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A FACIES ANALYSIS OF THE
UPPER GREAT OOLITE GROUP IN CENTRAL
AND EASTERN ENGLAND

VOLUME I

DAVID WILLIAM CRIPPS

Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM

October 1986

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The University of Aston in Birmingham

A facies analysis of the upper Great Oolite Group
in central and eastern England

David William Cripps
Doctor of Philosophy

1986

The results of a field-based sedimentological/palaeontological study of Middle-Upper Bathonian sediments from the east Midlands and Oxfordshire are presented. The lithostratigraphy of these beds is revised. 'Blisworth/Great Oolite Clay' and 'Blisworth/Great Oolite Limestone' are abandoned. The areas of usage of the Ardley and Bladon Members (White Limestone) and the White Limestone and Forest Marble Formations are extended northeastwards. Three lithostratigraphic units are introduced: the Thrapston Clay Formation (replacing 'Blisworth Clay' throughout much of the east Midlands) and the Irchester and Longthorpe Members. The latter occupy the same stratigraphic interval as the Ardley and Bladon Members combined.

Time-correlation has been achieved using event-stratigraphy and ammonite, gastropod and brachiopod biostratigraphy. The bases of sedimentary rhythms are taken as time-lines.

The sediments studied are shallow marine to coastal plain, siliciclastic/carbonate sediments, mostly deposited landward of the 'Cotswold-Weald Shelf' ooid shoals. They accumulated in the slowly subsiding area between the London-Brabant Massif and Pennine High, tectonically-positive features emergent throughout the Bathonian. The position of coastlines changed continually in response to sea level fluctuations, tectonic movements and coastal progradation. The east Midlands were emergent at times, but were periodically inundated by transgressions from the Wessex and Anglo-Dutch Basins.

Nine lithofacies and five lithofacies associations have been recognised. The nine biofacies identified are associated with particular lithofacies, reflecting the control exerted by substrate on faunal distribution. Biofacies composition was also affected by environmental stress/salinity variations. 'Normal' marine, marginal marine and freshwater biotas have been encountered. Mollusc-dominated faunas of slightly less than 'normal' marine type are most common.

The sediments studied were deposited as stacked 'rhythms'. Seven depositional units are recognised. Regional lithofacies/biofacies distribution within each is discussed.

KEY WORDS: Jurassic, Great Oolite, facies analysis, rhythmic sedimentation, east Midlands.

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LIST OF CONTENTS

VOLUME I

	<u>Page No.</u>
Chapter 1 INTRODUCTION	
1.1 Aims of the study	14
1.2 Methods of research	18
1.2.1 Fieldwork	18
1.2.2 Literature	19
1.2.3 Petrographic study	19
1.2.4 Faunal study	20
1.3 Lithological nomenclature	20
1.3.1 Carbonate lithologies	20
1.3.2 Siliciclastic lithologies	26
Chapter 2 THE GENERAL SETTING	
2.1 Introduction	28
2.2 Structural setting	28
2.3 Patterns of subsidence	42
2.4 Palaeogeographic setting	46
2.5 Middle Jurassic climate	51
2.6 Timescale	55
Chapter 3 LITHOSTRATIGRAPHY	
3.1 The development of the existing lithostratigraphy	58
3.1.1 Introduction	58
3.1.2 North Gloucestershire and Oxfordshire	60
3.1.2.1 Base of the White Limestone Formation	61
3.1.2.2 Subdivision of the White Limestone Formation	63
3.1.2.3 The Forest Marble-White Limestone boundary	69
3.1.2.4 Subdivision of the Forest Marble Formation and the status of the 'Kemble Beds'	71
3.1.2.5 Cornbrash Formation	74

	<u>Page No.</u>
3.1.3 East Midlands	74
3.1.3.1 Nomenclature: White Limestone Formation	75
3.1.3.2 Base of the White Limestone Formation	77
3.1.3.3 Subdivision of the White Limestone Formation	78
3.1.3.4 Nomenclature: 'Forest Marble' v 'Blisworth Clay'	81
3.1.3.5 Top of the White Limestone Formation	82
3.1.3.6 Cornbrash Formation	84
3.2 Proposed revision of the lithostratigraphy	84
3.2.1 Introduction	84
3.2.2 White Limestone Formation	85
3.2.2.1 Shipton Member	85
3.2.2.2 <u>Kallirhynchia sharpi</u> Beds	87
3.2.2.3 Ardley Member	90
3.2.2.4 Bladon Member	91
3.2.2.5 ?Great Oolite	93
3.2.2.6 Irchester Member	93
3.2.2.7 Longthorpe Member	95
3.2.3 Forest Marble Formation	96
3.2.4 Thrapston Clay Formation	97
 Chapter 4 BIOSTRATIGRAPHY	
4.1 Introduction	104
4.2 Ammonites	105
4.3 Gastropods	113
4.4 Ostracods	116
4.5 Brachiopods	118
4.6 Dinoflagellates	123
4.7 Foraminifers	125
4.8 Time-correlative methods adopted in this thesis	125

