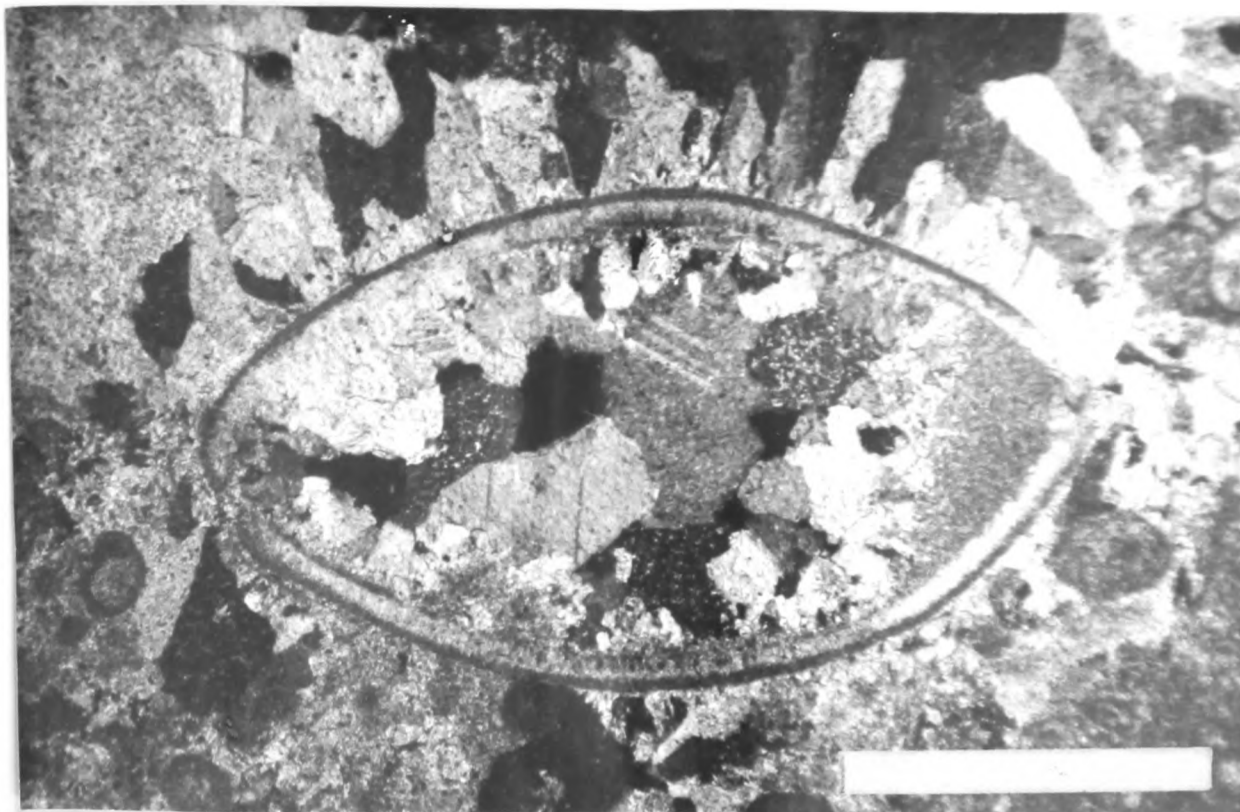


Fig 5.2 Ostracode with sparry calcite fill.

From Manifold Valley loc. 500. (scale = 1 mm, crossed polars).

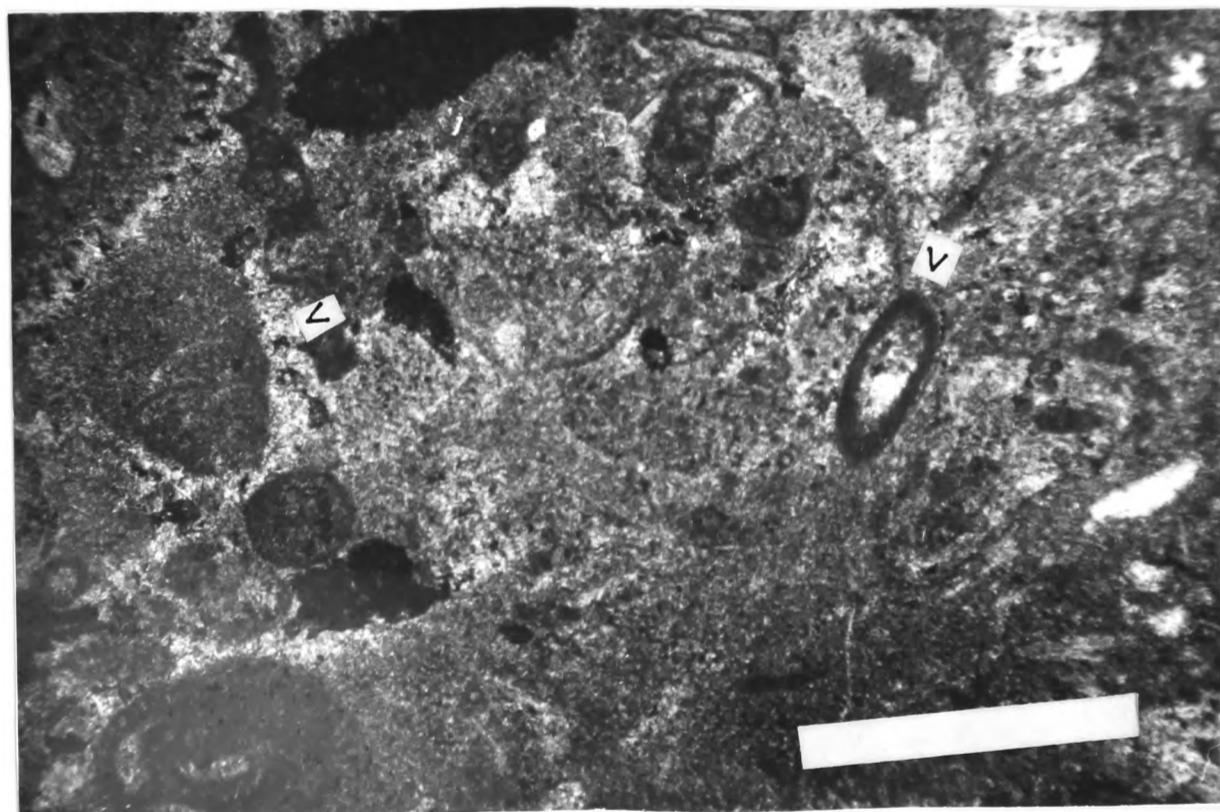
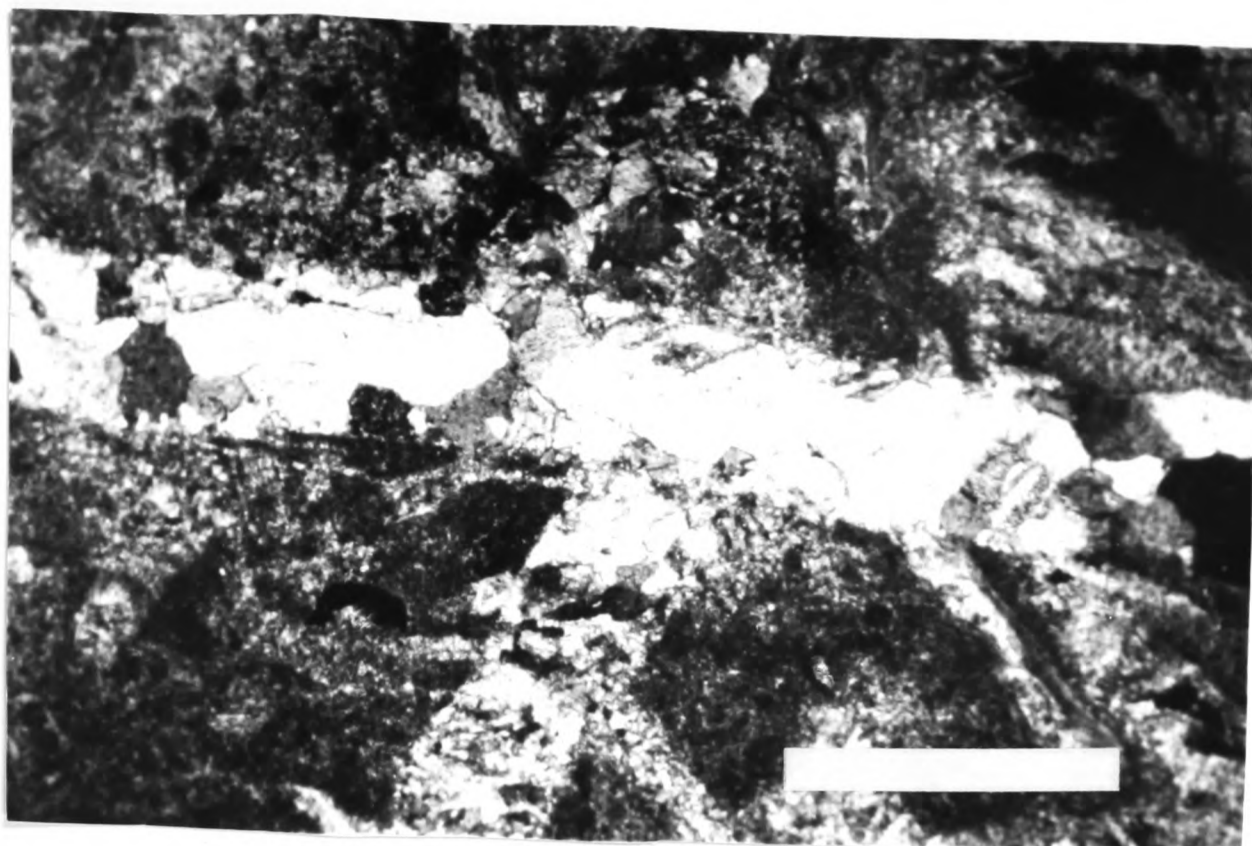
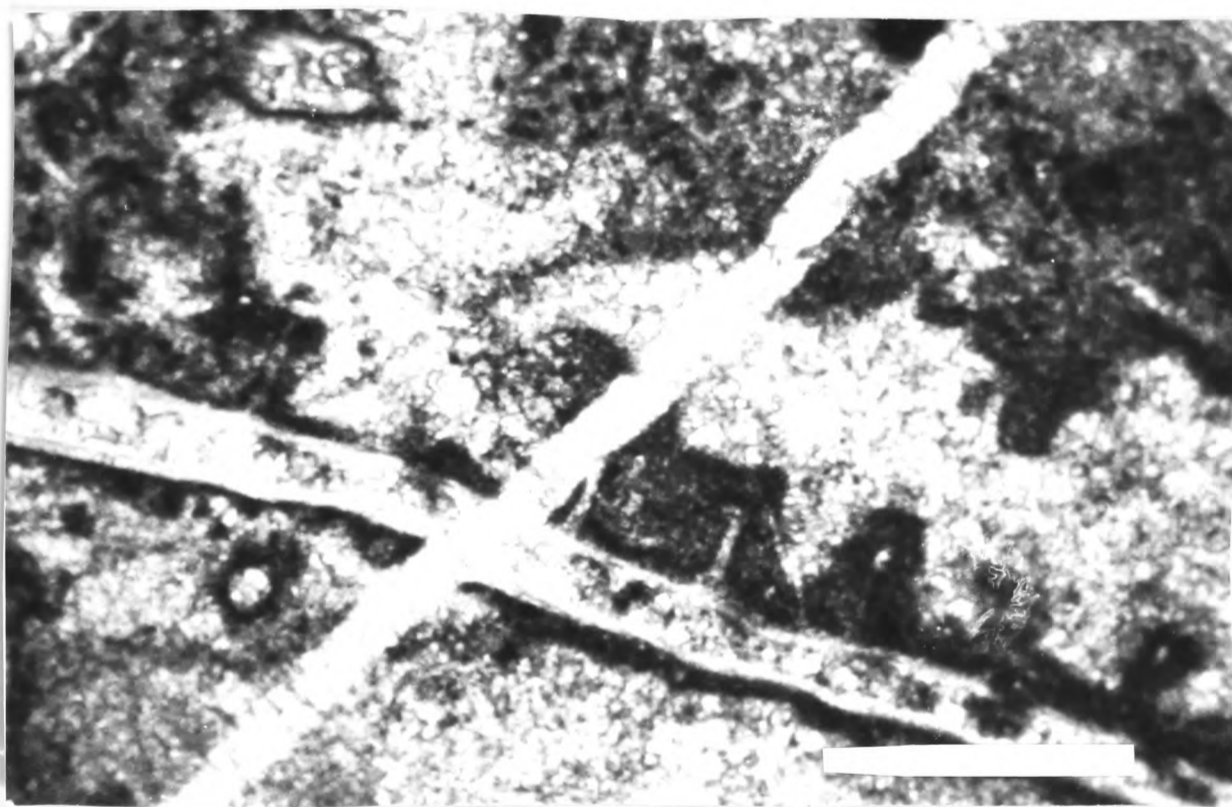


Fig 5.3 Bioclasts and intraclasts with sparry cement rims (arrows).
Micrite in lower part of photograph.

From Manifold Valley loc. 500. (scale = 1 mm, plane light).



A



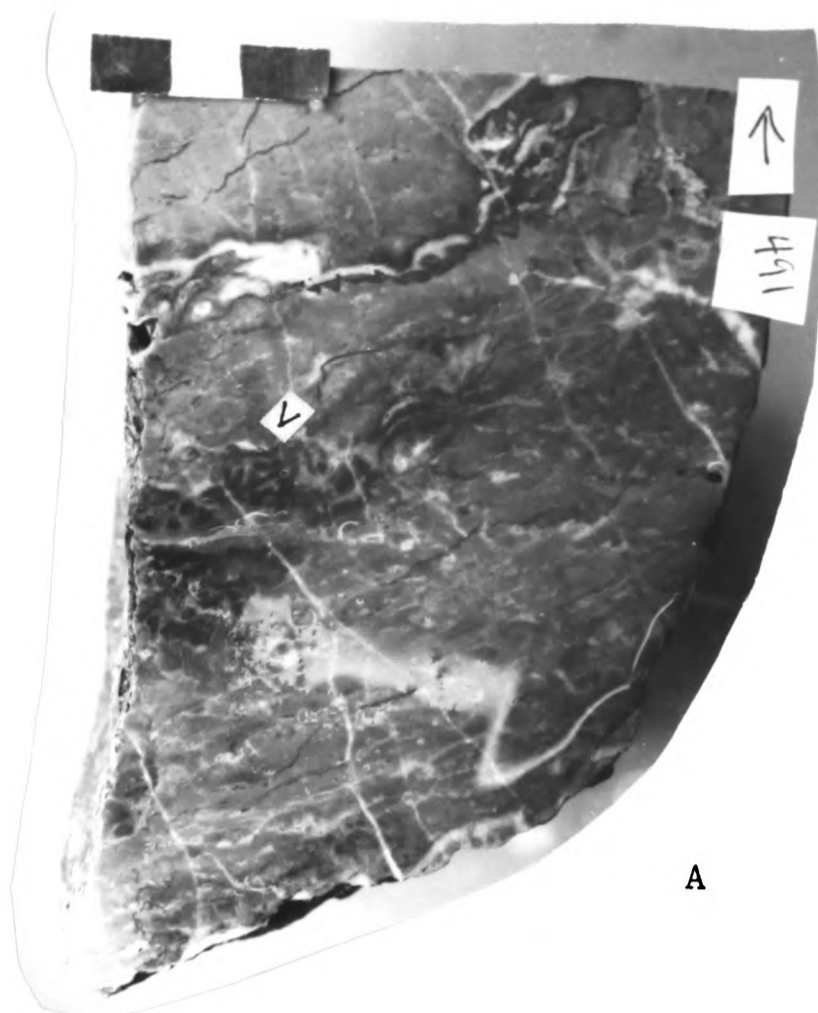
B

Fig 5.4 Cross-cutting veins.

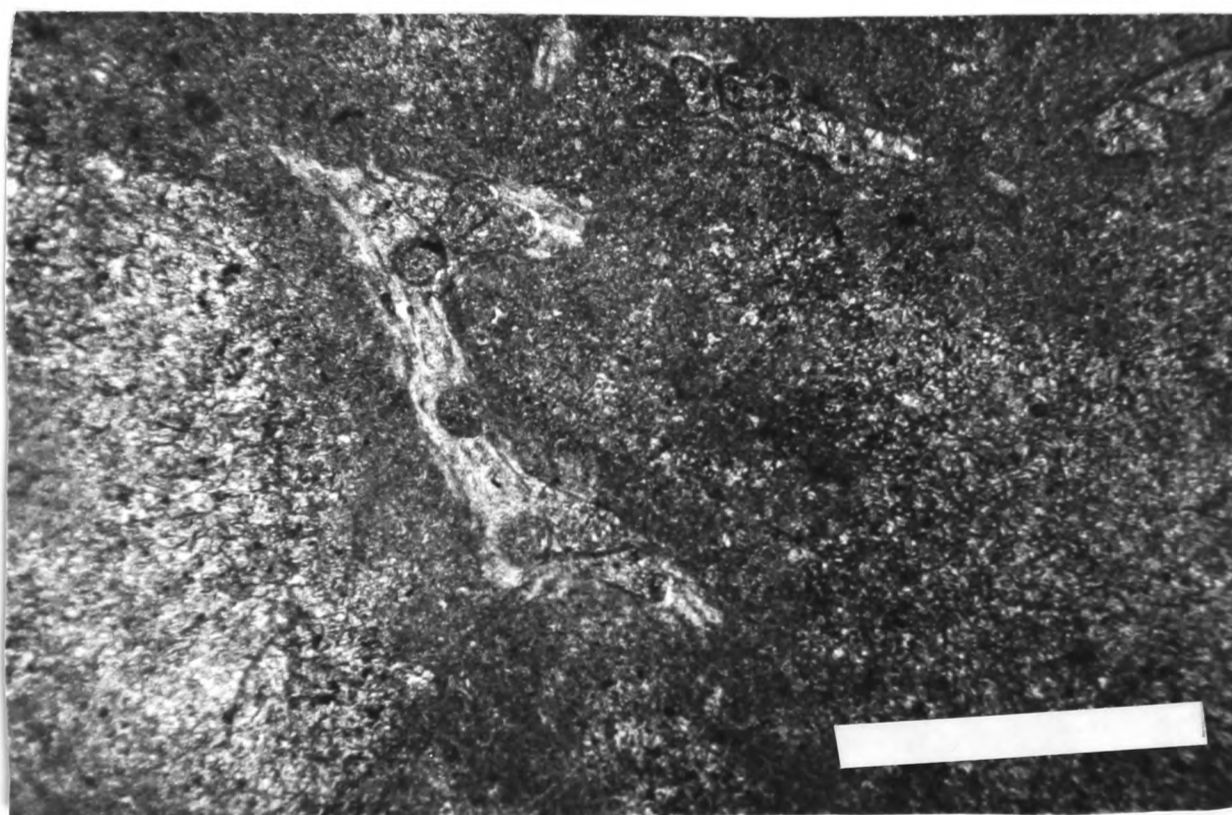
A Cross-cutting vein with blocky calcite cement.
(scale = 1 mm, crossed polars).

B Straight sided bright vein, cutting across duller earlier
cements and bryozoa fragment. (scale = 1 mm, plane light).

Both from Manifold Valley loc. 492.



A



B

Fig 5.5 A Shows mottled micrite due to patchy distribution of micrite and microspar. (polished block, scale in cms).

B Part of a peel taken near arrow on A showing micrite (centre) with microspar on either side. (scale = 1 mm).

Both from Manifold Valley loc. 491.

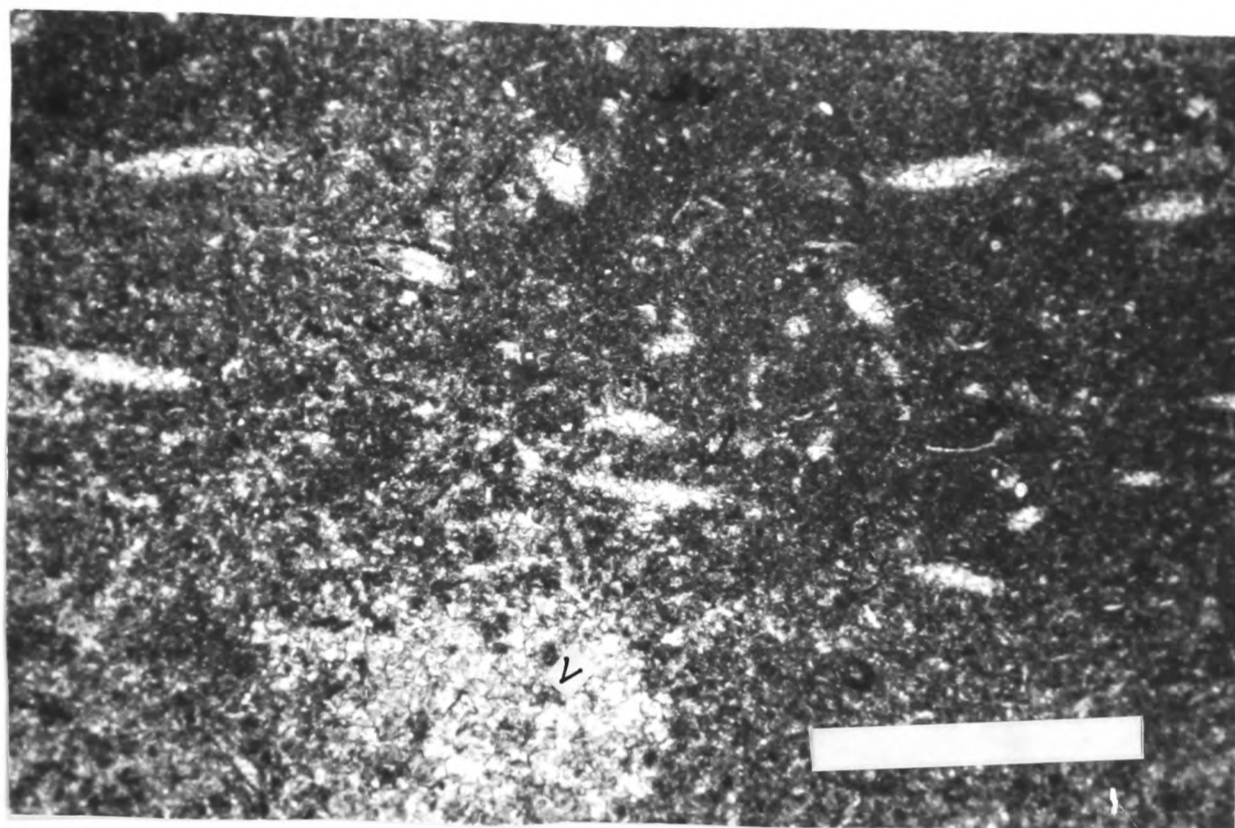


Fig 5.6 Dark micrite with sponge spicules, contrasts with bright microspar (arrow) and vaguely clotted micrite (near scale bar and left half of photograph).

Manifold Valley loc. 488. (scale = 1 mm, plane light).

section and hand specimen, rather than by actual measurement of grain size. Folk (1962), in defining the term, specified that it should be restricted to crystals in the 1-4 micron size range. However, he also indicated that the upper limit is somewhat arbitrary. The term micrite is used in the description of the Manifold Valley rocks because it forms a natural category in which to place the very fine-grained sediments which can be easily differentiated from other lithological components by characteristics other than grain size.

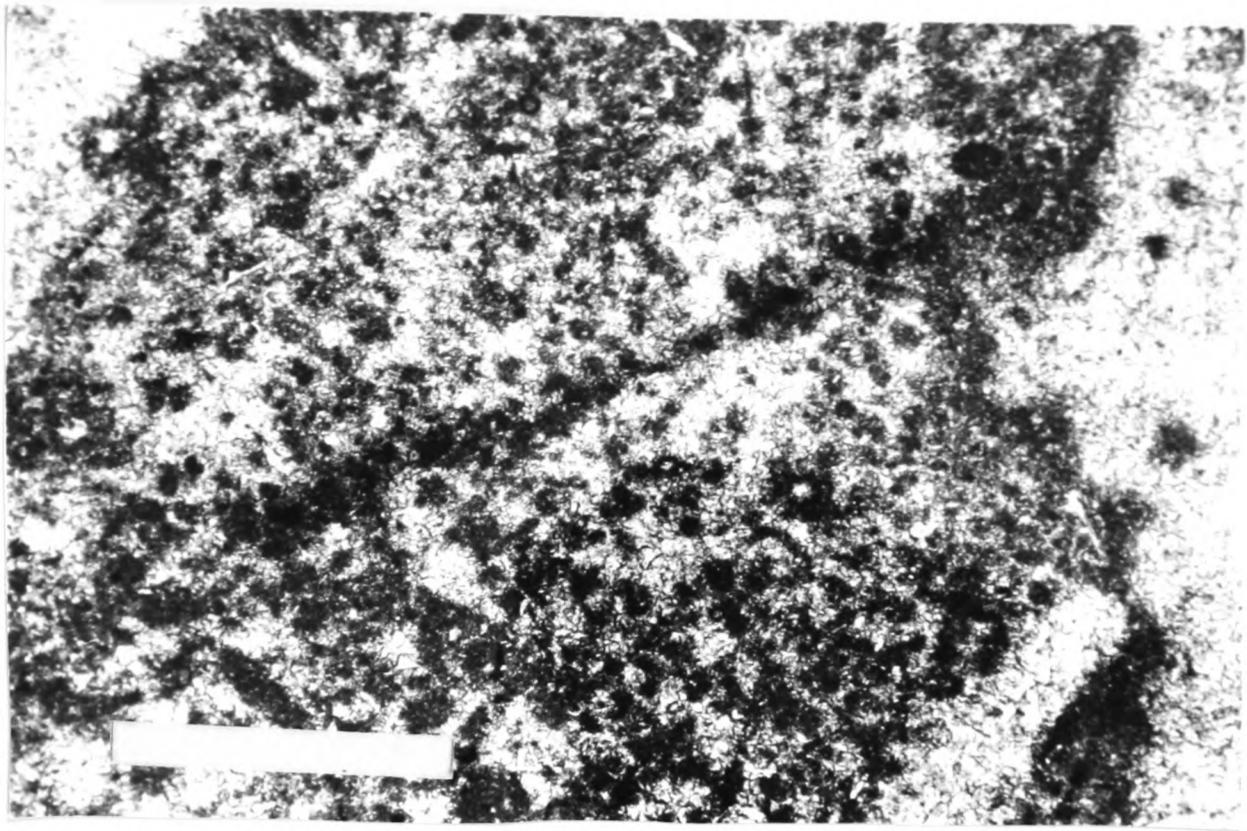
5.2.4 Clotted micrite

Clotted micrite, which is similar to the 'structure grumeleuse' of Cayeux (1935) and the pelleted limestone of Beales (1965), consists of small clots or pelloids of micrite in a matrix of microspar. The terms clot and pelloid are used interchangeably here to describe material which has been assembled by some form of organic or inorganic agglutination. In some clotted micrites found in the Manifold Valley the boundaries between the clots and the microspar appear sharp (figure 5.7). In others the boundaries appear less sharply defined and the pellets are more rounded (figure 5.8a). These two variants form part of a spectrum of variation and often appear in the same thin section (figure 5.8b).

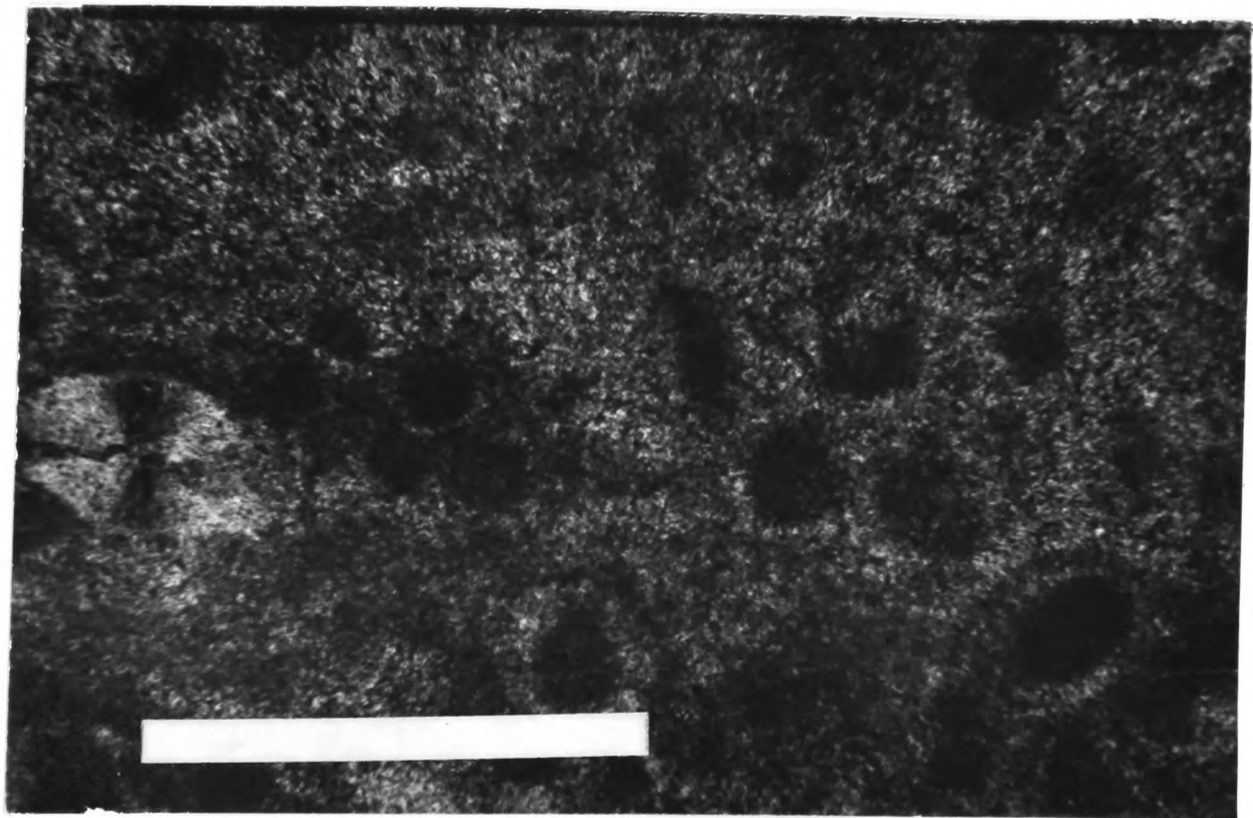
5.2.5 Bioclasts

Bioclasts are skeletal fragments or small organisms which are found as lithological components throughout the Manifold Valley mounds.

5.3 Lithological trends in the Manifold Valley



A

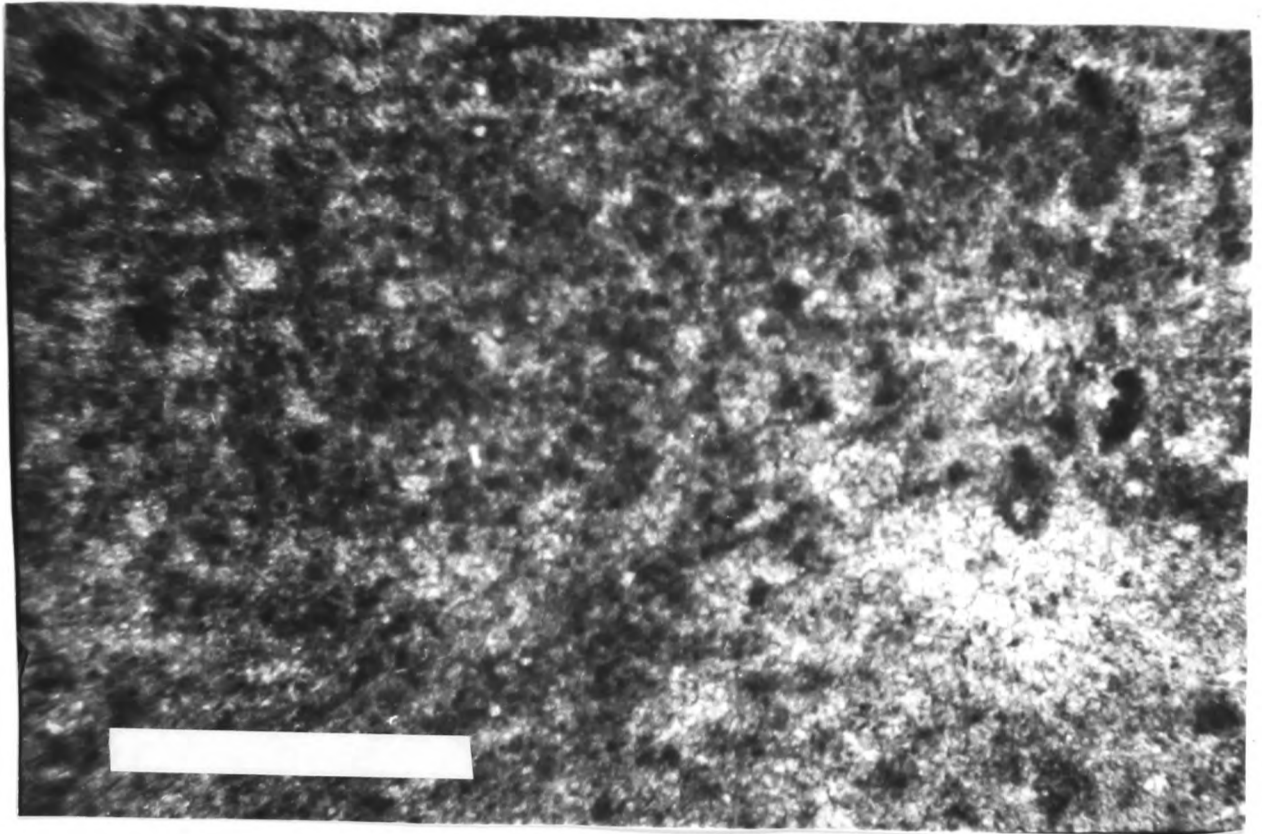


B

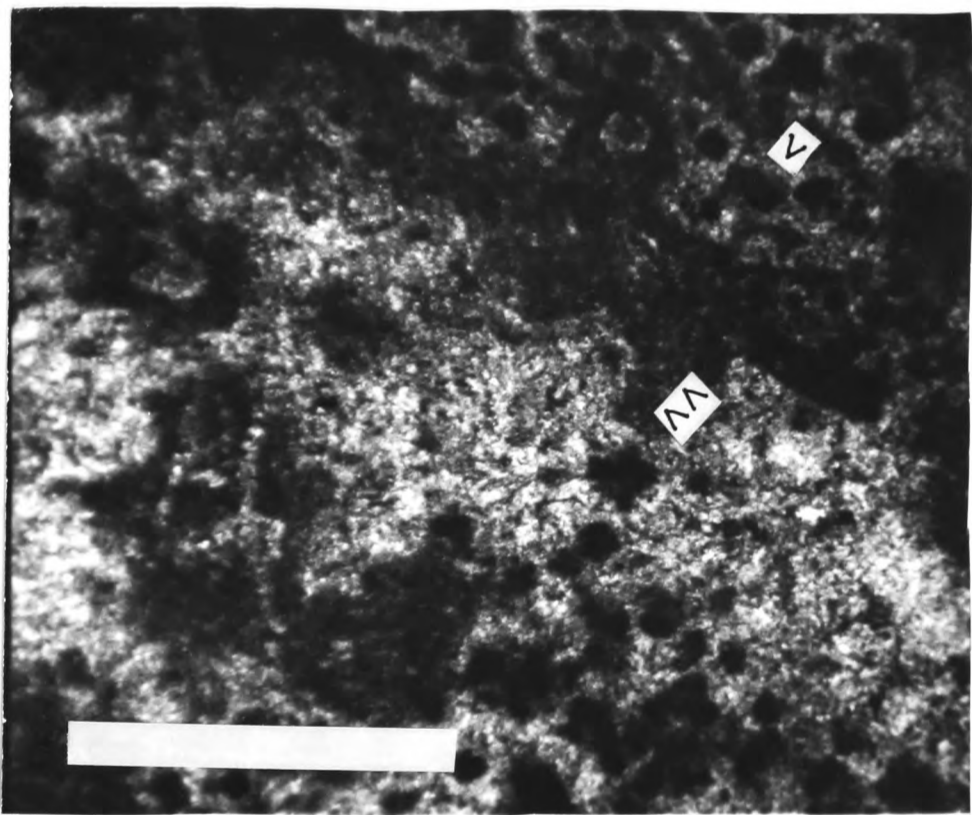
Fig 5.7 Clots with cement rims.

A From Manifold Valley loc. 492. (scale = 1 mm, plane light).

B From Manifold Valley loc. 461. (scale = .5 mm, crossed polars).



A



B

Fig 5.8 A Micrite clots in microspar, note vague boundaries. Manifold Valley loc. 487. (scale = 1 mm, plane light).
 B Vague clots (double arrow) in association with angular clots with cement rims (single arrow). Manifold Valley loc. 461. (scale = 1 mm, crossed polars).

5.3.1 Methods of determination

In order to determine the stratigraphic distribution of lithological components just described and to determine possible lithological trends, an average of 450 points were counted on each of forty-six thin sections sampled from the Eastern, Central and Western mounds which span the stratigraphic range of mound development in the Manifold Valley. Locality information is given in Appendix 2 and data is given in Appendix 4, section A4.2.1. The results are shown in figure 5.9.

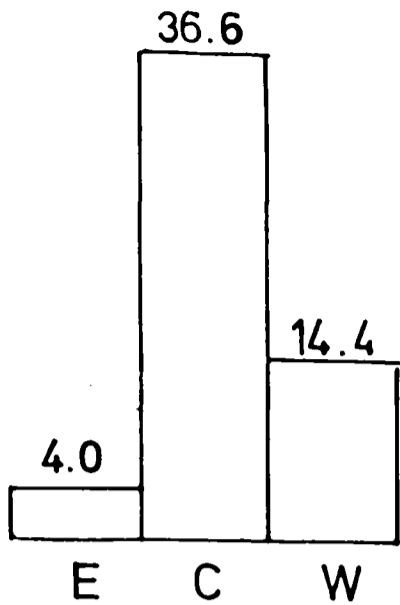
5.3.2 Description and discussion of trends

There is no significant difference between proportions of microspar, micrite and clotted micrite. There appears, however, to be a trend towards increase in microspar and a corresponding decrease in amounts of micrite in the younger Central and Eastern mounds. If, as Folk (1965) suggests, microspar is taken to represent a neomorphic alteration of micrite, the larger proportions of microspar in the Eastern and Central mounds may indicate that they were exposed to more diagenesis than was the Western mound. This may be related to their relative geographic positions with respect to the tectonic folding in the area.

The only significant differences are those in amounts of cement and bioclasts. The differences in the amounts of bioclasts, as might be expected, closely reflect the faunal density trends described in Chapter 4 (figure 4.6), which show a trend toward increase in faunal density in the younger parts of the complex.

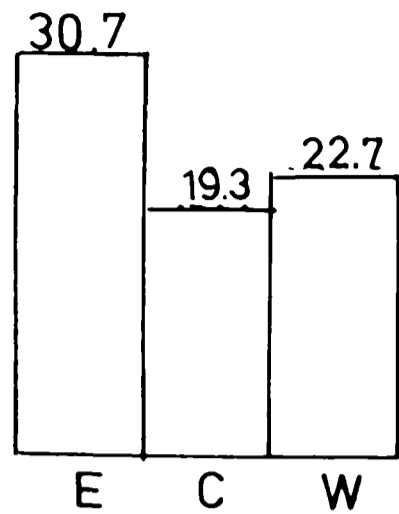
The greatest amounts of cement are found in the Central mound. This is best explained by the presence of a higher proportion of late vein fillings there than in the other two mounds. Approximately 70% of the thin sections examined from the Central mound contain one or more cross-cutting veins, whereas only 17% of the slides examined from the Western mound

% Cement



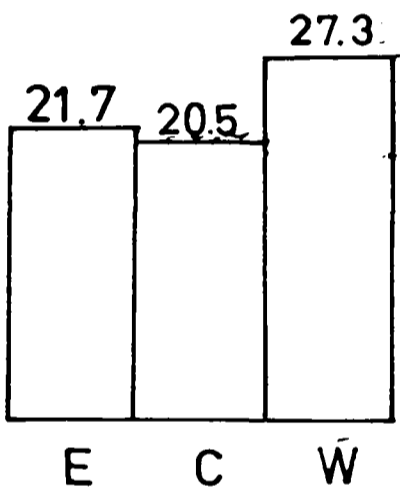
	E	C	W
E	X		
C	99	X	
W	70	99	X

% Microspar



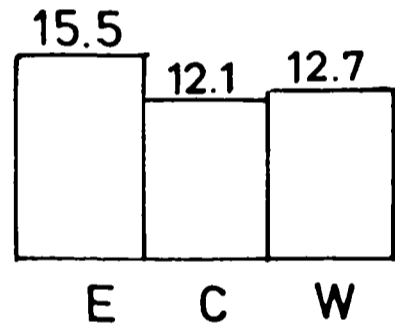
	E	C	W
E	X		
C	70	X	
W	60	40	X

% Micrite



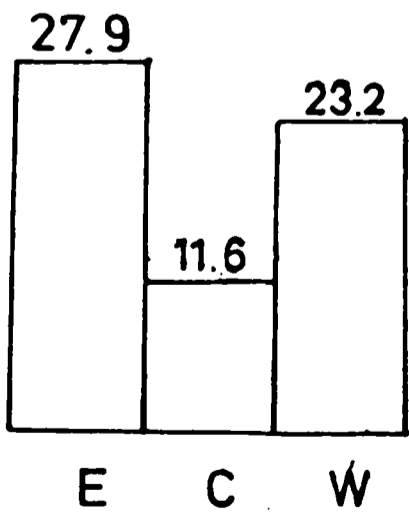
	E	C	W
E	X		
C	10	X	
W	50	80	X

% Clotted Micrite



	E	C	W
E	X		
C	30	X	
W	30	10	X

% Bioclasts



	E	C	W
E	X		
C	95	X	
W	40	98	X

KEY

E= Eastern (youngest) mound
 C= Central mound
 W= Western (oldest) mound

Matrices next to histograms show at what % confidence level the differences are significant as shown by Analysis of variance

Measurements made as described in text. Data & calculations in Appendix 4: (see sections A4.2.1 and A4.2.3)

Figure 5.9 Lithological trends in the Manifold Valley

and none from the Eastern mound show this feature. Hand specimens show a similar trend.

The presence of a large number of straight edged cross-cutting veins in the Central mound implies that the sediment must have had a firm or hard consistency when it was subjected to stress. Ignoring the anomalously high percentage of cement in the Central mound, there is a suggestion of a trend towards a decrease in cement in the younger mounds. This tendency may be related to trends within the lithological facies within the Waulsortian (Lees et al., 1977) and to an upward increase in sedimentation rates. This will be discussed in sections 5.5.2 and 5.7.2

5.4. Submarine Lithification

5.4.1 Significance in the Manifold Valley

The consistently large percentage of surface-dwelling and pedically-attached brachiopods and byssally-attached bivalves which make up the fauna suggest that while the Manifold Valley mounds were developing the substrate must have been by and large firm (see Chapter 4). This implies that early submarine lithification of the carbonate sediment was an important process.

5.4.2 Features recognised in recent sediments

Submarine lithification, both shallow and deep marine, has been recognised from several modern environments (see Milliman (1974) for a review of occurrences). Dating of submarine lithified sediments in modern reef environments indicates that lithification can proceed rapidly, in thousands of years, and, in some cases, considerably less (Shinn, 1969; Land and Goreau, 1970; Ginsburg et al., 1971; Ginsburg and James, 1973; James et al., 1976).

The recognition of submarine lithification as a significant process in the formation of limestones has led to further study of the fabrics contained in such rocks. Clotted micrite and radiaxial fibrous spar are thought by many recent workers to be indicative of early submarine lithification (Alexandersson, 1972; Kendall and Tucker, 1973; Lohmann and Meyers, 1977; Davies, 1977). Both of these features are found in the Manifold Valley rocks, and their occurrence and interpretation are discussed below.

5.4.3 Clotted micrite

The origin of the pelley structure of clotted micrites has long been a problem in the understanding of these lithologies (for example, Cayeux, 1935; Beales, 1965; Carozzi, 1960). Many origins for the texture have been suggested, including fecal pelleting (Beales, 1965), bacterial decomposition causing clotting in the surrounding sediments (Hadding, 1958), the binding activity or breakdown of algae (Beales, 1965; Purdy, 1965) and patchy recrystallisation of micrite (Cayeux, 1935).

5.4.3.1 Clotted micrite in the Manifold Valley

In the Manifold Valley clotted micrites are of two different types. In one the clots are surrounded by cement rims; in the second the clots are in a microspar matrix. In the first type the pelloids are sometimes angular and range up to larger intraclasts (1 mm or more in some cases) which are often composed of micrite which is itself vaguely clotted (see figure 5.10). The pelloids and intraclasts are surrounded individually by small cement crystals (see figures 5.7 and 5.10).

The cement rims which surround both the pelloids and the intraclasts are proof that they were redeposited. The fact that they occur intermixed

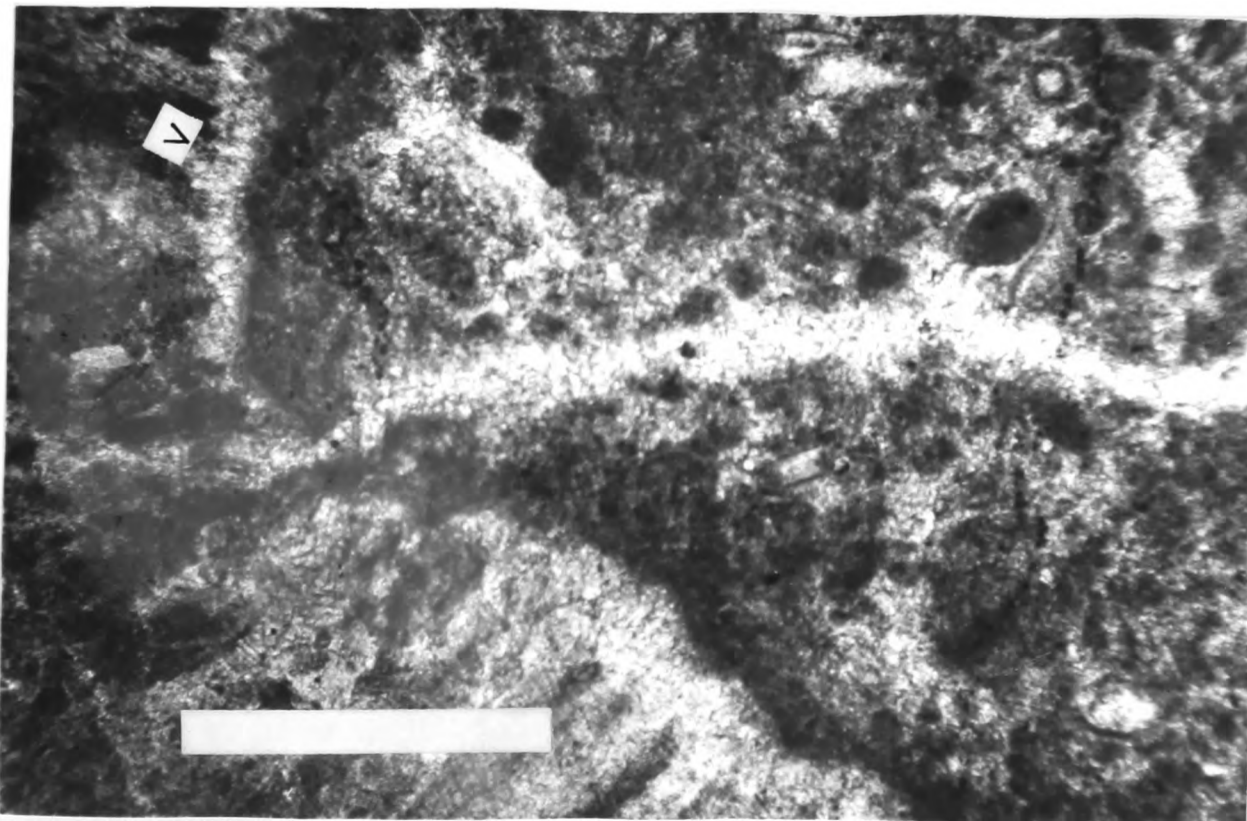
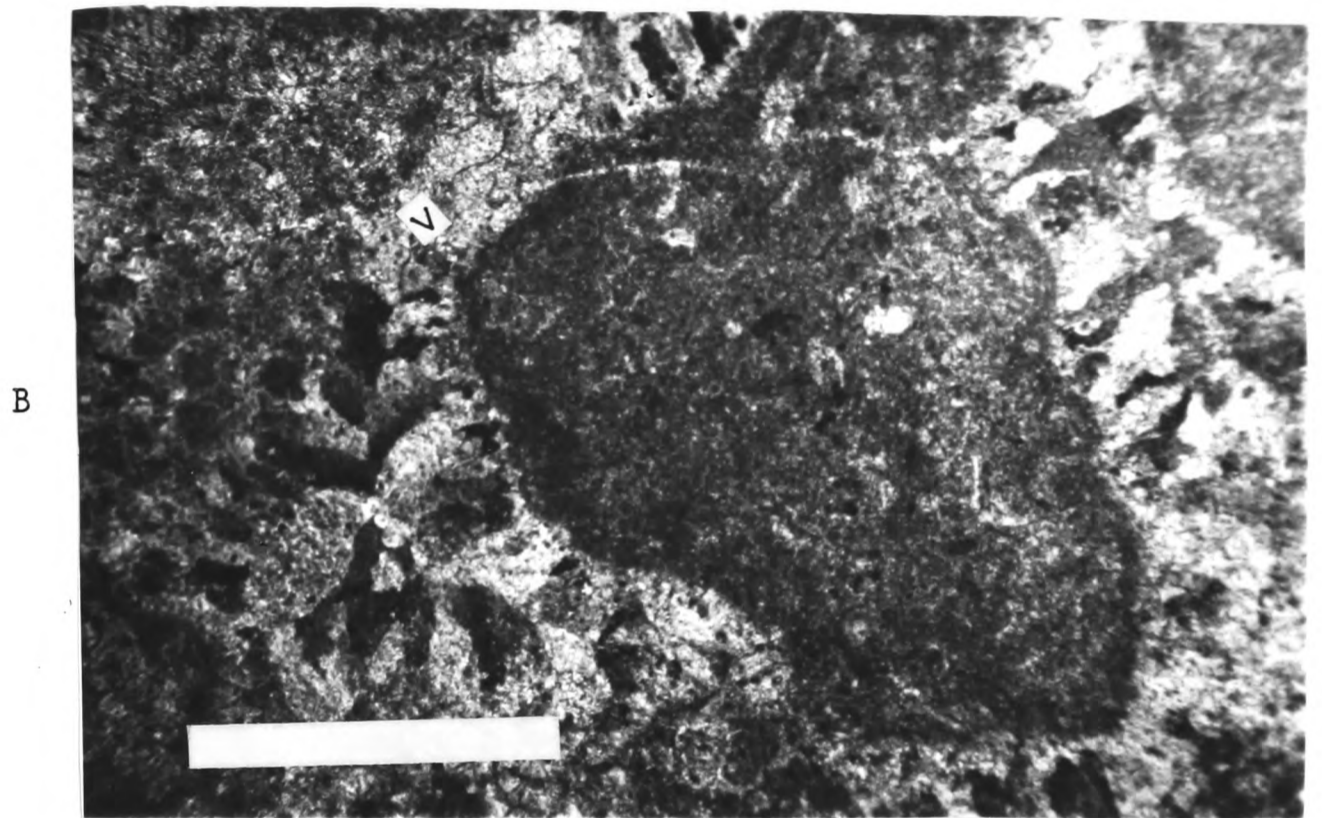
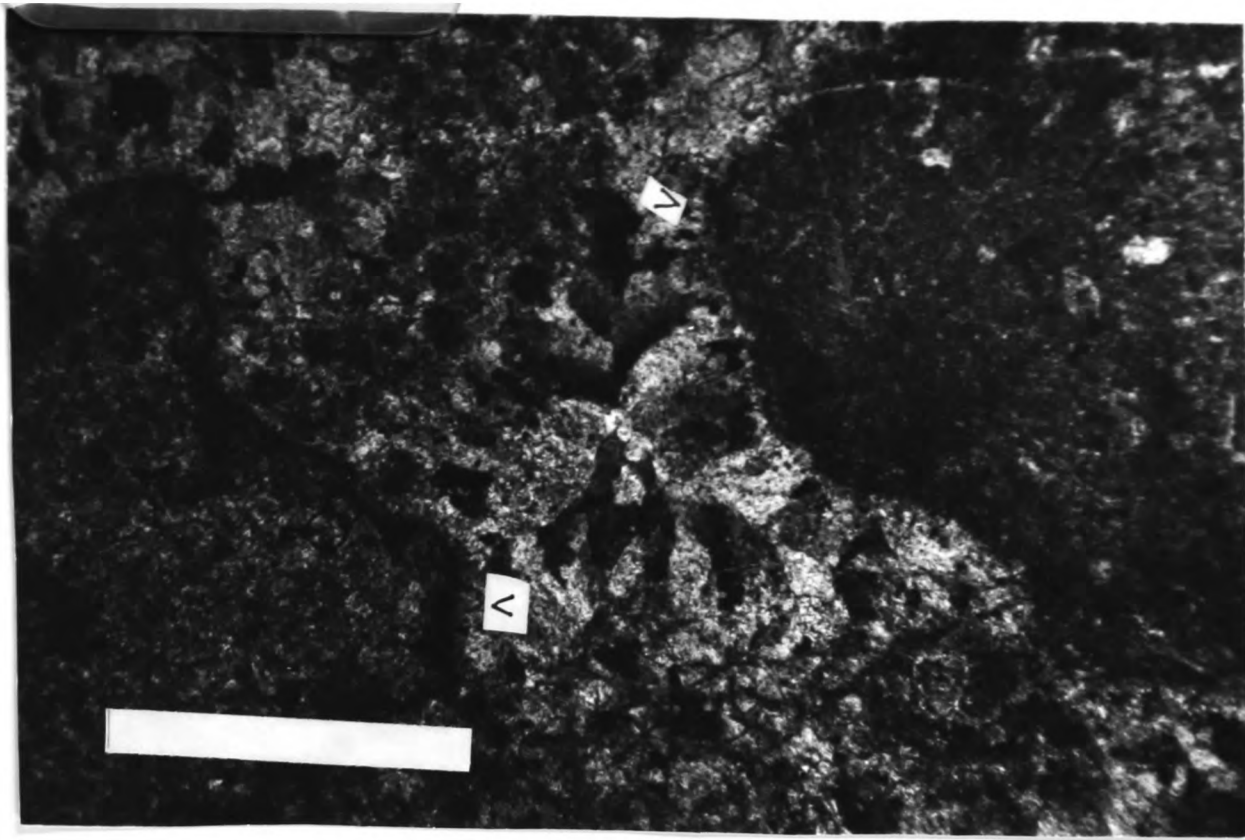


Fig 5.10 Intraclasts of clotted micrite in sparry cement, (scale bar = 1 mm), arrows point to thin cement rims.

A, B, Loc. 456, Manifold Valley (intraclast in B is the intraclast on the right in A). (crossed polars).

C Loc. 492, Manifold Valley, note vein fill in intraclast.

with areas of vaguely clotted micrite in a microspar matrix or with non-clotted micrite suggests that they were being redeposited while deposition of the mounds was still taking place. The sediment which makes up the clasts must have been lithified enough to have held together during erosion and redeposition. In the second type of clotted micrite the clots have indistinct boundaries, are not angular and are not surrounded by individual cement rims (see figure 5.8). They occur in a matrix of microspar, and pieces of this type of clotted micrite are sometimes redeposited as intraclasts (see above).

5.4.3.2 Origin of clotted micrites

A possible origin for this fabric is suggested by Alexandersson (1972) who studied the growth of aragonite and Mg calcite in West Indian and Mediterranean near-shore calcareous sediments. His scanning electron micrographs show that micrite crystals normally grow in the shape of small, rosette-like aggregates, which, he claims, commonly results in globular, pellet-like growth structures. The time needed for this type of precipitation is estimated to be 100 - 1,000 years. This process may be responsible for the formation of some of the indistinctly bounded pellets in microspar which comprise clotted micrite in many ancient limestones. If so, the presence of some clotted micrites suggests early submarine lithification.

5.4.4 Radial fibrous spar

Radial fibrous spar was defined by Bathurst (1959). It is commonly turbid with inclusions and is characterised by curved twin lamellae, optic axes that converge away from the substrate and sub-crystals which diverge in this same direction. The main features are shown in figure 5.11.

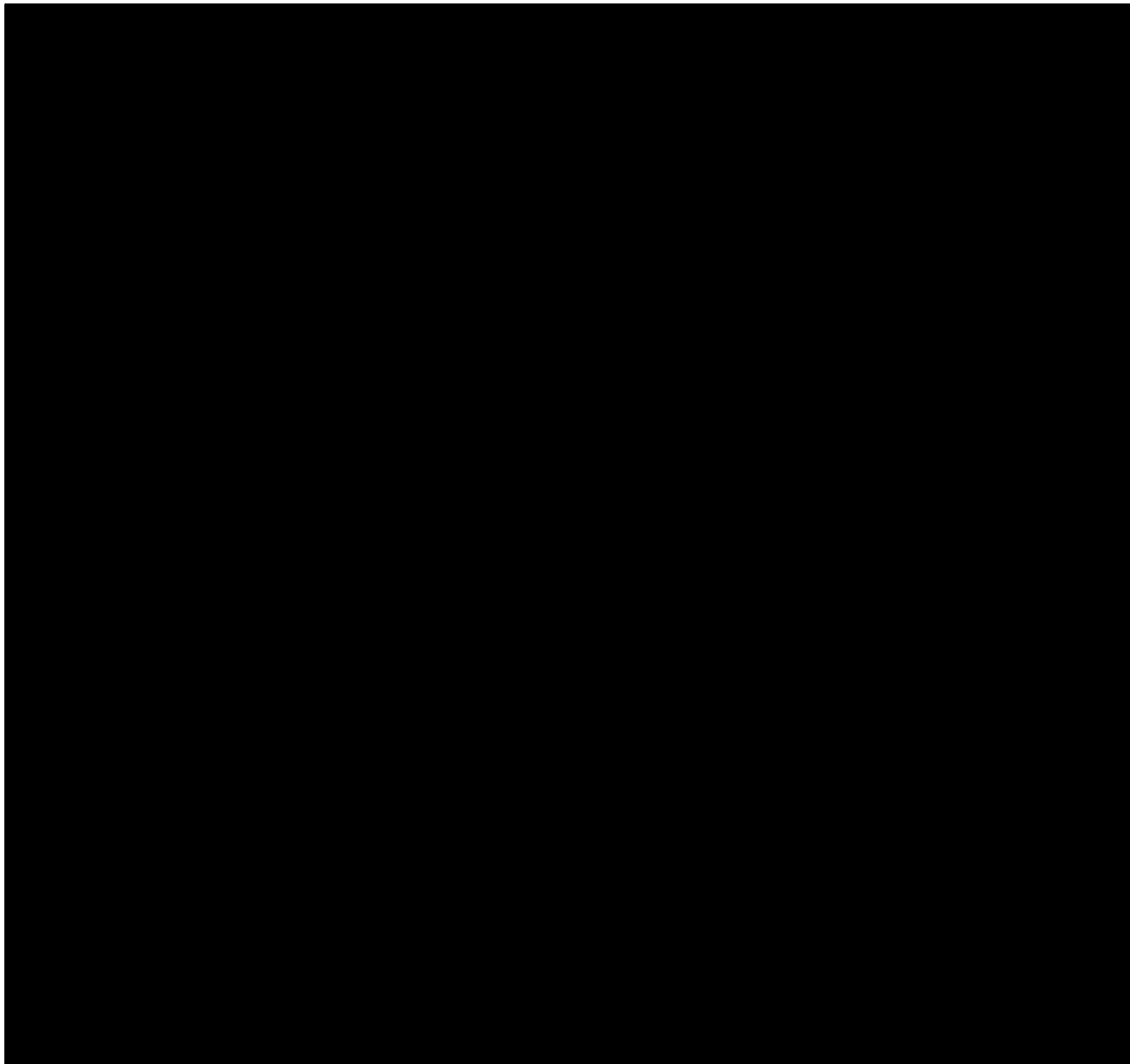


Figure 5.11 Diagrams to illustrate the main fabrics of radiaxial fibrous mosaics.

- a) subcrystals divergent away from substrate, irregular intercrystalline boundaries.
- b) optic axes (arrows) convergent away from substrate in longitudinal section of fibrous crystals.
- c) section transverse to crystal elongation showing arrangement of optic axes which radiate about axes shared by adjacent crystals.

(Figure from Kendall and Tucker, 1973)

5.4.4.1 Radiaxial fibrous spar in the Manifold Valley

In the Manifold Valley radiaxial fibrous spar, along with all other types of cements, is more common in the stratigraphically lower parts of the complex. It has several modes of occurrence. In the small patches of Blue Vein lithologies which occur in the lower parts of the complex, radiaxial fibrous spar encrusts the bryozoan fronds and fills much of the space between adjacent fronds. In areas of Biomicrite Facies lithologies radiaxial fibrous spar is often found as a cavity fill in shelter cavities below shell fragments. It also fills elongate, sub-parallel cavities which range in size from less than 1 mm to several centimetres. These cavities are separated from each other by marine sediments. They are usually completely filled with radiaxial fibrous spar, but where they are incompletely filled by radiaxial fibrous spar, they are often filled with a later clear cement.

5.4.4.2 Origin of radiaxial fibrous spar

It has been suggested that radiaxial fibrous mosaics may be the result of neomorphic alteration of micrite (Black, 1952; Ross et al., 1975). Bathurst (1959, 1977) questioned these ideas and argued that radiaxial fibrous spar is a space-filling fabric because it is always orientated with its long axis normal to surfaces which can be shown to have existed prior to its precipitation, such as the edge of a cavity or a bit of skeletal debris. This view has been accepted by many other workers including, among others, Schwarzacher (1961); Philcox (1963, 1971); Lees (1961, 1964); and Wolf (1965).

The fact that radiaxial fibrous spar often occurs interlaminated with marine sediments (Schwarzacher, 1961; Philcox, 1963; Lees, 1964; and section 5.4.4.1 this thesis) suggests that it, or its precursor, were formed in a marine environment and possibly early in the diagenetic history.

It was originally suggested that radiaxial fibrous spar represents a primary marine cement (Bathurst, 1959). However, Kendall and Tucker (1973) show that it is not a primary cement, but is instead a replacement of an earlier acicular cement. Lohman and Meyers (1977) documented the occurrence of microdolomite inclusions in radiaxial fibrous spars and showed that the source of the Mg enrichment must have been local because adjacent micrites and later cement generations contain no dolomite. They suggest a fibrous Mg calcite as the precursor, as does Davies (1977). Modern examples of early submarine cementation by high Mg calcite have been reported by Schroeder (1972), James et al. (1976). Lohman and Meyers (1977) argue, following Louchs and Folk (1976), and Folk and Asserto (1976), that the bladed crystal shape of radiaxial fibrous spar is not consistent with an aragonite precursor which would probably have crystals with flat terminations such as those found in modern aragonite cements. Magnesian calcites have, on the other hand, pointed terminations and are thus a more likely precursor.

5.5 Lithological trends in the Belgian Waulsortian

5.5.1 Methods

The carbonate mound complex in the Manifold Valley exposes only the upper part of the Waulsortian (section 3.5) the lower facies occurring below ground (section 4.5). In order to gain an idea of the distribution of lithological components throughout a more complete exposure of the Waulsortian sequence, several localities in the Belgian Waulsortian were examined. The localities studied by Bouw (1971) and Noel (1973) were visited and the thin sections collected for their studies examined. An average of 450 points were counted in each of 14 thin sections which were selected to cover the entire stratigraphic and lithological range

of the Waulsortian and because they were relatively unaffected by dolomitisation. Locality information is given in Appendix 2. The results are shown in figure 5.12.

5.5.2 Description and discussion of trends

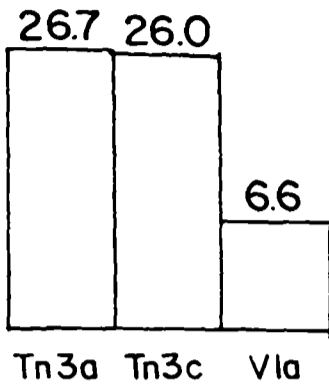
The lithologies and fabrics found in the Belgian Waulsortian are very similar to those found in the Manifold Valley. The main lithological components include cement, microspar, micrite, clotted micrite and bioclasts.

The samples examined show a significant drop in the percentage of cement in the Visean and corresponding increases in the percentage of microspar. This equates well with the Lees et al. (1977) model which shows that the Blue Vein Facies, which is very cement-rich, occurs mainly in the Tournaisian.

Much of the cement observed is either cavity filling, as in the sparry masses, or encrusting, covering bryozoan fronds and filling the empty spaces between them. Radial fibrous spar is very common. This trend towards increasing amounts of microspar (which may represent a neomorphic alteration of micrite (Folk, 1965)) and decreasing amounts of void filling cements towards the Visean suggests a net increase in sediment production over time.

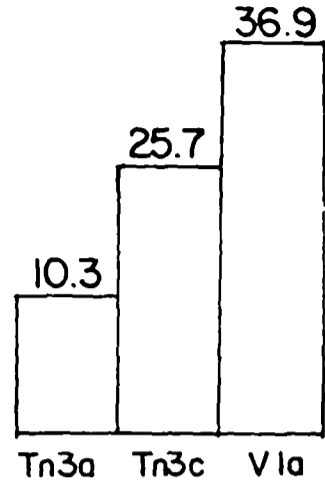
The percentage of bioclasts tends to decrease through time (figure 5.12). Unlike the percentage of bioclasts determined from the Manifold Valley (figure 5.9) which reflects faunal density patterns, the percentages obtained from the Belgian point counts seem largely to reflect an upward decrease in amounts of bryozoa and crinoid fragments, which constitute a greater percentage of the total bioclasts in the lower Tn3 than they do in Vla (figure 5.13). This general upward decrease in the amount of crinoid and bryozoa may be due to higher sedimentation rates because these organisms are sensitive to sedimentation (see section 4.4.4).

% Cement



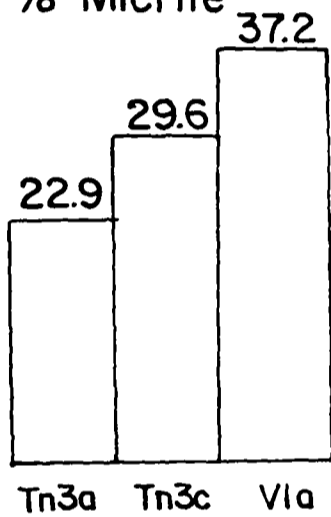
	Tn3a	Tn3c	Vla
Tn3a	X		
Tn3c	0	X	
Vla	95	90	X

% Microspar



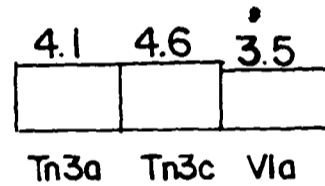
	Tn3a	Tn3c	Vla
Tn3a	X		
Tn3c	99	X	
Vla	99	99	X

% Micrite



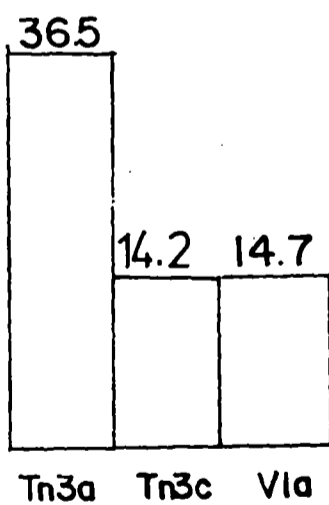
	Tn3a	Tn3c	Vla
Tn3a	X		
Tn3c	50	X	
Vla	30	50	X

% Clotted Micrite



	Tn3a	Tn3c	Vla
Tn3a	X		
Tn3c	10	X	
Vla	10	20	X

% Bioclasts



	Tn3a	Tn3c	Vla
Tn3a	X		
Tn3c	98	X	
Vla	98	0	X

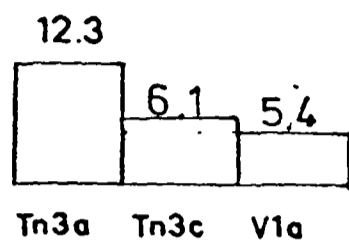
Matrices next to histograms show at what % confidence level the differences are significant as shown by Analysis of variance

Measurements made as described in text. Data & calculations in Appendix 4.

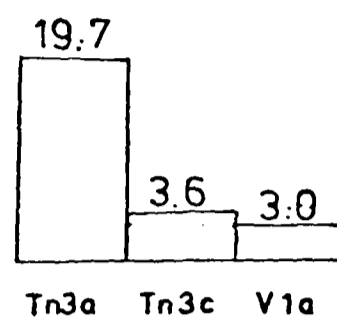
(see sections A4.2.2 and A4.2.3.)

Figure 5.12 Lithologic trends in the Belgian Waulsortian

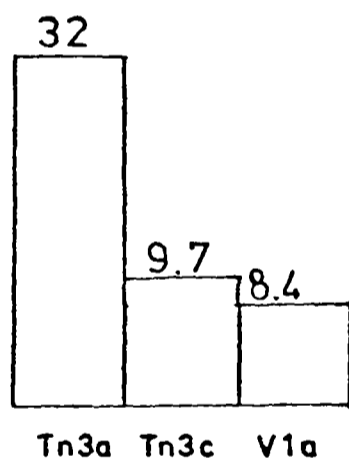
% Bryozoa



% Crinoid debris



% Crinoid + Bryozoa debris



% of total bioclasts composed of crinoid & bryozoa debris

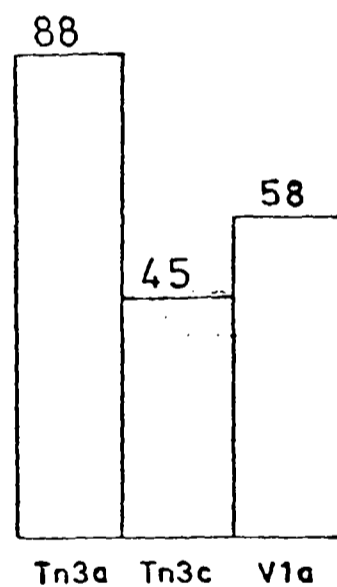


Figure 5-13 Breakdown of percentages of bryozoa and crinoid debris in Belgian point count data

(Data in Appendix 4, section A4.2.2)

The notion of increased sedimentation towards the top of the Waulsortian seems at first sight to contradict the observation that the mound to off-mound thickness ratio drops significantly from the Blue Vein to the Biomicrite Facies (Lees et al., 1977). However, it must be recalled that the Blue Vein Facies would have had a considerably higher initial porosity, due to the great number of fenestrate bryozoan fronds which were spar-encrusted without being completely compacted. Schwarzacher (1961) proved the lack of compaction of bryozoan fronds in similar lithologies in Ireland by measurement of their orientation. Further evidence for the non-compaction of the bryozoa is found in the large amounts of void-filling radiaxial fibrous spar around them. Thus it is preservation of initially greater primary porosity in the Blue Vein Facies, rather than high sedimentation rates which is responsible for the higher mound to off-mound thickness ratios found in the Blue Vein Facies.

5.6 Significance of early lithification in the Waulsortian

The presence of radiaxial fibrous spar and of clotted micrite in both the Manifold Valley mounds, and the Belgian Waulsortian provides evidence that early submarine lithification was an important process in the deposition of these mounds (see sections 5.4.2; 5.4.3.2; 5.4.4.2). The lithologies observed in the Manifold Valley carbonate mounds and in the Belgian Waulsortian are very similar to those described from the Waulsortian of Eire (Lees, 1961; 1964; Philcox, 1963) and of North America (Pray, 1958; Cotter, 1966). Therefore, it is reasonable to suppose that early submarine lithification occurred in and influenced the Waulsortian facies as a whole.

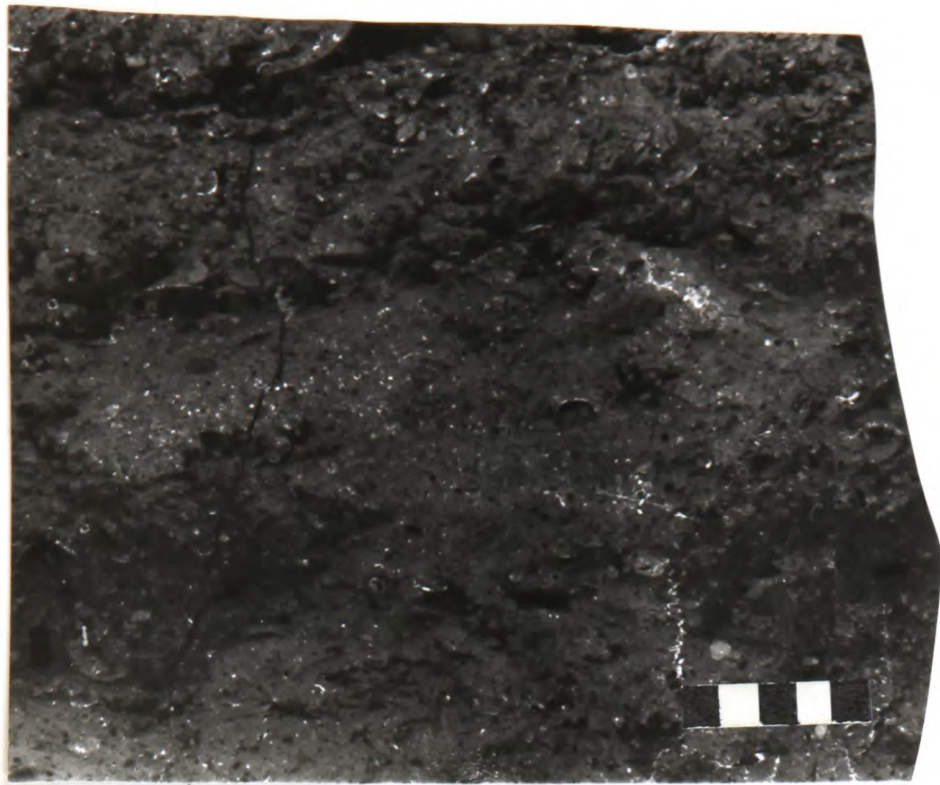
Early submarine lithification could produce a firm sediment capable of maintaining the depositional slopes of more than 30° which are common

in the Waulsortian (see Chapter 1) and also provide the firm substrate for which many of the organisms seem to have been adapted (see Chapter 4). This process could have been augmented by the formation of thin lithified crusts and layers such as are found in the modern day Persian Gulf (Shinn, 1969).

5.7 Origin of spar-filled cavities

The possibility that thin lithified crusts may have developed on the depositional surfaces of Waulsortian mounds suggests a mechanism for the formation of the various sparry masses orientated parallel to depositional slopes which are commonly found in the Waulsortian (Lees, 1961, 1964; Philcox, 1963; Pray, 1958; Cotter, 1966; E. Dupont, 1863; Lees et al., 1977) and in many other Palaeozoic carbonate mounds (see for example Lecompte, 1937; Heckel, 1973; Davies, 1977). The fact that the spar is of void filling rather than neomorphic origin has been shown many times (for example Bathurst, 1959; Lees, 1964), and it is for this reason that the masses are thought to represent spar-filled cavities. These cavities have in common their radiaxial fibrous spar linings and orientation of their long axes roughly parallel to depositional surfaces. Their actual shape can vary considerably from the flat-bottomed cavity, with a finely digitate top referred to as Stromatactis (Dupont, 1881; Bathurst, 1959) to sheet spars (Lees, 1964) and Zebra rock (Ross et al., 1975), which have roughly parallel undulose tops and bottoms (see also figure 5.14).

If early lithified thin crusts were present, the cavities could have formed by a removal of sediment below a crust. The lithified crusts could have supported cavity networks while they became wholly or partially filled with early submarine high Mg bladed calcite cements which were later altered to radiaxial fibrous spar (Bathurst, 1979).



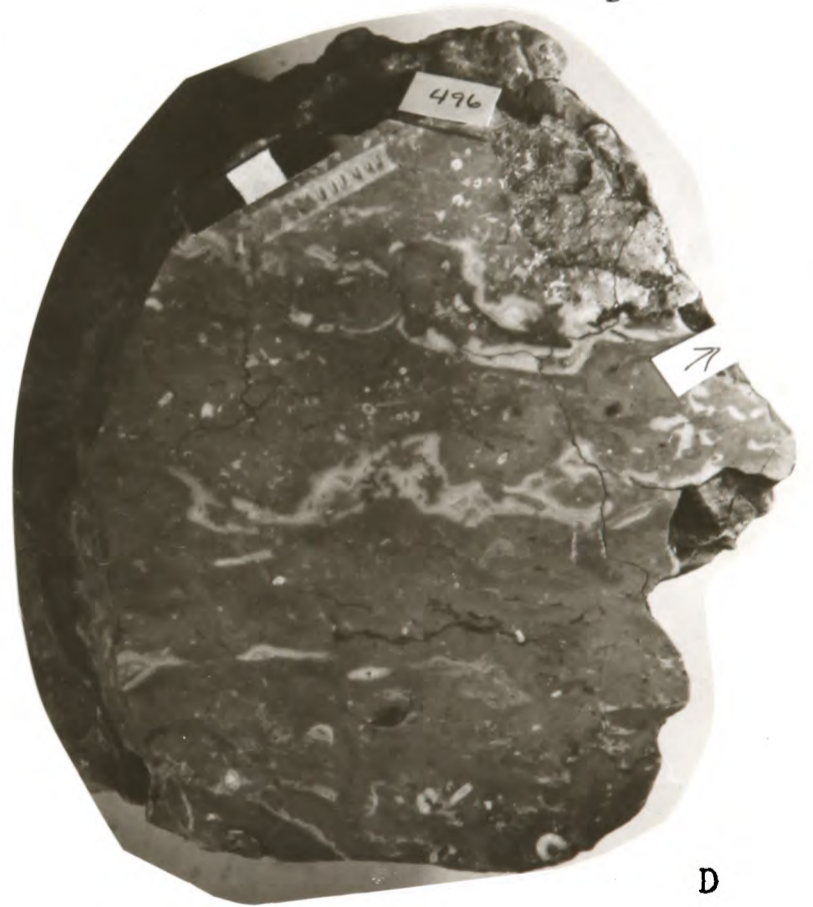
A



B



C



D

Fig 5.14 Several varieties of radiaxial spar-filled cavities.

A, B, C, Negative prints of thin sections, (scale is in mm), all orientated right way up. From Alstonfield borehole core samples. Spar-filled cavities appear black on prints. (A shows Stromatactis).

D Radiaxial spar-filled cavities parallel to inclined depositional surfaces (arrow shows way up). From Manifold Valley loc. 496. Polished block, (scale in cms).

The idea that initial cementation must have occurred early in the diagenetic history and in a submarine environment is supported by the fact that the cavities often contain layers of marine sediments interbedded with the cements (for example see Lees, 1964). Some of the larger cavities have a final filling of blocky calcite, which is sometimes ferroan. The sequence of formation of sparry masses may be summarised as follows: Thin crusts were formed on the surface of the sediment due to early submarine lithification; cavities were formed by removal of sediment underneath these crusts; early bladed high Mg calcite cements were precipitated around the edges of the cavities, thus providing additional mechanical support of what were often very extensive cavity networks; sea water flowing through the cavities contributed to the cementation process and also brought in the internal sediments which are often interbedded with the cement. If the cavities were not filled completely by these two processes, they occasionally remained unfilled, but more often were filled with a later blocky spar. The alteration of the early high Mg calcite cements to radiaxial fibrous mosaics must have occurred prior to the deposition of any such later cements because the blocky spar is sometimes ferroan, whereas the radiaxial fibrous mosaic never is (Bathurst, 1979).

The mechanism by which the cavities are formed is uncertain. The great variation in shapes of cavities would argue for some physical process such as development along planes of shear failure in a deformational setting influenced by the mound slope (as suggested by Schwarzacher, 1961), or by differential settling of sediments influenced by the presence of the upper lithified crust. The idea that sediment mechanics must be involved, as opposed to excavation by organisms for example, (suggested by Shinn, 1968) is supported by the fact that these cavities are mainly restricted to sediments which are composed of very pure

carbonate and are absent from sediments which contain as little as 2 - 3% clay (Heckel, 1972), although exceptions have been noted (Mountjoy, pers. com.). It is unlikely that an organism would be so specific. The differences in the shapes of cavities may be due, in part, to the degree of lithification or firmness present in the sediment below the thin crust. Lees (1964) shows a series of radial spar-filled cavities aligned parallel to depositional surfaces which range from cavities with highly digitate tops to those with tops which are almost mirror images of their bottom surfaces. The slightly undulose tops and bottoms of the latter cavities suggest a process approaching brittle fracture, which would produce straight mirror image tops and bottoms. In contrast, cavities with highly irregular tops and smooth lower surfaces have been produced experimentally by shaking wet unconsolidated carbonate sediment in a jar (Lees, 1964).

5.7.1 Stromatactis cavities

There has been much discussion about the uniqueness of one end member of this spar-filled cavity series, namely Stromatactis (see figure 5.14a). Stromatactis characteristically forms a sheet-like mass of sparry calcite with a thickness from about 1 mm to 3 cm (Bathurst, 1979), though larger examples are known (Philcox, 1963). The cavities usually have a smooth base, which is flat to undulose, and which dips as much as 25° from the original horizontal. The roof is finely, though irregularly, digitate with fingers extending into the host biomicrite. It does not depend upon the shelter of skeletal debris for its support, although bioclasts may locally affect its shape.

There is some advantage in adhering to a strict definition for Stromatactis in that it helps to prevent confusion of these structures with other primary cavities of different origins, such as birds eye

vugs, and with cavities of much later origin, such as filled fractures. However, in light of the above paragraphs it seems likely that Stromatactis is one end member in a series of cavities which were formed in sediments of varying degrees of firmness under thin submarine lithified crusts early in the diagenetic history of pure carbonate bodies. Therefore, it is perhaps more productive to consider the spectrum of cavities as a whole, rather than emphasising the importance of Stromatactis which is one end member of the series.

5.7.2 Factors influencing cavity distribution

Although radiaxial fibrous spar-filled cavities are common in many Palaeozoic carbonate buildups, they are by no means ubiquitous. This non-uniform distribution of the sparry masses may be related to the presence or absence of lithified crusts on the sediment surface. Recent crusts on the sea floor have generally a patchy distribution (Fischer and Garrison, 1967; Bartlett and Greggs, 1970; Neumann et al., 1977). It has been suggested that increased sedimentation may prevent the formation of lithified crusts (Shinn, 1969; Milliman, 1971; Kennedy and Garrison, 1975; Neumann et al., 1977). Thus, the distribution of the sparry masses in the Waulsortian and elsewhere may be a reflection of changing rates of sedimentation, or, in the case of in situ sediment production as may have occurred in many carbonate buildups, of changes in the rate of sediment production.

The percentage data of lithological components in the Manifold Valley (figure 5.9) suggests a trend towards decrease in cement from lower to higher stratigraphic levels (section 5.3.2). Because much of the cement in the Manifold Valley is void filling (sections 5.2.1 and 5.4.4.1) this decrease in cement reflects a decrease in the number of spar-filled cavities. If the formation of cavities is influenced by the formation

of lithified crusts whose distribution is restricted to some degree by high sedimentation rates, then the upward decrease in cement and in sparry cavities in the Manifold Valley suggests an upward increase in sedimentation. This hypothesis is given further support when it is recalled that fenestrate bryozoa and crinoid debris are sparse in the Manifold Valley and that these organisms are limited by high sedimentation rates (Lagaaij and Gautier, 1965; Schopf, 1969 and see also section 4.4.4).

An upward decrease in amounts of cement and bryozoan and crinoid debris is observed in the Belgian Waulsortian (Lees et al., 1977; see also figures 5.12 and 5.13 and section 5.5.2) which suggests that there is an upward increase in sedimentation rates in the Belgian mounds as well. The trends in the distribution of cement and bryozoa also reflect the distribution of the cement and bryozoan-rich Blue Vein Facies, which occurs stratigraphically below the more micrite and microspar rich, bryozoan and cement-poor Biomicrite Facies in the Belgian Waulsortian. The faunas found in the Blue Vein Facies and in the Biomicrite Facies are very similar (see Chapter 4), which suggests that a major environmental change did not occur in conjunction with the change in lithological facies. Instead, differences in sedimentation rates may be a principal cause of the facies change in the Waulsortian.

A postulated upward increase in sedimentation rates implies that features restricted by high sedimentation rates, such as the formation of lithified crusts and spar-filled cavities, would be on the whole more common in the lower parts of the Waulsortian. This is in fact the case. The Manifold Valley mounds expose rocks comparable to the upper part of the Waulsortian (the Biomicrite Facies; see section 3.5). Sparry masses are relatively sparse in these mounds when they are compared with exposures in the lower facies of the Waulsortian which

were examined in Clitheroe, Lancashire, Belgium and Eire, and described in the United States by Pray (1958) and Cotter (1966).

5.8 Depositional slopes

Lithified crusts may also be one of the factors involved in the maintenance of steep depositional slopes (which are sometimes greater than 30°). Therefore, the lower parts of the Waulsortian, which seem to have had the lowest sedimentation rates and thus greater areas of lithified crusts, would be expected to exhibit the steepest slopes. This idea is supported by the observations of Lees et al. (1977) who note that depositional dips can be up to 50° in the Blue Vein Facies, but that there is no evidence for significant depositional slopes in the Biomicrite Facies. However, the Manifold Valley mounds, which are largely of Biomicrite Facies (section 3.5) do have significant depositional slopes (figure 3.4a). The steepness of dip may be somewhat exaggerated by later folding in the area which has not been subtracted from the dips shown and by the method of measurement used. Examination of the Kniveton and Alstonefield boreholes (Appendix 1) has shown that dips based on geopetals are consistently shallower than those based on surfaces outlined by bioclastic debris and bryozoan fronds. Because geopetals are rather rare in outcrops in the Manifold Valley most of the dips shown are based on orientation of surfaces. While the direction of dip is never in doubt, the magnitude of the dip may be exaggerated.

Even so, there do seem to be significant depositional dips in the example of the Biomicrite Facies exposed in the Manifold Valley, which must have been supported by some means. Additionally, the faunas found in the Biomicrite Facies in both Belgium and the Manifold Valley suggest that the substrate was firm (section 4.5). These two observations along with the presence of radiaxial fibrous spar and clotted micrite, indicate

that submarine lithification, although not necessarily in the form of crusts, continued in the Biomicrite Facies and was important in the maintenance of depositional slopes and firm substrates. Algal mats could have fulfilled a similar role, but the virtual absence of recognisable preserved algae in these mounds argues against their existence.

5.9 Origin of the micrite

The question of the origin of the large amounts of micrite which make up much of the Waulsortian remains unanswered. There are two possible ways to account for it: by trapping and binding of carbonate sediments produced on a regional scale or by local in-place production of carbonate sediment.

5.9.1 Trapping of sediment

One of the main problems with the trapping hypothesis is the lack of any organisms capable of trapping and binding fine-grained sediment. The bryozoa which are abundant in the lower part of the Waulsortian have often been supposed to have filled this role (for example Pray, 1958), but this seems a less plausible idea when it is realised that sediment accumulation seems to have increased in the upper parts of the Waulsortian where the numbers of bryozoa are considerably less. In any case, the large amounts of void filling radiaxial fibrous spar and correspondingly low amounts of micrite in the bryozoan-rich Blue Vein Facies argue that even when abundant, bryozoa did not trap much sediment.

Another argument against the sediment trapping hypothesis is that the surrounding sediments, though often very fine-grained and sometimes carbonate-rich, usually contain a much higher proportion of clastic sediments. For example, the bedded sediments associated with the

Manifold Valley mounds have shaley interbeds; Waulsortian at Clitheroe in Lancashire has a shaley interbank facies (Miller and Grgyson, 1972); the Waulsortian mounds in the Dublin basin and in Co. Cork are contemporaneous with shaley deposits (Hudson et al., 1966; Turner, 1937) and the Molinee off-mound facies in the Belgian Waulsortian has shaley interbeds (Lees et al., 1977).

In order to accumulate very pure carbonate mounds only the pure carbonate fraction must have been trapped and this degree of selectivity is difficult to imagine.

5.9.2 In situ production

In situ production of carbonate sediment could explain the presence of pure carbonate buildups when ambient sediments are often clastic-rich. Early submarine lithification combined with quiet water conditions (see Chapters 3 and 4) could explain the restriction of the carbonate to localised areas. Calcareous algae have been suggested as the sediment producers (Laudon and Bowsher, 1941), and it is known that calcareous algae, such as Penicillus can produce large amounts of fine-grained carbonate (Stockman et al., 1967). However, very little good evidence of preserved algae has ever been found in these mounds. Thus, at present, the identity of the carbonate producer remains unknown.

5.10 Conclusions

The similarity in lithological facies and faunas suggests that the Manifold Valley carbonate mounds, the Belgian Waulsortian, and the Waulsortian in Clitheroe, Lancashire, Eire and the United States had a similar origin and development. Functional morphological analysis of faunas from the Manifold Valley and the Belgian Waulsortian suggests that the substrate was, by and large, a firm one (Chapter 4).

Early submarine lithification, which has been reported from many Holocene shallow and deep water environments, is suggested as a possible mechanism for providing a firm substrate. The presence in the Manifold Valley, and in all Waulsortian rocks, of clotted micrites, which could represent high Mg calcite rosettes, which are thought to be an early lithification feature (Alexandersson, 1972) and of radiaxial fibrous spar, which is thought to be an early replacement fabric of an even earlier fibrous high Mg calcite cement (Kendall and Tucker, 1973; Lohman and Meyers, 1977) provides some evidence that this process occurred.

Early lithification producing thin crusts on depositional surfaces suggests a mechanism for the formation of the range of radiaxial fibrous spar-filled cavities commonly orientated parallel to depositional surfaces, of which Stromatactis is one end member. The actual mechanism of cavity formation is not known, but the restriction of this type of cavity to more or less pure carbonate sediments suggests that sediment mechanics, rather than excavation by organisms, is responsible. The actual shape of the cavity produced may be a function of the degree of firmness of the sediment below the crusts. Very soupy sediment under the crusts could produce Stromatactis-like cavities, while firmer underlying sediments might produce cavities where the top and bottom surfaces tend to mirror each other.

The distribution of the cavities could be controlled by the distribution of the crusts. Surface cementation may be related to sedimentation rates, high rates being an inhibiting factor. Therefore, when sedimentation rates, or in the case of these carbonate mounds, in-place production increases, the crusts will not be formed. It follows that in areas of high sediment production sparry cavities will be sparse or lacking.

In both the Manifold Valley and the Belgian Waulsortian there is an upward decrease in the percentage of cement and corresponding increase in amounts of micrite and microspar. This suggests an increase in sedimentation towards the top of the Waulsortian, as does the upward decrease in the numbers of sparry cavities and sedimentation sensitive fenestrate bryozoa and crinoids.

Early submarine lithification was an important process in the development of Waulsortian mounds. It accounts for the presence of steep depositional slopes, extensive internal cavity networks and organisms adapted to life on firm substrates. The lithification process may have been in turn regulated by the rate of sedimentation, which increased as the Waulsortian developed. The largest and perhaps most important question - the identity of the sediment source - remains unanswered.

CHAPTER 6

MODERN ANALOGUES

6 MODERN ANALOGUES

6.1 Partial analogues

No modern analogues for the Waulsortian have yet been reported. However, studies of two modern carbonate environments published in recent years may have particular bearing on the interpretation of Waulsortian environments. These include an analysis of grain components in temperate water carbonates by Lees and Buller (1972) and a related study of the influences of salinity and temperature on carbonate sedimentation by Lees (1975); and descriptions of deep water 'lithoherms' in the Straits of Florida by Neumann et al. (1972, 1977).

6.2 Temperate water carbonates

Lees and Buller (1972) studied grain types in carbonate sediments in shelf areas between latitudes 60° south and 60° north. They recognised two major skeletal grain associations; one almost entirely restricted to warm tropical waters, and one which is characteristic of temperate waters, but which sometimes extends into the tropics.

The temperate water grain assemblage, which is termed foramal by Lees and Buller (1972), includes skeletal debris of molluscs, benthonic forams, echinoderms, bryozoans, barnacles, ostracodes, sponges, worm tubes and occasionally of ahermatypic corals. All of these constituents are not necessarily present in any particular area. The warm water association, which the same authors call chlorozoan, may include most of the temperate water grain types, but differs in that it always contains significant contributions from corals or calcareous algae or both. In addition, barnacles and bryozoans are rare.

The warm water assemblage is most often found in the 30° south to 30° north latitude belt. However, there are a significant number of

occurrences of the temperate water grain assemblage in this latitude belt as well, for example in the eastern Pacific. Thus latitude alone cannot explain their distribution.

Lees (1975) concluded that temperature and salinity are the most important factors in influencing the distribution of grain types on a global scale, although other factors such as currents and substrate types may be influential locally. He notes that the separation between the warm water and temperate water assemblages appears to be influenced by both temperature and salinity in such a way that high temperature compensates for low salinity and vice versa. This interplay between temperature and salinity explains why temperate water assemblages sometimes occur in low latitudes.

When these ideas are applied to the Waulsortian sediments the results are very interesting. According to the Lees and Buller (1972) model the grain assemblage in the Waulsortian is clearly a temperate water one because it contains significant amounts of bryozoans, which are rare in warm water assemblages, as well as ostracodes, sponge spicules, mollusc and echinoderm debris, all of which are components of the temperate water association. It lacks the significant amounts of coral and algal debris which are characteristic of warm water assemblages. However, when plotted on a Lower Carboniferous palaeolatitude map (see figure 1.1), the Waulsortian is found to occur exclusively in low latitudes. This is outside the usual range of temperate water associations. Lees' (1975) theories suggest that either salinity or temperature must provide the compensating effect. Because the major components of the Waulsortian fossil assemblage, such as brachiopods, and the locally important bryozoa are restricted to normal marine salinities, salinity is not likely to be the compensating factor in this case. Lower water temperature, however, is a possibility and the

lower temperatures are most likely to be found in deep water. Thus the occurrence of the Waulsortian temperate water grain association in low latitudes provides an indication of a deep water depositional environment for the Waulsortian. This idea has been previously suggested because of the lack of current-structures and algae in the Waulsortian and its palaeogeographic position below shelf edges (Pray, 1969; Stone, 1972; Wilson, 1975). A deep water depositional environment has also been suggested in this thesis (section 4.4.4) because of the abundance of fenestrate bryozoa which occur in the Blue Vein Facies. Continued study of the controls of temperate water carbonate sedimentation, therefore, seem likely to provide additional information about the controls on sedimentation in the Waulsortian facies.

6.3 Lithoherms

6.3.1 Description

The reports by Neumann et al. (1972, 1977) of carbonate mounds in the Straits of Florida, which they term lithoherms, may also have some bearing on the interpretation of Waulsortian environments. The following description is based on their papers. Lithoherms are mud mounds composed of surface-hardened concentric crusts of submarine lithified carbonate mud hundreds of metres long and up to fifty metres high which are found in depths of 600 - 700 metres in the northeastern Straits of Florida. They are exposed on the present day sea floor as clusters of mounds, but seismic profiles reveal stacked sequences of lithoherms beneath the modern occurrences. The lithoherms provide local areas of hard surfaces in an environment of unconsolidated sediment and seem to be preferentially selected habitats for a diverse community of benthic organisms such as crinoids, corals and sponges. When compared to the surrounding sea floor, they exhibit a dense cover of organisms.

The lithoherms are thought to be the product of in situ accumulation and lithification of pelagic sediments, and to contain also sediments derived on the surface of the mounds by the breakdown of calcareous skeletons and the accumulation of faecal matter and sediments trapped by the baffling effect of the dense organic growth. The distribution of the mounds is influenced by the prevailing current directions, and the lithoherms are elongated in the direction of bottom flow. Filter-feeding organisms have also responded to the currents and have positioned themselves so as to allow maximum cross sectional exposure to the current flow. These features could presumably be preserved in the rock record.

The surface crusts, which support the deposition slopes of the lithoherms (up to 30°) are cemented with high Mg calcite. When the crusts are broken on the surface, the softer sediment below is often excavated, leaving cavities. Neumann et al. (1977) suggest that these, when filled with sparry cement, would resemble Stromatactis-like cavities. The occurrence of high Mg calcite early cements may provide the precursor for the radiaxial fibrous spar which characteristically fills such cavities (see Chapter 5).

The controls of the lithification are not understood, but it is thought that the process is affected by the oceanographic regime, rate of deposition of the sediment and the sediment texture and mineralogy.

6.3.2 Similarities to the Waulsortian

Wilson (1975) suggested that lithoherms may represent a modern analogue for the Waulsortian. Neumann et al. agree with some reservations. Lees et al. (1977) reject this idea because they believe the Waulsortian mounds were soft-surfaced mud producers rather than hard-surfaced mud traps. However, in the light of evidence presented in this thesis which indicates that firm substrates and early submarine

lithification were important in the development of the Waulsortian, the similarities between lithoherms and Waulsortian mounds are worth reconsidering.

The deep water occurrence of lithoherms is similar to that suggested for the Waulsortian (Wilson, 1975; Stone, 1972; Pray, 1969). The sediment which makes up the lithoherms is largely micrite, some of which is clotted, owing to the activity of organisms and to the textures of the early cements. When fully lithified, this could produce fabrics very similar to those found in the Waulsortian. The fact that lithoherms possess steep depositional slopes of at least 20° to 30° and seem to have formed stacked complexes recalls the analysis of mound geometry in the Irish Waulsortian by Lees (1964), its application to the Derbyshire and Staffordshire region by Thach (1965) and specifically to the Manifold Valley in this thesis. Additionally, the lithoherms, presumably because of their firm surfaces, support communities of organisms which are different from those in the surrounding sediments. Similar differences between fossil communities in the Waulsortian and the off-mound sediments are also noted (for example, Dupont, 1863; Prentice, 1951; Hudson et al., 1966) in the European examples. DeKeyser (1978) claims that the faunas in the Waulsortian in New Mexico are identical to those found in the adjacent platform, but as he has not yet published any data to support his claims, they cannot be evaluated.