Chapter 5	SEDIMENTOLOGY OF THE UPPER GREAT OOLITE GROUP	
5.1	Introduction	128
5.2	The general setting of Middle and Late Bathonian sedimentation in southern and central England	128
5.3	Lithofacies and Lithofacies associations	133
5.3.1	Lithofacies 1: Cross-bedded, offshore lime sands	134
5.3.2	Lithofacies 2: Winnowed, shifting lime sands	136
5.3.3	Lithofacies 3: Muddy, stable lime sands	138
5.3.4	Lithofacies association A: Cross-bedded lime sands and terrigenous muds	141
5.3.5	Lithofacies association B: Cross-bedded lime sands; interlayered lime sands and lime muds; bioclastic/oolitic lime muds	145
5.3.6	Lithofacies 4: Pelletal lime sands	150
5.3.7	Lithofacies 5: Bioturbated, pelletal lime muds	151
5.3.8	Lithofacies association C: Pelletal lime sands/ lime muds and oolitic/bioclastic lime sands	154
5.3.9	Lithofacies 6: Lime muds	161
5.3.10	Lithofacies 7: Oyster 'reefs'	166
5.3.11	Lithofacies 8: Hardgrounds and pebble-beds	168
5.3.12	Lithofacies 9: Interlayered sands and terrigenous muds	172
5.3.13	Lithofacies association D: Interbedded argillaceous, bioclastic lime muds and interlayered sands and terrigenous muds	175
5.3.14	Lithofacies association E: Homogeneous, terrigenous muds and fossiliferous, terrigenous muds	178

	<u>Page No.</u>
Chapter 6	FAUNA OF THE UPPER GREAT OOLITE GROUP
6.1	Introduction 182
6.2	Environmental controls on faunal distribution 183
6.2.1	Physical controls 183
6.2.1.1	Temperature 183
6.2.1.2	Salinity 184
6.2.1.3	Substrate 185
6.2.1.4	Other physical controls 186
6.2.2	Biological controls 187
6.2.2.1	Food availability 187
6.2.2.2	Predation 187
6.2.3	Environmental stress 188
6.3	Life habits and taxonomic comments 189
6.3.1	Corals 189
6.3.2	Bryozoa 190
6.3.3	Echinoids 191
6.3.4	Brachiopods 194
6.3.5	Bivalves 200
6.3.6	Gastropods 217
6.3.7	'Vermes' 218
6.4	Fossil assemblages 219
6.4.1	Biofacies 1: Shifting lime sand communities 219
6.4.2	Biofacies 2: Unstable lime sand communities 220
6.4.3	Biofacies 3: Stable, lime sand communities 221
6.4.4	Biofacies 4: Stable sandy lime mud communities 223
6.4.5	Biofacies 5: Coral bed communities 225
6.4.6	Biofacies 6: <u>Aphanoptyxis</u> bed communities 227
6.4.7	Biofacies 7: Oyster bed communities 228
6.4.8	Biofacies 8: Firm and hard substrate communities 230
6.4.9	Biofacies 9: Freshwater communities 231