Perhaps the most significant similarity between lithoherms and the Waulsortian is the fact that in both early submarine lithification by high Mg calcite, augmented by the formation of concentric layers of lithified crusts separated by thicknesses of softer sediments seems to play a major role in their development (Neumann et al., 1977; Chapter 5 this thesis).

There are some features of lithoherms which differ greatly from those observed in Waulsortian mounds. The orientation and shape of lithoherms is clearly related to currents as is the ecological zonation of the organisms (Neumann, 1978). This is not the case in the European examples of the Waulsortian, although the orientation of the Waulsortian mounds in New Mexico may be influenced by current directions (Wilson, 1975). Another contrast is that lithoherms are developing in an area of regional carbonate sedimentation and are thought to accumulate by means of sediment trapping. Most Waulsortian mounds do not originate in environments similar to the Straits of Florida (although here again the New Mexico mounds may be an exception) and evidence of organisms capable of trapping large amounts of sediment is lacking. Also missing is any evidence in the lithoherms of a modern analogue for the bryozoa and spar-rich, but micrite-poor, Blue Vein Facies. Lithoherms, if they are analogous to the Waulsortian in any way, can only be compared with the Biomicrite Facies.

Although it is clear that there are some major differences between lithoherms and Waulsortian mounds, the modern example of micritic mounds developing largely owing to localisation of sediment by early submarine lithification provided by the lithoherms in the Straits of Florida is of very great interest. Continued study of these deposits seems certain to promote a greater understanding of the development of the Waulsortian and many other micritic mounds.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7 CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1 Summary of conclusions

Mapping and plotting of available stratigraphic information in the carbonate mound complex in the Manifold Valley has shown that mound development began in the Courceyan (Tn3c) and continued through the Arundian (V1b). The complex youngs towards the east. It is composed of at least five smaller mounds which have coalesced to form a large mass. The contact between the mounds and the off-mound sediments is abrupt. Fingers of off-mound sediment interdigitate with the unbedded mound limestone and in some areas off-mound sediments are seen to envelop small carbonate mounds. The predominant lithology of the mound complex is medium to light grey biomicrite which is similar to that found in the Biomicrite Facies of the Belgian Waulsortian recognised by Lees et al. (1977). Occasionally there are small patches of a fenestrate bryozoan and spar-rich lithology similar to their Blue Vein Facies (Chapter 3).

Similarities in age and lithology suggest that the Manifold Valley carbonate mounds represent examples of Waulsortian 'reefs'. Comparison with the model developed for the Belgian Waulsortian by Lees et al. (1977) indicates that only the upper parts of the Waulsortian, the Transitional and Biomicrite Facies, are exposed in the Manifold Valley. The Blue Vein Facies, which is characteristic of the lower parts of the Waulsortian is thought to be present below ground (Chapters 2 and 3).

A comparison of the Manifold Valley faunas with those from other localities, of both Blue Vein and Biomicrite lithologies, shows no significant difference between them except for a significant decrease in the numbers of fenestrate bryozoa in the Biomicrite Facies. Thus the faunal trends found in the Manifold Valley, although the faunas

come primarily from Biomicrite lithologies, are likely to be representative of Waulsortian faunas as a whole (section 4.2.4).

Morphological and structural analysis of the faunas in the Manifold Valley suggests that the substrate of the mounds was by and large a firm one because the majority of the organisms are adapted to life on firm, but not necessarily hard, substrates. The most significant components of faunal variation in the Manifold Valley are changes in diversity, density/maximum size and amount of fenestrate bryozoa. Generally, density tends to increase from the older to the younger mounds. However, the distribution of the fauna is clumped and areas of high faunal density sometimes occur near areas of much lower density. The patchy variation in faunal density may be due, in part, to substrate heterogeneity.

The faunal diversity trends in the Irish and Belgian Waulsortian follow the trends predicted by the community succession model of Johnson(1972) and Walker and Alberstadt(1975). According to this model, the diversity trends in the Manifold Valley predict the existence of earlier phases of community development which are not exposed. This gives further weight to the supposition, based on lithological evidence, that an earlier facies of the Waulsortian will be found below the surface (section 4.4.2).

The rarity of fenestrate bryozoa and the paucity of crinoid debris in the Manifold Valley is compatible with the idea that it is the upper part of the Waulsortian, the Biomicrite Facies, which is exposed there. Modern fenestrate bryozoa are limited in their

distribution by high sedimentation rates (Lagaaij and Gautier, 1965; Schopf, 1969). There are indications that crinoids also may have been sensitive to sedimentation (section 4.4.4). The decrease in amount of bryozoa and crinoid debris towards the top of the Waulsortian may be due to an increase in the rate of sedimentation as the mounds developed.

The lack of any organisms capable of trapping sediment and the common occurrence of the pure carbonate Waulsortian "reefs" interbedded with shaley deposits leads to the conclusion that the sediment was produced in situ. Presumably mound growth stopped when sediment production ended. The identity of the producer is unknown.

Principal lithological components and fabrics are comparable in the Belgian Waulsortian and in the Manifold Valley. In fact, the Waulsortian facies as a whole is remarkably similar petrographically in all of its occurrences (Wilson, 1975). These similarities suggest that the depositional and diagenetic histories were similar within the Waulsortian, wherever it developed.

Early submarine lithification, which has been reported from many Holocene marine environments is a likely mechanism for providing the firm substrates for which a large percentage of the fauna were adapted. The development of a cohesive sediment surface due to lithification also provides a mechanism for the maintenance of steep depositional slopes. The presence in the Waulsortian of clotted micrites and radiaxial fibrous spar provides evidence that this process occurred. The degree of lithification may not have been uniform. In some areas the sediment remained soft while in others thin lithified crusts were formed. The development of thin crusts on depositional surfaces suggests a mechanism for the formation of the range of radiaxial fibrous spar-filled cavities

commonly orientated parallel with depositional surfaces by removal of sediment below the crusts. Formation of crusts is thought to be restricted by high sedimentation rates. It follows that sparry cavities will be lacking in areas of high sediment production. There is a decrease in the amount of sparry cavities towards the younger parts of both the Manifold Valley mounds and the Belgian Waulsortian. This distribution, as well as the large amounts of void filling radiaxial fibrous spar in the Blue Vein Facies and increase in amounts of micrite in the Biomicrite Facies provides evidence that sediment production increased as the Waulsortian developed (Chapter 5).

7.2 A model for the development of the Waulsortian

7.2.1 Sources of information

It has been argued throughout this thesis that the faunas and lithologies studied in detail in the Manifold Valley are comparable to those observed in the Belgian Waulsortian, and that hypotheses derived from the study of these two occurrences are applicable to the Waulsortian facies as a whole. The following model has been developed from conclusions drawn in this thesis based on data gathered in the Manifold Valley and in the Belgian Waulsortian. It is presented as a working model for the development of the Waulsortian facies as a whole, in the hope of stimulating further research into the origin and development of the Waulsortian and other fine-grain carbonate mounds.

7.2.2 The model

The Waulsortian may have begun with the growth of dense populations of fenestrate bryozoa in a fairly deep marine environment in areas of relatively low sedimentation. The actual water depth cannot be estimated,

but must have been below wave base, may have been below the photic zone and was certainly above the carbonate compensation depth. Some micrite was produced during this phase, but it must have been on a small scale because it did not restrict the growth of bryozoa to a great extent. The bryozoan fronds were quickly encrusted with early high Mg calcite cements. The cementation prevented, to some degree, the compaction of bryozoan fronds due to overburden, and the cemented bryozoa formed a topographic high on the sea floor. This stage of development is represented by the Blue Vein Facies.

Later, the sedimentation rate seems to have greatly increased and, except in localised patches, bryozoan growth largely ceased. There appear to have been a number of centres of sediment production which caused the formation of numerous small mounds. These often coalesced to form mound complexes. Occasionally the rate of sediment production must have dropped, allowing the development and cementation of small patches of bryozoa. Sediment production locally ceased from time to time and some of the small mounds were draped with basinal sediments. This phase is represented by the transitional part of the Biomicrite Facies.

Early submarine lithification was an important process in cementing the bryozoan fronds as well as in stabilising the micrite. Growth of early cements produced a cohesive sediment which provided firm substrates for the organisms and helped to maintain steep depositional slopes. The degree of cementation was not uniform. Sometimes the sediment remained soft and was populated by organisms adapted for life on soft substrates. In other areas cementation produced thin lithified crusts. Removal of sediment of varying degrees of firmness below the crusts formed cavities which were soon filled with cement. These are preserved as the range of radiaxial fibrous spar-filled cavities

orientated parallel to depositional surfaces, of which Stromatactis is one end member.

The sediment production rate increased as the Waulsortian facies developed. Although early lithification continued to some extent to provide firm substrates for the fauna and to maintain depositional slopes, the distribution of crusts, and hence of cavities, was limited by the higher rate of sedimentation. This is represented by the Biomicrite Facies, where, except for a decrease in the amount of bryozoa, the fauna remains similar to that of the earlier phases while the percentage of micrite increases and the numbers of sparry cavities decreases.

Finally, the localised production of carbonate in the mounds ceased, while basinal sedimentation continued. This must have happened rather abruptly, because there was no return to the development of crusts, as evidenced by the scarcity of sparry cavities at the top of the Waulsortian. Eventually the mounds were buried by basinal sediments.

7.3 Suggestions for further research

Submarine cementation appears to have been a very important process in the development of Waulsortian 'reefs' and there is scope for a great deal more work on the details of this process. Isotope, trace element and electron microscopic studies have proved useful in understanding the sequence and mechanisms of early diagenesis in both recent and ancient sediments (see for example Neumann et al., 1977; Mountjoy and Walls, 1977; Davies, 1977; Lohman and Meyers, 1977). Studies of this type would be of great use in the recognition of the similarities between the Waulsortian and some examples of recent carbonate mounds.

The model presented in this thesis suggests only a bare outline of the process of the growth of the Waulsortian and many details need to be filled in. Its value as a predictive model should be tested by

application to a region of more complete and extensive Waulsortian development than exists in either England or Belgium. The Irish Waulsortian would seem to be an excellent area for further development of this model, but a number of stratigraphic and mapping problems would have to be solved first.

Some aspects of the fauna of the Waulsortian are confusing. Many features of bryozoan and crinoid palaeoecology have not been worked out and a better understanding of these organisms, which are so important in the lower part of the Waulsortian, will undoubtedly aid in the understanding of the origin of the facies. Additionally, although the steep depositional slopes, presence of intraclasts and the dominance of genera adapted for life on firm substrates suggests that the sediment became cohesive very soon after deposition, and the presence of early formed cavities suggests thin lithified crusts may have formed, there is an absence of encrusting and boring organisms in the fauna. The rarity of encrusting and boring forms and of hardground faunas in general has been noted throughout the Carboniferous (T. Palmer, pers. com.) and this absence is quite puzzling. Work towards the understanding of this anomaly would also aid in the understanding of the Waulsortian.

The model proposed in this thesis leaves two very important questions unanswered. Firstly, it provides no reason for the localisation of Waulsortian mounds, although it suggests that the occurrence of fenestrate bryozoa may be significant in this respect. Secondly, no theories are proposed to indicate the source of the micrite. This question has not been satisfactorily answered in most ancient carbonate mounds and an understanding of in situ micrite production would be of great significance in many geological settings.

APPENDIX 1








BOREHOLE LOGS

Kniveton Borehole.

The borehole was drilled at grid reference SK 2122 5087. The upper parts of the core are heavily dolomitised and no lithological or sedimentary features could be observed. Therefore the log begins at 19 metres. It ends at a depth of 100 metres.

The core is the property of the Institute of Geological Sciences.

KEY

-  micrite
-  pellety micrite
-  pink coloured micrite
-  mottled micrite
-  Blue Vein
-  dolomite
-  core broken or missing

-  dip of surface
-  cavities
-  clasts
-  spar
-  pellets
-  crinoid debris
-  whole brachiopods
-  single brachiopod valves
-  cephalopods
-  gastropods
-  corals
-  bryozoa
-  bioclasts (unspecified)

Blue Vein with scattered crinoid debris and patches of light grey micrite; numerous small whole brachiopods, but no geopetals

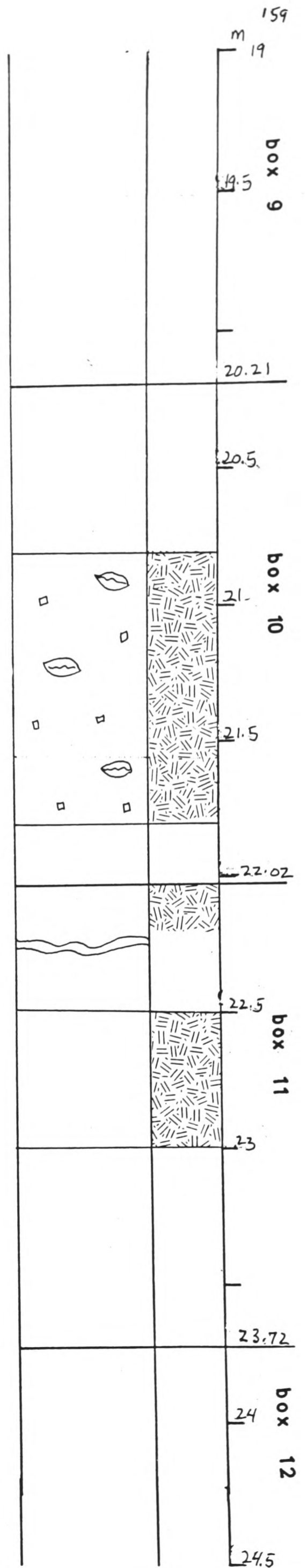
Blue Vein and patches of light grey micrite

dolomite

dolomite

Fe-rich secondary vein

dolomite



medium grey biomicrite, lots of small brachiopods; some geopetals show dips of 20°; a few patches of Blue Vein

biomicrite with some patches of Blue Vein; geopetals in several small brachiopods show dips of approximately 30-35° at 25.6m

two corals
brachiopod geopetal

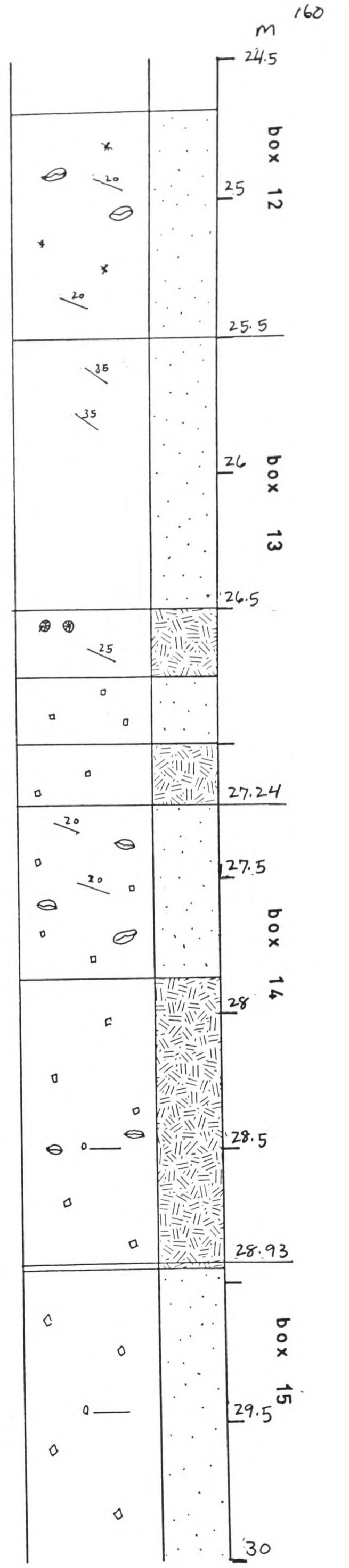
Blue Vein, with intervals of up to 25 cms of grey biomicrite with scattered crinoid debris

medium light grey biomicrite with some patches of Blue Vein at 27.5m and 27.6m; geopetals in brachiopods show 20° dip; bioclasts include small brachiopods and scattered crinoid debris

two brachiopod geopetals show horizontal surface

Blue Vein with some medium light grey biomicrite patches in intervals of up to 4 cms; scattered crinoid debris throughout

two geopetals show horizontal surface



slightly reddish stained micrite with occasional patches of Blue Vein; scattered crinoid debris

medium light grey biomicrite, scattered crinoid debris and small clear spar-filled cavities

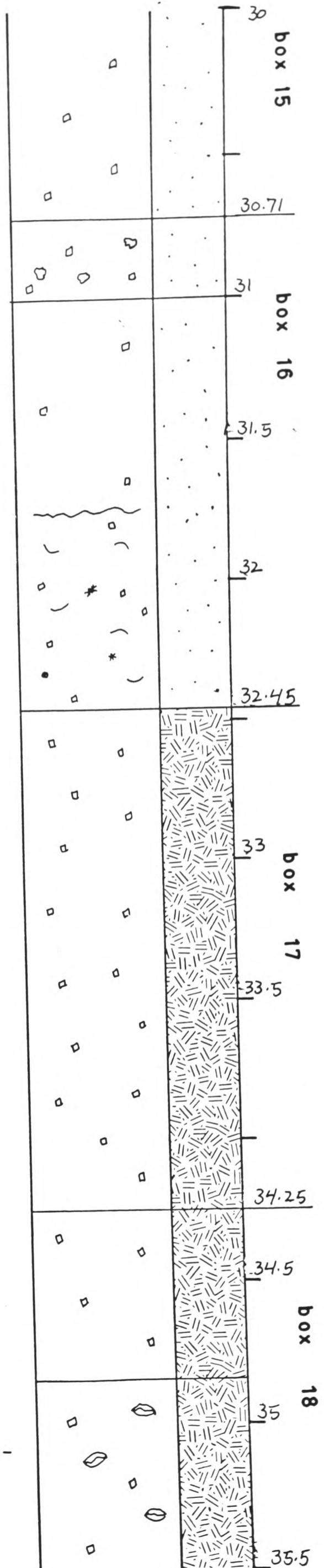
patches of Blue Vein in biomicrite with scattered crinoid debris

Fe stain

very bioclastic micrite with crinoid debris, brachiopod shells and small corals (rare)

Blue Vein with some reddish stained biomicrite, scattered crinoid debris

Blue Vein with patches of reddish stained biomicrite; some large crinoid ossicles and brachiopods, but no reliable geopotals



m

35.5

36

box 19

36.5

37

medium light grey biomicrite, common crinoid debris

37.5

reddish stained biomicrite with common bryozoa fronds

37.77

brachiopod geopetal

38

box 20

38.5

Blue Vein with patches of reddish stained biomicrite

39

39.45

geopetal shows horizontal surface

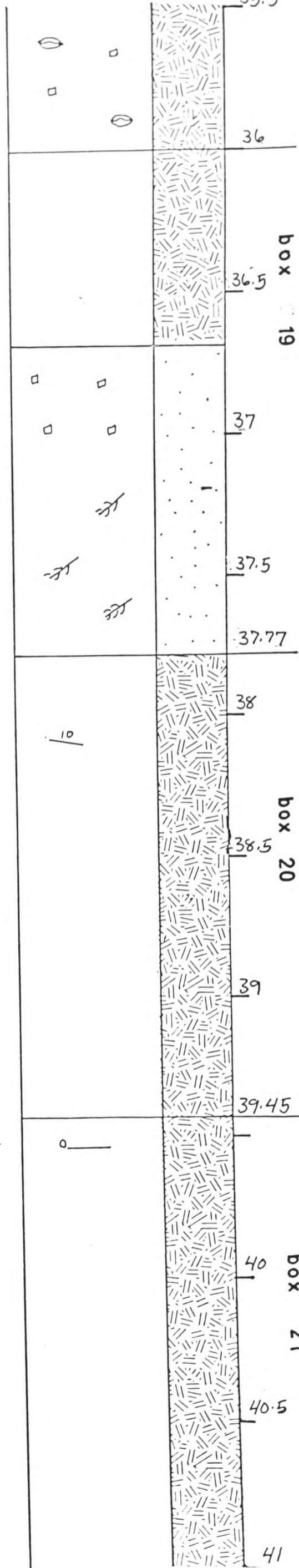
40

box 21

40.5

Blue Vein with patches of reddish stained biomicrite

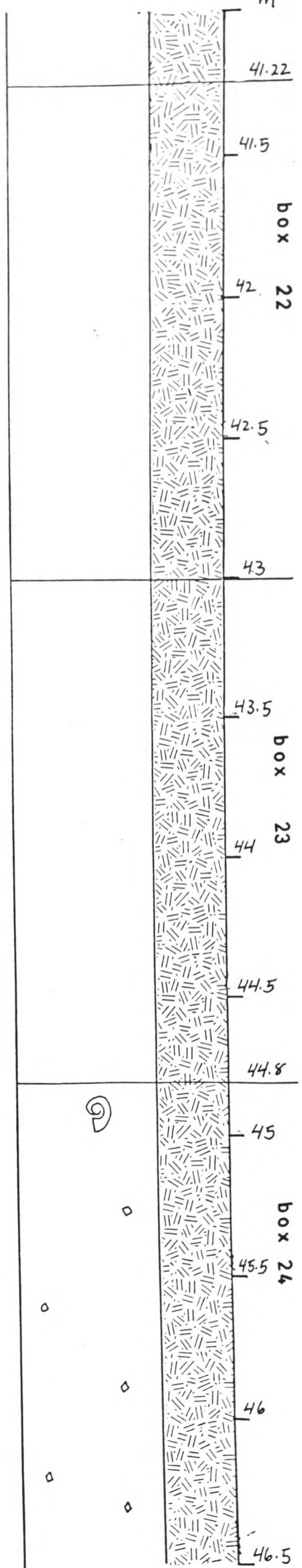
41



Blue Vein with patches of reddish stained biomicrite

cephalopod cross section

Blue Veins with patches of reddish stained micrite and scattered crinoid debris



brachiopod geopetal shows horizontal surface

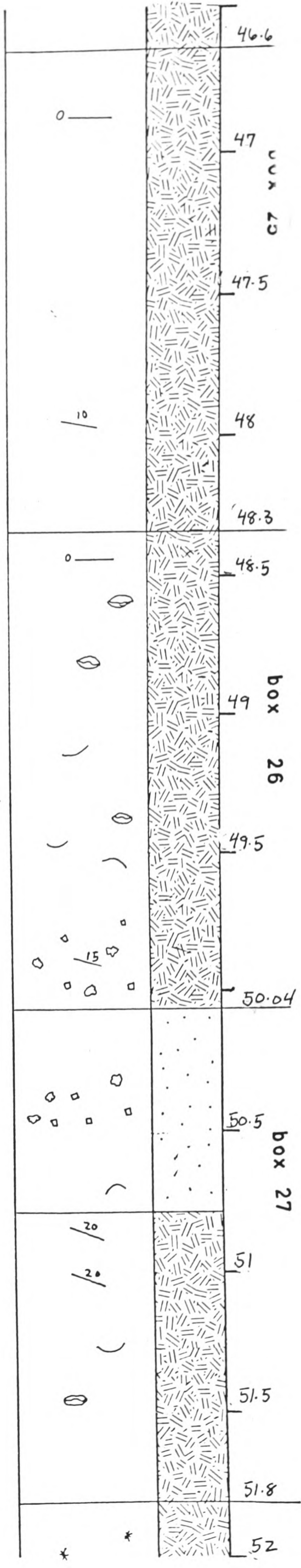
surfaces with dips of 10°

brachiopod geopetal shows horizontal surface

red stain gradually ends; several brachiopods noted

matrix of medium grey biomicrite with some patches of Blue Vein, scattered crinoid debris and small clear spar-filled cavities; surfaces dip 15°

bryozoa surfaces and brachiopod geopetals show a dip of 20°



M

52

box 28

52.5

53

53.54

surfaces dipping 15°

trend towards more bioclasts

? horizontal surfaces

box 29

54

54.5

55

55.3

55.5

box 30

56

56.5

parallel spar veins and brachiopod geopetal show 20° dip

medium light grey biomicrite, occasional bryozoa, some intervals of scattered small crinoid debris and some whole brachiopods, generally small; brachiopod geopetals show 15° dip

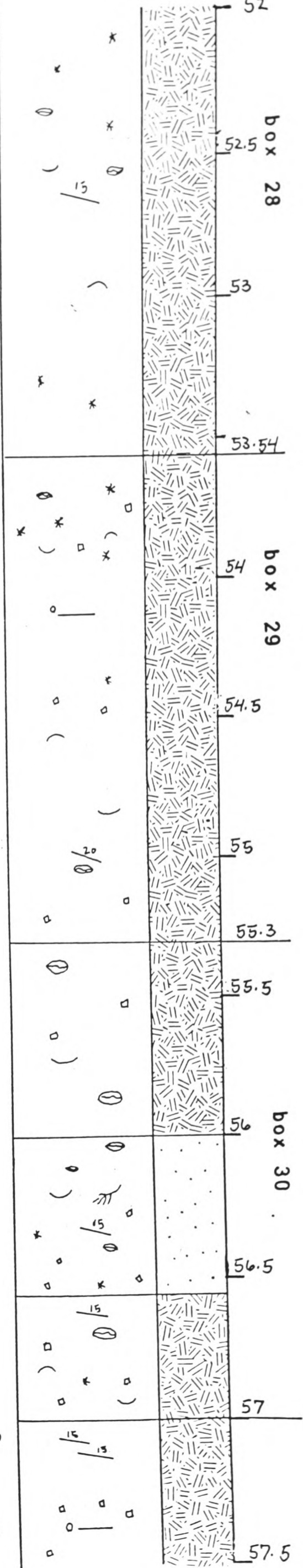
brachiopod geopetal

57

parallel spar veins dip 15°

parallel spar veins show horizontal surface, scattered crinoid debris

57.5



parallel spar veins dip 20°

20°

57.5

box 31

58

58.5

58.79

59

box 32

59.5

laminations in micrite plus spar veins dip 30°



60

medium light grey micrite with bioclasts; some whole brachiopods with geopetals show horizontal surface



60.5

Blue Vein, some dolomitisation

surfaces dip 35°



61

box 33

61.5

62.20

cephalopod



62.5

63

core heavily dolomitised; appears to consist of Blue Vein with brachiopod, crinoid and cephalopod debris

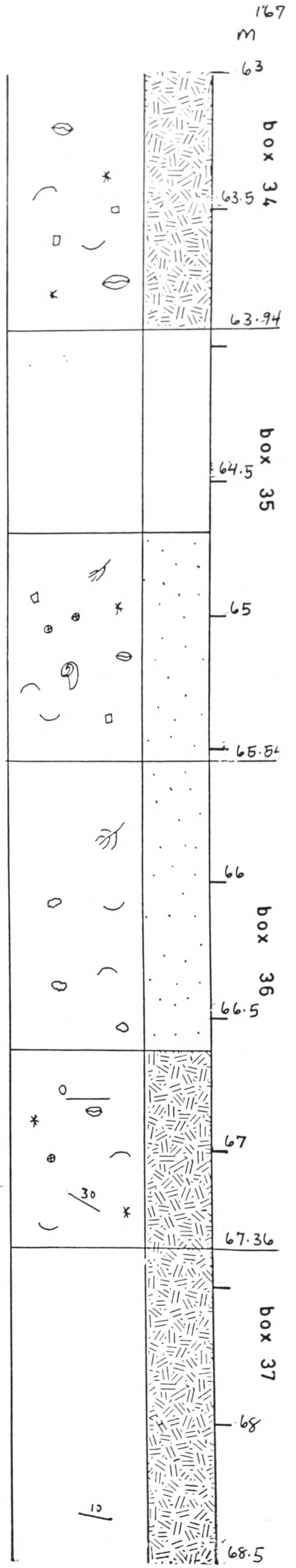
dolomite

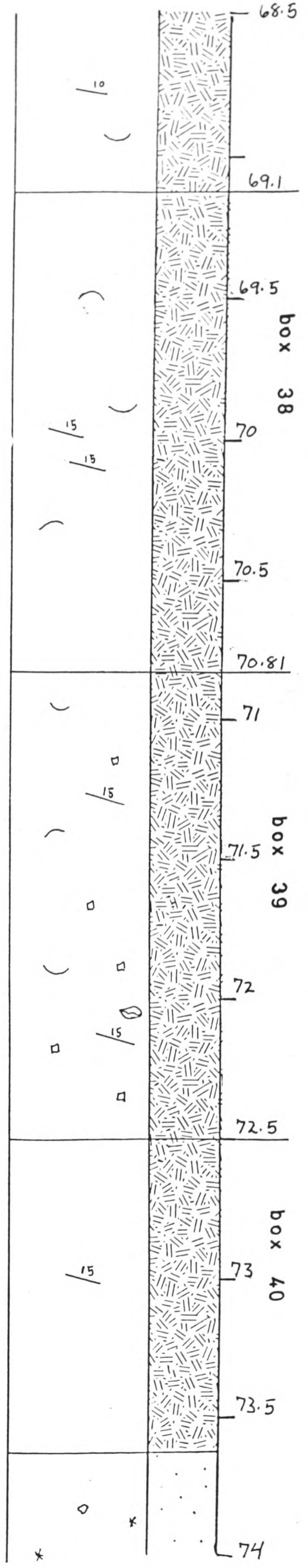
medium grey biomicrite with patchy red staining; some bryozoa, other bioclasts include brachiopod shells, cephalopod fragment and crinoid debris; also several small corals

some small clear spar-filled cavities

Blue Vein, surfaces dip 30° ; bioclasts include a small coral and brachiopods with geopetal dips of 0°

surfaces dip 10°





surfaces dip 15°

dips of 15°

bryozoa and brachiopod geopetal dip 15°

surfaces dip 15°

medium light grey biomicrite, with occasional bio-
clasts and small clear spar-filled cavities

biomicrite with some patches of Blue Vein; little
or no crinoid debris

Blue Vein, lots of bioclasts and crinoid debris

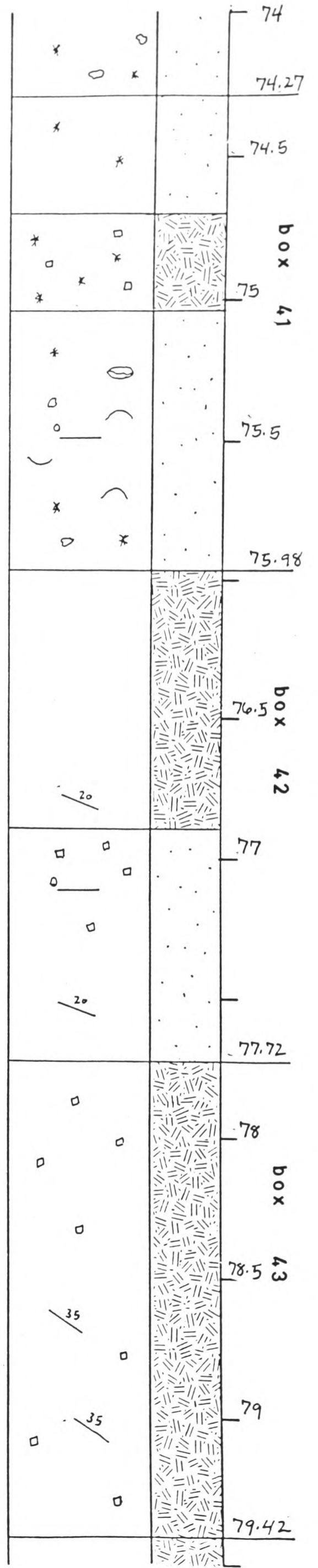
biomicrite with small clear spar-filled cavities;
brachiopod geopetals show horizontal surfaces

Blue Vein, bryozoa dip 20°

two geopetals with 0° dip, scattered crinoid debris

surfaces dip 20°

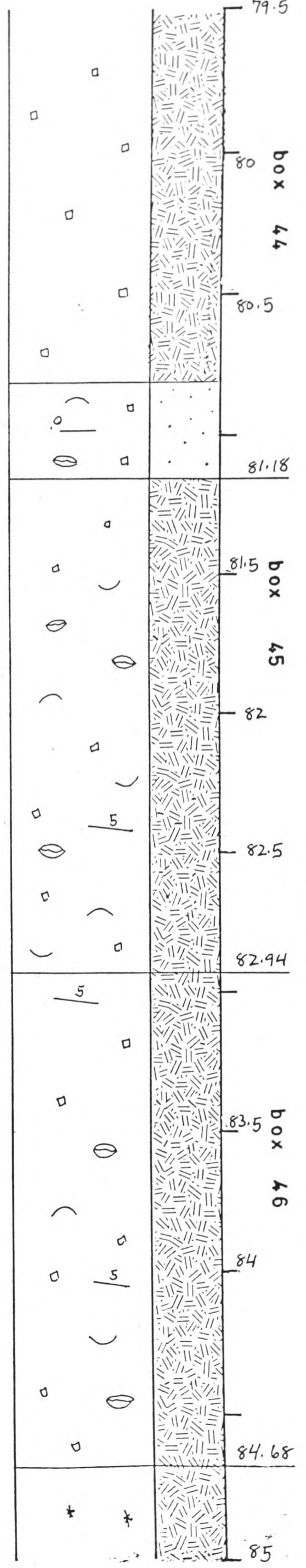
Blue Vein with scattered crinoid ossicles; surfaces
dip 35°



biomicrite with bioclasts, scattered crinoid debris, rare bryozoa; geopetals show horizontal dip

Blue Vein with some whole brachiopods and crinoid debris; surfaces dip 5°

surfaces dip 5°

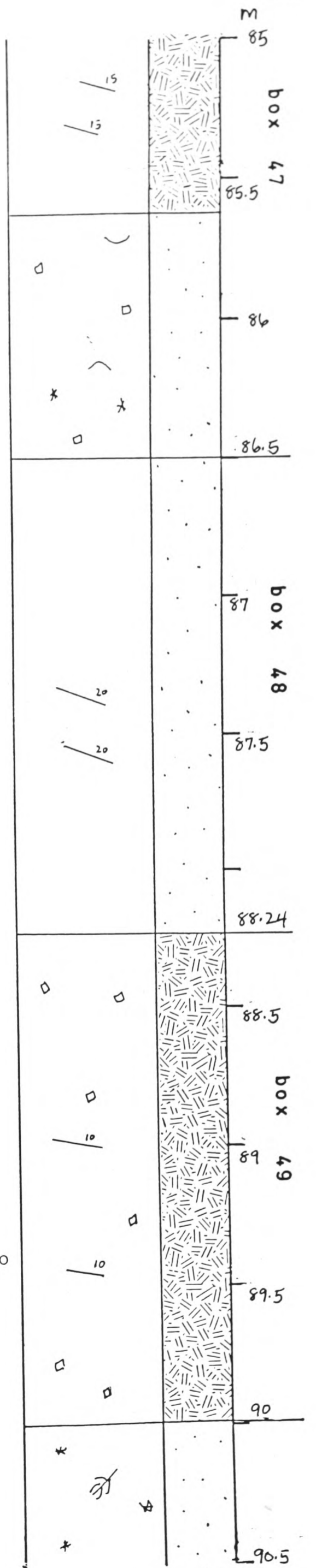


surfaces dip 15°

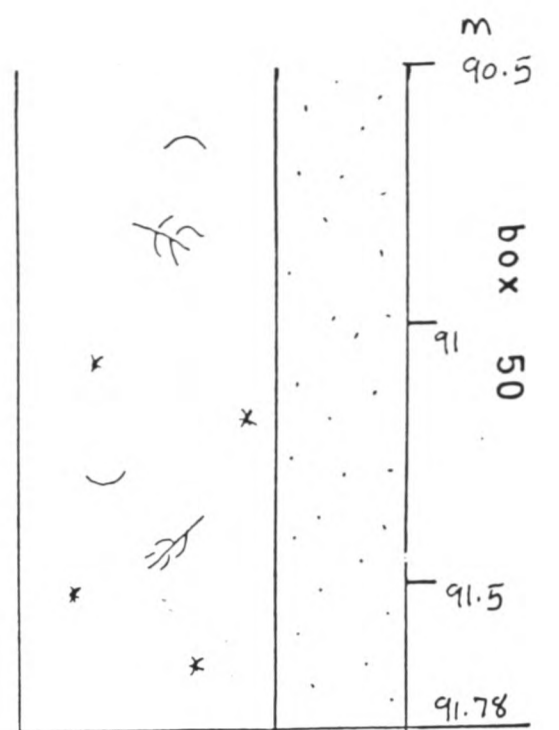
medium grey biomicrite with some patches of Blue Vein and some crinoid debris

surfaces dip 20°; increase in abundance of Blue Vein patches

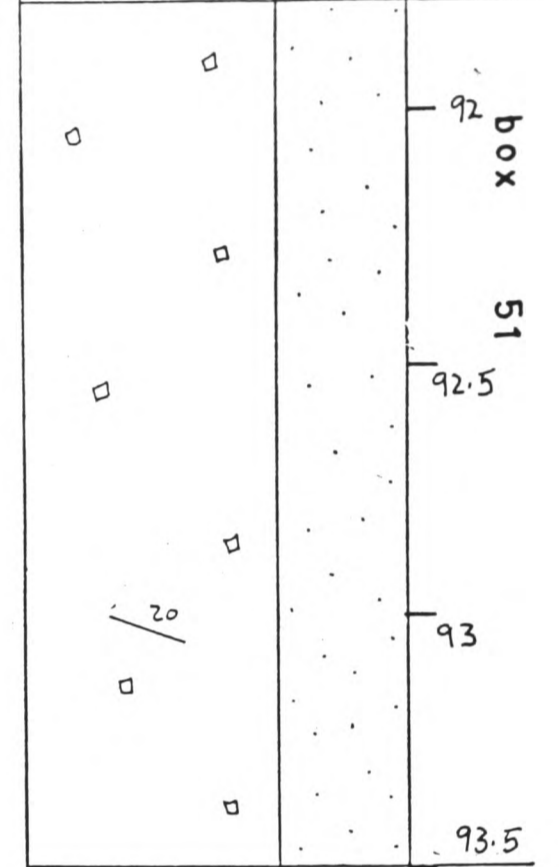
surfaces dip 10°



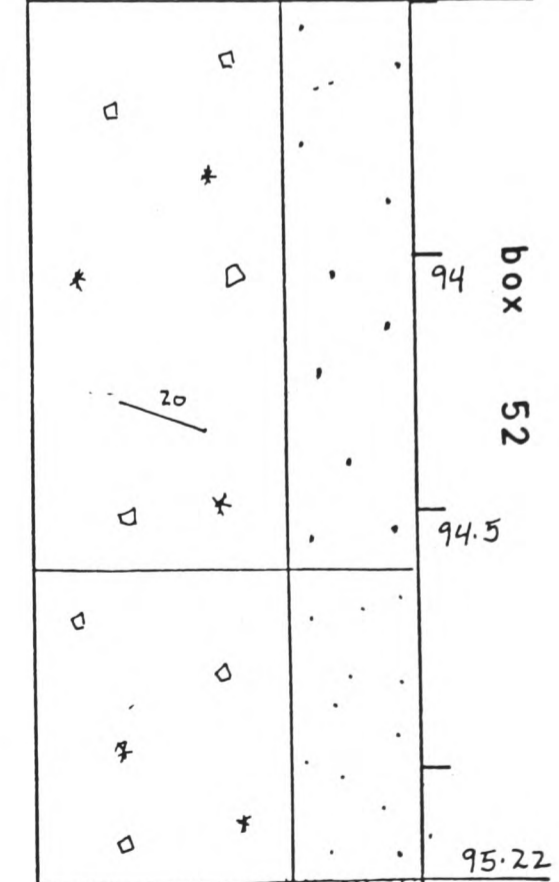
medium grey bioclastic limestone with lots of spar encrusted bryozoa



darker biomicrite - increase in crinoid debris

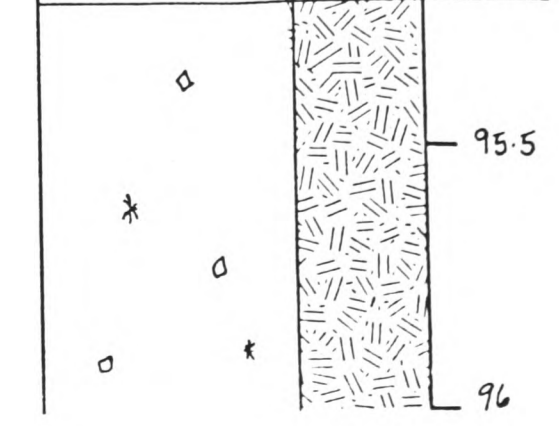


biomicrite with crinoid debris; 'laminations' due to alignment of bioclasts dip 20°



'laminations' due to alignment of bioclasts dip 20°

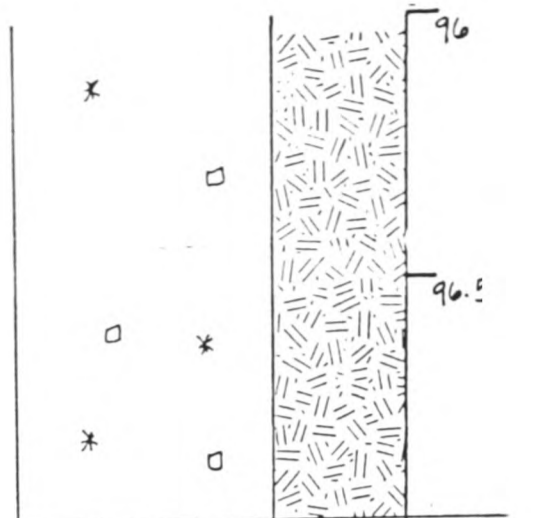
medium grey slightly pelley micrite, small bioclasts and scattered crinoid debris



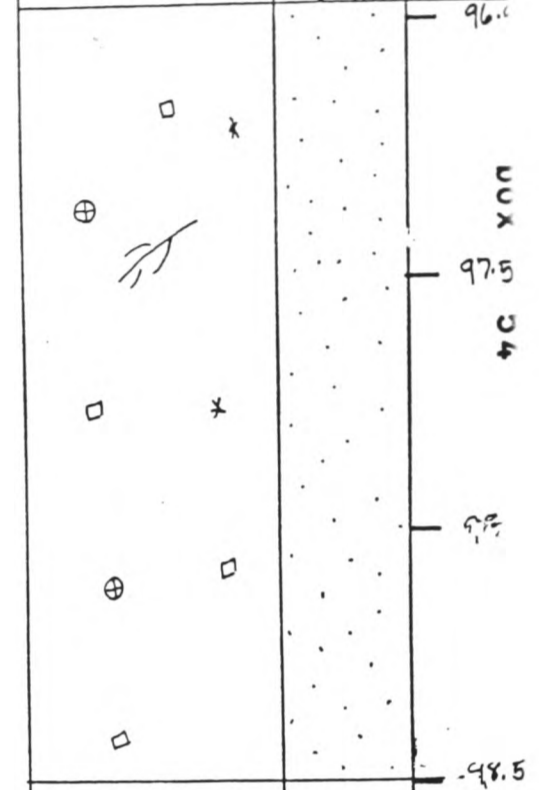
brownish biomicrite with some patches of Blue Vein, some clasts of lighter coloured micrite, some crinoid debris

173
m

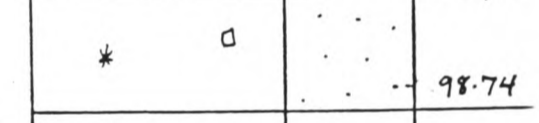
Blue Vein, scattered crinoid debris; some white spar veins



medium grey micrite with spar and some bryozoa

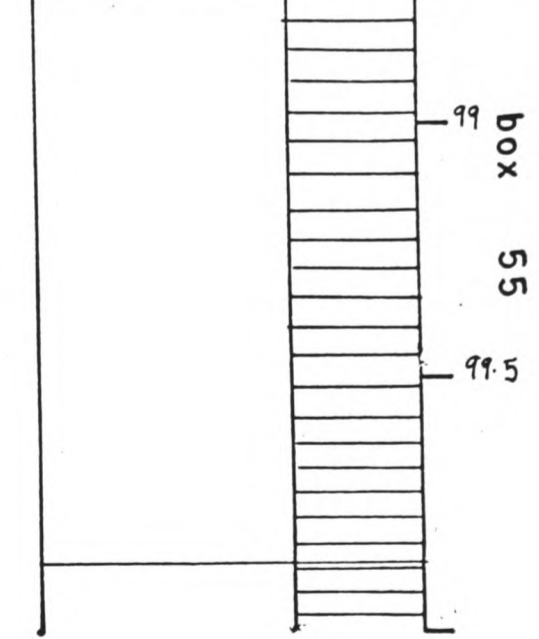


medium dark grey biomicrite with scattered crinoid debris; some intraclasts and a few small corals



abrupt contact

dark lime mudstone



Alstonefield Borehole.

The borehole was drilled at grid reference SK 1371 5563. It reaches a depth of 100 metres. The key is the same as for the Kniveton Borehole.

• The core is the property of the Institute of Geological Sciences.

some small cavities, some brachiopods; whole lino-productid near 0m

at 1m large cavity encircled with laminations
mottled micrite with little or no crinoid debris

core broken into small pieces

mottled micrite, small spar-filled cavities, increase in crinoid debris

5 cm band of laminated pellets and small crinoid debris, grades upwards into cross beds at top; sharp upper boundary with mottled micrite

small (2 cm) clasts of pellets and 'brecciated' micrite (sampled)

pellet layer c. 2 cms

very mottled micrite with numerous small spar-filled cavities, some crinoid debris

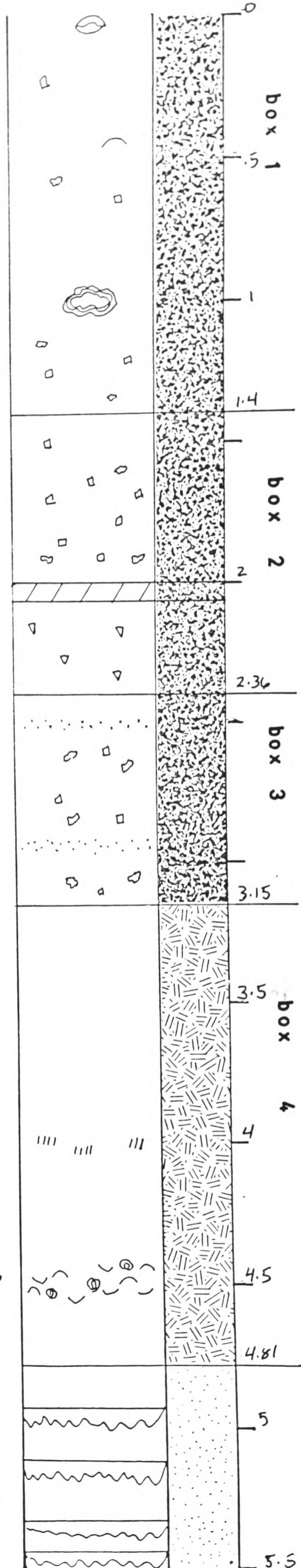
pellet layer c. 2 cms

Blue Vein

thick white small spar patches

9 cm thick very shelly band, mostly brachiopods, some gastropods, ?1 cephalopod; 6 brachiopods concave up, 4 concave down

pinkish grey micrite separated by linear spar to form horizontal surfaces; layers 1 cm or less thick



very mottled micrite (seems to be dark biomicrite and light microspar)

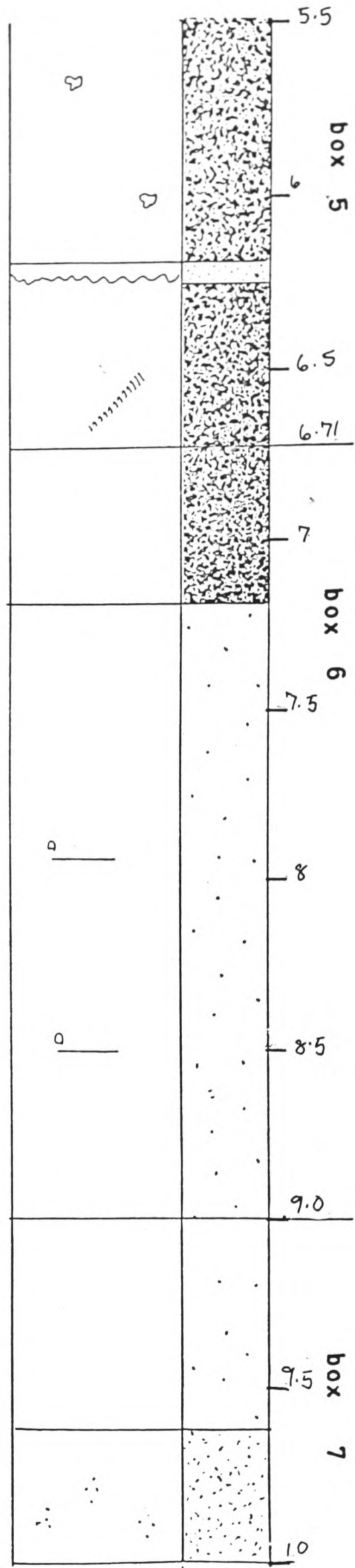
at 6.2m, 2 cm band of linear structures

diagonal spar vein

similar to below, but with more spar

light coloured, less mottled pelletal micrite with small clear spar-filled cavities; some pellets are large and spar is dark; cavity orientations show horizontal surface

some darkening of micrite and appearance of pinkish patches which are not pelletal, some pelletal patches also



mottled, dark grey and pink biomicrite; some dark patches due to pellets with clear spar matrix

mottled grey and pinkish as below
patch of angular crinoid debris

c. 12.20m noticeable scattered bioclasts (sampled)

mottled but with more linearity and more bioclasts;
horizontal surfaces

some cavities surrounded by laminations

semi-horizontal mottling of dark and light grey
biomicrite; small bioclasts

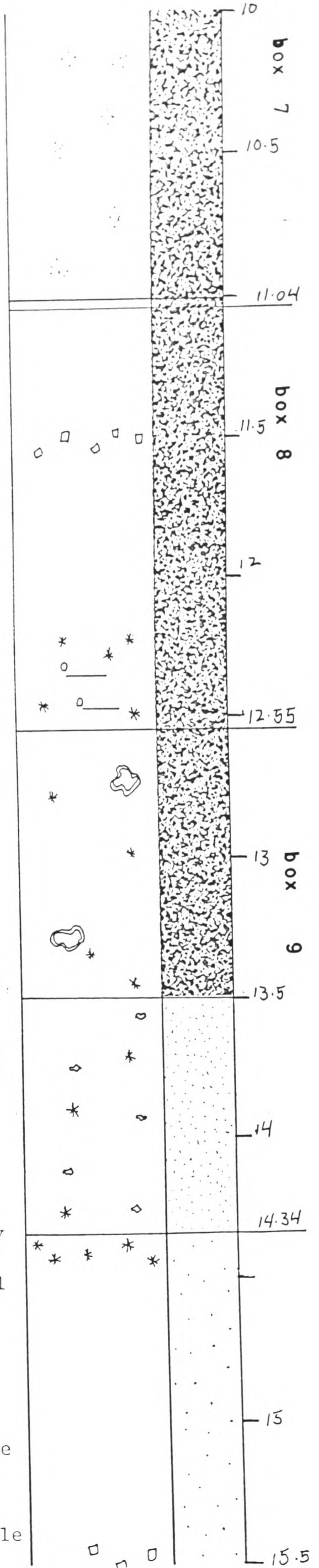
pinkish micrite with small bioclasts and small
clear spar-filled cavities; wisps of darker
grey micrite

'surface' marks boundary

light medium grey micrite with lots of small
bioclasts

gradual increase in pinkish micrite and more
mottling developed

c. 15.5 relatively unmottled patch with noticeable
crinoid debris (c. 20 cms)



178

m

15.5

16

16.45

17 box 11

17.5

18

18.5

19 19.10

19.5 box 12

20

20.5

21

medium light grey pelletal and small bioclastic micrite; core broken therefore contact is not seen

medium light grey pelley micrite

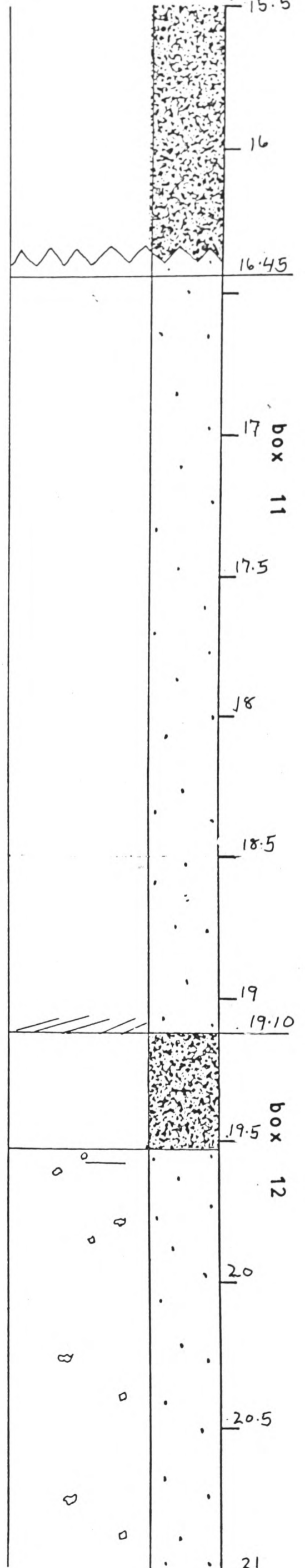
very low angle cross beds

darkish grey non-pelleted mottled micrite with rusty patches

darker colour and rust more pronounced

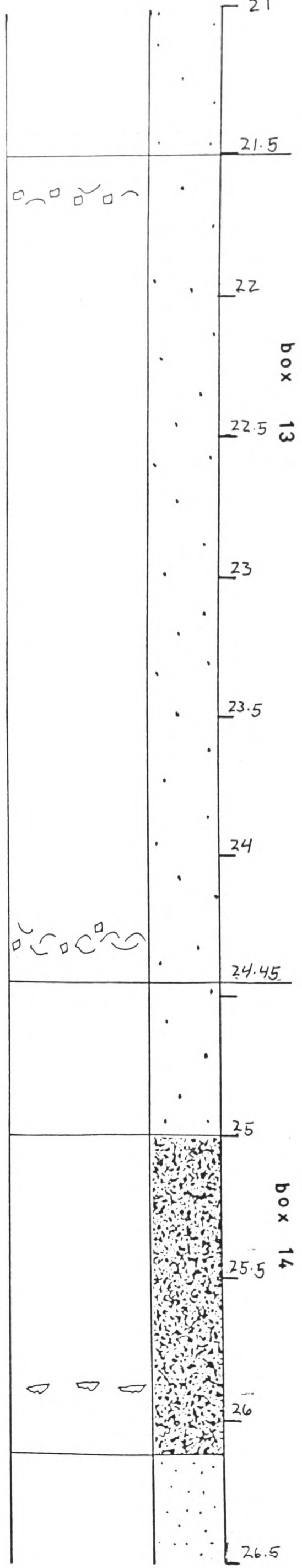
dark limestone with rust mottling (sampled)

medium light grey very pelley micrite, some small spar-filled cavities, some visible bioclasts (mostly crinoid); not obviously laminated except at 19.5m which shows horizontal surfaces



179
m

shelly band (c. 3 cms) crinoid, brachiopods and ostracodes



21

21.5

22

22.5

23

23.5

24

24.45

25

25.5

26

26.5

box 13

box 14

pellety light grey biomicrite with some bands of more concentrated bioclasts as shown

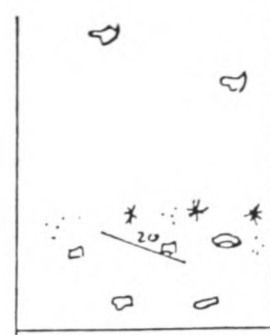
shelly band with lots of brachiopods (6 concave up, 4 concave down)

darker grey limestone, very mottled with white microspar. Fe stains extensive in parts; some dolomite

small stromatactis-like cavities

lessening of alteration, mottling ends abruptly, but without sharp surface; light grey biomicrite with small cavities

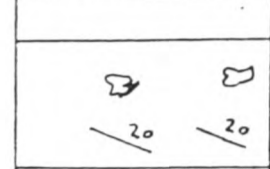
7 cm thick band of visible bioclasts and pellets; noticeable whole brachiopods, crinoid debris and ostracodes, topped by several rows of small spar cavities defining surface dipping 20°



27.07

Fe stained with small cavities

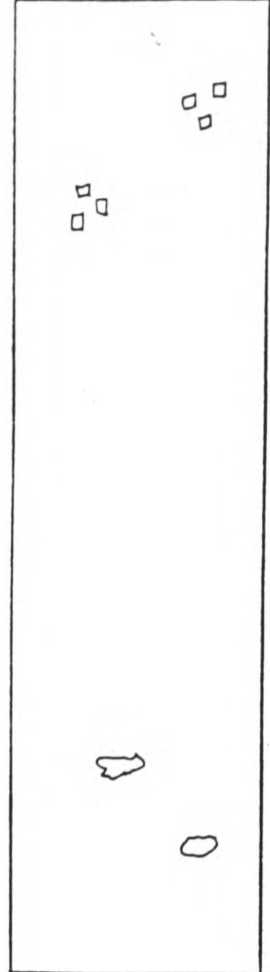
2.5 cm laminated pellets; light medium grey pelley limestone with small cavities



27.5

occasional pods of crinoid debris

light medium grey micrite with occasional mottling

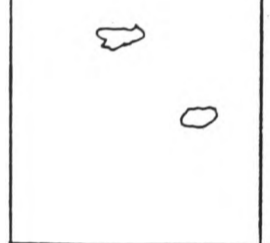


box 15

28

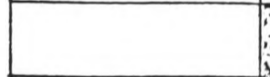
28.5

heavily altered; some unfilled cavities



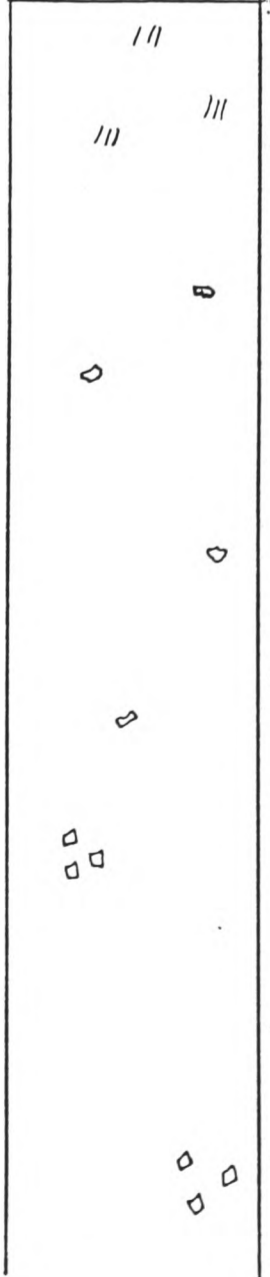
29

light grey mottled microspar



29.5

mostly heavily altered, but seems to be dark grey limestone with white sparry streaks



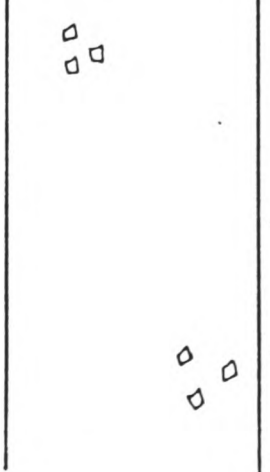
30

box 16

30.5

31

medium grey biomicrite, small spar cavities, some crinoid debris in patches

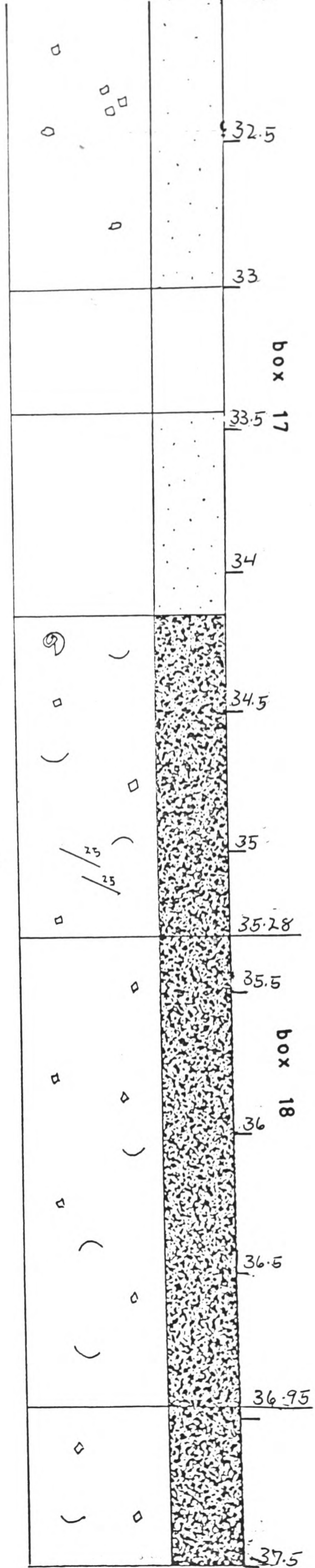


31.5

32

181

m
32



core very broken

heavily altered

light and medium grey mottled limestone with elongate spar cavities, some bioclastic debris mostly crinoidal, some brachiopods and an ? orthocone

spar layers suggest surfaces dipping 25-30°

similar to above

medium grey pellets in clear spar matrix; a few small bioclasts

4 cm clast of non-pellety biomicrite

medium and light grey micrite and microspar; some small spar cavities, some mottling

medium grey micrite, some bioclastic debris including whole brachiopods and some fenestellids

disturbed looking non-pelletal micrite and microspar (breccia-like) some small bioclasts (sampled)

pellety micrite; near 40m vaguely laminated and more bioclastic; dips of 25°

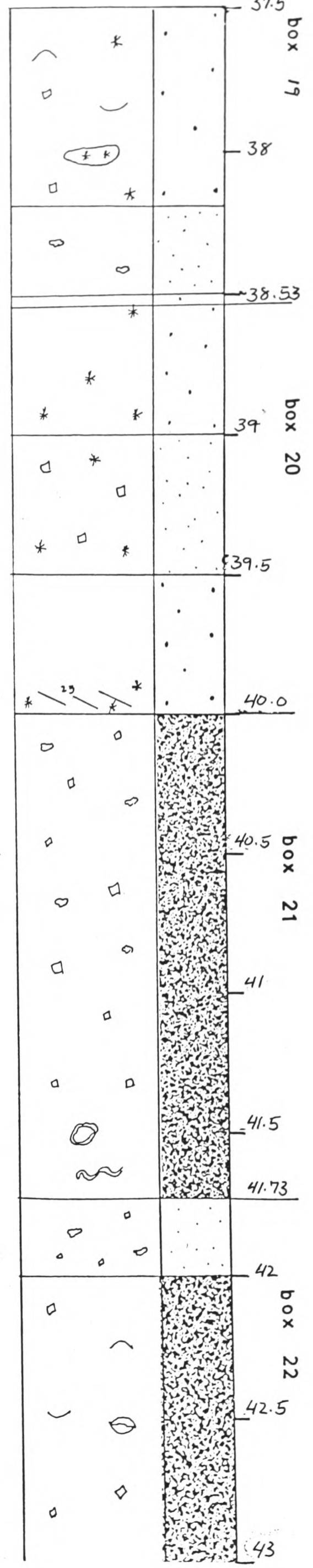
light grey with pinkish grey mottles, small clear spar-filled cavities, some crinoid debris (some large)

gradually grades into dark and medium grey more mottled lst.; some crinoid debris

wrap around laminations

light grey micrite with spar cavities; some crinoid debris

darker micrite mixed with lighter micrite; bioclasts include crinoid, whole brachiopods and brachiopod fragments



light grey micrite with clear sparry elongate cavities (thin) probably horizontal dips; bioclasts include crinoid debris, but at least one whole small productid

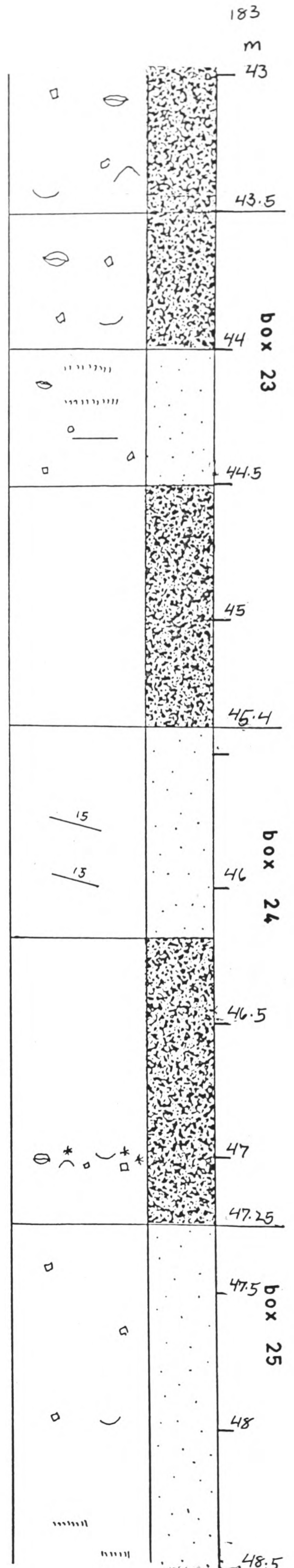
grades into mottled dark and light micrite

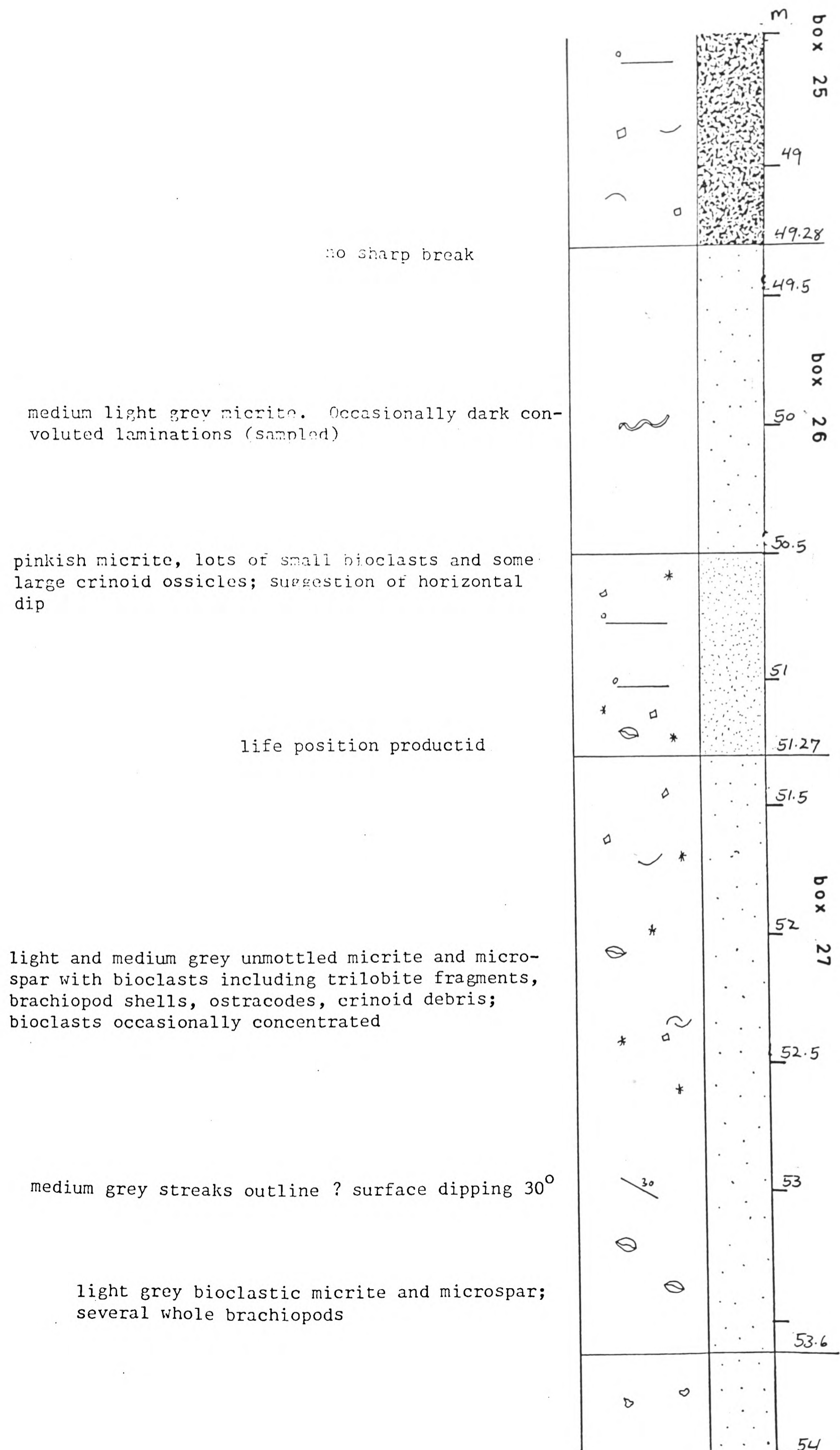
light grey micrite with clear sparry elongate cavities; dip of 15°

somewhat more mottled limestone with more dark micrite

10 cm bioclastic interval, crinoid ossicles, brachiopod valves and whole brachiopods

mottled dark and medium grey limestone, semi-layered (? horizontal dip) with some 10-15 cm intervals of light grey micrite with elongate clear spar cavities; small amounts of crinoid debris some brachiopod valves, some small whole productids





box 25

box 26

box 27

49

49.28

49.5

50

50.5

51

51.27

51.5

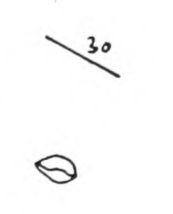
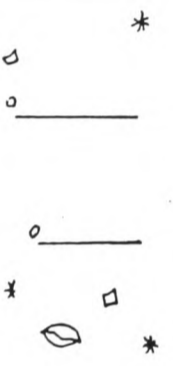
52

52.5

53

53.6

54



light grey micrite and microspar with bioclasts, more small cavities than below

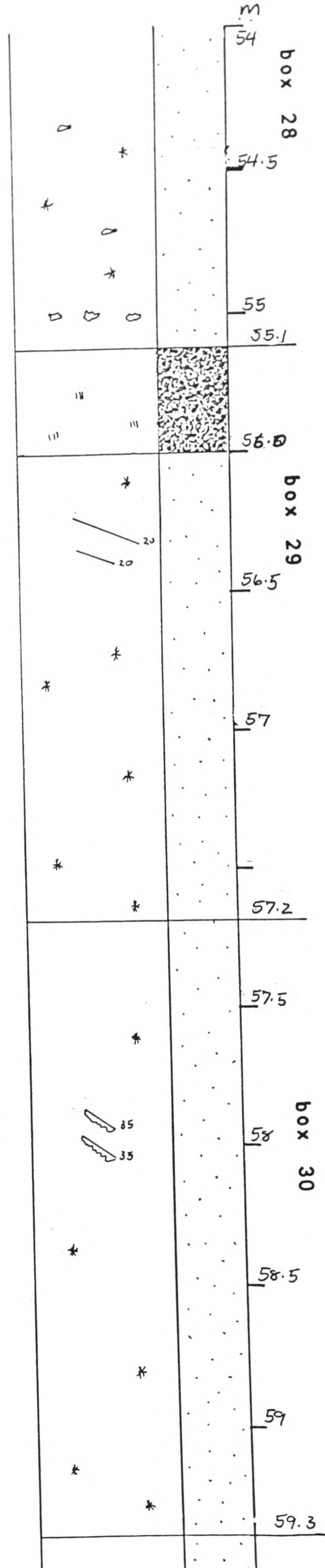
line of small cavities, but dip hard to determine

mottled light and medium grey micrite and microspar, some spar patches

development of sparry streaks along ? surfaces in light grey biomicrite: dips of 20°

biomicrite with lessening of spar along surfaces

some good examples of spar structures near surfaces dipping 35°



m

light medium grey micrite and microspar with numerous small clear spar-filled cavities; bioclasts

development of darker grey streaks along cavities which outline surfaces which dip 35°; fenestrates

59.5

box 31



60



60.5

61.09

Blue Vein

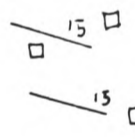
box 32

61.5

62

medium grey and pinkish micrite, some small cavities and pelley patches

Blue Vein with some crinoid debris, especially near 62.7m; dip of surfaces is 15°



62.5

62.7

geopetal in brachiopods with dip of 8°



63

Blue Vein

box 33

63.5

64

Pinkish grey micrite with darker streaks; small clear spar cavities; bioclastic



64.45

Blue Vein with occasional patches of medium grey biomicrite. Surfaces dip 10-15°; some crinoid debris and small spar-filled cavities in the biomicrite



65

187
m

65

box 34



65.5

66

66.17

Blue Vein, but with intervals of medium grey non-mottled micrite which contains small clear spar-filled cavities. Some crinoid debris

medium grey non-mottled micrite, occasional darker grey streaks with spar; cephalopod in a gastropod shows horizontal surface

parallel laminated thin layers of microspar 0° dip; sharp lower contact, less sharp at top

medium grey with darker grey mottled biomicrite, some intervals of crinoid debris

stringers of small white spar cavities

medium grey micrite with microspar

cephalopod

increase in spar veins and crinoid debris

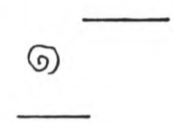
parallel laminated pelley limestone topped by spar cavities

medium grey micrite with small spar-filled cavities, some fenestellids

66.5

box 35

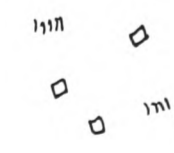
67



67.5

67.80

68.5 box 36



69.65

box 37

70



70.5

increase in spar cavities and crinoid debris (poorly sorted); other bioclasts include whole brachiopods

large spar-filled cavity

decrease in crinoid debris; some pink staining

more bioclasts and crinoid debris; geopetal in gastropod shows 10° dip

sharp contact

medium grey micrite with thin laminations of white spar dips of 25°

laminations gradually die out

light medium grey bioclastic limestone; near 72.4m is a dense concentration of ? spines and other bioclasts

limestone broken and infilled with red (? Triassic) sandstone

infills of sandstone into medium grey slightly mottled bioclastic micrite some small spar cavities; some whole brachiopods

parallel laminated ? pelley micrite, bottom sharp, top gradational

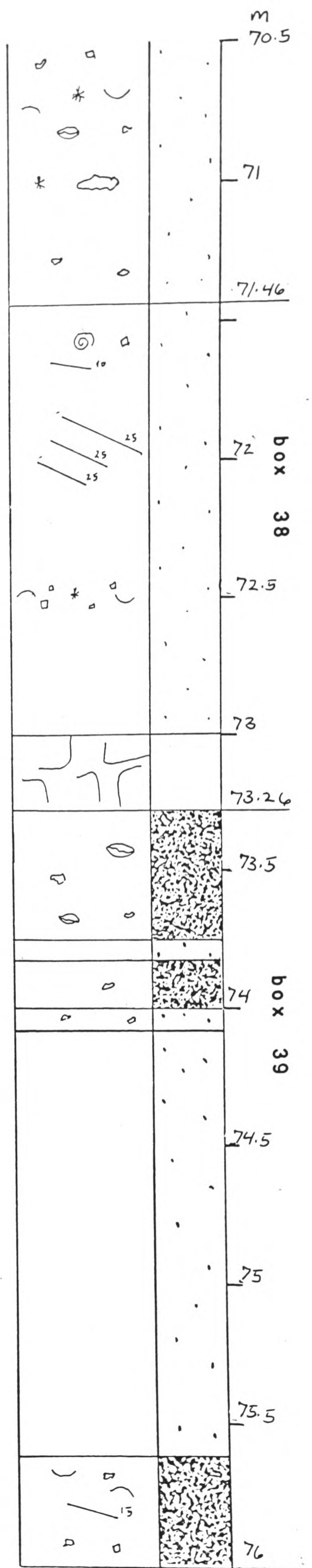
medium grey to light pinkish grey limestone with small spar cavities

clear spar vein with limestone clasts

1 cm pelley limestone

medium grey featureless pelley limestone

medium light grey mottled micrite and microspar, small spar veins and cavities and some bioclasts (brachiopod shells and crinoid debris); surfaces dip 15°



m

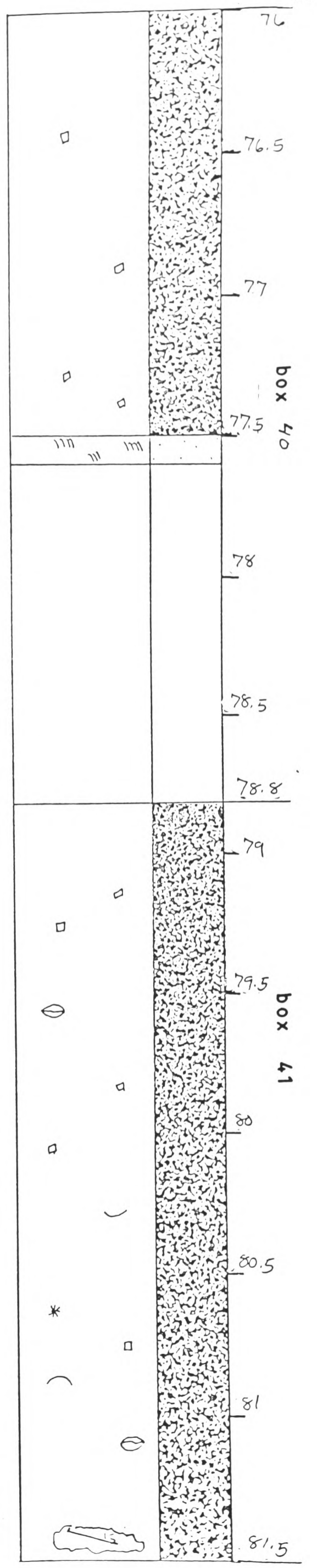
core somewhat broken, mainly brownish grey mottled micrite with some crinoid debris

some large white spar patches in unmottled micrite

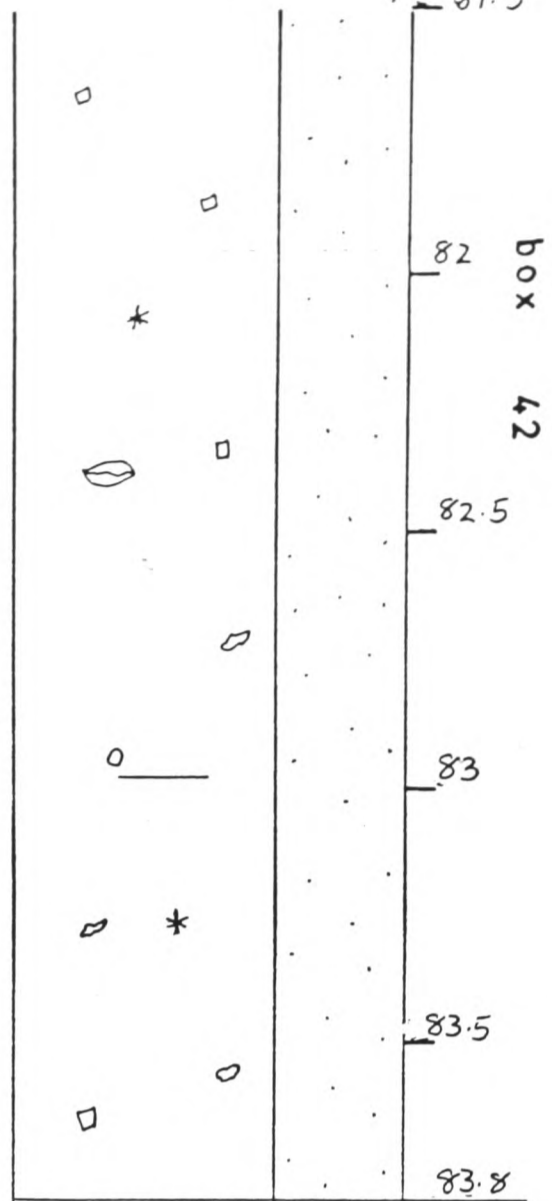
core very broken

medium grey slightly mottled micrite with varying amounts of crinoid debris; bioclasts throughout, several whole brachiopods

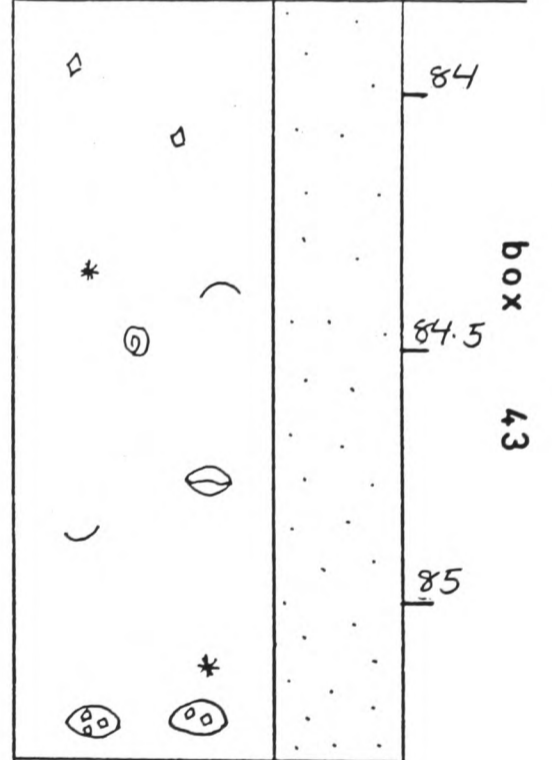
cavity with internal sediments dipping 15°



medium grey micrite with small spar cavities and bioclasts; some crinoid debris, geopetals in whole brachiopods show 0° dip

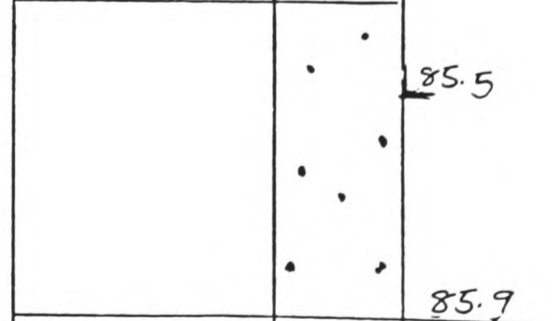


medium grey micrite, very bioclastic in places some darker streaks; bioclasts include brachiopods, crinoid debris and trilobite and gastropod fragments



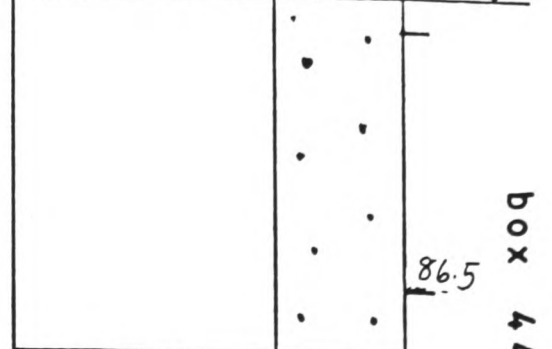
gradual lessening of bioclasts clasts of crinoidal coarse limestone (? breccia); some clasts are pelley; grades up into smooth micrite

medium grey pelley micrite - variable packing of the pellets and some small spar cavities

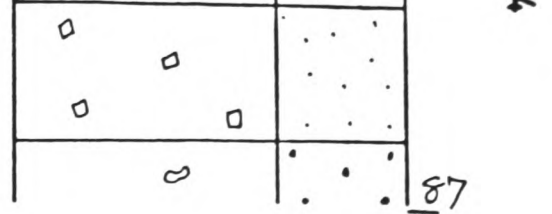


'pseudo-lamination' due to microspar core broken

pelley micrite with 5 cm interval of red sandstone (? Triassic)



bioclastic micrite and microspar, crinoid debris



medium grey pelley micrite, occasional crinoid debris and spar-filled cavities

non-pelley micrite clasts

medium grey pelley micrite with more bioclasts, somewhat mottled appearance

light medium grey pelley micrite, with mixtures of pellets of different sizes and packings which gives a mottled appearance; vague surfaces dip 15°

increase in crinoid debris

unusual sequence; interval of loose packed but crinoidal pellets, 4 cm laminated pelleted limestone - bottom contact unclear, top contact gradual and dips 5°; topped by 2 cm spotted limestone (small gastropods); then 2 cm pelley limestone with pink angular clasts; then 1 cm parallel laminations which dip 10°

pelley limestone

loose packed pelley limestone with small spar cavities, some bioclasts, mainly brachiopod shells and some crinoid debris

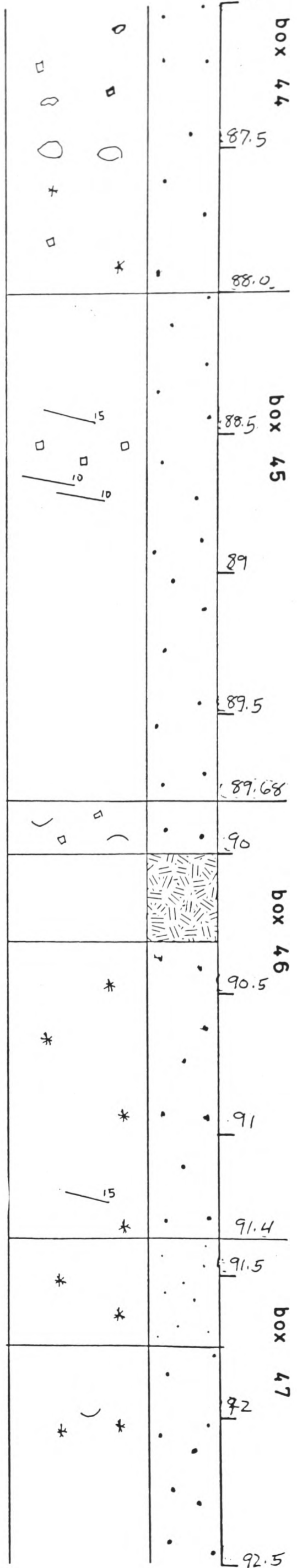
Blue Vein with sediment-filled cavity (or clast) at c. 90.1m

pelley limestone, light medium grey with some bioclasts and patches of Blue Vein

pelley limestone, more bioclastic than above and laminations which dip at 15°

gradual change from bioclastic medium grey micrite to pelley medium grey micrite

several bioclastic intervals less than 10 cms thick



1972
m

medium grey pelley micrite; some graded areas,
but in other places grain size distribution is
patchy

medium light grey pelley limestone, some bio-
clasts, occasional concentrations of crinoid
debris

brachiopod geopetal and surfaces dip at 30°

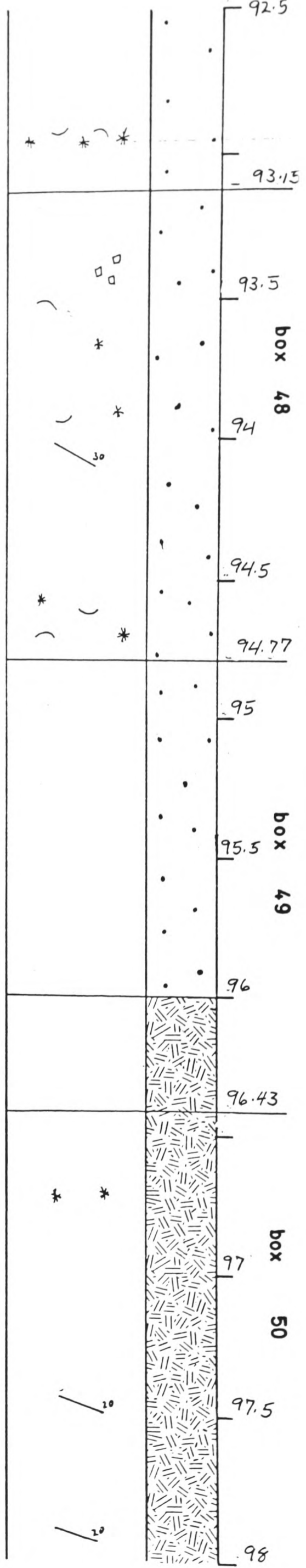
pelley but not very bioclastic, streaks of
microspar

bioclasts in pelley micrite

medium grey not very bioclastic pelley micrite,
occasionally mottled with darker material

Blue Vein

Blue Vein with intervals of bioclastic micrite/
microspar, some spar cavities; surfaces dip 20°



198

m

98

98.23

98.5

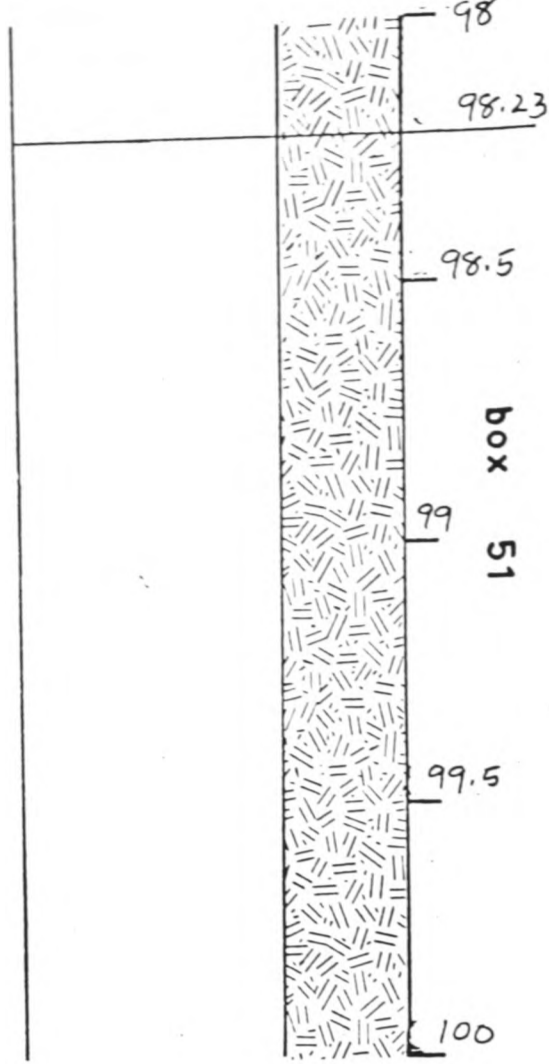
box 51

99

99.5

100

Blue Vein



APPENDIX 2

LOCALITY DETAILS

English Localities

(Localities are listed and grid references given. Types of collections made at each locality are indicated by an "X")

All material collected for this study was housed in the Palaeontology Dept., Institute of Geological Sciences, Leeds.

Locality	Grid reference	Faunal collections made	Thin sections examined and point counted	Peels examined	Sampled for conodonts
Dovedale					
319	SK 1405 5397		X		
320	SK 1406 5396		X		
321	SK 1407 5395		X		
322	SK 1408 5394		X		
324	SK 1409 5393		X		
325	SK 1410 5392		X		
326	SK 1411 5391		X		
327	SK 1412 5390		X		
328	SK 1413 5389		X		
329	SK 1414 5387		X		
330	SK 1415 5386		X		
331	SK 1415 5384		X		
Manifold Valley					
424	SK 0989 5589		X		
426	SK 0999 5653		X		
427	SK 0999 5635		X		
428	SK 0998 5636		X		
429	SK 0998 5636		X		
430	SK 0997 5637		X		
431	SK 0997 5637		X		
432	SK 0996 5638		X		
433	SK 0995 5638		X		
434	SK 0994 5639		X		

Locality	Grid reference	Faunal collections made	Thin sections examined and point counted	Peels examined	Sampled for conodonts
Manifold Valley (cont.)					
435	SK 0993 5639		X		
436	SK 0992 5640		X		
437	SK 0992 5640		X		
438	SK 0992 5640		X		
439	SK 0991 5641		X		
440	SK 0991 5641		X		
441	SK 0990 5642		X		
442	SK 0990 5642		X		
443	SK 0990 5642		X		
444	SK 0989 5643		X		
445	SK 0989 5643		X		
446	SK 0988 5644		X		
447	SK 0988 5644		X		
449	SK 1007 5633		X		
451	SK 1009 5630		X		
452	SK 1012 5627		X		
453	SK 1016 5625		X		
455	SK 1018 5623		X		
456	SK 1022 5620		X		
458	SK 1027 5618		X		
459	SK 1030 5614		X		
460	SK 1034 5612		X		
461	SK 1039 5608		X		

Locality	Grid reference	Faunal collections made	Thin sections examined and point counted	Peels examined	Sampled for conodonts
Manifold Valley (cont.)					
487	SK 0977 5678	X	X	X	
488	SK 0976 5708	X	X	X	
490	SK 1024 5710	X	X	X	
491	SK 1010 5721	X	X	X	
492	SK 1010 5681	X	X	X	
493	SK 1079 5657	X	X	X	
494	SK 1058 5623	X	X	X	
495	SK 1079 5604	X	X	X	
496	SK 1002 5663	X			
497	SK 1057 5648	X	X	X	
499	SK 1009 5625	X	X		
500	SK 0988 5647	X	X	X	
501	SK 0967 5623	X		X	
502	SK 0976 5586	X	X		
503	SK 1136 5611	X	X	X	
504	SK 0965 5613	X	X	X	
505	SK 1098 5587	X	X	X	
507	SK 1065 5405			X	
508	SK 1139 5654	X	X	X	
509	SK 1138 5616	X		X	
510	SK 116 517			X	
511	SK 117 572		X	X	X
518	SK 1059 5402	X			

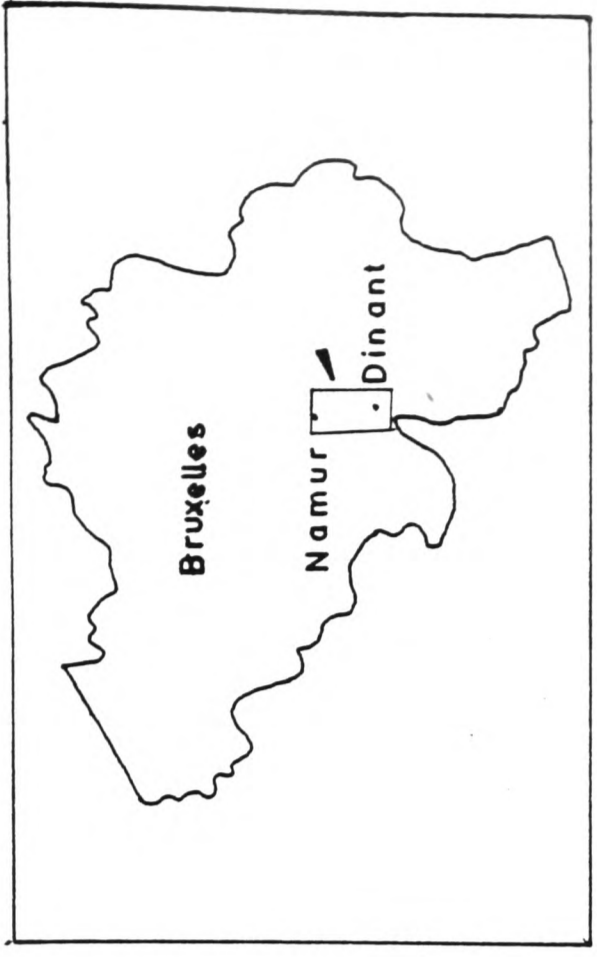
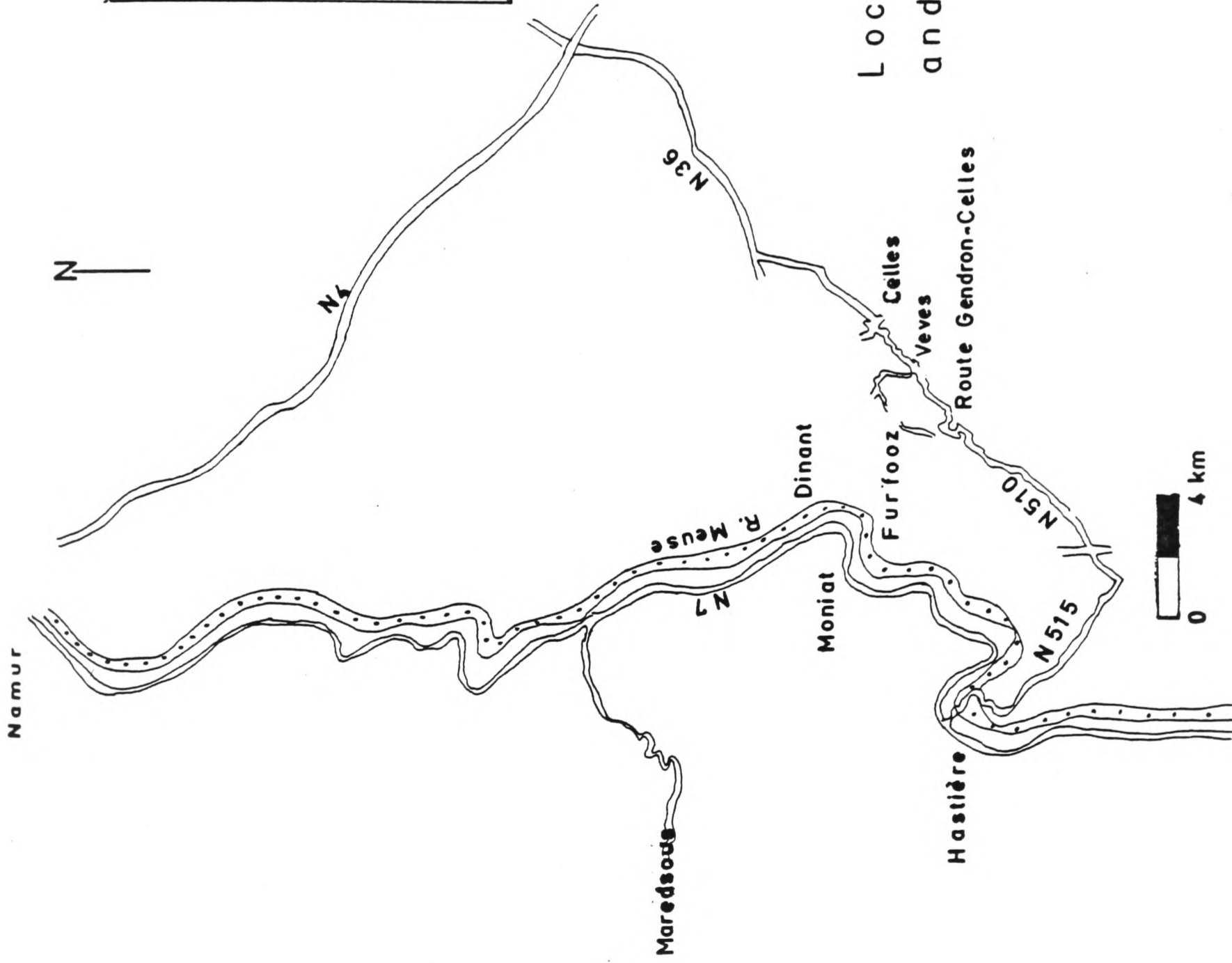
Locality	Grid reference	Faunal collections made	Thin sections examined and point counted	Peels examined	Sampled for conodonts
Manifold Valley (cont.)					
519	SK 1057 5408	X			
520	SK 1535 5100	X			
521	SK 0983 5612	X			
522	SK 1008 5529	X			
523	SK 1090 5653	X			
77	SK 1006 5637				X
121	SK 1082 5683				X
Gateham	SK 116 571				X
Alstonefield Borehole	SK 1371 5563				
3.65m			X		
5.38m			X		
12.20m			X		
19.16m			X		
19.54m			X		
37.45m			X		
49.22m			X		
59.36m			X		
88.73m			X		
88.77m			X		
88.83m			X		