Chapter 7	RHYTHMIC SEDIMENTATION	
7.1	Introduction	233
7.2	Rhythm A	236
7.2.1	Introduction	236
7.2.2	Regional variation and facies distribution	239
7.3	Rhythm B	244
7.3.1	Introduction	244
7.3.2	Regional variation and facies distribution	247
7.4	Rhythm C	250
7.4.1	Introduction	250
7.4.2	Regional variation and facies distribution	254
7.5	Rhythm D	261
7.5.1	Introduction	261
7.5.2	Regional variation and facies distribution	262
7.6	Rhythm E	265
7.6.1	Introduction	265
7.6.2	Regional variation and facies distribution	266
7.7	Forest Marble 'Rhythm'	268
7.7.1	Introduction	268
7.7.2	Regional variation and facies distribution	274
7.8	Lower Cornbrash 'Rhythm'	278
7.8.1	Introduction	278
7.8.2	Regional variation and facies distribution	280
7.9	Upper Cornbrash	283
7.10	Controls on rhythmic sedimentation	284
7.11	Rhythms and time-correlation	291
Chapter 8	PALAEOGEOGRAPHY AND DEPOSITIONAL HISTORY	
8.1	Palaeogeography	293
8.1.1	Palaeogeography and distribution of facies in Rhythm C times	295
8.2	Depositional history	299
Chapter 9	CONCLUSIONS	305

List of Figures

1.1	Lithostratigraphic subdivision of the Great Oolite Group employed in this thesis	15
1.2	Map of study area, showing the locations of measured sections	16
2.1	Major structural elements of Jurassic England and adjacent areas	31
2.2	Major structural elements of Middle Jurassic central England	37
2.3	Stratigraphic cross section across the 'Oxfordshire High'	41
2.4	Lincolnshire Limestone isopach map	45
2.5	Rutland Formation isopach map	45
2.6	Major palaeogeographic features of the British area in the Middle Jurassic	48
2.7	Recent numerical time scales for the Jurassic showing estimates for the upper and lower limits of the Bathonian	56
3.1	Area of usage: <u>Kallirhynchia sharpi</u> Beds and Shipton Member	100
3.2	Area of usage: Ardley, Bladon, Irchester and Longthorpe Members	101
3.3	Maximum extent of the White Limestone Formation	102
3.4	Area of usage: Forest Marble and Thrapston Clay Formations	103
4.1	Development of the English Bathonian ammonite zonation	106
4.2	Development of the English Bathonian ostracod zonation	117
4.3	Comparison of the Bathonian ammonite and dinocyst zonations	124
4.4	Vertical distribution within the study area of selected faunal elements, related to ammonite zones and rhythmic units	127
5.1	Bathonian deposition in southern and central England related to Irwin's (1965) model for carbonate sedimentation in an epeiric area	130
5.2	Production of muddy lime sand and sandy lime mud substrates	140

	<u>Page No.</u>
5.3 Idealised storm couplet of Lithofacies association C	155
7.1 Sedimentary rhythms recognised within the study area	235
7.2 Rhythm A: geographical limits and isopachs	238
7.3 Distribution of Rhythm A sediments in quarries in the Cranford-Finedon district	241
7.4 Lateral facies and thickness variation within Rhythm A in Cranford North and South Pits	242
7.5 Rhythm B: geographical limits, distribution of <u>K. sharpi</u> and maximum southwestward extent of coastal progradation	245
7.6 Rhythm B: facies distribution in mid-Rhythm B times	248
7.7 Rhythm C: geographical limits and distribution of <u>D. digonoides</u>	253
7.8 Rhythm C: facies distribution in early Rhythm C times	259
7.9 Rhythm C: facies distribution in late Rhythm C times	260
7.10 Rhythm D: geographical limits and maximum southwestward extent of coastal progradation	263
7.11 Rhythm E: geographical limits and maximum southwestward extent of coastal progradation	267
7.12 Forest Marble 'Rhythm': geographical limits	269
7.13 Map illustrating the distribution of 'Bradfordian' faunas in the Oxfordshire Forest Marble	272
7.14 Geographical limits of the Lower Cornbrash	279
7.15 Chart comparing the eustatic sea level curves of Vail & Todd (1981) and Hallam (1978)	287
8.1 Generalised Bathonian palaeogeography of southern and central England	294
8.2 Palaeogeography of the English area in Rhythm C times (<u>hodsoni</u> Zone)	296
8.3 Schematic distribution of facies in mid to late Rhythm C times (<u>hodsoni</u> Zone) between Dorset and the east Midlands	298

List of Tables

4.1	Extant ammonites from the White Limestone of Gloucestershire, Oxfordshire and the east Midlands	111
4.2	Non-extant ammonites from the White Limestone of Oxfordshire and the east Midlands	112