Belgian Localities

(Localities are listed and referred to their original sources. Locality maps accompany the lists. Types of collections made at each locality are indicated by an "X")

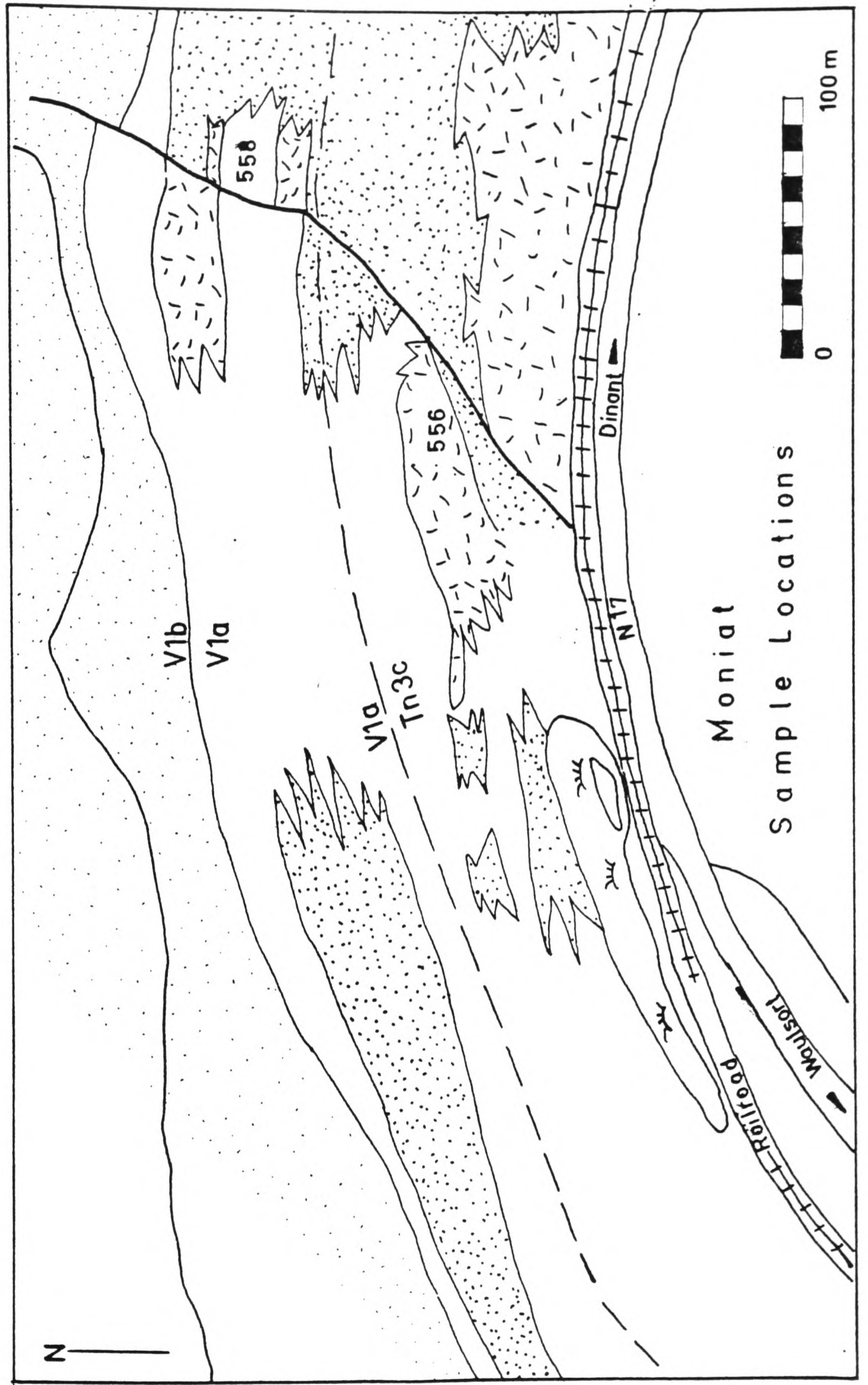
Locality	Faunal collections made	Thin sections examined and point counted
550 (includes the following Bouw (1971) localities):	X	
Aff. 18		X
551 (includes the following Bouw (1971) localities):	X	
Aff. 11 sta.124		X
" sta.123		X
" sta.122		X
" sta.121		X
" sta.120		X
" sta.119		X
552 (includes the following Bouw (1971) localities):	X	
Aff. 28-3 sta.331		X
" sta.332		X
" sta.333		X
553 (includes the following Bouw (1971) localities):	X	
Aff. 27-3 sta.310		X
" sta.311		X
" sta.312		X
" sta.313		X
" sta.314		X
" sta.315		X
" sta.316		X

Locality	Faunal collections	Thin sections examined and point counted
554 (includes the following Bouw (1971) localities):	X	
Aff. 20E sta.186		X
" sta.187		X
" sta.188		X
" sta.189		X
" sta.190		X
556 (includes the following Noel (1973) localities):	X	
Coupe D sta.39		X
" sta.41		X
" sta.43		X
" sta.45		X
557 (includes the following Bouw (1971) localities):	X	
Aff. 20W sta.212		X
" sta.213		X
" sta.214		X
" sta.216		X
" sta.218		X
" sta.219		X
" sta.220		X
" sta.221		X
558 (includes the following Noel (1973) localities):	X	
Coupe D sta.15		X
" sta.17		X
" sta.19		X



Location of Moniat
and Furfooz Sections

-  Waulsortian Dolomite
-  Waulsortian Biomicrite
-  Waulsortian Blue Vein
-  V1b limestones



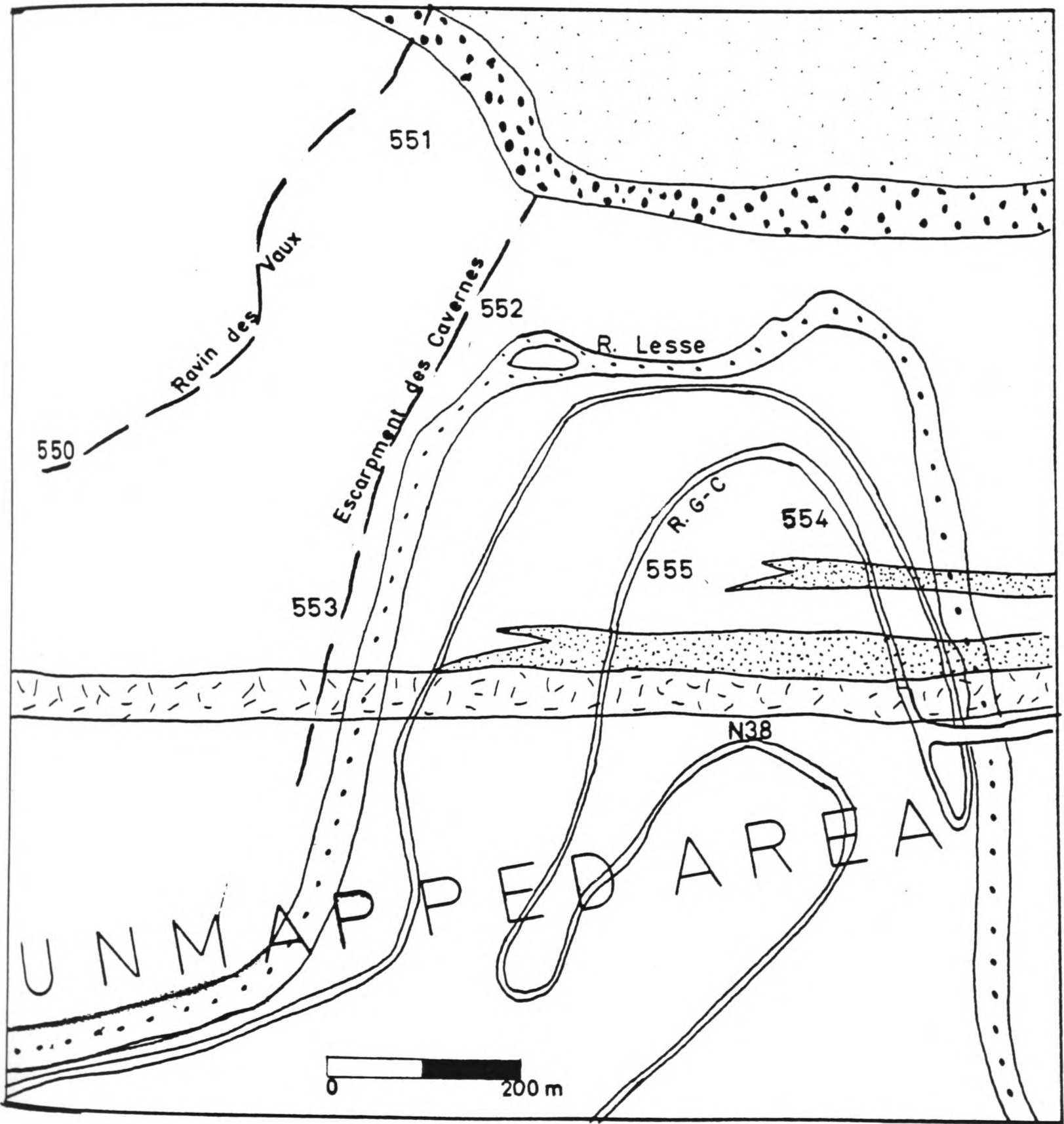
□ Waulsortian

▣ V1b black limestones

▣ Bayard faciés

▣ Leffe faciés

▣ Calcshistes de Maredsous



Furfooz Localities

APPENDIX 3

RAREFACTION AND DOCUMENTATION OF COMPUTER PROGRAMS

APPENDIX 3 RAREFACTION AND DOCUMENTATION OF COMPUTER PROGRAMS

A3.1 Rarefaction theory

There are many problems associated in sampling groups of organisms. If a sample of a group contains several thousand specimens, the number of species in the resulting faunal lists will almost certainly be larger than if the sample contained only tens or a few hundreds of specimens. Thus apparent relative changes in species numbers may be an artifact of the numbers sampled. This problem can only be avoided when sample sizes are consistently large enough to contain all species present. However, this is often an impossibility in many biological and palaeontological sampling situations.

Sanders (1968) developed the technique of rarefaction to help deal with this problem. Rarefaction is basically an interpolation method which makes it possible to estimate how many species would have been found had the sample been smaller than it actually was. This allows comparison of relative diversities of samples of different sizes and also makes it possible to determine roughly how complete a representation of the species present has been found. The technique was developed for use at the species level, but it can also be applied at higher taxonomic levels so long as the same taxonomic level is used throughout (Raup, 1975).

Rarefaction is derived from an analysis of relative frequencies of specimens of each species found. The formula for the calculation of rarefaction coefficients is :

$$E(S_n) = \sum_{i=1}^s \left(\frac{N - N_i/n}{N/n} \right) \quad \text{where } E(S_n) \text{ is the estimated}$$

number of species for a given number of specimens (n). S is the number of species in the original sample and N_i is the number of individuals in the i^{th} species. N is the total number of individuals.

In this thesis rarefaction coefficients were calculated in order to ensure that a sufficient sample size had been achieved, implying that most of the genera actually present had been found. When this was done, the number of genera present in various samples were compared in order to discover relative diversity trends. The coefficients were calculated and plotted using the computer program described in section A3.2, which is modified from Calef (1972).

A3.2 Rarefaction computer program

Purpose: The purpose of this FORTRAN program is to calculate values of rarefaction coefficients for a rarefaction curve at "rarefied collection sizes" of 10, 20, 30, etc. individuals. A list of cards used in the program is shown in table A3.1 and a sample of the output is given in table A3.2. In the output AV is the list of species abundances in order of increasing size. The column headed PER is the percentage of the total number of individuals which belong to that species, while CUPER is the cumulative percentage. The number of species and the number of individuals are also listed. Finally, a plot of the number of species vs the number of individuals for various collection sizes in steps of ten is printed. The taxonomic unit species is printed on the output, but in fact any taxonomic unit may be used, so long as different units are not mixed. For example, in this thesis, genera, rather than species, is used.

Input data:

card 1 - gives the number of collections to be rarefied. Punch beginning in column 1.

Table A3.1 List of cards for rarefaction computer program.

*FORTRAN

```

PROGRAM(NMNM)
INPUT 1=CRO
OUTPUT2=LPO
TRACE 1
END
MASTER MAIN
INTEGER AV, TITLE(16)
DIMENSION AV(200), PER(200), CUPER(200), RARE(400)
10 FORMAT (100I0)
11 FORMAT (//6H AV,9H PER,10H CUPER/ (I5, F9.3, F10.3))
12 FORMAT (/19H NUMBER OF SPECIES=,I3/23H NUMBER IF INDIVIDUALS=,I4)
14 FORMAT (//15X, 11HRAREFACTION/(5F10.3))
READ(1,10)NCOLL
DO 77 LL=1,NCOLL
9 READ(1,9)TITLE
FORMAT(16A4)
READ(1,10)NS
READ (1,10) (AV(J), J=1,NS)
N=0
DO 17 J=1,NS
IF (AV(J) .EQ. 0) GO TO 17
N=N+1
17 CONTINUE
CALL SORT (AV, N)
NT=0
DO 16 J=1,N
16 NT=AV(J)+NT
CONTINUE
PER(1)=FLOAT(AV(1))/FLOAT(NT)
CUPER(1)=PER(1)
DO 22 J=2,N
PER (J)=FLOAT(AV(J))/FLOAT(NT)
CUPER(J)=PER(J)+CUPER(J-1)
22 CONTINUE
NC=0
DO 51 I=10, 1000, 10
IF (I .GT. NT) GO TO 99
P=1./FLOAT(I)
DO 52 K=1,NS
KK=K-1
IF (PER(K) .GE. P) GO TO 52
NC=NC+1
GO TO 53
52 CONTINUE
53 RARE(NC)=FLOAT(KK)+((1.-CUPER(KK))/P)
IF(RARE(NC).GE.FLOAT(N))GO TO 99
51 CONTINUE
99 CONTINUE
WRITE(2,18)TITLE
18 FORMAT(//,1X,16A4)
WRITE (2,11) (AV(J), PER(J), CUPER(J), J=1,N)
WRITE (2,12) N, NT
WRITE (2,13) DI
WRITE (2,14) (RARE(I), I=1,NC)
CALL GRAPH(NS,NC,RARE)
77 CONTINUE
STOP
END
SUBROUTINE SORT (C, NN)
INTEGER C
DIMENSION C(200)
L=NN-1
DO 60 I=1,L
JJ=NN-I
DO 50 J=1,JJ
IF (C(J) .GE. C(JJ+1)) GO TO 50
Z=C(JJ+1)
C(JJ+1)=C(J)

```

```

50 C(J)=Z
60 CONTINUE
CONTINUE
RETURN
END
SUBROUTINE GRAPH(NS,NC,RARE)
INTEGER BL,EX,BL2,EX2,SYM(120),NUM(120)
REAL RARE(400)
DATA BL/1H /,EX/1H./,BL2/2H /,EX2/2H ./
NS2=NS+1
NS1=(NS+10)/10
DO 1 I=1,NS1
I1=(I-1)*10
DO 2 J=1,10
NUM(I1+J)=J-1
2 CONTINUE
1 CONTINUE
20 WRITE(2,20)
FORMAT(/,1X,'PLOT OF N SPECIES (ACROSS PAGE) AGAINST',
* ' N OF INDIVIDUALS')
IF(NS.GT.50)WRITE(2,10)(NUM(I),I=1,NS2)
IF(NS.LE.50)WRITE(2,19)(NUM(I),I=1,NS2)
19 FORMAT(/,4X,117I2)
10 FORMAT(/,4X,117I1)
DO 3 I=1,NC
I1=10*I
JR=NINT(RARE(I))
JR1=JR+1
IF(JR.EQ.0)GO TO 5
DO 4 J=1,JR
SYM(J)=BL
4 IF(NS.LE.50)SYM(J)=BL2
5 SYM(JR1)=EX
IF(NS.LE.50)SYM(JR1)=EX2
IF(NS.GT.50)WRITE(2,11)I1,(SYM(J),J=1,JR1)
IF(NS.LE.50)WRITE(2,12)I1,(SYM(J),J=1,JR1)
12 FORMAT( 1X,I3,117A2)
11 FORMAT( 1X,I3,117A1)
3 CONTINUE
IF(NS.LE.50)WRITE(2,19)(NUM(I),I=1,NS2)
IF(NS.GT.50)WRITE(2,10)(NUM(I),I=1,NS2)
RETURN
END
FINISH
*END
****

```

TN3A

AV	PER	CUPER
25	0,221	0,221
12	0,106	0,327
11	0,097	0,425
9	0,080	0,504
8	0,071	0,575
7	0,062	0,637
7	0,062	0,699
5	0,044	0,743
4	0,035	0,779
3	0,027	0,805
3	0,027	0,832
3	0,027	0,858
2	0,018	0,876
2	0,018	0,894
2	0,018	0,912
2	0,018	0,929
1	0,009	0,947
1	0,009	0,955
1	0,009	0,973
1	0,009	0,982
1	0,009	0,991
1	0,009	1,000

NUMBER OF SPECIES= 23
 NUMBER IF INDIVIDUALS= 113

RAREFACTION				
8,726	13,018	15,637	17,664	19,080
20,186	20,717	21,248	21,779	22,310
22,841				

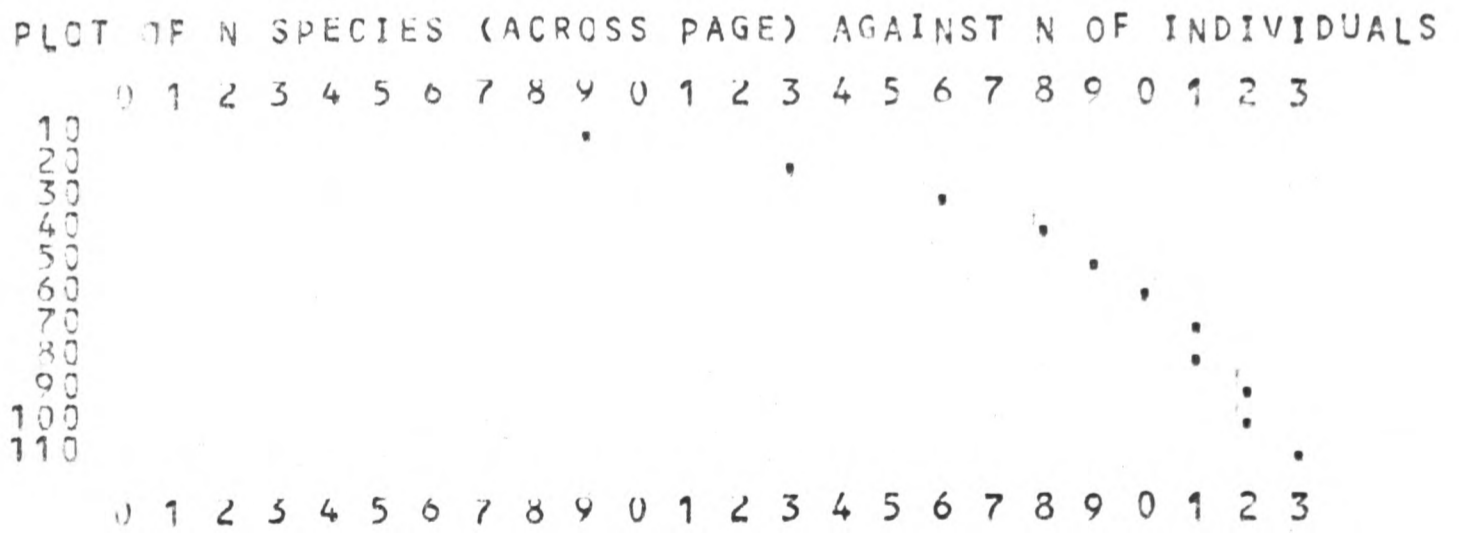


Table A3.2 Sample of rarefaction output.

The following three cards are repeated for each collection.

card 2 - title card. Start in column 1.

card 3 - number of species represented in the collection. Start in column 1.

card 4 - a list of the number of individuals in each species. Begin in column 1 and leave 1 space between entries.

A3.3 SPSS programs

Basic descriptive statistics and principal components analysis were done using the Statistical Package for the Social Sciences (SPSS) routines Condescriptive and Factor. These are well described in the SPSS manual by Nie et al. (1970).

SPSS has many advantages in its relative ease of use, easy accessibility and clear presentation of data and results. However, a limitation of SPSS is that it requires that there be only one value for each variable in each collection. This limitation is sometimes impracticable in geological situations. The program STATUS described in section A3.4 was designed to overcome this limitation.

A3.4 STATUS program

Purpose: The purpose of this FORTRAN program is to calculate descriptive statistics for variables which have numerous values, thus making them unsuitable for use in SPSS. An example of this type of data is data on the maximum size of individuals. The variable maximum size in each collection has as many values as there are individuals in the collection.

The statistics calculated by this program include the mean, median, skewness, kurtosis, variance, coefficient of variation and a measure of variation from normality called K.S.Dmax. The program also prints a histogram in which the class intervals may be varied. A list of

cards for the program is given in table A3.3 and a sample output is shown in table A3.4.

Input data:

cards 1-5 - Title cards.

card 6 - value of M which is the number of different variables being handled. In the version given only one variable can be run at a time, thus M must equal 1. The format is I4.

card 7 - The data input format (called FMT in program cards).

card 8 - M x variable names. In this version M must equal 1, therefore only one variable name can be given. Begin in column 1.

card 9 - M x values of class intervals for the histogram (again in this version only one value can be given). Format is 13 F 6.4.

next cards : this group of cards are repeated for each collection.

- 1) NCOL or the number of cards to be read for a given collection. Format is I4.
- 2) NG, which is a list of the number of values on each of the cards, there must be NCOL x values. For example, if NG reads 5, 3, 10, the collection would consist of three cards the first of which lists 5 values, the second three values and the third ten values. The format for this card is I3.
- 3) NCOL x data cards. These cards contain the raw data in the format F5.2. The number of values shown on a particular card must correspond to the number given for that card on the NG card.
- 4) values for alpha (degrees of freedom) and t (corresponding t-statistic value). Format is 2F6.4.

To end the program either:

- a) punch 0 for the NCOL value and follow with an alpha and t card. This will cause pooled statistics for all collections in the run to be computed.
- b) punch 1 for the NCOL value. This will cause the program to stop.

A3.5 SPECIES program

Purpose: The purpose of this FORTRAN program is to print standardised data lists. The program reads SPSS data cards. If the value of a variable is 0, nothing is printed. If the value of a variable is

Table A3.3 List of Cards for STATUS.

```

LINE NUMBER      PORTMAN TEXT
1                PROGRAM STATOS
2                DIMENSION A(2000),TITLE(20),Y(2000),E(4),C(4),D(4),
3                IE(4),F(4),EL,T(5),FMT(20),XS(2000),
4                ZVC(100),AA(200)
5                DO 10 J=1,5
6                READ(5,1001) TITLE
7                WRITE(6,2000) TITLE
8                10  CONTINUE
9                READ(5,1000)
10               READ(5,1001) FMT
11               READ(5,1002) EL,T
12               READ(5,1003) CINT
13               NI=1
14               NSUM=0
15               IF EL.T=1
16               200 READ(5,1000) NCOL
17               IF(NCOL) 205,201,206
18               205 READ(5,1004) (NF(K),K=1,NCOL)
19               NY=1
20               NL=0
21               DO 11 K=1,NCOL
22               NGEN=NG(K)
23               READ(5,FMT) (I(I),I=1,NGEN)
24               NX=NX+NG(K)
25               DO 12 I=1,NGEN
26               IA=I+NL
27               AA(IA)=I(1)
28               12  CONTINUE
29               NL=NL+NGEN
30               11  CONTINUE
31               READ(5,1005) ALPHA,TALPH
32               CONF=100.0-ALPHA*100.0
33               WRITE(6,2001)
34               READ(5,1001) TITLE
35               WRITE(6,2000) TITLE
36               N=NX
37               NSUM=NSUM+NX
38               NIN=NSUM-NY+1
39               DO 202 I=1,N
40               IR=I+NIN-1
41               XS(IR)=AA(I)
42               202 CONTINUE
43               GO TO 204
44               201 IF(NIN.LE.1) GO TO 205
45               WRITE(6,2001)
46               READ(5,1003) ALPHA,TALPH
47               CONF=100.0-ALPHA*100.0
48               IEXIT=0
49               N=NSUM
50               WRITE(6,2000)
51               DO 203 I=1,N
52               AA(I)=XS(I)
53               203 CONTINUE
54               204 SUMY=0.0
55               SUMY2=0.0

```

FORTRAN TEXT

```

SUMY3=0.0
SUMY4=0.0
EM=0.0
DO 101 I=1,N
Y(I)=AA(I)
SUMY=SUMY+Y(I)
101 CONTINUE
YEAR=SUMY/E
DO 104 I=1,N
YDEV=Y(I)-YEAR
YDEV2=YDEV*YDEV
SUMY2=SUMY2+YDEV2
YDEV3=YDEV2*YDEV
SUMY3=SUMY3+YDEV3
SUMY4=SUMY4+YDEV3*YDEV
104 CONTINUE
S2=SUMY2/(EM-1.0)
S=SQRT(S2)
CALL KSRD(N,Y,YEAR,S,OMAX)
IND1=(N+1)/2
IND2=(N+2)/2
F1EDN=(Y(IND1)+Y(IND2))/2.0
Q=2.0
CALL COOUT(N,ALPHA,TALPH,YEAR,S,S2,R,C,D,E,F,SUMY3,
1SUMY4,F1EDN)
G=S2
H=S
D=OMAX
NCLAS=0
WRITE(6,2003) N,NCLAS,CONF
WRITE(6,2004)
WRITE(6,2005) ELMT,B,C
WRITE(6,2006)
WRITE(6,2005) ELMT,E,F
WRITE(6,2007)
WRITE(6,2005) ELMT,C,H,D,DA
CALL HISTO(Y,FLAT,CINT,N)
IF(IEKIT.LE.0) GO TO END
GO TO 200
205 STOP
200 FORMAT(2I4)
201 FORMAT(20A4)
202 FORMAT(4(5A4))
203 FORMAT(13F4.4)
204 FORMAT(26I3)
200 FORMAT(1X(2A4))
201 FORMAT(1H1)
203 FORMAT(1X,20HNUMBER OF SAMPLES = ,I4//1X,20HNUMBER OF CLASSES = ,
1I4//1X,31HCONFIDENCE LIMITS (PER CENT) = ,F8.2//)
204 FORMAT(1X,'VARIABLE',19X,'MEAN',4X,'STD. ERR.',4X,'CONFIDENCE LIMITS',
19X,'MEDIAN',4X,'STD. ERR.',6X,'CONFIDENCE LIMITS')
205 FORMAT(1X,5A,3X,F10.4,3X,F10.4,2X,F10.4,3X,F10.4,3X,F10.4,
13X,F10.4,5X,F10.4,2X,F10.4)
206 FORMAT(5X,'SKEWNESS',4X,'STD. ERR.',6X,'CONFIDENCE LIMITS',7X,
1'KURTOSIS',4X,'STD. ERR.',6X,'CONFIDENCE LIMITS')
207 FORMAT(25X,'VARIANCE',4X,'STD. DEVI',3X,'COEFF. VAR',3X,'STD. ERR.

```

DL

FORTRAN 91.0.00 (01)

CO

FORTRAN TEXT

```

      1',BX,'CONFIDENCE LIMITS',BX,'K.S. (MAX)')
      4000 FORMAT(1X,'WHOLE SAMPLE, ALL COLLECTIONS',/)
      4001 END

```

[The following text is extremely faint and largely illegible, appearing to be a continuation of a document or a series of lines of code. It contains several lines of text that are difficult to decipher due to low contrast and blurring.]

0L

FORTRAN 51.1.60 (11)

COMPILATION 1

NUMBER FORTRAN TEXT

```

SUBROUTINE XISTO(X,ELMT,CINT,N)
DIMENSION X(L),XU(50),XL(50),SNX(50),SNY(50),STX(50),
1 INX(50),IOUT(100,101),ELMT(5)
DATA IFLNK,IPLUS,ISTAR/' ','+', '*'/
AM=FLOAT(N)
XMIN=X(1)
XMAX=XMIN
DO 1 I=1,N
XT=X(I)
IF(XT.LT.XMIN)XMIN=XT
IF(XT.GT.XMAX)XMAX=XT
CONTINUE
START=XMIN-CINT
L=
100 L=L+1
XAL=FLOAT(L)
COUNT=START+XAL*CINT
IF(COUNT-XMAX)100,101,101
101 XRIGHT=0.0
XLEFT=0.0
DO 9 II=1,L
XU(II)=START+CINT*FLOAT(II)+2.001
XL(II)=XU(II)-CINT
DO 10 I=1,N
IF(X(I).GE.XU(II)) GO TO 10
IF(X(I).LT.XL(II)) GO TO 10
XRIGHT=XRIGHT+1.0
10 CONTINUE
SNX(II)=XRIGHT
XMT=(XU(II)+XL(II))/2.0
9 CONTINUE
STX(1)=SNX(1)
DO 17 II=2,L
IIM=II-1
STX(II)=SNX(II)-SNX(IIM)
17 CONTINUE
DO 18 II=1,L
XMPX=STX(II)*100.0/AM
INX(II)=IFIX(XMPX)
SNY(II)=SNX(II)/AM
18 CONTINUE
INI=2*L+1
DO 22 IN=1,INI
DO 22 K=1,101
IOUT(IN,K)=IFLNK
22 CONTINUE
DO 23 IN=1,INI,2
DO 23 K=1,101,10
IOUT(IN,K)=IPLUS
23 CONTINUE
INIT=L*2
DO 24 IN=2,INIT,2
DO 24 K=1,101
II=IN/2
IF(K.GT.INX(II)) GO TO 24
IOUT(IN,K)=ISTAR

```

FORTRAN TEXT

```

01 CONTINUE
   DO 10 I=1,L
      XU(I)=XU(I)-0.001
      XL(I)=XL(I)-0.001
30 CONTINUE
   WRITE(6,2001) (TL(I),K),K=1,5)
   WRITE(6,2002) CINT
   WRITE(6,2003)
   WRITE(6,2004) XL(1),(IOUT(1,K),K=1,101)
   DO 29 IN=1,INIT,2
      II=IN/2
      WRITE(6,2005) STX(II),(IOUT(IV,K),K=1,101)
      IN=IN+1
      WRITE(6,2004) XU(II),(IOUT(IV,K),K=1,101)
29 CONTINUE
   RETURN
2001 FORMAT(//11X,9HHISTOGRAM,5X,5A//)
2002 FOR AT(1X,17-CLASS INTERVAL = ,F15.5/1X,84COUNTS,
114X,1HEFREQUENCY AS PER CENT OF SAMPLE/)
2003 FOR AT(21X,11-01.00 15.00 20.00 30.00 40.00 5
1.00 60.00 70.00 80.00 90.00 100.00)
2004 FORMAT(11X,F10.1,1X,1-141)
2005 FORMAT(1X,F6.1,15X,101A1)
   END

```

MAIN TEXT

```

SUBROUTINE C04OUTCN,ALPHA,TALPH,YEAR,S,S2,B,C,D,E,F,SUMY3,
1SU,Y4,FR,EDN)
DIMENSION B(4),C(4),D(4),E(4),F(4)
E1=E
CV=(S/YBAR)*100.0
G1=(E/(E1-1.0))*SUMY3/((E1-2.0)*S2*S)
G2=((E1+1.0)/(E1-1.0))*(E1/(E1-2.0))*(SUMY4/((E1-3.0)*S2*S2))-3.0*
1(E1-1.0)*(E1-1.0)/((E1-2.0)*(E1-3.0))
SYBAR=S/SQRT(E1)
YBARL1=YEAR-TALPH*SYBAR
YBARL2=YEAR+TALPH*SYBAR
SMED=1.25E3*SYBAR
YMEDL1=FR,EDN-TALPH*SMED
YMEDL2=FR,EDN+TALPH*SMED
SCV=CV*SQRT((1.0+2.0*(CV/100.0)*(CV/100.0))/(2.0*E1))
CVL1=CV-TALPH*SCV
CVL2=CV+TALPH*SCV
SG1=S*SQRT(1.0*(E1-1.0)/((E1-2.0)*(E1+1.0)*(E1+3.0)))
FND=FND*MD(ALPHA/2.0)
G1L1=G1-FND*SG1
G1L2=G1+FND*SG1
SG2=S*SQRT(24.0*(E1-1.0)*(E1-1.0)/((E1-3.0)*(E1-2.0)*(E1+3.0)*(E1
1+5.0)))
G2L1=G2-FND*SG2
G2L2=G2+FND*SG2
B(1)=YEAR
B(2)=SYBAR
B(3)=YBARL1
B(4)=YBARL2
C(1)=FR,EDN
C(2)=SMED
C(3)=YMEDL1
C(4)=YMEDL2
D(1)=CV
D(2)=SCV
D(3)=CVL1
D(4)=CVL2
E(1)=G1
E(2)=SG1
E(3)=G1L1
E(4)=G1L2
F(1)=C2
F(2)=SG2
F(3)=G2L1
F(4)=G2L2
RETURN
END

```

0101

FORTRAN 77 (1)

NUMBER FORTRAN TEXT

```

SUBROUTINE KEND(N, Y, YEAR, S, DMAX)
DIMENSION Y(100)
E=0
DELTA=1./5
CALL H SORT(Y, N)
D=MAX= .
YOUT=1.0
DO 10 I=1, N
YOUT=YOUT+DELTA
YLOC=PROB(Y(I), YEAR, S)
ARDIFF=ABS(YOUT-YLOC)
IF(ARDIFF-1.0) 10, 10, 3
5   MAX=ARDIFF
10  CONTINUE
RETURN
END

```

FORTRAN TEXT

```
      SUBROUTINE B SORT(NAME, IROW)
      REAL NAME(1000)
1     NSWIT=1
      I-ROW=1=I-ROW-1
      DO 10 I=1, IROW-1
      IF (NAME(I)-NAME(I+1)) 10, 10, 9
8     NSWIT=2
      TEMP=NAME(I)
      NAME(I)=NAME(I+1)
      NAME(I+1)=TEMP
10    CONTINUE
      GO TO (10, 1), NSWIT
15    RETURN
      END
```

FORTRAN TEXT

```
FUNCTION F10E10(PAGE)
  T=SQRT(ALOG(1.0/(PAGE**2)))
  F10E10=T*(2.015517+T*(0.302353+T*0.010325))/(1.0+T*(1.432785+T*(0.
  111925+T*.7130)))
  RETURN F10E10
END
```

FORTRAN TEXT

```

FUNCTION PROBN(Y, YHAP, S)
  Z=(Y-YHAP)/S
  X=ABS(Z)
  T=1.0/(1.0+.2515+1.+X)
  PROBN=1.0-0.5959423*EXP(-X*X/2.0)*T*(0.3143+150+T*(-0.25653378+T*(
11.70117794+T*(-1.213539+T*1.50127443))))
  IF(Z) S,10,10
5  PROBN=1.0-PROBN
10 RETURN
END

```

COLLECTION 500
 NUMBER OF SAMPLES = 1112
 NUMBER OF CLASSES = 0

CONFIDENCE LIMITS (PER CENT) = 95.00

VARIABLE	MEAN	STD. ERR.	CONFIDENCE LIMITS	MEDIAN	STD. ERR.	CONFIDENCE LIMITS
MAXIMUM SIZE IN CMS	0.6895	0.0446	0.6141 0.7650	0.6200	0.0561	0.5254 0.7146
MAXIMUM SIZE IN CMS	1.1567	0.2391	0.6881 1.6254	3.0096	0.4736	2.0809 3.9387
MAXIMUM SIZE IN CMS	0.2047	0.4525	65.6192 6.2677	55.0643	76.1740	K.S. DMAX 0.1188

HISTOGRAM MAXIMUM SIZE IN CMS

CLASS INTERVAL = 0.20000 FREQUENCY AS PER CENT OF SAMPLE

10.0	0.00	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
	-0.2000 +	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +		
4.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			
12.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			
25.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			
19.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			
19.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			
6.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			
1.0	0.0000 +	0.2000 +	0.4000 +	0.6000 +	0.8000 +	1.0000 +	1.2000 +	1.4000 +			

Table A3.4 Sample of output from STATUS.

greater than 0, a label and the value are printed. The pattern of spacing between entries can be altered. A list of cards used in the program is shown in table A3.5. Samples of the output are shown in Appendix 4.

Input data:

- card 1 - number of collections (NS) and number of variable names (MV). Format is I4.
- card 2 - list of variable names, starting in columns 1, 21, 41, 61. There can be a maximum of four names per card and as many cards as necessary may be used.
- next card - this defines the pattern of spacing between the lines. The format is I4. The first number is the total number of entries which are included on this card (i.e. the number of spaces to be made). Subsequent numbers are the variable after which the space is to be made. For example, if 5 is punched in this position, a line will be skipped after printing the fifth variable which was listed on the variable names cards and before the sixth variable is printed. As many cards as necessary may be used.
- next cards - SPSS data cards, unchanged.

note: for each run the format card 1002 must be altered to correspond with the format of the SPSS data cards.

L JOB SPECIES FORTRAN F1.2.60 (01) COMPILATION

BER FORTRAN TEXT

```

DIMENSION VNAM(60,5) , ISPACE(20) , A(100,60) , IA(100,60)
READ(5,1000) NS,MV
READ(5,1001) ((VNAM(J,K),K=1,5),J=1,MV)
READ(5,1000) NL, (ISPACE(L),L=1,NL)
DO 1 I=1,NS
READ(5,1002) (A(I,J), J=1,MV)
DO 5 J=1,MV
IA(I,J)= A(I,J)
5 CONTINUE
1 CONTINUE
DO 2 I=1,NS
ICOUNT=1
WRITE(6,2000)
DO 3 J=1,MV
IF(J-ISPACE(ICOUNT)) 4,4,7
7 ICOUNT=ICOUNT+1
WRITE(6,2001)
4 IF(IA(I,J).LE.0) GO TO 3
IF(J.EQ.1.OR.J.GT.3) GO TO 6
WRITE(6,2002) (VNAM(J,K),K=1,5),A(I,J)
GO TO 3
6 WRITE(6,2003) (VNAM(J,K),K=1,5) ,IA(I,J)
3 CONTINUE
2 CONTINUE
STOP
1000 FORMAT (20I4)
1001 FORMAT(4(5A4))
1002 FORMAT(F3.0,2X,7(F4.1,1X))
2000 FORMAT(1H1)
2001 FORMAT(//)
2002 FORMAT(1X,5A4,F8.2)
2003 FORMAT(1X,5A4,I5)
END

```

Table A3.5 List of Cards for SPECIES.

Appendix 4

DATA

A4.1. Faunal Data

A4.1.1. Faunal Data Lists and Rarefaction Coefficients

COLLECTION NUMBER	554
	(Tn3a)
DENSITY	2.80
AMOUNT BRYOZOA	12.45
CORALS	1
BIVALVES	2 lpe
LEPTAENID	2
SPIRIFER	1
MARTINIA	1
PRODUCTINA	1
BABY BRACHS	14

COLLECTION 558

AV	PER	CUPER
15	0.600	0.600
5	0.200	0.800
3	0.120	0.420
1	0.040	0.960
1	0.040	1.000

NUMBER OF SPECIES= 5
 NUMBER OF INDIVIDUALS= 25

3.800 RAREFACTION
 4.600

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS

	0	1	2	3	4	5
10					.	
20					.	
	0	1	2	3	4	5

Note: for calculation of rarefaction curves bivalves, cephalopods, corals, gastropods, trilobites and other organisms have been counted as one genera each, except where noted.

(Tn3a)

Collection Number	557
Density	4.20
Amount Bryozoa	9.31
Bivalves	1
Gastropods	5
Other Strophs	2
Other Orthid	5
Pugnax	1
Spirifer	8
Other Smooth Spirif	8
Martinia	2
Athyrid	2
Phricodothyris	1
Other Brachythyrid	4
Other Productid	5
Quasiavonia	3
Krotovia	5
Echinochonus	1
Baby Brachs	30

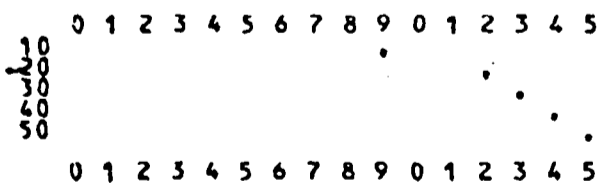
COLLECTION 557

AV	PER	CUPER
8	0.151	0.151
8	0.151	0.302
5	0.094	0.396
5	0.094	0.491
5	0.094	0.585
5	0.094	0.679
4	0.075	0.755
3	0.057	0.811
2	0.038	0.849
2	0.038	0.887
2	0.038	0.925
1	0.019	0.943
1	0.019	0.962
1	0.019	0.981
1	0.019	1.000

NUMBER OF SPECIES = 15
 NUMBER IF INDIVIDUALS = 53

8.981 RAREFACTION 11.774 13.264 14.019 14.774

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



Collection Number 556
(Tn30)

Density 21.20

Corals 1
Trilobites 3
Bivalves 15
Gastropods 13
Cephalopods 1

Schizophoria 3
Orthotides 1
Other Strophs 5
Leptagonia 1
Other Orthid 14
Rhipidomella 5
Pugnax 1
Pleuropugnoides 4

COLLECTION 556

AV	PER	CUPER
25	0.151	0.151
15	0.090	0.241
15	0.090	0.331
14	0.084	0.416
13	0.078	0.494
13	0.078	0.572
12	0.072	0.645
7	0.042	0.687
6	0.036	0.723
6	0.036	0.759
5	0.030	0.789
5	0.030	0.819
4	0.024	0.843
3	0.018	0.861
3	0.018	0.880
3	0.018	0.898
2	0.012	0.916
2	0.012	0.928
1	0.006	0.946
1	0.006	0.952
1	0.006	0.958
1	0.006	0.964
1	0.006	0.970
1	0.006	0.976
1	0.006	0.982
1	0.006	0.988
1	0.006	0.994
1	0.006	1.000

Spirifer 1
Other Smooth Spirif 25
Other Rib Spirif 1
Phricodothyris 3
Martinia 2
Athyrid 7
Reticularia 1
Punctate Spirifer 1
Cruryth/ris 1
Other Brachythyrid 6

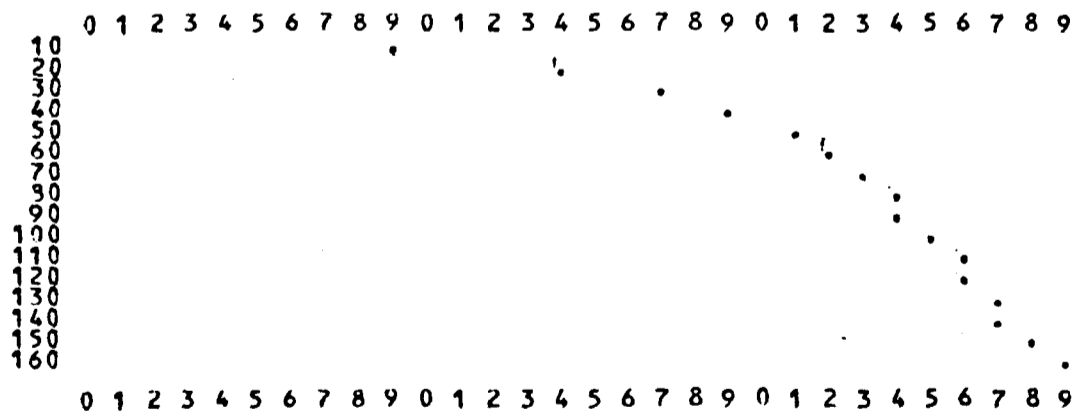
Other Productid 13
Productina 2
Echinochonus 3
Avonia 6
Plicatifera 12
Krotovia 15

Baby Brachs 104

NUMBER OF SPECIES= 29
NUMBER IF INDIVIDUALS= 166

RAREFACTION				
9.494	14.108	17.229	19.229	20.831
22.060	22.904	23.747	24.422	25.024
25.627	26.229	26.831	27.434	28.036
28.639				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER	554
	(Tn3a)
DENSITY	2.80
AMOUNT BRYOZOA	12.43
CORALS	1
BIVALVES	2 lpe
LEPTAENID	2
SPIRIFER	1
MARTINIA	1
PRODUCTINA	1
BABY BRACHS	14

COLLECTION 554

AV	PER	CUPER
2	0.250	0.250
2	0.250	0.500
1	0.125	0.625
1	0.125	0.750
1	0.125	0.875
1	0.125	1.000

NUMBER OF SPECIES = 6
 NUMBER OF INDIVIDUALS = 8

9.494 RAREFACTION

PLGT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS

10	0	1	2	3	4	5	6
	0	1	2	3	4	5	6

Collection Number	553
(Tn3a)	
Density	19.30
Corals	1
Bivalves	2
Trilobites	3
Others	2
Other Strophs	3
Leptaenid	2
Other Orthid	2
Schizophoria	1
Pugnax	1
Pleuropugnoides	11
Dielasma	1
Spirifer	4
Other Smooth Spirif	12
Martinia	1
Brachythyris	3
Other Productid	7
Quasiavonia	7
Productina	1
Plicatifera	2
Linoproductid	9
Antiquatonia	5
Krotovia	8
Baby Brachs	25

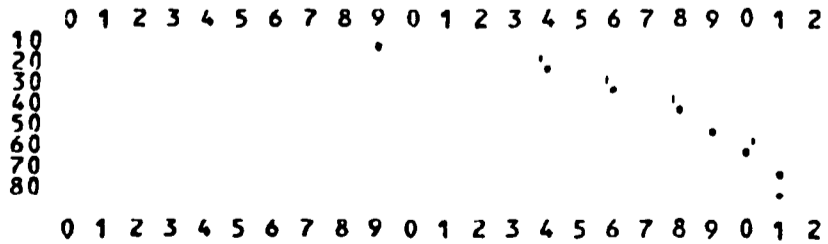
COLLECTION 553

AV	PER	CUPER
12	0.136	0.136
11	0.125	0.261
9	0.102	0.364
8	0.091	0.455
7	0.080	0.534
7	0.080	0.614
5	0.057	0.670
4	0.045	0.716
3	0.034	0.750
3	0.034	0.784
3	0.034	0.818
2	0.023	0.841
2	0.023	0.864
2	0.023	0.886
2	0.023	0.909
2	0.023	0.932
1	0.011	0.943
1	0.011	0.955
1	0.011	0.966
1	0.011	0.977
1	0.011	0.989
1	0.011	1.000

NUMBER OF SPECIES= 22
 NUMBER IF INDIVIDUALS= 88

		RAREFACTION				
9.364	13.541	16.455	18.273	19.409		
20.091	20.773	21.455				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 552
(Tn3c)

DENSITY 8.00

BIVALVES 1
OTHERS 5

LEPTAGONIA 1
OTHER ORTHID 7
RHIPIDOMELLA 4

SPIRIFER 1
OTHER SMOOTH SPIRIF 2
ATHYRID 1
CRURITHYRIS 1
PUNCTATE SPIRIFER 1

QUASIAVONIA 2
PRODUCTINA 2
AVONIA 1

BABY BRACHS 16

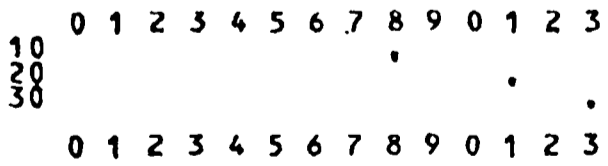
COLLECTION 552

AV	PER	CUPEP
7	0.226	0.226
5	0.161	0.387
4	0.129	0.516
3	0.097	0.613
2	0.065	0.677
2	0.065	0.742
2	0.065	0.806
1	0.032	0.839
1	0.032	0.871
1	0.032	0.903
1	0.032	0.935
1	0.032	0.968
1	0.032	1.000

NUMBER OF SPECIES= 13
NUMBER OF INDIVIDUALS= 31

7.839 RAREFACTION 10.871 12.806

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



Collection Number (Vla)	551
Density	1.50
Gastropods	1
Corals	1
Others	1
Other Orthid	3
other Strophs	1
Schizophoria	1
Pleuropugnoides	1
Spirifer	5
Smooth Spirif	3
Crurithyris	1
Antiquato nia	1
Baby Brachs	10

COLLECTION 551

AV	PER	CUPER
5	0.263	0.263
3	0.158	0.421
3	0.158	0.579
1	0.053	0.632
1	0.053	0.684
1	0.053	0.737
1	0.053	0.789
1	0.053	0.842
1	0.053	0.895
1	0.053	0.947
1	0.053	1.000

NUMBER OF SPECIES= 11
 NUMBER IF INDIVIDUALS= 19

7.211 RAREFACTION

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS

10	0	1	2	3	4	5	6	7	8	9	0	1
	0	1	2	3	4	5	6	7	8	9	0	1

Collection Number (Tn3c)	550
Density	6.40
Bivalves	11
Gastropods	1
Orthotetes	1
Schizophoria	3
Other Ribbed Spirif	1
Athyrid	2
Phricodothyris	2
Reticularia	1
Other Brachythyrid	1
Other Productid	2
Avonia	1
Plicatifera	3
Krotovia	3
Echinochonus	2
Baby Brachs	14

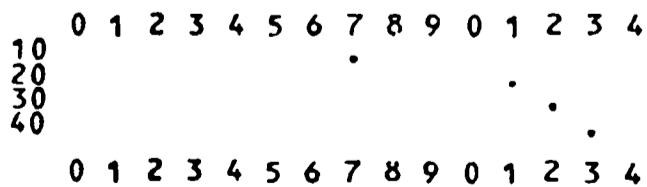
COLLECTION 550

AV	PER	CUPER
14	0.298	0.208
11	0.234	0.532
3	0.064	0.506
3	0.064	0.660
3	0.064	0.723
2	0.043	0.766
2	0.043	0.809
2	0.043	0.851
2	0.043	0.894
1	0.021	0.915
1	0.021	0.936
1	0.021	0.957
1	0.021	0.979
1	0.021	1.000

NUMBER OF SPECIES = 14
 NUMBER OF INDIVIDUALS = 47

6.681 RAREFACTION 10.532 12.191 13.255

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



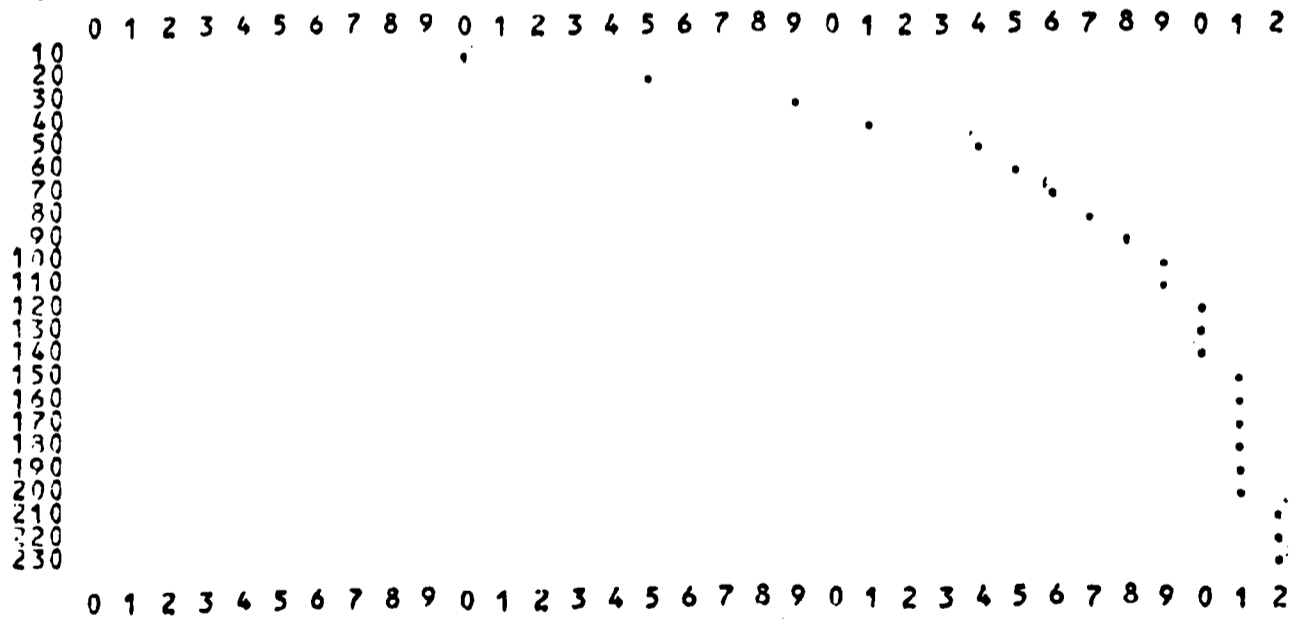
T43C
(lots 550, 552, 556)

AV	PER	CUPER
227	0.116	0.116
227	0.116	0.233
227	0.095	0.328
150	0.078	0.405
150	0.065	0.470
150	0.065	0.534
150	0.060	0.595
100	0.045	0.638
100	0.035	0.677
72	0.030	0.707
72	0.030	0.737
50	0.020	0.763
50	0.020	0.784
50	0.020	0.806
50	0.020	0.828
50	0.020	0.849
50	0.017	0.866
50	0.017	0.884
50	0.015	0.901
50	0.009	0.914
50	0.009	0.922
50	0.009	0.931
50	0.009	0.940
50	0.009	0.948
50	0.009	0.957
50	0.009	0.966
50	0.009	0.974
50	0.009	0.983
50	0.009	0.987
50	0.009	0.991
50	0.009	0.996
50	0.009	1.000

NUMBER OF SPECIES = 32
NUMBER OF INDIVIDUALS = 232

RAREFACTION				
29.672	15.103	18.698	21.483	23.543
24.948	25.940	26.897	27.759	28.621
30.463	30.069	30.241	30.414	30.586
30.759	30.931	31.103	31.276	31.448
31.621	31.793	31.966		

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 523

DENSITY 37.50

other organisms = 0
 other brachiopods = 29.55
 spirifers = 7.58
 smooth spirifers = 31.82
 non-trail productids = 13.64
 trail productids = .76
 juveniles = 15.91
 bivalves = .76

OTHER STOPHS 10
 LEPTAENID 2
 RHIPIDOMELLA 1
 SCHIZOPHORIA 13
 OTHER RHYNCH 2
 PUGNAX 2
 PLEUROPUGNACIDES 4
 DIELASKA 5

SPIRIFER 10

OTHER SMOOTH SPIRIF. 3
 MARTINIA 4
 PHRICOOTHYRIS 6
 RETICULARIA 7
 BRACHYTHYRIS 16
 CRURATHYRIS 6

OTHER PRODUCTID 5
 QUASIAVONIA 2
 PUSTULA 1
 PLICATIFERA 1
 OVERTONIA 1
 EOPARGINIFERA 9

BASY BRACHS 21

PTEROMOPHS 1

average maximum size = .9041 cms
 biovolume = 33.9

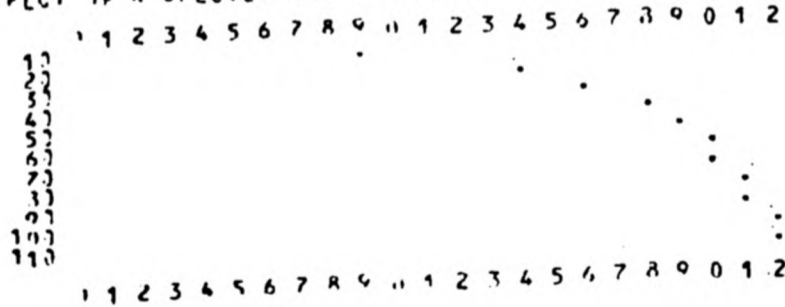
COLLECTION 523

	PER	CUPFR
10	0.144	0.144
15	0.117	0.251
16	0.090	0.351
17	0.043	0.441
18	0.041	0.523
19	0.063	0.586
20	0.054	0.640
21	0.054	0.694
22	0.045	0.740
23	0.045	0.786
24	0.035	0.820
25	0.035	0.856
26	0.027	0.891
27	0.014	0.907
28	0.014	0.910
29	0.014	0.927
30	0.014	0.937
31	0.013	0.955
32	0.000	0.964
33	0.000	0.973
34	0.000	0.982
35	0.000	0.991
36	0.000	1.000

NUMBER OF SPECIES = 22
 NUMBER OF INDIVIDUALS = 111

	RAPEFACTION			
0.347	14.126	16.324	17.605	18.856
10.703	20.153	20.604	21.054	21.505
21.955				

PLCT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 522

DENSITY 2.70

other organisms = 0
 other brachiopods = 25.30
 spirifers = 3.61
 smooth spirifers = 19.28
 non-trail productids = 19.28
 trail productids = 0
 juveniles = 0
 bivalves = 32.53

OTHER STOPHS 12
 LEPTAENID 3
 SCHIZOPHORIA 4
 PUGNAX 2

SPIRIFER 3

OTHER SMOOTH SPIRIF 5
 MARTINIA 5
 ATHYRID 2
 BRACHYTHYRIS 2
 CRURITHYRIS 2

OTHER PRODUCTID 3
 QUASIAVONIA 13

PERNOPECTINIS 1
 SMOOTH PECTINIDS 26

average maximum size = .8142 cms
 biovolume = 7.08

COLLECTION 522

AV	PER	CUPER
20	0.315	0.315
15	0.157	0.470
12	0.145	0.614
5	0.067	0.675
5	0.061	0.765
5	0.048	0.783
5	0.035	0.810
5	0.036	0.855
5	0.036	0.892
2	0.024	0.918
2	0.024	0.940
2	0.024	0.964
2	0.024	0.988
1	0.012	1.000

NUMBER OF SPECIES = 14
 NUMBER OF INDIVIDUALS = 33

		PAPEFACTION				
2.955	10.301	12.253	13.357	13.602		
13.723	13.843	13.904				

PLCT OF N SPECIES (ACROSS PAGE) AGAINST H OF INDIVIDUALS



COLLECTION NUMBER 521

DENSITY 15.90

% other organisms = 0
 % other brachiopods = 20.55
 % spirifers = 8.68
 % smooth spirifers = 17.35
 % non-trail productids = 12.79
 % trail productids = 0
 % juveniles = 21.46
 % bivalves = 19.18

OTHER STOPHS 2
 LEPTAENID 1
 OTHER ORTHID 7
 SCHIZOPHORIA 5
 PUGNAX 7
 PLEUROPUGHOIDES 21
 DIELASMA 2
 SPIRIFER 19
 OTHER SMOOTH SPIRIF 8
 MARTINIA 8
 ATHYRID 3
 PHRICODOTHYRIS 2
 RETICULARIA 1
 BRACHYTHYRIS 11
 CRURITHYRIS 5

COLLECTION 521

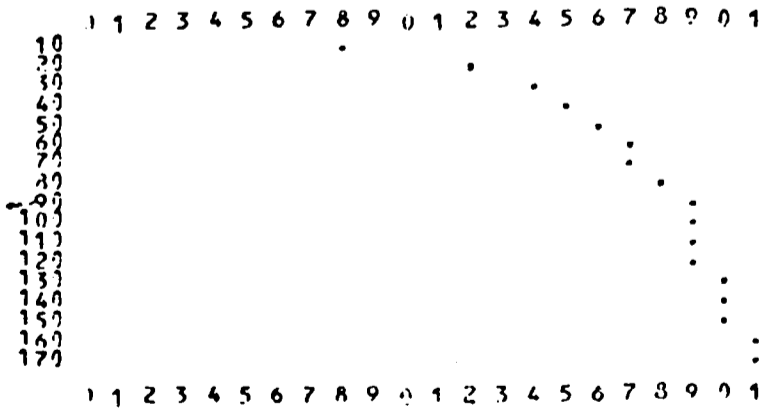
AV	PER	CUPED
42	0.244	0.244
23	0.122	0.366
19	0.110	0.477
19	0.110	0.587
11	0.064	0.651
8	0.047	0.698
8	0.047	0.744
7	0.041	0.785
7	0.041	0.826
6	0.035	0.860
5	0.029	0.890
5	0.029	0.919
3	0.017	0.936
3	0.017	0.942
2	0.012	0.959
2	0.012	0.971
1	0.006	0.977
1	0.006	0.981
1	0.006	0.982
1	0.006	0.994
1	0.006	1.000

OTHER PRODUCTID 1
 GUASIAVONIA 19
 PRODUCTINA 1
 GVERTGNIA 1
 EOMARGINIFERA 6
 BAEY BRACHS 47
 SMOOTH PECTINIDS 42
 average maximum size = .5857 cms
 biovolume = 9.3

NUMBER OF SPECIES = 21
 NUMBER OF INDIVIDUALS = 172

RAREFACTION				
3.128	11.977	14.186	15.256	16.070
10.857	17.477	18.116	18.616	18.907
10.198	19.488	19.770	20.070	20.360
20.651	20.942			

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 520

DENSITY 81.20
 AMT BRYOZOA CM2/KG 2.40

GASTROPODS 9

OTHER STOPHS 4
 ORTHOTETES 9
 SCHELLWIENELLA 2
 SCHUCHERTELLA 30
 LEPTAENID 3
 OTHER ORTHID 2
 PUGNAX 6
 PLEUROPUGNOIDES 41

other organisms = 3.83
 other brachiopods = 41.28
 spirifers = 10.21
 smooth spirifers = 18.72
 non-trail productids = 6.81
 trail productids = 1.28
 juveniles = 0
 bivalves = 17.87

SPIRIFER 24

MARTINIA 6
 ATHYRID 5
 BRACHYTHYRIS 23
 CRUR THYRIS 10

COLLECTION 520

AV	PER	CUPFR
.41	0.174	0.174
.37	0.157	0.332
.30	0.124	0.460
.24	0.102	0.552
.23	0.093	0.650
.10	0.043	0.702
.9	0.038	0.740
.9	0.038	0.779
.7	0.031	0.809
.0	0.026	0.834
.0	0.026	0.860
.5	0.021	0.881
.5	0.021	0.902
.5	0.021	0.923
.4	0.017	0.940
.3	0.013	0.953
.3	0.013	0.966
.3	0.013	0.979
.2	0.009	0.987
.2	0.009	0.996
.1	0.004	1.000

QUASIAVONIA 3
 PRODUCTINA 1
 PUSTULA 5
 LINOPRODUCTID 3
 EOMARGINIFERA 7

SMOOTH PECTINIDS 37
 PTEROMOPHS 5

NUMBER OF SPECIES = 21
 NUMBER OF INDIVIDUALS = 235
 average maximum size = 1.591 cms
 biovolume = 129.2

PERCENTAGE				
3.33	11.809	14.638	16.617	17.830
5.74	19.170	19.702	19.615	20.128
13.40	20.511	20.553	20.506	20.638
21.631	20.723	20.766	20.609	20.851
21.894	20.936	20.979		

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 518

DENSITY 17.20

other organisms = 0
 other brachiopods = 43.75
 spirifers = 0
 smooth spirifers = 11.46
 non-trail productids = 15.62
 trail productids = 3.12
 juveniles = 13.54
 bivalves = 12.50

OTHER ORTHID 2
 PUGNAX 4
 PLEUROPUGNOIDES 35
 DIELASMA 1

MARTINIA 4
 ATHYRID 2
 BRACHYTHYRIS 5

OTHER PRODUCTID 3
 PRODUCTINA 4
 AVONIA 2
 PLICATIFERA 1
 LINOPRODUCTID 2
 KRCTOVIA 3
 EOMARGINIFERA 3

BABY BRACHS 13
 SMOOTH PECTINIDS 11
 PTERIDOPHS 1

COLLECTION 518

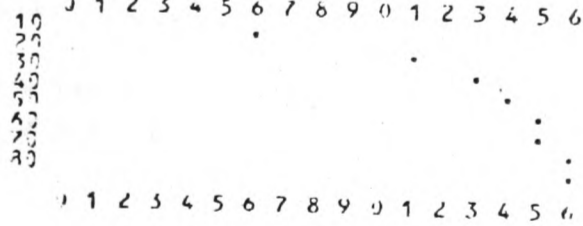
AV	PER	CUPER
35	0.422	0.422
11	0.133	0.554
5	0.069	0.614
4	0.048	0.663
4	0.048	0.711
3	0.036	0.759
3	0.036	0.795
3	0.036	0.831
3	0.036	0.867
2	0.024	0.892
2	0.024	0.916
2	0.024	0.940
1	0.012	0.964
1	0.012	0.976
1	0.012	0.988
1	0.012	1.000

NUMBER OF SPECIES = 16
 NUMBER OF INDIVIDUALS = 87

average maximum size = .4155 cms
 biovolume = 7.15

3.458 10.711 12.976 14.301 14.807
 15.169 15.530 15.892

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



1

COLLECTION NUMBER 509

DENSITY 63.50

% other organisms = 9.34
 % other brachiopods = 15.
 % spirifers = 8.17
 % smooth spirifers = 10.8

CORALS 1
 TRILOBITES 2
 GASTROPODS 14
 OTHERS 7

% other organisms = 9.34
 % other brachiopods = 15.18
 % spirifers = 8.17
 % smooth spirifers = 10.89
 % non-trail productids = 12.84
 % trail productids = 11.28
 % juveniles = 5.84
 % bivalves = 26.46

OTHER STOPHS 15
 SCHELLWIENELLA 2
 SCHUCHERTELLA 2
 LEPTAENID 1
 SCHIZOPHORIA 12
 PLEUROPUGNOIDES 2
 DIELASMA 5

SPIRIFER 21

OTHER SMOOTH SPIRIF 14
 MARTINIA 2
 BRACHYTHYRIS 12

COLLECTION 509

AV	PER	CUPER
63	0.281	0.241
21	0.087	0.368
16	0.066	0.434
15	0.062	0.496
14	0.058	0.554
14	0.058	0.612
14	0.058	0.669
12	0.051	0.719
12	0.051	0.769
11	0.045	0.814
7	0.029	0.863
5	0.021	0.864
4	0.017	0.840
4	0.017	0.897
3	0.012	0.909
3	0.012	0.921
2	0.008	0.930
2	0.008	0.938
2	0.008	0.946
2	0.008	0.955
2	0.008	0.963
2	0.008	0.971
2	0.008	0.979
2	0.008	0.988
1	0.004	0.992
1	0.004	0.996
1	0.004	1.000

OTHER PRODUCTID 2
 QUASIAVONIA 4
 PRODUCTINA 4
 PUSTULA 3
 PLICATIFERA 2
 LINOPRODUCTID 11
 ANTIQUATONIA 16
 KROTOVIA 1
 OVERTONIA 2
 CHONETIPUSTULA 3
 EOMARGINIFERA 14

BABY BRACHS 15

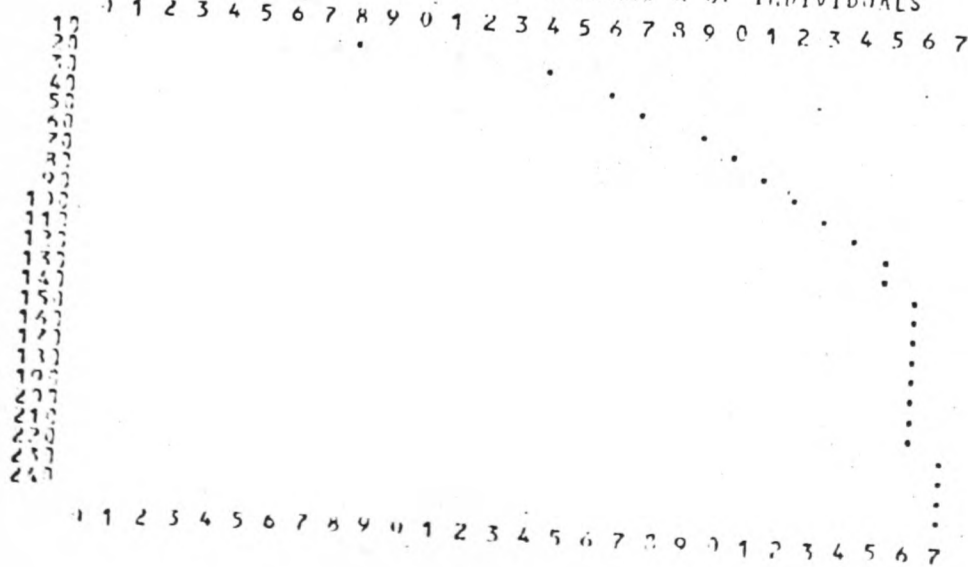
SMOOTH PECTINIDS 68

NUMBER OF SPECIES = 27
 NUMBER OF INDIVIDUALS = 242

average maximum size = 1.393 cms
 biovolume = 88.4

RARIFICATION				
3.100	13.612	15.574	17.261	18.813
21.142	21.251	22.204	23.066	23.851
24.636	25.421	25.612	25.736	25.860
25.933	26.107	26.251	26.355	26.479
25.693	26.727	26.651	26.675	

PLCT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 508

DENSITY 56.80
 AMT BRYOZOA CM2/KG 1.18

GASTROPODS 7
 OTHERS 3

OTHER STROPHS 3
 LEPTAENID 3

SPIRIFER 4

OTHER SMOOTH SPIRIF 10
 ATHYRID 2
 BRACHYTHYRIS 4

OTHER PRODUCTID 15
 QUASIAVONIA 24
 PLICATIFERA 3
 KROTOVIA 12
 EOPARGINIFERA 15
 ECHINOCHONCUS 3

BABY BRACHS 16

SMOOTH PECTINIDS 7

- X other organisms = 7.63
- X other brachiopods = 4.58
- X spirifers = 3.05
- X smooth spirifers = 12.21
- X non-trail productids = 50.38
- X trail productids = 4.58
- X juveniles = 12.21
- X bivalves = 5.34

COLLECTION 508

AV	PER	CUPEP
24	0.209	0.214
15	0.130	0.334
15	0.130	0.470
12	0.104	0.574
10	0.087	0.661
7	0.061	0.722
7	0.061	0.743
4	0.035	0.817
4	0.035	0.852
3	0.026	0.877
3	0.026	0.904
3	0.026	0.950
3	0.026	0.957
3	0.026	0.943
2	0.017	1.000

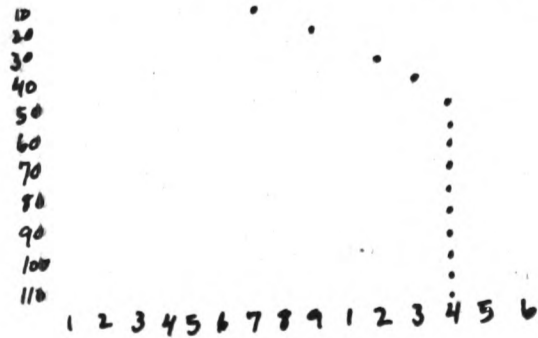
NUMBER OF SPECIES = 15
 NUMBER OF INDIVIDUALS = 115

average maximum size = 1.048 cms
 biovolume = 59.5

Rarefaction

8.26 11.34 13.48 14.68 15.04
 15.04 15.04 15.04 15.04 15.04
 15.04

1 2 3 4 5 6 7 8 9 1 2 3 4 5 6



COLLECTION NUMBER 505

DENSITY 31.10

other organisms = 0
 other brachiopods = 21.48
 spirifers = 8.89
 smooth spirifers = 23.7
 non-trail productids = 11.85
 trail productids = 6.67
 juveniles = 4.44
 bivalves = 22.96

OTHER STOPHS 4
 LEPTAENID 2
 OTHER ORTHID 2
 RHIPIDOWELLA 1
 SCHIZOPHORIA 11
 PUGNAX 1
 PLEUROPUGNOIDES 8
 SPIRIFER 12
 MARTINIA 8
 ATHYRID 1
 PHRICODOTHYRIS 1
 RETICULARIA 4
 CRUR THYRIS 17
 RETZIID 1

COLLECTION 505

AV	PER	COPER
31	0.240	0.240
17	0.132	0.372
12	0.095	0.465
11	0.085	0.550
8	0.062	0.612
8	0.062	0.674
4	0.031	0.736
4	0.031	0.798
4	0.031	0.829
4	0.031	0.860
3	0.023	0.891
3	0.023	0.915
2	0.016	0.930
2	0.016	0.946
2	0.016	0.961
1	0.008	0.977
1	0.008	0.984
1	0.008	0.992
1	0.008	1.000

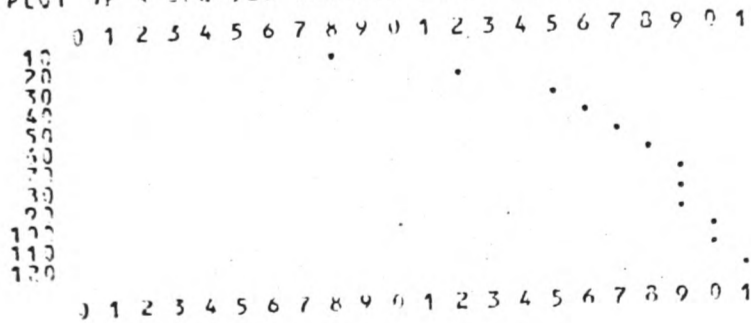
QUASIAVONIA 8
 PRODUCTINA 4
 PPLICATIFERA 4
 LINOPRODUCTID 3
 ANTIQUATONIA 2
 EOMARGINIFERA 4
 BABY BRACHS 6
 SMOOTH PECTINIDS 31

NUMBER OF SPECIES = 21
 NUMBER OF INDIVIDUALS = 120

average maximum size = .7195 cms
 biovolume = 22.4

RAREFACTION				
3.274	12.271	14.007	16.341	17.264
13.115	18.713	19.191	19.458	19.876
21.264	20.651			

PLOT OF N SPECIES (ACROSS PAGE) AGAINST M OF INDIVIDUALS



COLLECTION NUMBER 504

DENSITY 43.10

CORALS 2
 TRILODITES 3
 GASTROPODS 4
 CEPHALOPODS 1

% other organisms = 5.49
 % other brachiopods = 31.32
 % spirifers = 6.04
 % smooth spirifers = 13.74
 % non-trail productids = 14.29
 % trail productids = .55
 % juveniles = 14.29
 % bivalves = 14.29

OTHER STOPHS 32
 ORTHOT 2
 SCHUCHERTELLA 2
 OTHER ORTHID 7
 SCHIZOPHORIA 10
 PLEUROPUGNOIDES 2
 DIELASMA 2

SPIRIFER 11

MARTINIA 5
 PHRICODOTHYRIS 1
 ERACHYTHYRIS 12
 CRUR THYRIS 7

COLLECTION 504

AV	PER	CUPER
3	0.205	0.205
2	0.167	0.372
1	0.077	0.249
11	0.071	0.519
10	0.064	0.583
9	0.053	0.641
8	0.045	0.686
7	0.045	0.731
6	0.038	0.769
5	0.032	0.801
4	0.026	0.827
3	0.019	0.846
2	0.019	0.865
1	0.013	0.885
1	0.013	0.897
1	0.013	0.910
1	0.013	0.923
1	0.013	0.936
1	0.013	0.949
1	0.013	0.962
1	0.013	0.974
1	0.006	0.981
1	0.006	0.987
1	0.006	0.994
1	0.006	1.000

OTHER PRODUCTID 2
 GUASIAVONIA 9
 PRODUCTINA 6
 PUSTULA 3
 LINOPRODUCTID 1
 KROTOVIA 3
 CVERTONIA 1
 EOMARGINIFERA 2

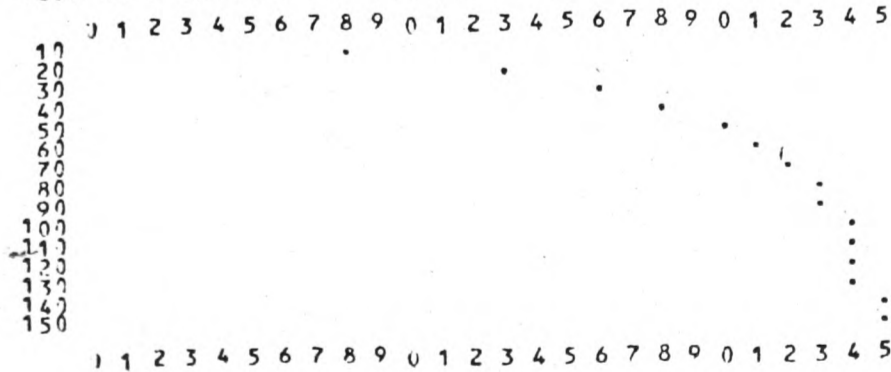
BABY ERACHS 26

SMOOTH PECTINIDS 26
 average maximum size = .9613 cms
 biovolume = 41.4

NUMBER OF SPECIES = 25
 NUMBER OF INDIVIDUALS = 150

RAREFACTION				
1.232	13.179	15.923	17.923	19.654
21.923	22.077	23.051	23.308	23.504
23.821	24.077	24.333	24.590	24.846

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 503

DENSITY 22.90

GASTROPODS 3
 CEPHALOPODS 1

OTHER STOPHS 21
 OTHER ORTHID 3
 RHIPIDOMELLA 19
 SCHIZOPHORIA 12
 PLEUROPUGNOIDES 9
 DIELASMA 3

SPIRIFER 3

OTHER SMOOTH SPIRIF 8
 MARTINIA 8
 ATHYRID 4
 PHACODOTHYRIS 2
 BRACHYTHYRIS 10
 CRUP THYRIS 1

other organisms = 2.47
 other brachiopods = 41.36
 spirifers = 1.85
 smooth spirifers = 20.37
 non-trail productids = 8.64
 trail productids = 5.56
 juveniles = 15.43
 bivalves = 4.32

OTHER PRODUCTID 7
 QUASIAVONIA 4
 PRODUCTINA 1
 PUSTULA 2
 PPLICATIFERA 1
 LIOPRODUCTID 8

BAEY BRACHS 25

SMOOTH PECTINIDS 7

average maximum size = .8378 cms
 biovolume = 19.2

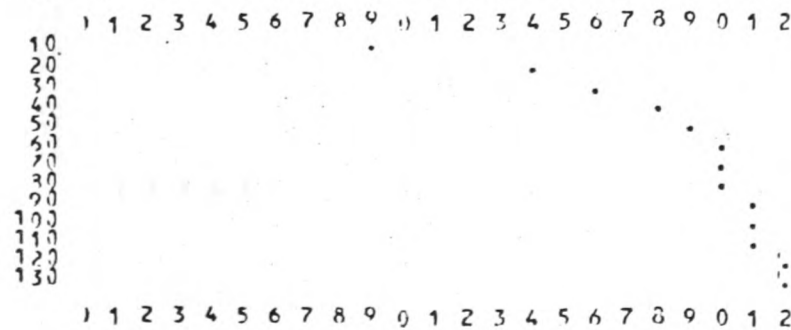
COLLECTION 503

A''	PER	CUPFP
21	0.153	0.153
19	0.139	0.292
12	0.038	0.340
10	0.073	0.453
8	0.066	0.518
8	0.054	0.577
8	0.054	0.635
3	0.054	0.693
7	0.051	0.745
7	0.051	0.796
4	0.029	0.825
4	0.029	0.854
3	0.022	0.876
3	0.022	0.898
3	0.022	0.920
3	0.022	0.942
2	0.015	0.956
2	0.015	0.971
1	0.007	0.978
1	0.007	0.985
1	0.007	0.993
1	0.007	1.000

NUMBER OF SPECIES = 22
 NUMBER OF INDIVIDUALS = 137

PAREFACTION				
9.030	14.088	16.131	17.850	18.920
19.504	20.044	20.330	20.628	20.920
21.212	21.504	21.796		

PLOT OF 4 SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 502

DENSITY 23.10
 AMT BRYOZOA CM2/KG 3.44

TRILOBITES 2
 GASTROPODS 1
 CEPHALOPODS 1

other organisms = 3.08
 other brachiopods = 13.08
 spirifers = 6.92
 smooth spirifers = 3.08
 non-trail productids = 23.08
 trail productids = 4.62
 juveniles = 13.85
 bivalves = 32.32

OTHER STROPHS 3
 SCHELLWIENELLA 4
 LEPTAENID 1
 RHIPIDOMELLA 2
 SCHIZOPHORIA 7

SPIRIFER 9

PHRICODOTHYRIS 1
 BRACHYTHYRIS 3

COLLECTION 502

AV	PER	CUPER
41	0.366	0.366
14	0.125	0.491
9	0.080	0.571
9	0.080	0.652
7	0.063	0.714
4	0.036	0.750
3	0.027	0.777
3	0.027	0.804
3	0.027	0.830
3	0.027	0.857
3	0.027	0.884
2	0.018	0.902
2	0.018	0.920
2	0.018	0.937
1	0.009	0.946
1	0.009	0.955
1	0.009	0.964
1	0.009	0.973
1	0.009	0.982
1	0.009	0.991
1	0.009	1.000

OTHER PRODUCTID 9
 QUASIAVONIA 14
 PRODUCTINA 1
 AVONIA 3
 PLICATIFERA 3
 LINOPRODUCTID 2
 KROTOVIA 3
 BUXTONIA 1

EAERY BRACHS 18

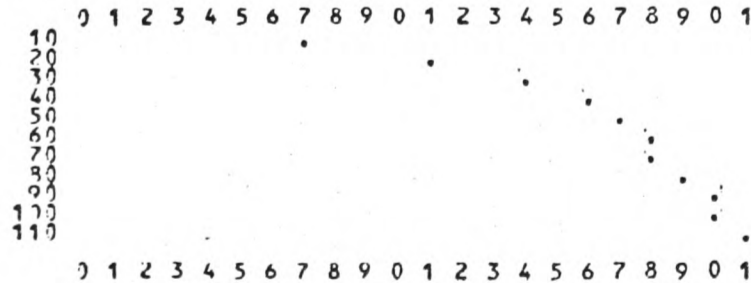
SMOOTH PECTINIDS 41
 PTEROMOPHS 1

NUMBER OF SPECIES = 21
 NUMBER OF INDIVIDUALS = 112

average maximum size = .7013
 biovolume = 16.2

RARFFACTION				
7.089	10.714	13.500	15.643	16.804
17.750	18.375	19.000	19.625	20.250
20.275				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



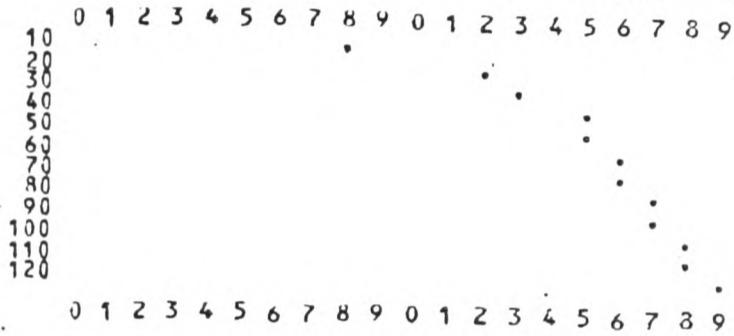
COLLECTION 501

AV	PER	CUPER
33	0.214	0.214
10	0.141	0.418
9	0.071	0.516
8	0.070	0.516
7	0.070	0.516
6	0.065	0.636
5	0.055	0.719
4	0.055	0.719
3	0.054	0.813
2	0.054	0.832
1	0.051	0.843
0	0.025	0.906
0	0.025	0.930
0	0.025	0.933
0	0.008	0.961
0	0.008	0.969
0	0.008	0.977
0	0.004	0.984
0	0.004	0.992
0	0.008	1.000

NUMBER OF SPECIES = 19
 NUMBER OF INDIVIDUALS = 123

RAREFACTION				
7.625	11.551	13.453	14.687	15.344
15.812	16.281	16.750	17.219	17.687
18.156	18.625			

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER	501
DENSITY	27.30
AMT BRYOZOA CM ² /KG	3.46
GASTROPODS	4
OTHER STOPHS	8
LEPTAENID	3
PHIPIDOMELLA	1
SCHIZOPHORIA	1
PUGNAX	9
PLEUROPUGNOIDES	10
SPIRIFER	9
MARTINIA	3
ATHYRID	1
BRACHYTHYRIS	5
CPUR THYRIS	1
OTHER PRODUCTID	1
QUASIAVONIA	19
PLICATIFERA	7
LINOPRODUCTID	5
CHONETIPIUSTULA	3
BABY BRACHS	50
SMOOTH PECTINIDS	37
PTEROMOPHS	1

% other organisms = 2.25
 % other brachiopods = 17.98
 % spirifers = 5.06
 % smooth spirifers = 5.62
 % non-trail productids = 12.92
 % trail productids = 6.74
 % juveniles = 28.09
 % bivalves = 21.35

average maximum size = .6978 cms
 biovolume = 19.0

COLLECTION NUMBER 500

DENSITY 50.7

CORALS 1
 TRILOBITES 2
 GASTROPODS 15
 CEPHALOPODS 1
 OTHERS 5

%Other organisms = 15.76
 %Other brachiopods = 15.76
 %Spirifers = 4.24
 %Smooth spirifers = 13.33
 %Non-trail productids = 24.24
 %Trail productids = 3.03
 %Juveniles = 0
 %Bivalves = 23.64

OTHER STROMA 6
 SCHELLWINKELLA 1
 LEPTAENID 4
 SCHIZOPHOKIA 5
 PUGNAX 5
 PLEUROPUGNOIDES 4
 DIELASMA 1

SPIRIFER 7

MARTINIA 2
 PHRECODOTHYRIS 1
 RETICULARIA 2
 OTHER BRACHYTHYRID 11
 CRURITHYRIS 6

COLLECTION 500

AV	PER	CUPER
35	0.212	0.212
17	0.103	0.315
15	0.091	0.406
11	0.067	0.473
10	0.061	0.533
7	0.042	0.576
6	0.036	0.612
6	0.036	0.648
6	0.036	0.685
5	0.030	0.715
5	0.030	0.745
5	0.030	0.776
4	0.024	0.800
4	0.024	0.824
4	0.024	0.848
4	0.024	0.873
4	0.024	0.897
4	0.024	0.921
3	0.018	0.939
2	0.012	0.952
2	0.012	0.964
1	0.006	0.970
1	0.006	0.976
1	0.006	0.982
1	0.006	0.988
1	0.006	0.994
1	0.006	1.000

OTHER PRODUCTID 10
 PRODUCTINA 17
 PUSTULA 4
 LINOPRODUCTID 4
 ANTIQUATONIA 1
 KROTOVIA 6
 CHONETIPUSTULA 3

SMOOTH PECTINIDS 35
 PTERIDOMORPHS 4

average maximum size = .6895 cms
 biovolume = 39.1

NUMBER OF SPECIES = 27
 NUMBER OF INDIVIDUALS = 165

RAREFACTION				
1.848	14.333	13.455	20.970	21.939
22.636	23.242	23.848	24.273	24.636
25.000	25.364	25.727	26.091	26.455
24.818				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



DENSITY 16.80

GASTROPODS 1

other organisms = .84
 other brachiopods = 21.85
 spirifers = 2.52
 smooth spirifers = 23.53
 non-trail productids = 5.88
 trail productids = 3.36
 juveniles = 3.36
 bivalves = 38.66

ORTHOT. 4
 LEPTAENID 1
 RHIPIDOMELLA 3
 SCHIZOPHORIA 5
 PUGNAX 5
 PLEUROPUGNOIDES 8

SPIRIFER 3

OTHER SMOOTH SPIRIF 5
 MARTINIA 5
 ATHYRID 6
 PHRICODOTHYRIS 3
 BRACHYTHYRIS 5
 CRURLIHYRIS 4

COLLECTION 497

AV	PER	CUPER
4.5	0.391	0.391
6	0.0711	0.461
5	0.052	0.513
5	0.043	0.557
5	0.043	0.600
5	0.043	0.643
4	0.043	0.687
4	0.035	0.722
4	0.035	0.757
4	0.035	0.791
4	0.035	0.826
3	0.026	0.852
3	0.026	0.878
3	0.026	0.904
3	0.026	0.930
3	0.026	0.957
1	0.009	0.965
1	0.009	0.974
1	0.009	0.983
1	0.009	0.991
1	0.009	1.000

QUASIAVONIA 4
 LINOPRODUCTID 3
 OVERTONIA 3
 ECHINOCORCHUS 1

BABY BRACHS 4

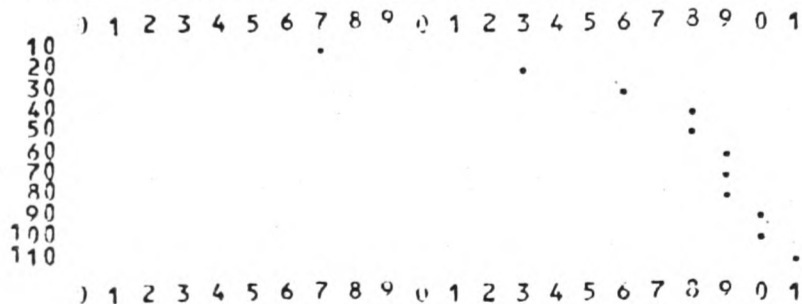
PERNOPECTINS 1
 SMOOTH PECTINIDS 44
 PTEROMOPHS 1

average maximum size = .6100 cms
 biovolume = 10.2

NUMBER OF SPECIES = 21
 NUMBER OF INDIVIDUALS = 115

RAREFACTION				
7.037	12.739	16.217	17.739	18.174
13.509	19.043	19.478	19.913	20.348
21.733				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 496

DENSITY 18.60
 AMT BRYOZOA CM2/KG 9.00

CORALS 6
 GASTROPODS 6

LEPTAENID 1
 SCHIZOPHORIA 4
 PLEUROPUGNOIDES 13
 DIELASMA 2

SPIRIFER 5

OTHER SMOOTH SPIRIF 1
 MARTINIA 2
 ATHYRID 4
 PHRICODOTHYRIS 1
 RETICULARIA 5
 BRACHYTHYRIS 4
 CRURITHYRIS 1
 MUSTIDIA 1

other organisms = 7.5
 other brachiopods = 12.5
 spirifers = 3.13
 smooth spirifers = 11.88
 non-trail productids = 36.25
 trail productids = 4.38
 juveniles = 16.25
 bivalves = 8.13

COLLECTION 496

AV	PER	CUPER
20	0.149	0.149
15	0.112	0.261
13	0.097	0.358
13	0.097	0.455
11	0.082	0.537
0	0.045	0.582
0	0.045	0.627
5	0.037	0.664
5	0.037	0.701
5	0.037	0.739
4	0.030	0.769
4	0.030	0.799
4	0.030	0.828
4	0.030	0.858
4	0.030	0.888
2	0.015	0.903
2	0.015	0.918
2	0.015	0.933
1	0.007	0.940
1	0.007	0.948
1	0.007	0.955
1	0.007	0.963
1	0.007	0.970
1	0.007	0.978
1	0.007	0.985
1	0.007	0.993
1	0.007	1.000

OTHER PRODUCTID 11
 QUASIAVONIA 15
 PRODUCTINA 20
 AVONIA 1
 PUSTULA 4
 PLICATIFERA 1
 LINOPRODUCTID 4
 KROTOVIA 1
 OVERTONIA 1
 EOMARGINIFERA 5
 ECHINCHONCHUS 2

BABY BRACHS 26

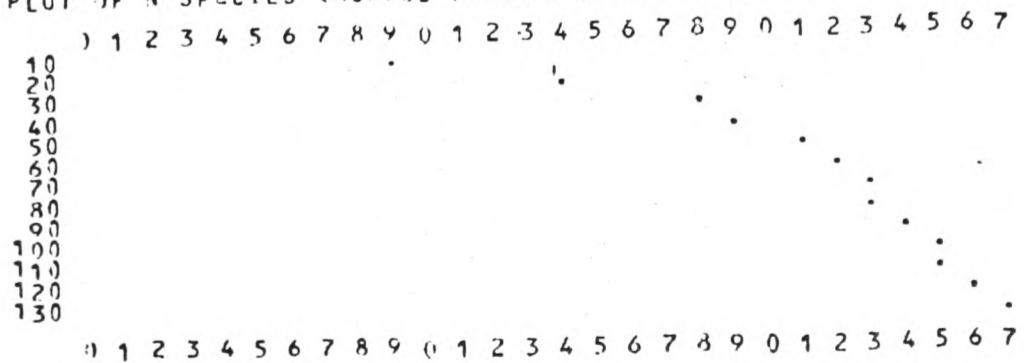
SMOOTH PECTINIDS 13

average maximum size = .8814 cms
 biovolume = 16.4

NUMBER OF SPECIES = 27
 NUMBER OF INDIVIDUALS = 134

PAREFACTION				
0.338	14.254	17.836	19.478	20.597
21.716	22.701	23.373	24.045	24.716
25.338	26.060	26.731		

PLOT OF N SPECIES (ACROSS PAGE) AGAINST H OF INDIVIDUALS



COLLECTION NUMBER 495

DENSITY 16.30

CORALS 1
 TRILOBITES 1
 GASTROPODS 5
 OTHERS 1

%Other organisms = 5.71
 %Other brachiopods = 17.86
 %Spirifers = 3.57
 %Smooth spirifers = 17.86
 %Non-trail productids = 17.86
 %Trail productids = 7.86
 %Juveniles = 4.29
 %Bivalves = 14.21

OTHER STROMA 3
 LEPTAENID 7
 OTHER ORTHID 5
 SCHIZOPHORIA 3
 PLEUROPUENCOIDES 2

SPIRIFER 5

MARTINIA 2
 ATHYRID 1
 PHRIGODOTHYRIS 1
 BRACHYTHYRIS 17
 CURVITHYRIS 3
 RETZIID 1

COLLECTION 495

AV	PER	CUPER
35	0.263	0.263
17	0.128	0.391
12	0.090	0.431
9	0.068	0.549
9	0.068	0.617
3	0.060	0.677
7	0.053	0.729
5	0.033	0.767
5	0.033	0.805
5	0.033	0.842
4	0.030	0.872
3	0.023	0.895
3	0.023	0.917
2	0.015	0.932
2	0.015	0.947
1	0.003	0.955
1	0.003	0.962
1	0.003	0.970
1	0.003	0.977
1	0.003	0.985
1	0.003	0.992
1	0.003	1.000

OTHER PRODUCTID 4
 QUASIAVONIA 12
 PLOCATIFERA 9
 LENOPRODUCTID 2
 EOMARGINIFERA 9

BABY BRACHS 6

SMOOTH PECTINIDS 35

average maximum size = .9294 cms
 biovolume = 15.1

NUMBER OF SPECIES = 22
 NUMBER OF INDIVIDUALS = 133

RAREFACTION				
1.090	12.414	14.737	16.113	17.135
17.962	18.684	19.211	19.737	20.263
21.739	21.316	21.342		

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER	696
DENSITY	27.50
TRILOBITES	2
GASTROPODS	1
CEPHALOPODS	2
OTHERS	1

%Other organisms = 6.32
 %Other brachiopods = 15.79
 %Spirifers = 4.21
 %Smooth spirifers = 37.37
 %Non-trail productids = 5.79
 %Trail productids = 2.63
 %Juveniles = 13.68
 %Bivalves = 14.21

OTHER SPIRIFERS	4
LEPTAEMID	1
OTHER ORTHID	3
SCHIZOPHORIA	13
PUGNAX	1
PLEUROPUGNOIDES	2
DIPLASHA	6

SPIRIFER	3
----------	---

COLLECTION 494

AV	PEP	CUPEP
27	0.165	0.165
21	0.123	0.293
16	0.098	0.390
14	0.085	0.476
13	0.079	0.555
12	0.075	0.628
8	0.049	0.677
3	0.049	0.726
0	0.057	0.762
0	0.057	0.799
4	0.024	0.823
3	0.013	0.841
3	0.013	0.860
3	0.013	0.878
2	0.012	0.890
2	0.012	0.902
2	0.012	0.915
2	0.012	0.927
2	0.012	0.939
2	0.012	0.951
2	0.012	0.963
1	0.006	0.970
1	0.006	0.976
1	0.006	0.982
1	0.006	0.988
1	0.006	0.994
1	0.006	1.000