Plates

1	Photomicrographs: grain types	313
2	Photomicrographs: grain types and fabrics	315
3	Field photographs: base of the Ardley and Irchester Members	317
4	Field photographs: miscellaneous	319
5	Field photographs: miscellaneous	321
6	Miscellaneous photographs	323
7	Field photographs: Forest Marble and Thrapston Clay	325
8	Field photographs: Lithofacies associations B and C	327
9	Field photographs: Lithofacies association C	329
10	Polished slabs: Lithofacies association C sediments	331
11	Field photographs: Lithofacies 7, Wellingborough	333
12	Miscellaneous photographs: Lithofacies 6	335
13	Field photographs: miscellaneous	337
	REFERENCES	339

VOLUME II

Appendix 1 LOCALITY DETAILS

1.1	Introduction	3
1.2	Outcrop	3
1.2.1	Gloucestershire	3
1.2.2	Oxfordshire	4
1.2.3	Buckinghamshire	27
1.2.4	Bedfordshire	40
1.2.5	Northamptonshire	47

	<u>Page No.</u>
1.2.6 Cambridgeshire	89
1.2.7 Leicestershire	94
1.2.8 Lincolnshire	95
1.3 Boreholes	100
1.3.1 Oxfordshire	100
1.3.2 Buckinghamshire	102
1.3.3 Northamptonshire	105
1.3.4 Bedfordshire	107
1.3.5 Cambridgeshire	110
1.3.6 Hertfordshire	116
1.3.7 Norfolk and Suffolk	118
1.3.8 Lincolnshire and Humberside	125
1.3.9 Other areas	133

Appendix 2 KEY TO SYMBOLS AND CODES USED IN FIGURED SECTIONS (ENCLOSURES A-1 TO A-16)	140
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List of Figures

A-1 Deposition of the 'Kirtlington Mammal Bed'	19
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Enclosures

2.1 Great Oolite Group isopach map

A-1 to A-16 Measured sections

CHAPTER 1

INTRODUCTION

1.1 Aims of the study

The English Middle Jurassic, which has been studied by stratigraphers, palaeontologists and sedimentologists for well over 150 years, might be considered by some to be a subject exhausted of research potential; however, this is not true. The English Bathonian is a complex mixture of marine to freshwater siliciclastic and carbonate sediments which were deposited in a wide range of sedimentary environments. By adopting the integrated palaeoecological, sedimentological and stratigraphical approach which characterises 'facies analysis' (see Hallam, 1981a, for discussion), new light can readily be shed on the depositional history and regional setting of these strata.

The field area in which I have worked comprises the Middle Jurassic outcrop from Gloucestershire to the River Humber, but most especially the outcrop in Northamptonshire and Oxfordshire and adjoining parts of adjacent counties (Fig. 1.2). Information from the subcrop to the east has also been employed to give a greater spread of facies data. My intention has been to investigate the Middle Bathonian to lowermost Callovian upper Great Oolite Group of this study area, largely by the study of over 200 localities spread throughout the region. Sections and boreholes, from which data have been used, are discussed in detail in the appendix. They are located, wherever possible, using a six-figure (or greater) National Grid Reference.