OTHER SMOOTH SPIRIF	14
MARTINIA	3
ATHYRID	2
PHRICODOTHYRIS	12
RETICULARIA	2
BRACHYTHYRIS	16
CRURATHYRIS	21
HUSTIDIA	1

OTHER PRODUCTID	6
PUSIUEA	2
PLICATIFERA	2
LINOPRODUCTID	2
ANTIQUATONIA	1
ECOMARGINIFERA	3

BAY BRACHS	26
------------	----

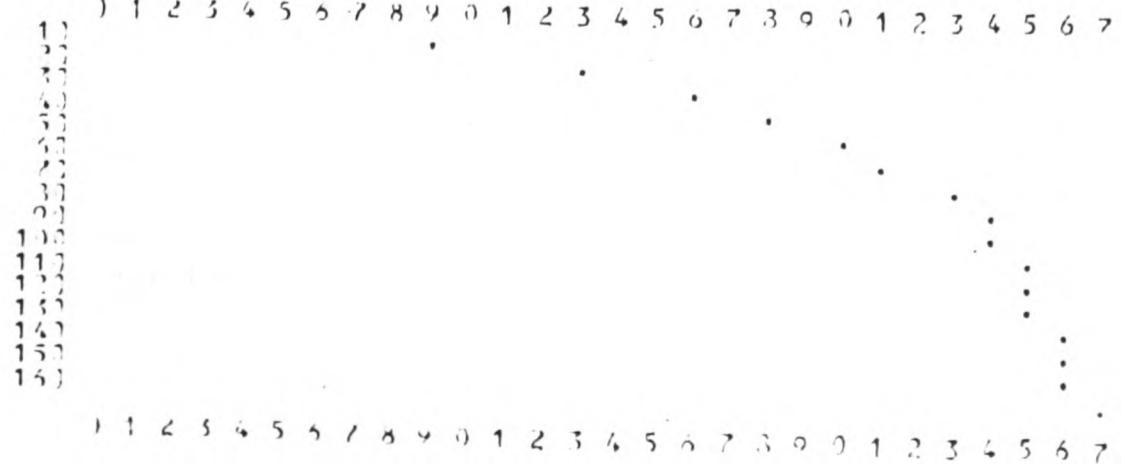
SMOOTH PECTINIDS	27
------------------	----

NUMBER OF SPECIES = 27
 NUMBER OF INDIVIDUALS = 164

average maximum size = .6683 cms
 biovolume = 18.2

RAREFACTION				
0.075	13.459	16.037	18.049	19.841
21.317	22.557	23.756	24.263	24.650
25.024	25.590	25.756	26.122	26.483
26.854				

PLT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



DENSITY 55.30

GASTROPODS 1

OTHER STROPHS 9
 LEPTAENID 2
 RHIPIDOMELLA 16
 SCHIZOPHORIA 53
 PLEUROPUGNOIDES 5
 DIELASMA 1

SPIRIFER 19

MARTINIA 9
 ATHYRID 3
 PHRICODOTHYRIS 7
 RETICULARIA 4
 BRACHYTHYRIS 1
 CRUR THYRIS 8

OTHER PRODUCTID 12
 QUASIAVONIA 5
 PRODUCTINA 6
 AVONIA 5
 PLICATIFERA 1
 LINOPRODUCTID 9
 KROTOVIA 3
 EOMARGINIFERA 7

BABY BRACHS 23

SMOOTH PECTINIDS 15

average maximum size = 1.2816 cms
 biovolume = 70.9

% other organisms = .45
 % other brachiopods = 38.39
 % spirifers = 8.48
 % smooth spirifers = 14.29
 % non-trail productids = 16.96
 % trail productids = 4.46
 % juveniles = 10.27
 % bivalves = 6.7

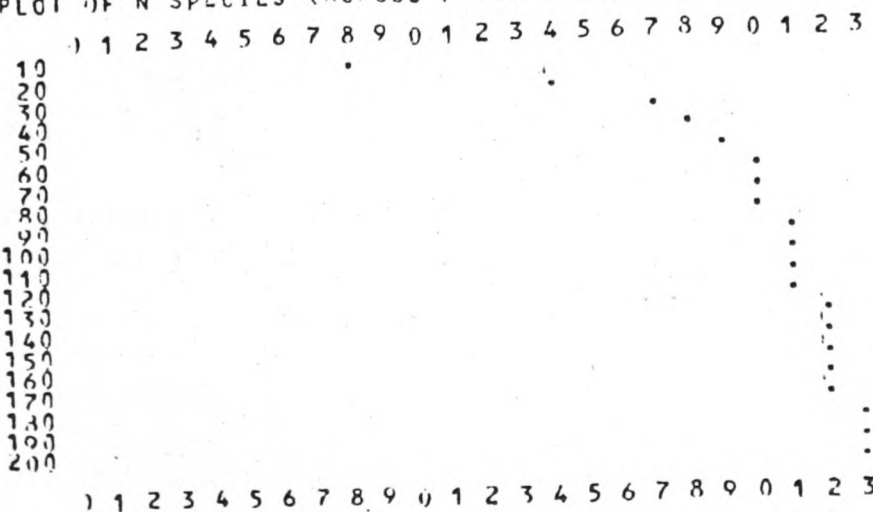
COLLECTION 493

AV	PER	CUPER
53	0.264	0.264
19	0.095	0.358
16	0.080	0.438
15	0.075	0.512
12	0.060	0.572
9	0.045	0.617
9	0.045	0.662
9	0.045	0.716
3	0.040	0.746
3	0.035	0.781
3	0.035	0.816
3	0.030	0.846
3	0.025	0.871
3	0.025	0.896
3	0.025	0.920
4	0.020	0.940
3	0.015	0.955
3	0.015	0.970
3	0.010	0.980
1	0.005	0.985
1	0.005	0.990
1	0.005	0.995
1	0.005	1.000

NUMBER OF SPECIES = 23
 NUMBER OF INDIVIDUALS = 201

RAREFACTION				
3.303	13.557	16.522	18.160	18.980
10.532	20.000	20.388	20.637	20.985
21.119	21.388	21.567	21.766	21.985
22.134	22.383	22.562	22.761	22.980

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 492

DENSITY 31.70

CORALS 1
GASTROPODS 2

CRANIA 1

OTHER STROPHS 6
LEPTAENID 1
OTHER RHYNCH 2
PUGNAX 3
PLEUROPUGNOIDES 3

SPIRIFER 9

OTHER SMOOTH SPIRIF 1
MARTINIA 1
ATHYRID 9
PHRICODOTHYRIS 8
BRACHYTHYRIS 11

OTHER PRODUCTID 3
QUASIAVONIA 18
PRODUCTINA 1
AVONIA 3
PLICATIFERA 3
LINOPRODUCTID 12
KROTOVIA 2
EOMARGINIFERA 6

BABY BRACHS 13

SMOOTH PECTINIDS 32

average maximum size = .7670 cms
biovolume = 24.3

other organisms = 2.65
other brachiopods = 9.93
spirifers = 5.96
smooth spirifers = 19.87
non-trail productids = 21.85
trail productids = 9.93
juveniles = 8.61
bivalves = 21.19

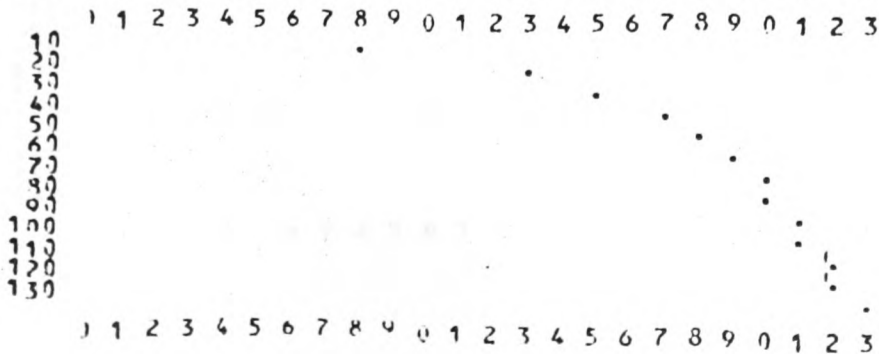
COLLECTION 492

AV	PER	CUPER
32	0.232	0.232
30	0.133	0.362
12	0.087	0.449
11	0.080	0.529
9	0.065	0.594
9	0.065	0.659
8	0.058	0.717
8	0.043	0.761
8	0.043	0.804
8	0.022	0.826
8	0.022	0.848
8	0.022	0.870
8	0.022	0.891
8	0.022	0.913
8	0.014	0.928
8	0.014	0.942
8	0.014	0.957
8	0.007	0.966
8	0.007	0.971
8	0.007	0.978
8	0.007	0.986
8	0.007	0.993
8	0.007	1.000

NUMBER OF SPECIES = 23
NUMBER OF INDIVIDUALS = 138

RAREFACTION				
1.377	12.652	14.870	16.826	18.348
10.217	20.043	20.478	20.913	21.348
21.733	22.217	22.652		

PLOT OF N SPECIES (ACROSS PAGE) AGAINST H OF INDIVIDUALS



COLLECTION NUMBER 491

DENSITY 30.90

GASTROPODS 1

CRANIA 1

OTHER STROPHS 5

LEPTAENID 5

LEPTAGONIA 1

RHIPIDOMELLA 4

PUGNAX 4

DIELASMA 10

SPIRIFER 16

TYLOTHYRIS 1

OTHER SMOOTH SPIRIF 1

ATHYRID 4

BRACHYTHYRIS 9

EXUR THYRIS 3

OTHER PRODUCTID 9

QUASIAVONIA 18

PRODUCTINA 15

AVONIA 2

PLICATIFERA 6

LINOPRODUCTID 15

ANTIQUATONIA 5

EUXTONIA 1

CHONETIPUSTULA 3

BABY BRACHS 4

SMOOTH PECTINIDS 24

average maximum size = .7468 cms
biovolume = 23.1

- % other organisms = 1.2
- % other brachiopods = 17.37
- % spirifers = 10.18
- % smooth spirifers = 10.18
- % non-trail productids = 28.14
- % trail productids = 16.17
- % juveniles = 2.40
- % bivalves = 14.37

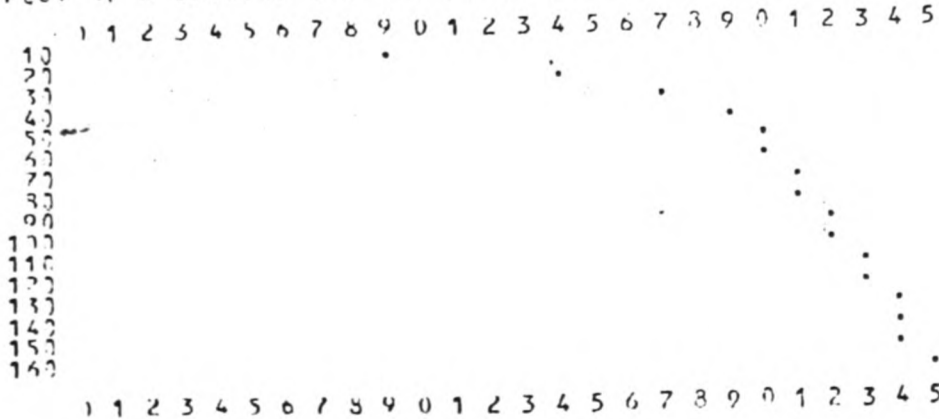
COLLECTION 491

AV	PER	CUPEP
24	0.146	0.146
14	0.110	0.256
10	0.094	0.354
15	0.091	0.443
15	0.091	0.537
10	0.061	0.598
9	0.055	0.652
9	0.055	0.707
6	0.037	0.744
5	0.030	0.774
5	0.030	0.805
5	0.030	0.855
4	0.024	0.890
4	0.024	0.844
4	0.024	0.909
3	0.018	0.927
3	0.018	0.945
2	0.012	0.957
1	0.006	0.965
1	0.006	0.970
1	0.006	0.976
1	0.006	0.982
1	0.006	0.988
1	0.006	0.994
1	0.006	1.000

NUMBER OF SPECIES = 25
NUMBER OF INDIVIDUALS = 164

	RAFFACTION			
0.434	13.324	16.683	18.505	19.573
11.293	20.841	21.390	21.841	22.268
22.605	23.122	23.549	23.976	24.402
24.829				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



COLLECTION NUMBER 490

DENSITY 21.6

TRILORITES	3
GASTROPODS	2
CEPHALOPODS	1
OTHERS	4

%Other organisms = 7.87
 %Other brachiopods = 18.90
 %Spirifers = 7.09
 %Smooth spirifers = 11.81
 %Non-trail productids = 38.58
 %Trail productids = 4.72
 %Juveniles = 7.09
 % Bivalves = 3.94

OTHER GASTROPODS	1
LEPTAENID	7
OTHER ORTHID	1
SCHIZOPHORIA	12
PLEUROPUGNOLIDES	3
SPIRIFER	9
MARGINIA	1
PHRI COOTHYRIS	1
RETICULARIA	5
ACTINOCCHONCUS	1
CRURID THYRIS	7
OTHER PRODUCTID	1
QUASIAVONIA	22
PRODUCTINA	6
AVONIA	3
PUSFUEA	2
PLICATIFERA	4
PRODUCTUS	2
EOMARGINIFERA	?

COLLECTION 490

AV	PER	CUPFR
22	0.136	0.186
12	0.102	0.248
9	0.076	0.364
3	0.063	0.432
3	0.063	0.500
3	0.063	0.564
7	0.059	0.627
7	0.059	0.686
5	0.042	0.729
4	0.034	0.763
4	0.034	0.797
4	0.034	0.831
3	0.025	0.856
3	0.025	0.881
2	0.017	0.898
2	0.017	0.915
2	0.017	0.932
1	0.003	0.941
1	0.003	0.949
1	0.003	0.958
1	0.003	0.966
1	0.003	0.975
1	0.003	0.983
1	0.003	0.992
1	0.003	1.000

BABY BRACHS 0

PERNOPECTINS 1

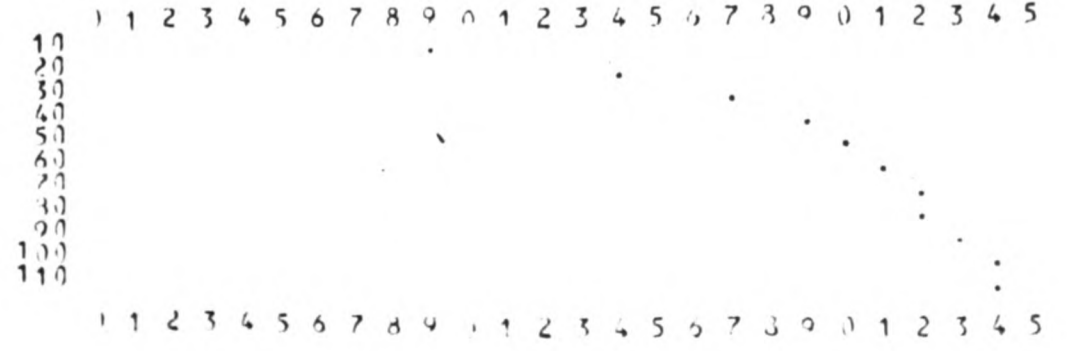
SMOOTH PECTINIDS 4

average maximum size = .5213 cms
 biovolume = 11.2

NUMBER OF SPECIES = 25
 NUMBER OF INDIVIDUALS = 113

RAREFACTION				
0.119	14.271	17.065	18.746	19.932
21.058	21.746	22.424	23.102	23.780
24.458				

PLOT OF N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



DENSITY 48.10
 AMT BRYOZOA CM2/KG 7.22

CORALS 2
 TRILOBITES 1
 GASTROPODS 3
 CEPHALOPODS 1
 OTHERS 1

OTHER STOPHS 3
 SCHELLWIENELLA 4
 LEPTAENID 2
 SCHIZOPHORIA 4
 PUGNAX 3

SPIRIFER 5

OTHER SMOOTH SPIRIF 4
 MARTINIA 5
 ATHYRID 3
 RETICULARIA 2
 BRACHYTHYRIS 18
 CRUR THYRIS 1

OTHER PRODUCTID 7

QUASIAVONIA 16
 PRODUCTINA 16
 PPLICATIFERA 4
 ANTIQUATONIA 3
 EUXTONIA 1
 PRODUCTUS 5
 ECHINOCHONC 8

EABY BRACHS 61

PERNOPECTINS 1
 SMOOTH PECTINIDS 66

% other organisms = 3.2
 % other brachiopods = 6.4
 % spirifers = 2.0
 % smooth spirifers = 13.2
 % non-trail productids = 15.6
 % trail productids = 8.4
 % juveniles = 24.40
 % bivalves = 26.8

COLLECTION 488

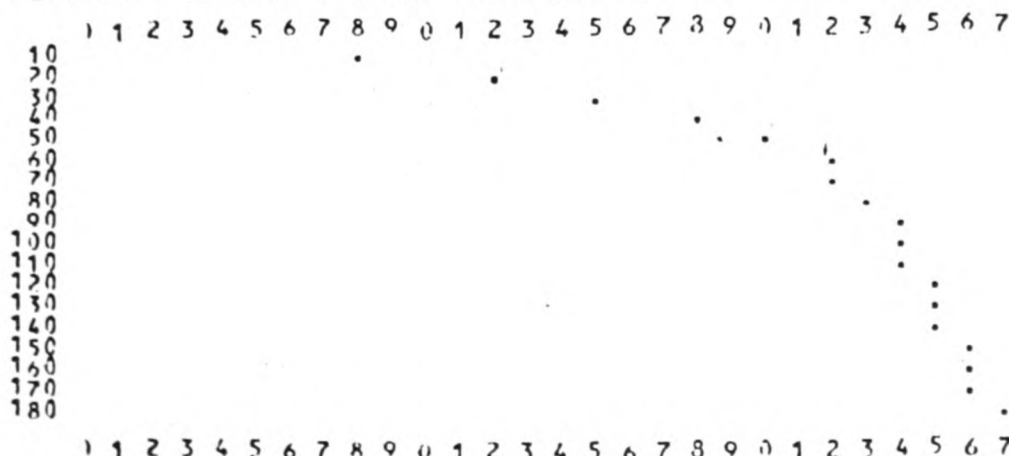
AV	PER	CUPER
66	0.349	0.349
10	0.095	0.444
10	0.085	0.529
10	0.085	0.614
8	0.042	0.656
7	0.037	0.693
5	0.026	0.720
5	0.026	0.746
5	0.026	0.772
4	0.021	0.794
4	0.021	0.815
4	0.021	0.836
4	0.021	0.857
3	0.016	0.873
3	0.016	0.890
3	0.016	0.905
3	0.016	0.921
3	0.016	0.937
2	0.011	0.947
2	0.011	0.958
2	0.011	0.968
1	0.005	0.974
1	0.005	0.979
1	0.005	0.984
1	0.005	0.989
1	0.005	0.995
1	0.005	1.000

average maximum size = .7240 cms
 biovolume = 34.8

NUMBER OF SPECIES = 27
 NUMBER OF INDIVIDUALS = 180

RAFFACTION				
7.518	11.725	15.296	18.101	20.143
21.571	22.444	23.079	23.714	24.175
24.442	24.810	25.127	25.444	25.762
25.079	26.397	26.714		

PLCT DE-N SPECIES (ACROSS PAGE) AGAINST N OF INDIVIDUALS



% other organisms = 3.14
 % other brachiopods = 18.24
 % spirifers = 3.14
 % smooth spirifers = 11.95
 % non-trail productids = 26.42
 % trail productids = 11.95
 % juveniles = 20.13
 % bivalves = 5.03

COLLECTION NUMBER 487
 DENSITY 23.20
 TRILOBITES 1
 GASTROPODS 3
 CEPHALOPODS 1

OTHER STILOPS 13
 SCHELLWIENELLA 3
 LEPTAENID 3
 LEPTAGONIA 1
 PUGNAX 2
 DIELASMA 7

SPIRIFER 5

OTHER SMOOTH SPIRIF 8
 MARTINIA 1
 ATHYRID 3
 PHRICODOTHYRIS 1
 RETICULARIA 2
 BRACHYTHYRIS 3
 CRURITHYRIS 1

QUASIAVONIA 22
 PRODUCTINA 8
 AVONIA 2
 PPLICATIFERA 3
 LINDPRODUCTID 12
 KRCTOVIA 5
 EOMARGINIFERA 5
 ECHINOCYONCHUS 4

BABY BRACHS 32

SMOOTH PECTINIDS 8

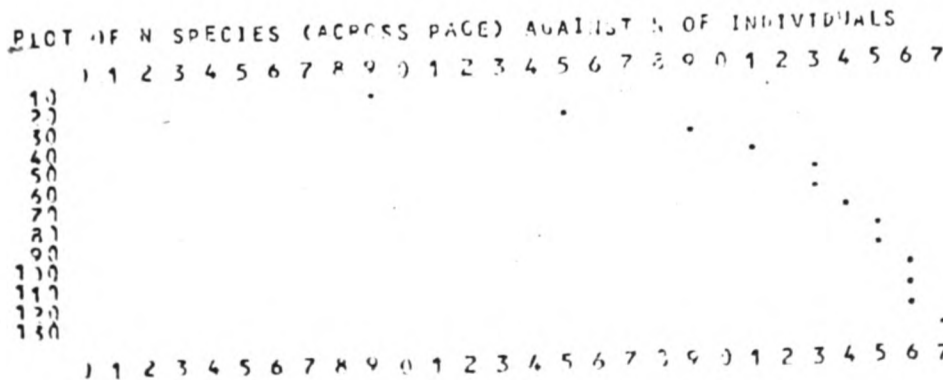
average maximum size = .7642 cms
 biovolume = 17.7

COLLECTION 487

NUMBER	PER	CUPER
2	0.163	0.163
1	0.099	0.267
1	0.092	0.359
1	0.061	0.420
1	0.051	0.481
1	0.051	0.542
1	0.055	0.535
1	0.038	0.634
1	0.038	0.672
1	0.038	0.710
1	0.031	0.740
1	0.031	0.771
1	0.025	0.724
1	0.023	0.817
1	0.023	0.840
1	0.023	0.853
1	0.023	0.835
1	0.023	0.908
1	0.015	0.924
1	0.015	0.930
1	0.015	0.954
1	0.004	0.962
1	0.004	0.969
1	0.003	0.977
1	0.003	0.985
1	0.003	0.992
1	0.003	1.000

NUMBER OF SPECIES = 27
 NUMBER OF INDIVIDUALS = 131

RAREFACTION		21.100	22.560
7.331	15.092	13.702	25.560
23.456	24.208	24.704	
25.038	26.496	20.154	



A4.1.3. Summary of Means, Variances and Standard Deviations for Manifold Valley Faunal Data

Group	Loc.	Other Org.	Other Brach.	Splrif. Sm.	Spirif. Prod.	Non-Tr Prod.	Trail Prod.	Juv.	Bv.	Div.	Dens.	Size	Biovol Amt.	Bry.
South*	519	0 ¹	37.62	5.56	12.21	14.29	1.56	14.18	14.58	14	19.15	.572	11.75	5
		0 ²	75.27	61.72	1.13	3.53	4.80	.81	8.70	8	7.6	.049	34.03	50
	518	0 ³	8.67	7.86	1.06	1.88	2.21	.90	2.95	2.82	2.75	.210	5.83	7.07
Pocket	493	2.14	39.84	9.34	16.51	11.89	2.87	5.13	12.29	22	68.25	1.437	100.0	1.2
		5.71	4.18	1.50	9.81	51.50	5.06	52.71	62.40	2	335.4	.048	1700	2.88
	520	2.39	2.04	1.22	3.13	7.17	2.25	7.26	7.90	1.41	18.31	.218	41.2	1.7
East	509	3.89	22.43	5.9	19.8	19.47	5.77	10.8	12.0	21.4	42.36	.931	44.7	.236
	508	18.99	195.3	10.37	74.25	302.2	14.43	28.6	139.73	18.3	296.1	.067	849	.278
	505	.4.36	14.0	3.22	8.61	17.4	3.8	5.35	11.82	4.3	17.2	.259	29.1	.528
	503													
	523													
Centre	494	2.6	20.27	4.5	23.1	12.32	2.77	8.6	25.9	21	17	.721	12.0	0
	495	10.0	13.44	5.8	69.7	40.87	10.41	77.8	97.3	21.5	44.2	.021	20.7	0
	497	3.2	3.67	2.4	8.4	6.4	3.2	8.8	9.9	4.6	6.6	.146	4.55	0
	522													
	521													
West	504													
	502													
	501													
	500													
	496	5.21	16.15	5.38	11.47	24.14	7.05	13.51	17.10	24.6	32.41	.745	24.3	2.31
	492	18.66	44.83	5.78	21.0	75.40	21.59	83.83	90.85	7.82	162.53	.014	110.5	11.50
	491	4.32	6.70	2.40	4.58	8.68	4.65	9.16	9.53	2.8	12.75	.117	10.51	3.4
	490													
488														
487														

¹Mean²Variance³Standard Deviation

*these collections are incomplete

A4.1.4 . Analysis of Variance Tables for coefficients of Association Matrix (Table 4-3) . (See A4.1.5 for explanation of symbols)

	d.f.	S.O.S.	M.S.	F
Groups	5	.01	.002	
W/in	49	.2	.004	.515
Total	54	.21		N/S

A4.1.5. Analysis of Variance Tables for Manifold Valley Faunal Data

Format used is as follows:

n= no. of cases

sum= sum of all values

SOS= sum of the squares of all values

CF= correction factor= $\frac{\text{sum}^2}{n}$

CSOS= corrected sum of squares= $\text{SOS}-\text{CF}$

In the analysis of variance table:

d.f.=degrees of freedom

SOS- total=CSOS; -groups=sum for each group/n. for each group, the results are summed and CF is subtracted. -within = total SOS-groups SOS

MS= mean squares = $\text{SOS}/\text{d.f.}$

F= $\text{MS}_{\text{groups}}/\text{MS}_{\text{within}}$. The significance of F is found by consulting a table of F values using d.f. for groups and within.

The within MS can be used to calculate the standard error which in turn can be used to calculate t values.

$$\text{Standard error} = \sqrt{s^2 \left(\frac{1}{n_1} + \frac{1}{n_2} \right)}$$

where s^2 = within MS and n_1 and n_2 = no. of cases in the groups being compared.

$t = \frac{\bar{x}_1 - \bar{x}_2}{\text{standard error}}$, where \bar{x}_1 and \bar{x}_2 are the means of the groups being compared.

Notes on the use of Analysis of Variance

Analysis of variance assumes that variation within the groups is approximately normal and with similar variances. It is, however, a robust procedure, and departure from these assumptions, unless it is large and obvious, will not invalidate the results. For comparing the means of a number of small groups it is much more useful to use simple t-tests on pairs. Using analysis of variance, the within-group variance can be estimated with reasonable accuracy and the variance can then be used in t-tests.

When t-tests are used to compare means of data expressed in percentage form (which total 100%), it should be noted that they are not independent. A large difference in one variable must be compensated for by corresponding differences in other variables. In these situations, if a t-test shows a significant difference in one variable, significant differences must also occur in one or more other variables. (Dr. F. Marriot, written communication, 1979)

Manifold Valley

Diversity		d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4		203	40.6	3.25	2 v 2=3.5
W/in	19		239	12.5	p > .05	2 v 5=2.9
Total	23		442			2 v 10= 2.7
						5 v 5= 2.2
						5 v 10=1.9

	S	P	E	C	W
S	X 95%				
P	2.3 98%	X 10%			
E	2.6 98%	.20 20%	X 10%		
C	2.4 99%	.34 80%	.18 90%	X 90%	
W	3.93	.96	1.69	1.89	X

Density		d.f.	S.O.S.	M.S.	F	STD. ERROR
Groups	4		4658	1165		2 v 2=12.8
W/in	19		3099	163	7.14	2 v 5=10.7
Total	23		7757		p > .01	2 v 10=9.9
						5 v 5=8.1
						5 v 10=7.0

	S	P	E	C	W
S	X 99%				
P	3.83 95%	X 97%			
E	2.17 10%	2.41 99%	X 99%		
C	.2 80%	4.8 99%	3.13 80%	X 97%	
W	1.34	3.62	1.42	2.2	X

Average Maximum Size		d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4		8.49	2.12		2 v 2=.17
W/in	19		.58	.03	70.75	2 v 5=.14
Total	23		9.07		p > .01	2 v 10=.13
						5 v 5=.11
						5 v 10=.06

	S	P	E	C	W
S	X 99%				
E	5.1 99%	X 99%			
E	2.9 70%	3.28 99%	X 95%		
C	1.06 80%	5.13 99%	2.35 99%	X 30%	
W	1.33	5.34	3.91	.40	

Manifold Valley

Biovolume

	d.f.	S.O.S.	M.S.	F	STD. ERROR
Groups	4	13,935	3484		2 v 2=17.4
W/in	19	5772	304	11.5	2 v 5=14.6
Total	23	19,707		p 7.005	2 v10= 13.5 5 v 5=11.0 5 v10=9.5

	S	P	E	C	W
S	X 99%				
P	5.15 95%	X 99%			
E	2.29 0%	3.86 99%	X 99%		
C	.05 60%	6.09 99%	2.97 95%	X 70%	
W	.96	5.68	2.75	1.21	X

Bryozoa

	d.f.	S.O.S.	M.S.	F	STD ERROR
Groups	4	50.5	12.6		2 v 2=2.87
W/in	19	157.5	8.29	1.52	2 v 5=2.4
Total	23	208		N/S	2 v10=2.2 5 v 5=1.8 5 v10=1.6

	S	P	E	C	W
S	X 80%				
P	1.32 90%	X 30%			
E	1.98 95%	.40 30%	X 10%		
C	2.08 70%	.5 30%	.129 80%	X 80%	
W	1.21	.5	1.32	1.46	

Manifold Valley
Other Organisms

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	65	16.3		2 v 2=3.9
W/in	19	290	15.2	1.07	2 v 5=3.3
Total	23	355		N/S	2 v 10=3.0
					5 v 5=2.5
					5 v 10=2.1

	S	P	E	C	W
S	X 40%				
P	.55 70%	X 40%			
E	1.18 50%	.53 10%	X 30%		
C	.79 90%	.14 70%	.52 40%	X 70%	
W	1.73	1.02	.63	1.24	X

Other Brachiopods

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	1490	373		2 v 2=8.3
W/in	19	1310	69	5.40	2 v 5=6.9
Total	23	2800		p>.01	2 v 10=6.4
					5 v 5=5.3
					5 v 10=4.5

	S	P	E	C	W
S	X 20%				
P	.265 95%	X 98%			
E	2.20 98%	2.52 99%	X 30%		
C	2.51 99%	2.82 99%	.396 80%	X 60%	
W	3.34	3.69	1.37	.91	X

Non-Trail Productids

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	622	156		2 v 2=10.5
W/in	19	2117	111	1.40	2 v 5=8.8
Total	23	2739		N/S	2 v 10=8.2
					5 v 5=6.7
					5 v 10=5.8

	S	P	E	C	W
S	X 10%				
P	.228 40%	X 60%			
E	.591 10%	.864 0%	X 70%		
C	.227 70%	.04 80%	1.07 50%	X 90%	
W	1.19	1.49	.79	2.01	X

Manifold Valley

Smooth Spirifers

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	563	141		2 v 2=6.4
W/in	19	770	40.5	3.48	2 v 5=5.3
Total	23	1333		p>.05	2 v 10=4.9 5 v 5=4.0 5 v 10=3.5

	S	P	E	C	W
S	X 40%				
P	.676 80%	X 40%			
E	1.43 95%	.623 70%	X 50%		
C	2.05 10%	1.24 60%	.825 95%	X 99%	
W	.148	1.03	2.38	3.32	X

Spirifers

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	51.4	13		2 v 2=2.9
W/in	19	164	8.6	1.51	2 v 5=2.5
Total	23	215		N/S	2 v 10=2.3 5 v 5=1.9 5 v 10=1.6

	S	P	E	C	W
S	X 80%				
P	1.3 10%	X 80%			
E	.14 30%	1.38 90%	X 50%		
C	.42 0%	1.94 90%	.74 20%	X 40%	
W	.07	1.71	.31	.56	X

Trail Productids

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	171	43		2 v 2=3.5
W/in	19	235	12.4	3.46	2 v 5=2.9
Total	23	406		p>.05	2 v 10=2.7 5 v 5=2.2 5 v 10=1.9

	S	P	E	C	W
S	X 20%				
P	.37 80%	X 60%			
E	1.46 30%	1.01 0%	X 80%		
C	.43 95%	.02 90%	1.36 60%	X 98%	
W	2.20	1.71	.89	2.47	X

Manifold Valley

Bivalves

	d.f.	S.O.S	M.S.	F	STD.ERROR
Groups	4	7	1.75		2 v 2=11.3
W/in	19	2418	127	.014	2 v 5=9.4
Total	23	2425		N/S	2 v 10=8.7 5 v 5=7.1 5 v 10=6.2

	S	P	E	C	W
S	X 10%				
P	.20 10%	X 0%			
E	.28 70%	.03 80%	X 90%		
C	1.20 20%	1.44 40%	1.96 60%	X 80%	
W	.29	.55	.88	1.42	X

Juveniles

	d.f.	S.O.S.	M.S.	F	STD.ERROR
Groups	4	187	47		2 v 2=8.1
W/in	19	1227	65	.719	2 v 5=6.7
Total	23	1414		N/S	2 v 10=6.2 5 v 5=5.1 5 v 10=4.4

	S	P	E	C	W
S	X 70%				
P	1.09 30%	X 50%			
E	.478 50%	.846 30%	X 30%		
C	.805 0%	.518 80%	.431 40%	X 70%	
W	.08	1.35	.613	1.11	X

A4.1.6. Faunal Lists from Shephard-Thorn (1963, p.279-284)

A4.1.7. Orientation Analysis

The randomness of the orientation of shells in the pockets was tested by means of a Chi-Square test, following the method described by Reyment (1971). In this test the uniform distribution of the theoretical universe is compared with the distribution of the observations in the sample. A significance level P (often 5%) is chosen, which is the probability that the computed value of Chi square exceeds a certain critical value (which is read off a table of Chi Square). The null hypothesis is that the sample and the universe are consistent. If the calculated value of Chi Square is greater than the critical value for the degrees of freedom involved, the null hypothesis is rejected. If the calculated value is less than or equal to the critical value, the null hypothesis is accepted and the sample and the universe are consistent.

To calculate the Chi Square statistic, the N observations must be divided into k groups such that 1) the expected frequency ($E_i = N/k$) of the uniform distribution must be at least 5; 2) the number of groups must be between $N/15$ and $N/5$; 3) the choice of the number of groups is in no way related to the nature of the observations. The test statistic is:

$$\chi^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i}$$

where O_i is the observed frequency for group i ($i=1,2,\dots,k$); and $k-1$ equals the number of degrees of freedom.

A4.2. Lithological Data

A4.2.1. Manifold Valley Point Count Data

Point Count Data - East (data expressed as % of total points counted)

Local-ity	Cement	Micro-spar	Micrite	Clotted Micrite	Bioclasts
493	4.0	4.0	8.3	7.4	75.2
505	8.5	29.2	43.6	5.4	13.5
508	0	33.0	6.2	43.0	18.0
522	3.3	56.5	28.7	6.2	5.1
Mean	3.75	30.7	21.7	15.5	27.9
Variance	12.24	462.0	361.1	336.8	1020.8
Std. Dev.	3.49	21.5	17.8	18.4	32.0

Point Count Data - Centre (data expressed as % of total points counted)

Local ity	Cement	Micro- spar	Micrite	Clotted Micrite	Bioclasts
451	52.9	26.7	12.5	2.6	5.1
452	63.0	3.7	18.9	5.2	9.3
453	40.9	12.8	31.2	3.9	11.4
455	53.0	8.1	23.4	6.4	9.1
456	37.3	13.2	18.7	15.7	15.1
458	76.0	8.3	1.4	3.4	10.7
459	23.3	17.0	12.2	18.0	29.7
460	46.5	9.5	26.6	9.7	8.8
461	9.4	12.7	30.5	34.2	14.3
494	47.2	3.6	17.4	18.2	14.0
495	.9	56.9	17.8	22.5	2.1
497	0	65.9	25.0	6.0	2.4
499	32.7	18.2	33.1	8.8	7.1
503	30.0	14.2	18.4	15.0	23.3
Mean	36.6	19.3	20.5	12.1	11.6
Variance .	507.9	355.9	74.2	81.3	57.5
Std. Dev.	22.5	18.8	8.6	9.0	7.6

Point Count Data - West (data expressed as % of total points counted)

Local- ity	Cement	Micro- spar	Micrite	Clotted Micrite	Bioclasts
426	.2	18.7	69.8	1.0	10.1
427	12.1	50.6	5.8	5.8	26.4
428	2.1	14.8	6.1	59.3	17.7
429	3.8	24.1	28.0	0	46.0
430	1.7	38.8	26.2	0	35.0
431	.7	45.0	8.1	.7	45.5
433	16.3	47.9	2.9	6.7	25.1
434	1.2	52.3	20.5	1.9	24.1
435	1.4	16.1	29.6	3.9	50.3
436	4.0	12.0	46.0	4.5	33.5
437	26.3	20.3	25.1	18.1	10.5
438	14.5	14.4	31.0	22.8	17.8
439	23.4	12.6	36.8	13.6	14.0
440	30.6	10.8	24.2	18.4	16.2
441	7.8	31.1	25.3	18.9	17.6
442	24.6	6.3	27.8	26.2	15.1
443	5.0	6.4	41.4	27.6	19.5
444	46.0	20.2	13.3	7.5	12.9
445	32.1	6.7	28.1	18.1	15.0
447	35.3	8.6	31.2	17.5	7.3
504	12.0	36.6	20.8	2.4	28.1
502	1.2	2.8	51.2	6.8	37.9
500	2.5	25.3	27.2	11.2	34.5
492	57.2	6.9	33.4	0	2.4
491	25.7	19.6	30.7	2.0	23.8

Point Count Data - West (continued)

Local- ity	Cement	Micro- spar	Micrite	Clotted Micrite	Bioclasts
490	7.3	11.3	49.2	5.4	26.8
488	1.8	41.6	7.1	21.1	28.4
487	5.0	34.1	17.5	34.4	8.7
Mean	14.35	22.7	27.3	12.7	23.2
Variance	234.2	227.4	232.0	178.4	153.0
Std. Dev.	15.3	15.0	15.2	13.4	12.4

Belgian Point Count Data - Tn3a levels (data expressed as% of total points counted)

Locality	Cement	Microspar	Micrite	Clotted Micrite	Bioclasts	Breakdown of Bioclasts Bryozoa	Crinoid	Foram	Other
Tn 3a levels									
B313	17.8	1.9	35.1	1.9	43.2	11.1	16.8	0	15.3
B314	15.2	8.4	47.5	.6	28.2	6.1	8.6	0	13.5
B316	21.9	6.2	29.2	.7	42.6	18.9	22.3	0	1.4
B186	50.1	21.1	8.6	.7	22.7	5.1	17.6	0	0
B187	24.0	25.7	11.6	5.3	33.3	6.1	27.2	0	0
B213	44.0	4.4	10.3	12.0	29.2	19.4	8.8	0	1
B214	14.1	4.2	18.5	7.2	56.0	19.5	36.5	0	0
Mean	26.7	10.3	22.9	4.1	36.5	12.3	19.68	0	4.46
Variance	207.8	86.1	217.3	18.9	130.9	46.0	100.0	0	46.7
Std. Dev.	14.4	9.3	14.7	4.35	11.4	6.8	10.0	0	6.83
Tn3c levels									
N43	41.2	25.9	19.4	7.2	6.3	.9	1.4	1.2	2.8
N44	33.9	36.9	21.4	2.5	5.1	2.8	0	0	2.3
B331	7.0	24.5	32.0	7.5	29.8	14.3	5.0	.5	10.0
B332	22.0	15.4	45.6	1.2	15.7	6.3	8.0	.5	.9
Mean	26.02	25.7	29.6	4.6	14.225	6.1	3.6	.55	4.0
Variance	223.4	77.67	144.3	10.38	130.3	35.07	13.04	.243	16.6
Std. Dev.	14.9	8.8	12.0	3.22	11.4	5.92	3.6	.493	4.1

Belgian Point Count Data - continued

Locality V1a levels	Cement	Microspar	Micrite	Clotted Micrite	Bioclasts	Breakdown of Bioclasts			Other
						Bryozoa	Crinoid	Foram	
B122	7.5	43.3	29.1	1.0	16.0	4.1	4.1	6.2	1.6
B124	6.8	42.4	29.7	7.6	13.5	5.7	3.4	3.7	.7
N17	5.5	25.0	53.0	1.8	14.6	6.3	1.6	.9	5.8
Mean	6.6	36.9	37.2	3.46	14.7	5.36	3.03	3.6	2.7
Variance	1.03	106.4	185.7	12.97	1.57	1.29	1.66	7.03	7.41
Std. Dev.	1.01	10.3	13.6	3.6	1.25	1.14	1.29	2.65	2.72

Note: Localities labelled B refer to localities in Bouw (1971), those labelled N refer to localities of Noel (1973). Locality information is given in Appendix 2.

A4.2.3. Analysis of Variance Tables for Lithological Data

Manifold Valley

Cement

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	5722	2861		4 v 14=3.6
W/in	43	13007	302	9.47	4 v 28=9.2
Total	45	18729		P < .005	14v 28=5.6

	E	C	W
E	X		
	99%		
C	3.3	X	
	70%	99%	
W	1.13	3.82	X

Microspar

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	413	206.5		4 v 14=9.5
W/in	43	12186	283	F=.73	4 v 28=8.9
Total	45	12599		N/S	14v 28=5.6

	E	C	W
E	X		
	70%		
C	1.2	X	
	60%	40%	
W	.9	.61	X

Micrite

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	450	225		4 v 14=7.8
W/in	43	8197	191	1.18	4 v 28=7.3
Total	45	8647		N/S	14v 28=4.6

	E	C	W
E	X		
	10%		
C	.15	X	
	50%	80%	
W	.77	1.48	X

Manifold Valley

Clotted micrite

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	35.9	18		4 v 14 = 7.2
W/in	43	6897	160	.112	4 v 28 = 6.7
Total	45	6933		N/S	14v 28 = 4.2

	E	C	W
E	X 30%		
C	.47 30%	X 10%	
W	.41	.14	X

Bioclasts

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	1524	762		4 v 14 = 7.7
W/in	43	7970	185	4.12	4 v 28 = 7.2
Total	45	9494		P < .025	14v 28 = 4.5

	E	C	W
E	X 95%	X	
C	2.12 40%	X 98%	
W	.65	2.57	X

Belgium

Cement

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	930.6	465		4 v 3 = 10.1
W/in	11	1930	175.5	2.64	4 v 7 = 8.3
Total	13	2861		P 0.05	3 v 7 = 9.08

Tn3a	Tn3a	Tn3c	V1a
	X		
	0%		
Tn3c	.08	X	
	95%	90%	
V1a	2.21	1.93	X

Microspar

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	1658	829		4 v 3 = 2.26
W/in	11	963	87.5	9.47	7 v 3 = 2.03
Total	13	2621		P 0.01	7 v 4 = 1.85

Tn3a	Tn3a	Tn3c	V1a
	X		
	99%		
Tn3c	8.32	X	
	99%	99%	
V1a	13.1	4.92	X

Micrite

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	445	223		4 v 3 = 10.5
W/in	11	2108	192	1.58	7 v 3 = 9.5
Total	13	2553		N/S	7 v 4 = 8.7

Tn3a	Tn3a	Tn3c	V1a
	X		
	50%		
Tn3c	.77	X	
	30%	50%	
V1a	.45	.72	X

Belgium

Clotted Micrite

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	1.9	.95		4 v 3 = 3
W/in	11	171	15.6	0.06	7 v 3 = 2.7
Total	13	173		N/S	7 v 4 = 2.5

	Tn3a	Tn3c	V1a
Tn3a	X 10%		
Tn3c	.2 10%	X 20%	
V1a	.23	.29	X

Bioclast

	d.f.	S.O.S.	M.S.	F	Std. Error
Groups	2	1684	842		4 v 3 = 7.9
W/in	11	1194	108	7.79	7 v 3 = 7.1
Total	13	2878		P>0.01	7 v 4 = 6.5

	Tn3a	Tn3c	V1a
Tn3a	X 98%		
Tn3c	3.42 98%	X 0%	
V1a	3.06	.06	X

APPENDIX 5

CATHODOLUMINESCENCE PETROGRAPHY

APPENDIX 5 CATHODOLUMINESCENCE PETROGRAPHY

In cathodoluminescence petrography luminescent light is produced by the impact of a broad beam of low energy electrons on the surface of an uncovered thin section. Luminescence in calcite is due to the presence of Mn^{++} and is quenched by the presence of Fe^{+++} , Co^{++} and Ni^{++} . Differing degrees of luminescence, as well as luminescent banding, are caused by variations in the concentration of the Mn^{++} activator ions, the quenching ions, or both, in the solutions from which the crystals grow (Sipple and Glover, 1965).

Cathodoluminescent petrography has many uses. It can reveal zoning in crystals, cement overgrowths and recrystallised fossils which are not visible in polarised light (Sipple and Glover, 1965). Succeeding generations of cements often have a characteristic luminescence (Meyers, 1974; Lohman and Meyers, 1977) and this has aided in the recognition of different cement types. In some cases it has been possible to establish a cement stratigraphy which aids in the interpretation of complex cementation histories (Meyers, 1974). A major drawback of the technique, however, is that the results are often very difficult to interpret.

Cathodoluminescence petrography was carried out on polished, uncovered thin sections from the Manifold Valley which were mounted in araldite. The luminoscope at Edinburgh University was used. Thin sections were photographed first in plane polarised light and then under luminescent light, with no additional light source. FP 4 film was used and exposure times ranged from $\frac{1}{2}$ second for photographs in plane light to 120 seconds for photographs in luminescent light.

It was not possible to establish a cement stratigraphy within the thin sections examined, but various cements could be recognised by their unique properties under luminescence.

Radiaxial fibrous spar, which appears cloudy under plane light, appears in photographs taken under luminescent light as a slightly blotchy medium to light grey colour (figure A5.1). In contrast, cloudy granular spar, which can look superficially like radiaxial fibrous spar under plane light, appears black in photographs taken under luminescent light (figures A5.2 and A5.3). Micrite is often light coloured under luminescence (figure A5.3). Zoning of crystals, which is evident under luminescent light, is restricted in these rocks to the clear spar, which fabric evidence suggests is a late cement generation (figures A5.1 and A5.2).

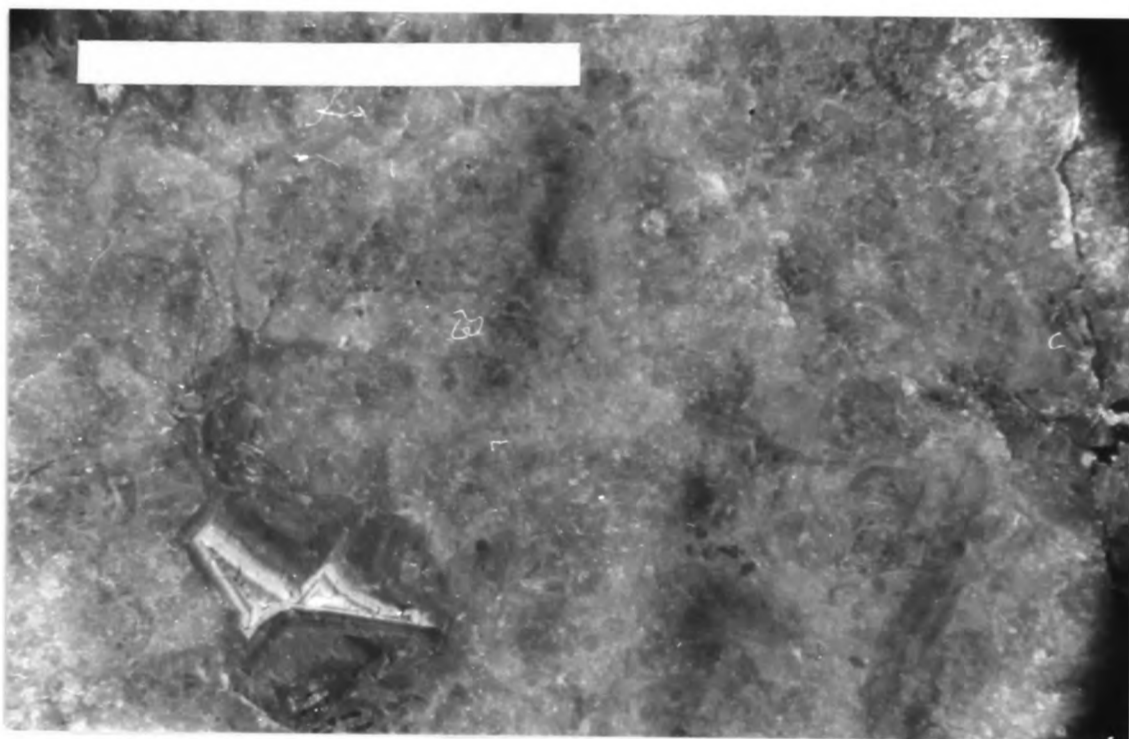
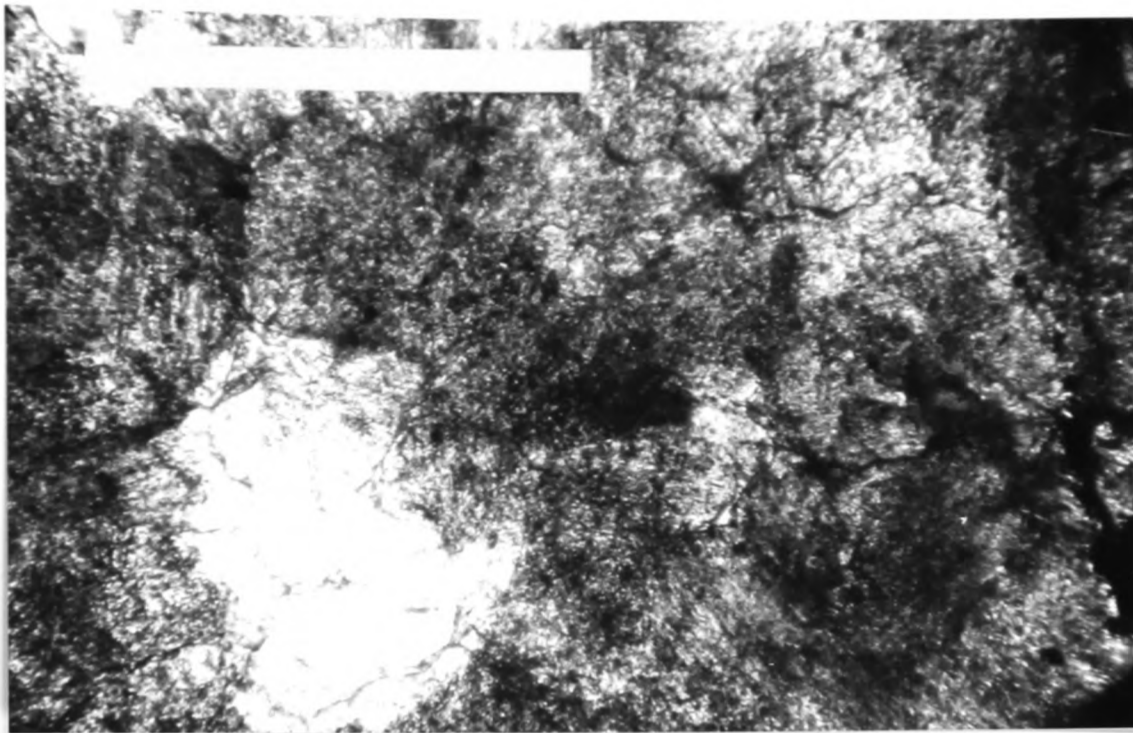


Figure A5.1 A. Bright late cement (lower left centre) fills the gap caused by incomplete filling of a cavity by the surrounding radiaxial fibrous spar.

B. The same area under luminescent light. The radiaxial fibrous spar appears a medium to light, slightly blotchy, grey while the late clear spar shows zoning.

Scale bar = 1 mm

From Manifold Valley locality 492

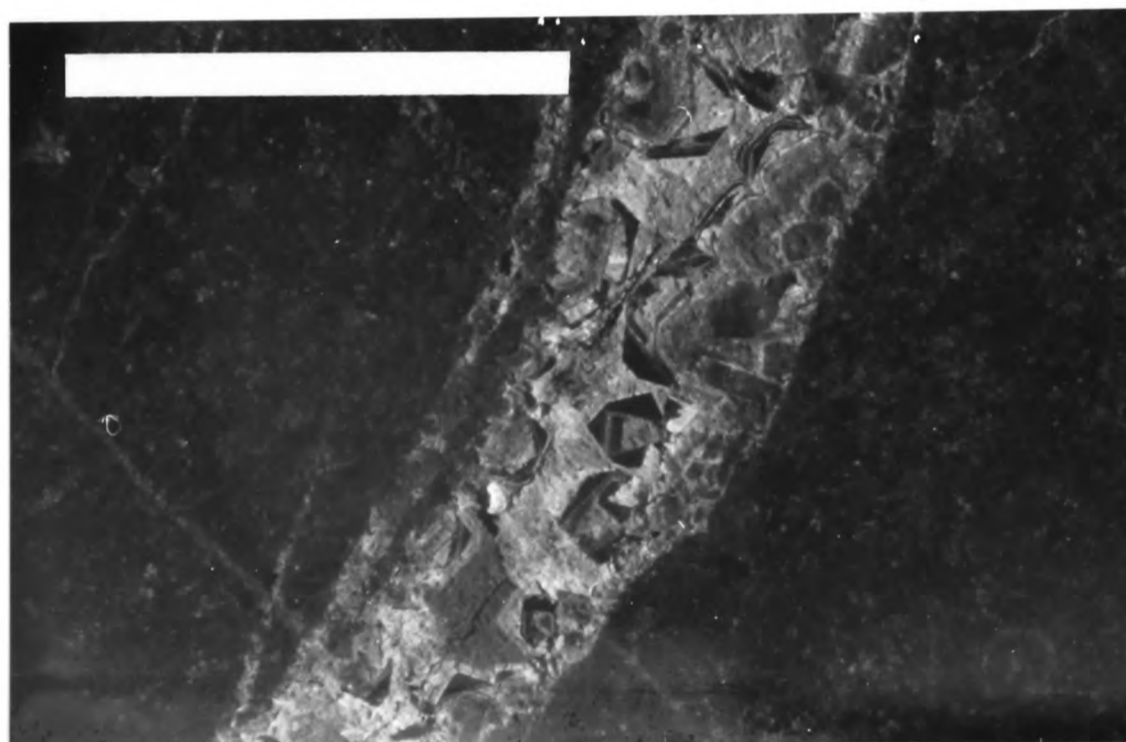
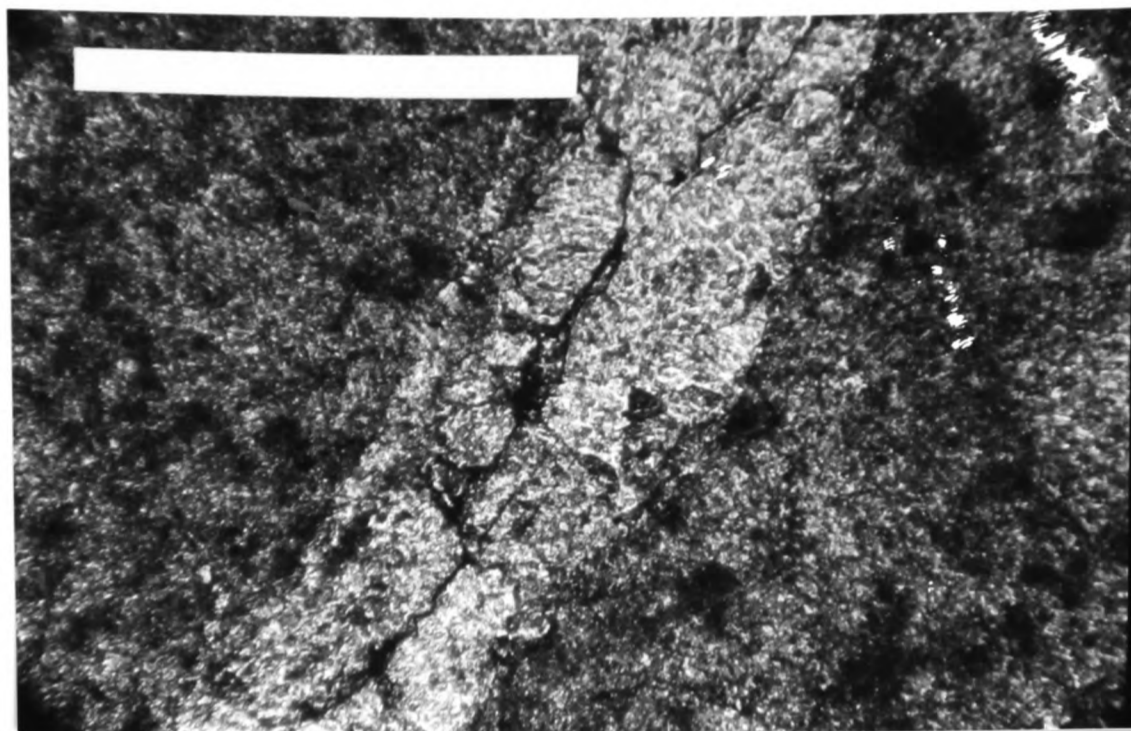


Figure A5.2 A. Vein filled with blocky clear spar cuts across cloudy granular spar which is not radiaxial.
B. The same area under luminescent light. The later clear spar of the vein is zoned, while the cloudy spar appears black.

Scale bar = 1 mm

From Manifold Valley locality 492

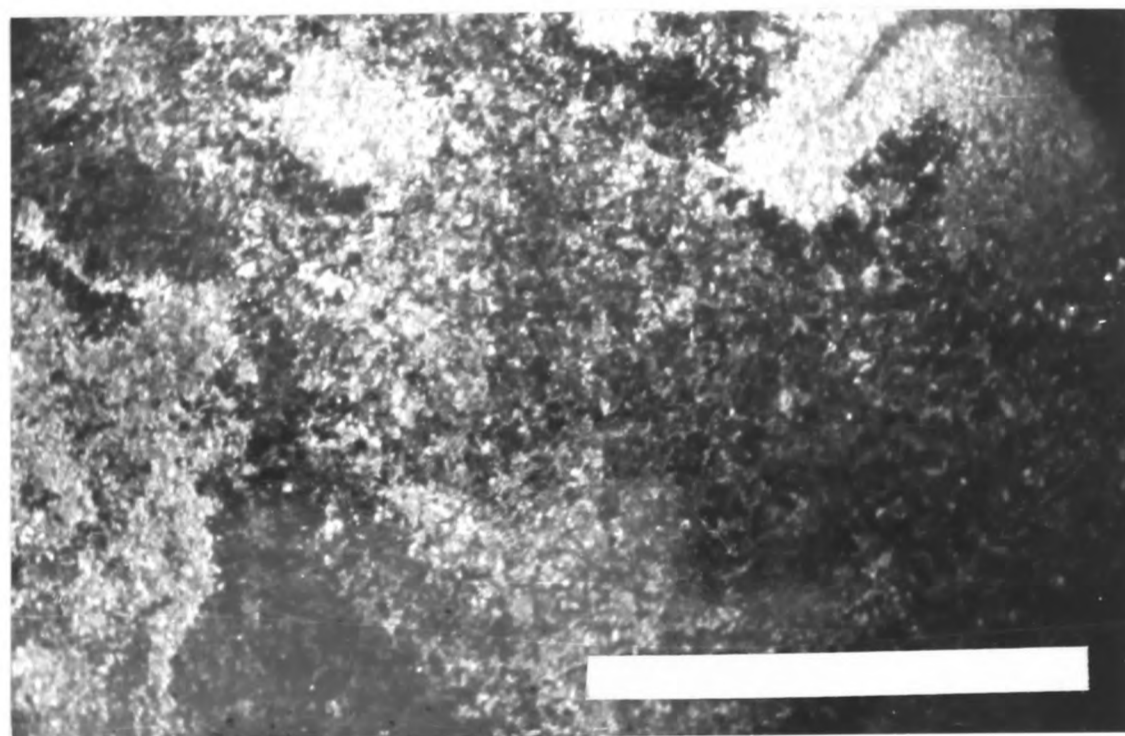
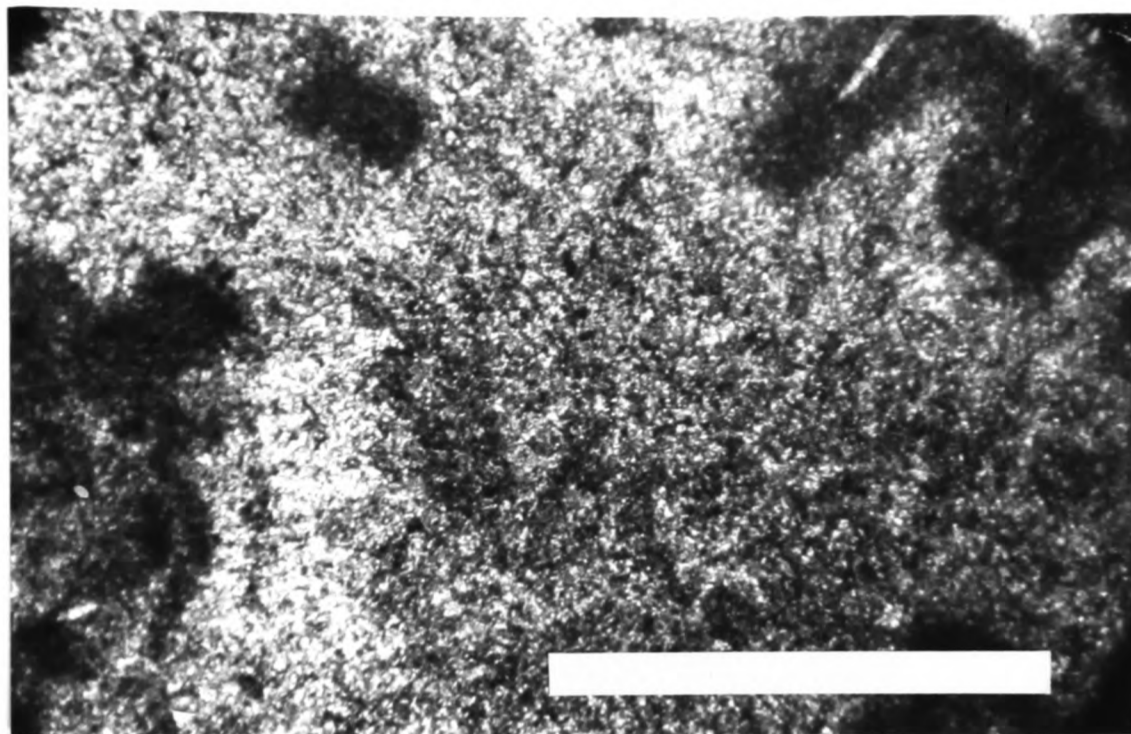


Figure A5.3 A. In the upper right a bryozoan fragment is surrounded by micrite. In lower left and upper left centre are pelloids of micrite. The matrix is cloudy granular spar.

B. The same area under luminescent light. The areas of micrite appear light coloured while the granular spar appears black.

Scale bar = 1 mm

REFERENCES

- Adams, A.E., and Evans, G.S., 1979. Deposition and diagenesis of Lower Carboniferous 'knoll-reefs', Derbyshire, England. Reef Newsletter 5, p.3.
- Aitkenhead, N., Chisholm, J., Ramsbottom, W., Reynolds, M., Mitchell, M., 1979. Guide for Palaeontological Association Carboniferous Group Annual field conference in Dovedale, Manifold Valley and Weaver Hills.
- Alexander, G.B., 1940. Report of field meeting to Buxton, 1939. Proc. Yorkshire geol. Soc. v.24, p.172-173.
- Alexandersson, T., 1972. Intragranular growth of Marine Aragonite and Mg-Calcite: Evidence of precipitation from supersaturated seawater. J. sediment. Petrol. v.42, p.441-460.
- Bartlett, G.A., and Greggs, R.G., 1970. The mid-Atlantic Ridge near 45°N VIII: Carbonate lithification on oceanic ridges and seamounts. Can. J. Earth Sci. v.6, p.257-267.
- Bathurst, R.G.C., 1958. Diagenetic fabrics in some British Dinantian limestones. Liverpool and Manchester geol. J. v.2, p.11-36.
- Bathurst, R.G.C., 1959. The cavernous structure of some Mississippian Stromatactis reefs in Lancashire, England. J. Geol. v.67, p.506-521.
- Bathurst, R.G.C., 1975. Carbonate sediments and their diagenesis., Elsevier.
- Bathurst, R.G.C., 1977. Ordovician Meiklejohn bioherm, Nevada. Correspondence in Geol. Mag. v.114, p.308-311.
- Bathurst, R.G.C., 1979. The excavation of Stromatactis cavities between submarine crusts in Ordovician, Devonian and Carboniferous limestones. Manuscript in preparation.

- Beales, F.W., 1965. Diagenesis in pelleted limestones. in Pray, L.C., and Murray, R.C., eds., Dolomitization and limestone diagenesis: A Symposium. Sp. Publ. soc. econ. Paleontol. Mineral. 13, p.49-70.
- Bisat, W.S., 1924. The Carboniferous goniatites of the north of England and their zones. Proc. Yorkshire geol. Soc. v.20, p.40-124.
- Black, W.W., 1950. The Carboniferous geology of the Grassington area, Yorkshire. Proc. Yorkshire geol. Soc. v.28, p.29-42.
- Black, W.W., 1952. The origin of supposed tufa bands in Carboniferous reef limestones. Geol. Mag. v.89, p.195-200.
- Black, W.W., 1954. Diagnostic characters of the Lower Carboniferous reef knolls in the north of England. Trans. Leeds geol. Assoc. v.6, p.262-297.
- Bond, G., 1950a. The Lower Carboniferous reef limestones of Cracoe, Yorkshire. Q.J. geol. Soc. London v.105, p.157-188.
- Bond, G., 1950b. The Lower Carboniferous reef limestone of Northern England. J. Geol. v.58, p.313-329.
- Bond, G., 1950c. The nomenclature of the Lower Carboniferous reef limestones of Northern England. Geol. Mag. v.87, p.267-278.
- Bouw, P., 1971. Le Waulsortien de la region de Furfooz. Memoire de license, Universite Catholique de Louvain, unpub.
- Bretsky P.W. and Bretsky, S.S., 1975. Succession and repetition of Late Ordovician fossil assemblages from the Nicolet River Valley, Quebec., Paleobiology, v. 1, p. 225-237.
- Bretsky, P.W., and Lorenz, D.M., 1970. Adaptive response to environmental stability: A unifying concept in palaeoecology. in Yochelson, E.L., ed., Proc. N. Am. Paleontological Convention (Chicago, 1969), p.522-549.
- Broadhurst, F.M., and Simpson, I.M., 1973. Bathymetry on a Carboniferous reef. Lethaia v.6, p.367-381.
- Calef, C.E., 1972. Palaeoecological and stratigraphical studies in Wales and the Welsh Borderland. Unpub. D.Phil. Oxford Univ. 239pp.

- Carozzi, A.V., 1960. Microscopic sedimentary petrography. John Wiley and Sons, Inc., London 485pp.
- Cayeux, L., 1935. Les roches sedimentaires de France: Roches carbonatees. Masson, Paris 463pp.
- Conil, R. and Dupont, H., 1965. Remarques sur l'extension verticale des facies Waulsortiens. Ann. Soc. geol. Belg. v.88, p.B45-60.
- Cope, F.W., 1973. The Woodale borehole near Buxton, Derbyshire. Nature (Physical Science) v.243, no.124, p.29-30.
- Cotter, E., 1965. Waulsortian type carbonate banks in the Mississippian Lodgepole Formation, Central Montana. J. Geol. v.73, p.881-888.
- Cotter, E., 1966. Limestone diagenesis and dolomitisation in Mississippian carbonate banks in Montana. J. sediment. Petrol. v.36, p.764-774.
- Cox, F.C., and Bridge, D., 1977. The limestone and dolomite resources of the country around Monyash, Derbyshire: Description of 1:25,000 resource sheet SK 16. Miner. Assess. Rep. Geol. Sci. no.26, 137pp.
- Cummings, E.R., 1932. Reefs or bioherms? Bull. geol. Soc. Am. v.43, p.331-352.
- Davidson, T., 1858-1863. A monograph of British fossil brachiopods. Palaeontogr. Soc. London 280pp.
- Davies, G.R., 1970. Carbonate bank sedimentation, Eastern Shark Bay, Western Australia. in Logan, B.W., ed., Carbonate sedimentation and environments, Shark Bay, Western Australia. Mem. Am. Assoc. Petrol. Geol. 13, p.85-168.
- Davies, G.R., 1977. Former magnesian calcite and aragonite submarine cements in Upper Paleozoic reefs of the Canadian Arctic: A summary. Geology v.5, no.1, p.11-16.
- Davis, J.C., 1973. Statistics and data analysis in geology. Wiley International 550pp.

- de la Vallee Poussin, C., 1888. Compte rendu de la session extraordinaire de la societe geologique tenue a Dinant les 1, 2, 3 et 4 septembre 1888. Ann. Soc. geol. de Belg. v.16, p.103-157.
- Delepine, G., and Milon, M., 1923. Sur la presence de recifs waulsortiens dans le calcaire carbonifere du bassin de Laval. C.r. Seances Acad. Sci. Paris v.175, p.1079-1080.
- Delepine, G., 1940. Contribution a l'etude des goniatites du Waulsortien d'Irlande et de Belgique. Ann. Soc. geol. Nord v.64, p.134-149.
- Delepine, G., 1949. Le Carbonifere d'Irlande et ses facies Waulsortiens. Ann. Hebert et Haug. v.7 (Livre jubilaire Charles Jacob), p.143-159.
- Delepine, G., 1951. Studies of the Devonian and Carboniferous of Western Europe and North Africa. Proc. Geol. Assoc. London v.62, p.140-166.
- De Keyser, T.L., 1978. Lithoherms in the Straits of Florida: Comment. Geology v.6, p.5-8.
- Demanet, F., 1923. Le Waulsortien de Sosoye et ses rapports faniques avec le Waulsortien d'age Tournaisien superior. Mem. Inst. geol. Univ. Louvain v.2, p.36-286.
- Demanet, F., 1958. Contribution a l'etude du Dinantien de la Belgique. Mem. Inst. R. Sci. nat. Belg. no.141, 152 pp.
- Dixon, E.L.L., 1921. The geology of the country around Pembroke and Tenby. Mem. geol. Surv. G.B. no.244-245, 220pp.
- de Dorlodot, H., 1893. Decouverte du Waulsortien dans le bassin de Namur. Ann. Soc. geol. Belg. v.20, p.33-36.
- Douglas, J.A., 1909. The Carboniferous limestone of County Claire (Ireland). Q.J. geol. Soc. London v.55, p.538-586.

- Dumestre, A., and Illing, L.V., 1967. Middle Devonian reefs in Spanish Sahara. in Oswald, D.H., ed., International symposium on the Devonian system, Calgary, Alberta. Alberta Soc. Petrol. Geol. v.2, p.333-350.
- Dunham, K.C., 1973. A recent deep borehole near Eyam, Derbyshire. Nature (Physical Science) v.241, no.108, p.84-85.
- Dunham, R.J., 1970. Stratigraphic reefs versus ecologic reefs. Bull. Am. Assoc. Petrol. Geol. v.54, p.1931-1932.
- Dupont, E., 1863. Sur le calcaire carbonifere de la Belgique et du Hainaut francaise. Bull. Acad. r. Belg. Cl. Sci. 2me. ser. v.15, p.86-137.
- Dupont, E., 1865. Essai d'une carte geologique des environs de Dinant. Bull. Acad. r. Belg. Cl. Sci. 2me. ser. v.20, nos.9 and 10, 42pp.
- Dupont, E., 1881. Sur l'origine des calcaires devoniens de la Belgique. Bull. Acad. r. Belg. Cl. Sci. 3me. ser. v.2, p.264-280.
- Dupont, E., 1883. Sur les origines du calcaire carbonifere de Belgique. Bull. Acad. r. Belg. Cl. Sci. 3me. ser. v.5, p.211-229.
- Dupont, H., 1969. Contribution a l'etude des facies du Waulsortien du Waulsort. Mem. Inst. geol. Univ. Louvain v.24, p.93-164.
- Fager, E.W., 1972. Diversity: A sampling study. Am. Nat. v.106, p.293-310.
- Falcon, N.L., and Kent, P.E., 1960. Geological results of petroleum exploration in Britain 1945-1957. Mem. geol. Soc. London no.2, 56pp.
- Fearnside, W.G., Bisat, W.S., Edwards, W., Lewis, H.P., Wilcockson, W.H., 1932. The geology of the eastern part of the Peak District. Proc. Geol. Assoc. London v.43, p.152-191.
- Fischer, A.G., and Garrison, R.E., 1967. Carbonate lithification on the sea floor. J. Geol. v.75, p.488-496.

- Folk, R.L., 1959. Practical petrographic classification of limestones.
Bull. Am. Assoc. Petrol. Geol. v.43, p.1-38.
- Folk, R.L., 1962. Spectral subdivision of limestone types. in Ham, W.E.,
ed., Classification of carbonate rocks. Mem. Am. Assoc. Petrol.
Geol. no.1, p.62-84.
- Folk, R.L., 1965. Some aspects of recrystallisation in ancient limestones.
in Pray, L.C., and Murray, R.C., eds., Dolomitization and lime-
stone diagenesis: A Symposium. Sp. Publ. soc. econ. Paleontol.
Mineral. 13, p.14-48.
- Folk, R.L., and Asserto, R., 1976. Comparative fabrics of length slow
and length fast calcite and calcitized aragonite in a Holocene
spelothem, Carlsbad Caverns, New Mexico. J. sediment. Petrol.
v.46, p.486-496.
- Foord, A.H., 1897-1903. A monograph of Carboniferous cephalopoda of
Ireland. Palaeontogr. Soc. London.
- Ford, T., 1977. Caves and geology of the Peak District. East Anglia
Press 469pp.
- Garwood, E.J., and Goodyear, E., 1924. The Lower Carboniferous succession
in the Settle district and along the line of the Craven faults.
Q.J. geol. Soc. London v.80, p.184-273.
- Geikie, A., 1903. Text Book of Geology 4 ed., 2 vols., Macmillan and Co.
London 1472pp.
- George, T.N., 1958. Lower Carboniferous palaeogeography of the British
Isles. Proc. Yorkshire geol. Soc. v.31, p.227-318.
- George, T.N., Johnson, G.A.L., Mitchell, M., Prentice, J.E.,
Ramsbottom, W.H.C., Sevastopulo, G.D., Wilson, R.B., 1976.
Dinantian: A correlation of Dinantian rocks in the British Isles.
Spec. Rep. geol. Soc. London no.7, 87pp.

- Ginsburg, R.N., Schroeder, J.H., and Shinn, E.A., 1971. Recent syn-sedimentary cementation in subtidal Bermuda reefs. in Bricker, O.P., ed., Carbonate Cements. The Johns Hopkins University Studies in Geology no.19, p.80-87.
- Ginsburg, R.N., and James, N.P., 1973. British Honduras by submarine. *Geotimes* v.18, p.23-24.
- Green, A.H., Foster, C. le N., Dakyn, S.J.R., 1869. The geology of the Carboniferous limestone, Yoredale rocks and Millstone Grit of North Derbyshire. England and Wales Geol. Surv. District Memoir 166pp.
- Hadding, A., 1958. Origin of the lithographic limestones. Publications from the Institutes of Mineralogy, Palaeontology and Quaternary Geology, Univ. of Lund, Sweden no.41.
- Hallam, A., 1965. Environmental causes of stunting in living and fossil marine invertebrates. *Palaeontology* v.8, p.132-155.
- Harbaugh, J.W., 1957. Mississippian bioherms in NE Oklahoma. *Bull. Am. Assoc. Petrol. Geol.* v.41, p.2530-2544.
- Heck, K.L., Belle, G., and Simberloff, D.S., 1975. Explicit calculation of the rarefaction diversity measurement and the determination of sufficient sample size. *Ecology* v.56, p.1459-1461.
- Heckel, P.H., 1972. Possible inorganic origin for Stromatactis in calcilutite mounds in the Tully Limestone, Devonian of New York. *J. sediment. Petrol.* v.42, p.7-18.
- Heckel, P.H., 1973. Nature, origin and significance of the Tully Limestone. *Spec. Pap. geol. Soc. Am.* 138, 244pp.
- Heckel, P.H., 1974. Carbonate buildups in the geologic record. in Laporte, L., ed., Reefs in time and space. Sp. Publ. soc. econ. Paleontol. Mineral. no.18, p.90-154.

- Hind, W., and Howe, J.A., 1901. The geological succession and palaeontology of the rocks between the Millstone Grit and the limestone massif at Pendle Hill and their equivalents in certain other parts of Britain. Q.J. geol. Soc. London v.57, p.347-404.
- Hind, W., 1896-1905. A monograph of the British Carboniferous lamelli-branchiata. Palaeontogr. Soc. London.
- Hudson, R.G.S., 1930. The Carboniferous of the Craven Reef Belt: The Namurian unconformity at Scaleber, near Settle. Proc. Geol. Assoc. London v.41, p.290-322.
- Hudson, R.G.S., 1932. The pre-Namurian knoll topography of Derbyshire and Yorkshire. Trans. Leeds Geol. Assoc. v.5, p.49.
- Hudson, R.G.S., 1942. The Upper Visean and Lower Namurian of North Staffordshire. Proc. Yorkshire geol. Soc. v.25, p.318-330.
- Hudson, R.G.S., and Cotton, G., 1945. The Carboniferous rocks of the Edale Anticline. Q.J. geol. Soc. London v.101, p.1-35.
- Hudson, R.G.S., Clarke, M.J., and Sevastopulo, G.D., 1966. A detailed account of the fauna and age of a Waulsortian reef knoll limestone and associated shales, Feltrim, Co. Dublin. Sci. Proc. R. Dubl. Soc. series A v.2, p.251-272.
- Jackson, J.B.C., 1972. The ecology of the molluscs of Thalassia communities, Jamaica, West Indies II: Mollusca population variability along an environmental stress gradient. Marine Biology v.14, p.304-337.
- Jackson, J.W., 1919. On the occurrence of Productus humerosus = sublaevis in Dovedale and its value as a zonal fossil. Geol. Mag. v.6, p.507-508.
- Jackson, J.W., 1941. Spirifer bollandensis Muir-Wood at Thorpe Cloud, with notes on the sequence in Dovedale, Derbyshire. J. Manchester geol. Assoc. v.1, p.233.

- James, N., Ginsburg, R., Marszalek, D., Choquette, P., 1976. Facies and fabric specificity of early subsea cements in shallow Belize (British Honduras) reefs. *J. Sediment. Petrol.* v.46, p.523-544.
- Johnson, R.G., 1972. Conceptual models of benthic marine communities. in Schopf, T., ed., *Models in Paleobiology*. Freeman Cooper and Co. San Francisco, p.148-159.
- Kendall, A.C., and Tucker, M.E., 1973. Radial fibrous calcite: a replacement after acicular carbonate. *Sedimentology* v.20, p.365-389.
- Kennedy, W.J., and Garrison, R.E., 1975. Morphology and genesis of nodular chalks and hardgrounds in the Upper Cretaceous of Southern England. *Sedimentology* v.22, p.311-386.
- Kennedy, W.J., and Juignet, P., 1974. Carbonate banks and slump beds in the Upper Cretaceous (Upper Turonian - Santonian) of Haute Normandie, France. *Sedimentology* v.21, p.1-42.
- Ladd, H.S., 1944. Reefs and other bioherms. National Research Council, Division Geology and Geography Ann. Rep. 4, appendix K, p.26-29.
- Lagaaij, R., and Gautier, Y.V., 1965. Bryozoa assemblages from marine sediments of the Rhone delta, France. *Micropaleontology* v.11, p.39-58.
- Land, L.S., and Goreau, J.F., 1970. Submarine lithification of Jamaican reefs. *J. sediment. Petrol.* v.40, p.457-462.
- Lane, N.G., and Burk, J., 1976. Arm movement and feeding mode of inadunate crinoids with biserial muscular arm articulations. *Paleobiology*, v.2, p. 202-208.
- Laudon, L.R., and Bowsher, A.L., 1941. Mississippian formations of the Sacramento Mountains, New Mexico. *Bull. Am. Assoc. Petrol. Geol.* v.25, p.2107-2160.
- Lecompte, M., 1937. Contribution a la connaissance des recifs du Devonien de l'Ardenne, sur la presence de structures conservees dans les efflorescences cristallines du type Stromatactis. *Bull. Mus. R. Hist. nat. Belg.* v.13, no.15, p.1-14.

- Lecompte, M., 1957. Les recifs devoniens de la Belgique. Bull. Soc. geol. Fr. v.6, p.1045-1068.
- Lees, A., 1961. The Waulsortian "reefs" of Eire: A carbonate mudbank complex of Lower Carboniferous age. J. Geol. v.69, p.101-109.
- Lees, A., 1964. The structure and origin of the Waulsortian (Lower Carboniferous) "reefs" of west central Eire. Philos. Trans. R. Soc. London series B, no.740, v.247, p.483-531.
- Lees, A., 1975. Possible influence of salinity and temperature on modern shelf carbonate sedimentation. Mar. Geol. v.19, p.159-198.
- Lees, A., and Buller, A.T., 1972. Modern temperate-water and warm-water shelf carbonate sediments contrasted. Mar. Geol. v.13, p.M67-M73.
- Lees, A., Noel, B., and Bouw, P., 1977. The Waulsortian "reefs" of Belgium: A progress report. Mem. Inst. geol. Univ. Louvain v.29, p.289-315.
- Levinton, J.S., 1970. The palaeoecologic significance of opportunistic species. Lethaia v.3, p.69-78.
- Lohman, K.C., and Meyers, W.J., 1977. Microdolomite inclusions in cloudy prismatic calcites: A proposed criteria for former high magnesium calcites. J. sediment. Petrol. v.47, p.1078-1088.
- Louchs, R.G., and Folk, R.L., 1976. Fan-like arrays of former aragonite in a Permian Capitan Reef pisolite. J. sediment. Petrol. v.46, p.483-485.
- Lowenstam, H.A., 1950. Niagaran reefs of the Great Lakes area. J. Geol. v.58, p.430-487.
- Ludford, A., 1951. The stratigraphy of the Carboniferous rocks of the Weaver Hills district, N. Staffordshire. Q.J. geol. Soc. London v.56, p.211-230.
- Ludford, A., 1970. The stratigraphy and palaeontology of Lower Carboniferous rocks of NE Staffordshire and adjacent parts of Derbyshire. Unpub. Ph.D. Chelsea College 471 pp.

- MacDermot, C.V., and Sevastopulo, G.D., 1972. The Upper Devonian and Lower Carboniferous stratigraphical setting of Irish mineralisation. *Bull. geol. Surv. Ireland* v.1, p.267-280.
- Marr, J.E., 1899. On the limestone knolls in the Craven District and elsewhere. *Q.J. geol. Soc. London* v.55, p.327-358.
- Menard, H.W., and Boucot, A.J., 1951. Experiments on the movement of shells by water. *Am. J. Sci.* v.249, p.131-151.
- Meyers, W.J., 1974. Carbonate cement stratigraphy of the Lake Valley Formation (Mississippian) Sacramento Mountains, New Mexico. *J. sediment. Petrol.* v.44, p.837-861.
- Miller, J., and Grayson, R.F., 1972. Origin and structure of the Lower Visean "reef" limestones near Clitheroe, Lancashire. *Proc. Yorkshire geol. Soc.* v.38, p.607-638.
- Milliman, J.D., 1971. Carbonate lithification in the deep sea. in Bricker, O.P., ed., *Carbonate Cements*. The Johns Hopkins University Studies in Geology, no.19, p.98-102.
- Milliman, J.D., 1974. *Marine Carbonates*. Springer-Verlag Berlin 375pp.
- Moore, R.C., ed., 1969, *Treatise on Invertebrate Paleontology*, Pt. N (Bivalvia) University of Kansas Press.
- Morgan, N. 1976. The Montenegro Bioherms: Their paleoecology, relation to other bioherms and to early Cambrian sedimentation, White and Inyo Mountains, California. *Pacific Coast Paleogeography field guide no.1, Soc. econ. Paleontol. Mineral.*, p.13-17.
- Mountjoy, E.W., and Walls, R.A., 1977. Some examples of early submarine cements from Devonian buildups of Alberta. *Proc. 3rd Int. Coral Reef Symposium, Univ. of Miami*, p.155-161.

Mundy, D.J.C., 1978. Reef communities. in McKerrow, W.S., ed., The ecology of fossils. Duckworth, London, p.157-167.

Neumann, A.C., Keller, G.H., Kofoed, J.W., 1972. "Lithoherms" in the Straits of Florida. Geol. Soc. Am. Abstracts with Programs v.4, no.7, p.611.

- Neumann, A.C., Kofoed, J.W., Keller, G.H., 1977. Lithoherms in the Straits of Florida. *Geology* v.5, no.1, p.4-11.
- Neumann, A.C., 1978. Lithoherms in the Straits of Florida: Reply. *Geology* v.6, no.1, p.8.
- Neville, W.E., 1958. The Carboniferous knoll-reefs of east central Ireland. *Sci. Proc. R. Dubl. Soc. series B* v.59, p.285-303.
- Newell, N.D., Rigby, J.K., Fischer, A.G., Whiteman, A.J., Hickox, J.E., and Bradley, J.S., 1953. The Permian reef complex of the Guadalupe Mountains Region, Texas and New Mexico: A study in paleoecology. Freeman and Co. San Francisco.
- Nie, N.H., Hull, C.H., Jenkins, J., Steinbrenner, K., Bent, D., 1970. SPSS: Statistical Package for the Social Sciences 2nd ed. McGraw Hill 676pp.
- Noel, B., 1973. Relations stratigraphiques et sedimentologiques entre le complexe Waulsortien de Moniat et les depots contemporains environants. Memoire de license, Universite Catholique de Louvain, unpub., 52pp.
- Odum, E.P., 1971. Fundamentals of ecology. Saunders Co. Philadelphia 574pp.
- Parkinson, D., 1926. The faunal succession in the Carboniferous limestone and Bowland shales at Clitheroe and Pendle Hill. *Q.J. geol. Soc. London* v.82, p.188-249.
- Parkinson, D., 1935. The geology and topography of the limestone knolls in Bolland (Bowland), Lancashire and Yorkshire. *Proc. Geol. Assoc. London* v.46, p.97-120.
- Parkinson, D., 1936. The Carboniferous succession in the Slaidburn District, Yorkshire. *Q.J. geol. Soc. London* v.92, p.294-331.
- Parkinson, D., 1944. The origin and structure of the Lower Visean reef-knolls of the Clitheroe District, Lancashire. *Q.J. geol. Soc. London* v.49, p.155-168.

- Parkinson, D., 1947. The Lower Carboniferous of the Castleton District, Derbyshire. Proc. Yorkshire geol. Soc. v.27, p.99-124.
- Parkinson, D., 1950. The stratigraphy of the Dovedale area, Derbyshire and Staffordshire. Q.J. geol. Soc. London v.55, p.265-294.
- Parkinson, D., 1954. Quantitative studies of brachiopods from the Lower Carboniferous reef limestone of England I: Schizophoria resupinata J. Paleontol. v.28, p.367-381.
- Parkinson, D., 1957. Lower Carboniferous reefs of Northern England. Bull. Am. Assoc. Petrol. Geol. v.46, p.511-537.
- Parkinson, D., 1964. The relationship of the Bowland shales to the Pendleside limestone in the Clitheroe, Slaidburn and Sykes Anticlines. Geol. J. v.4, p.157-165.
- Parkinson, D., 1969. Relative growth variation and evolutionary trends in Carboniferous Rhyconellid brachiopods. J. Paleontol. v.43, p.95-110.
- Pielou, E.C., 1966. Species diversity and pattern diversity in the study of ecological succession. J. Theoret. Biol., v. 10, p. 370-383.
- Pielou, E.C., 1974. Population and Community Ecology: Principles and Methods. Gordon and Breach Scientific Pubs. 424pp.
- Philcox, M.E., 1963. Banded calcite mudstone in the Lower Carboniferous "reef" knolls of the Dublin basin, Ireland. J. sediment. Petrol. v.33, p.904-913.
- Philcox, M.E., 1965. Sedimentation of Upper Devonian Stromatactis bioherms, Alberta, Canada. Spec. Pap. geol. Soc. Am. 82, p.150.
- Philcox, M.E., 1971. A Waulsortian bryozoa reef (cumulative biostrome) and its off-reef equivalents, Ballybeg, Ireland. Compte Rendu 6e Congres Intern. Strat. Geol. Carbonif. Sheffield, 1967 v.4, p.1359-1372.
- Pray, L.C., 1958. Fenestrate bryozoan core facies, Mississippian bioherms SW United States. J. sediment. Petrol. v.28, p.261-273.
- Pray, L.C., 1969. Micrite and carbonate cement: Genetic factors in Mississippian bioherms. J. Paleontol. v.43, p.895.

- Prentice, J.E., 1951. The Carboniferous limestone of the Manifold Valley region, N. Staffordshire. *Q.J. geol. Soc. London* v.56, p.171-210.
- Purdy, E.G., 1965. Diagenesis of recent marine sediments (abstract). in Pray, L.C., and Murray, R.C., eds., Dolomitization and limestone diagenesis. *Spec. Publ. Soc. econ. Paleontol. Mineral. no.13*, p.169.
- Pusey, W.C., 1964. Recent calcium carbonate sedimentation in northern British Honduras. Ph.D. Rice Univ. Houston, Texas 247pp.
- Raup, D.M., 1975. Taxonomic diversity estimation using rarefaction. *Paleobiology* v.1, p.333-342.
- Reyment, R.A., 1971. Introduction to Quantitative Paleoecology. Elsevier, 226 pp.
- Riding, R., 1977. Reef concepts. *Proc. 3rd Int. Coral Reef Symposium*, Univ. of Miami, p.209-213.
- Ross, R., Jaanusson, V., and Friedman, I., 1975. Lithology and origin of Middle Ordovician calcareous mudmound at Meiklejohn Peak, S. Nevada. *Prof. Pap. U.S. geol. Surv.* 871, 48pp.
- Rudwick, M.J.S., 1964. The inference of function from structure in fossils. *Br. J. Phil. Sci.* v.15, p.27-40.
- Rudwick, M.J.S., 1970. Living and fossil brachiopods. *Hutchison University Library*, 199pp.
- Sadler, H.E., and Wyatt, R.J., 1966. A Lower Carboniferous S2 inlier near Hartington, Derbyshire. *Proc. Geol. Assoc.* v.77, p.55-64.
- Sanders, H.L., 1968. Marine benthic diversity: A comparative study. *Am. Nat.* v.102, p.243-283.
- Schopf, T.J.M., 1969. Paleoecology of Ectoprocts (Bryozoans). *J. Paleont.* v.43, p.234-244.
- Schroeder, J.H., 1972. Fabrics and sequences of submarine carbonate cements in Holocene Bermuda cup reefs. *Geol. Rdsch.* v.61, p.708-730.

- Schwarzacher, W., 1961. Petrology and structure of some Lower Carboniferous reefs in north western Ireland. *Bull. Am. Assoc. Petrol. Geol.* v.45, p.1481-1503.
- Schwarzacher, W., 1963. Orientation of crinoids by current orientation. *J. sediment. Petrol.* v.33, p.580-586.
- Shephard-Thorn, E.R., 1963. The Carboniferous limestone succession in NW Co. Limerick, Ireland. *Proc. R. Irish Acad.* v.62, p.267-294.
- Shinn, E., 1968. Burrowing in recent lime sediments of Florida and the Bahamas. *J. Paleontol.* v.42, p.129-147.
- Shinn, E., 1969. Submarine lithification of Holocene carbonate sediments in the Persian Gulf. *Sedimentology* v.12, p.109-144.
- Shirley, J., 1958. The Carboniferous limestone of the Monyash-Wirksworth area, Derbyshire. *Q.J. geol. Soc. London* v.114, p.411-429.
- Shirley, J., and Horsfield, E.L., 1940. The Carboniferous limestone of the Castleton-Bradwell area, N. Derbyshire. *Q.J. geol. Soc. London* v.96, p.271-299.
- Sibly, T.F., 1908. The faunal succession in the Carboniferous limestone of the Midland area. *Q.J. geol. Soc. London* v.64, p.34-82.
- Simberloff, D.S., 1972. Properties of the rarefaction diversity measurement. *Am. Nat.* v.106, p.414-418.
- Simpson, I.M., and Broadhurst, F.M., 1969. A boulder bed at Treak Cliff, N. Derbyshire. *Proc. Yorkshire geol. Soc.* v.37, p.141-151.
- Sipptè, R.F., and Glover, 1965. Structures in carbonate rocks made visible by luminescence petrography. *Science* v.150, p.1283-1287.
- Slobodkin, L.B., and Sanders, H.L., 1969. On the contribution of environmental predictability to species diversity. *Brookhaven Symposium in Biology* v.22, p.82-95.
- Smith, A.G., Briden, J.C., and Drewry, G.E., 1973. Phanerozoic world maps. in Hughs, N.F., ed., *Organisms and continents through time.* *Spec. Pap. Palaeontol.* 12, p.1-42.

- Southwood, T.R.E., 1976. Bionomic strategies and population parameters. in May, R.M., ed., Theoretical ecology, principles and applications. Blackwell Scientific Publications p.26-48.
- Stanley, S.M., 1970. Relation of shell form to life habits of the Bivalvia (Mollusca). Mem. geol. Soc. Am. 125, 296pp.
- Stanley, S.M., 1972. Functional morphology and evolution of byssally attached bivalve molluscs. J. Paleontol. v.46, p.165-212.
- Stevenson, I.P., and Gaunt, G.D., 1971. Geology of the country around Chapel en le Frith. Mem. geol. Surv. U.K. no.99, 444pp.
- Stockman, K.W., Ginsburg, R.N., and Shinn, E.A., 1967. The production of lime mud by algae in South Florida. J. sediment. Petrol. v.37, p.633-648.
- Stone, R.A., 1972. Waulsortian type bioherms of Mississippian age, Central Bridger Range, Montana. Montana Geol. Soc. Guidebook, 21st Ann. Field Conf. p.37-55.
- Sylvester-Bradley, P.C., and Ford, T.D., eds., 1968. The geology of the East Midlands. Leicester Univ. Press 400pp.
- Thach, T.K., 1965. Sedimentology of the Lower Carboniferous (Visean) limestone in N. Staffordshire and SW Derbyshire. Unpub. Ph.D. Univ. of Reading.
- Tiddeman, R.H., 1889. On concurrent faulting and deposition in Carboniferous times in Craven, Yorkshire with a note on Carboniferous reefs. Rep. British Assoc. (Newcastle) p.600-603.
- Tiddeman, R.H., 1890. Physical history of the Carboniferous rocks in Upper Airedale. Proc. Yorkshire Geol. Soc. v.11, p.482-492.
- Tiddeman, R.H., 1892. The theory of reef knolls. The Craven Herald, 29 January 1892 (quoted in Kendall and Wroot, 1924. The geology of Yorkshire. p.92-99).
- Tiddeman, R.H., 1900. On the formation of reef knolls. Report British Assoc. (Bradford), p.740-742.

- Timms, A.E., 1973. Aspects of the palaeoecology of the Lower Carboniferous apron-reef at Castleton, Derbyshire., Unpub. MsC. thesis, Manchester Univ.
- Timms, A.E., 1978. Aspects of the palaeoecology of productoid and associated brachiopods in the Middle to Upper Visean reef limestones of Derbyshire. Unpub. Ph.D. Univ. of Manchester.
- Troell, A.R., 1962. Lower Mississippian bioherms of SW Missouri and NW Arkansas. *J. sediment. Petrol.* v.32, p.629-644.
- Turner, G., 1957. Paleozoic stratigraphy of the Ft. Worth Basin. Field Trip Guidebook 61, Ft. Worth and Abilene Geol. Societies.
- Turner, J.S., 1937. The faunal succession in the Carboniferous limestone near Cork. *Proc. R. Irish Acad.* v.43B, p.193-209.
- Turner, J.S., 1938a. Upper Palaeozoic stratigraphy of the Dublin district. *Proc. R. Irish Acad.* v.45B, p.25-32.
- Turner, J.S., 1938b. The Dublin district vis-a-vis the Craven-Bowland lowlands. *Trans. Leeds Geol. Assoc.* v.5, p.208-216.
- Turner, J.S., 1962. The age of reef limestones in the Carboniferous limestone of the Maine Valley, Co. Kerry. *Proc. Leeds philos. lit. Soc.* v.8, p.247-250.
- Valentine, J.W., 1971. Resource supply and species diversity patterns. *Lethaia* v.4, p.51-61.
- Vaughan, A., 1905. The palaeontological sequence in the Carboniferous limestone of the Bristol area. *Q.J. geol. Soc. London* v.61, p.181-307.
- Vaughan, A., 1916. The knoll region of Clitheroe, Bowland and Craven. *Proc. Yorkshire geol. Soc.* v.19, p.41-50.
- Wain, E.B., and Stobbs, J.T., 1906. Notes on Cauldon Lowe and the Manifold Valley. *Trans. Instn. Ming. Eng.* v.32, p.193-196.
- Walker, K.R., and Alberstadt, L.P., 1975. Ecological succession as an aspect of structure in fossil communities. *Paleobiology* v.1, p.238-257.

- Watkins, R., 1975. Palaeoecology of some Carboniferous Pectinacea. *Lethaia* v.8, p.125-131.
- Whitbread, D.R., 1963. Facies change in the Carboniferous successions of Southern Ireland. Unpub. Ph.D. Univ. of Reading 250pp.
- Wilmore, A., 1907. On the structure and origin of the Craven limestone knolls. *Proc. Yorkshire geol. Soc.* v.16, p.158-169.
- Wilson, J.L., 1975. Carbonate Facies in Geologic History. Springer-Verlag 471pp.
- Wolf, J.H., 1965. Petrogenesis and palaeoenvironment of Devonian algal limestones of New South Wales. *Sedimentology* v.4, p.113-178.
- Wolfenden, E.B., 1958. Paleoecology of the Carboniferous reef complex and shelf limestones in NW Derbyshire, England. *Bull. Geol. Soc. Am.* v.69, p.871-898.
- Ziegler, A.M., Cocks, L.R.M., Bambach, R.K., 1968. The composition and structure of Lower Silurian marine communities. *Lethaia* v.1, p.1-27.