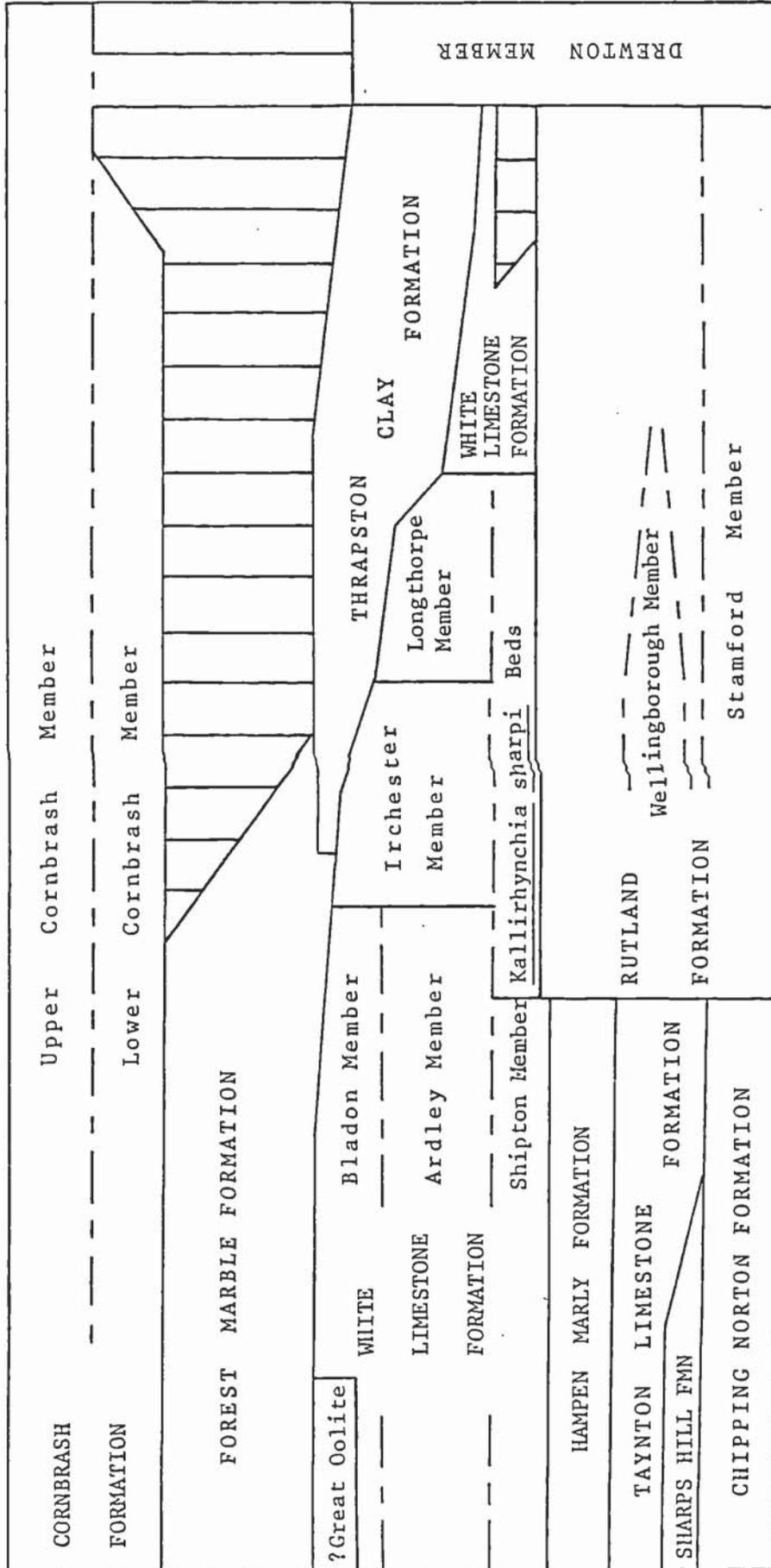


FIGURE 1.1 Lithostratigraphic subdivision of the Great Oolite Group employed in this thesis.

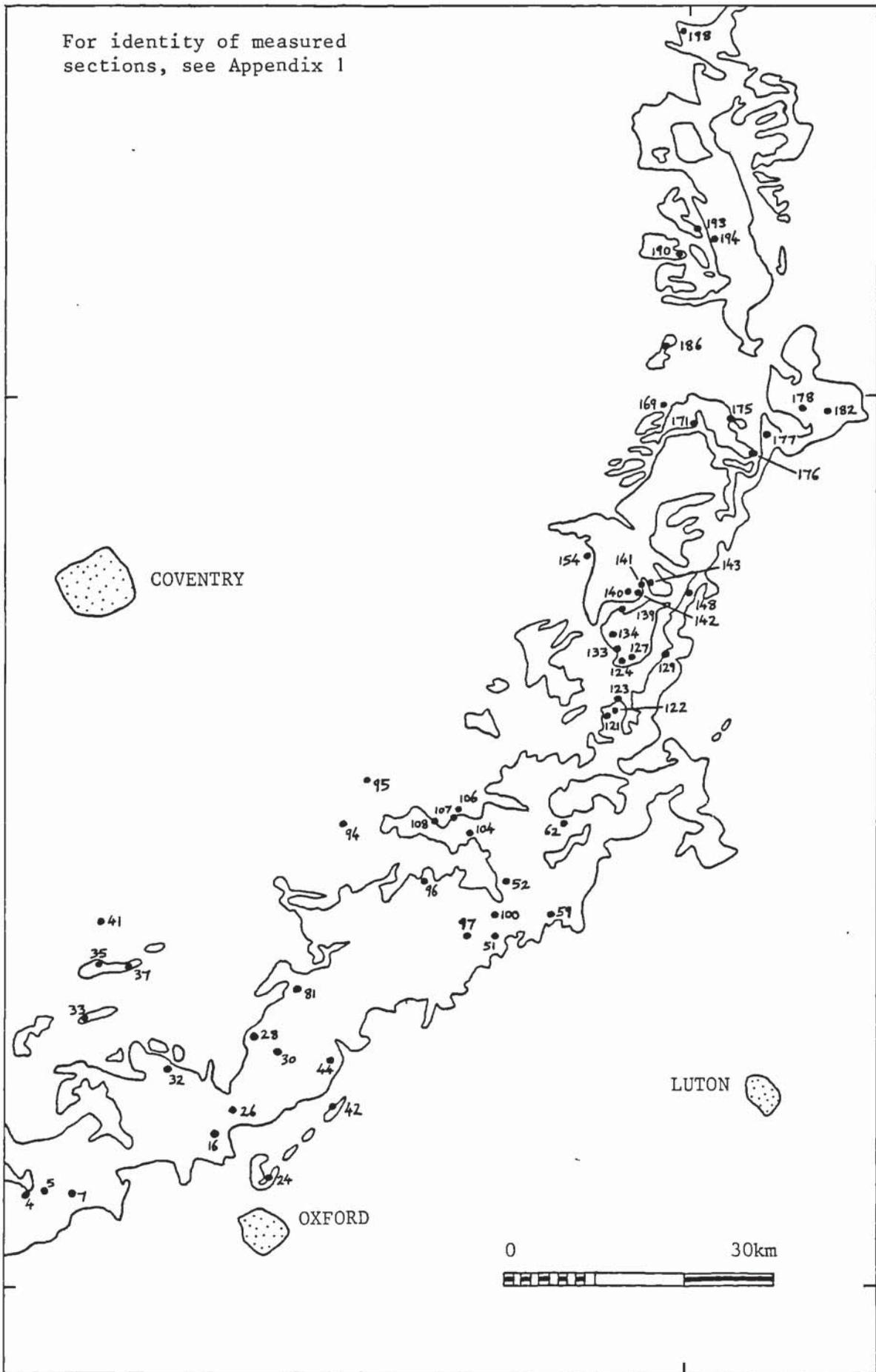


FIGURE 1.2 Map of study area, showing the locations of measured sections.

Rhythmic sedimentation in the lower Great Oolite Group of the east Midlands was first identified by Aslin (1965) and later studied in considerable detail by Bradshaw (1978). The latter not only recognised the correlatability of laterally extensive sedimentary rhythms but also successfully traced them from the east Midlands into Oxfordshire. As rhythmic sedimentation had also been recognised within the upper Great Oolite Group of Oxfordshire (T. Palmer, 1974, 1979), it was my hope that I would be able to recognise rhythmic events within the upper Great Oolite Group of east Midlands, follow them laterally into those encountered by Palmer in Oxfordshire and thus, by using event stratigraphy, be able to greatly improve the correlation between the two areas.

It was also hoped that the study of rhythmic sedimentation in the Bathonian of central and southern England might improve our understanding of sea level change during the period, and possibly also of the 'Callovian transgression', an apparently global event which on a more detailed level was interrupted by several temporary regressions.

By improving the correlation of upper Great Oolite Group strata in Oxfordshire and the east Midlands, I would be able to map more accurately lateral changes of lithofacies and biofacies at any given point in time. This was essential if I was going to fully understand the changes in palaeogeography which occurred in the study area as the sediments of the upper Great Oolite Group were deposited.

1.2 Methods of research

1.2.1 Fieldwork

Extensive fieldwork throughout a large study area has provided the foundations upon which this thesis is based. The majority of the extant sections in the study area have been visited and over sixty have been logged in detail; these sections are illustrated in Enclosures A-1 to A-16. The scale and quality of the remaining exposures varies considerably. Exposures in White Limestone quarries in Oxfordshire/Northamptonshire that are still active or have recently been worked are excellent and generally extensive. The same applies to many of the former ironstone pits in the Northamptonshire Sand Ironstone Field, although access to the upper part of the White Limestone at these sites is frequently precarious; a large number of the latter are land-fill sites and their future as geological exposures is sadly in doubt (sections at Irchester New Lodge and Geddington have vanished since I visited them). Most of the small village quarries which once provided stone and lime for local use throughout the east Midlands, where extant, are invariably badly overgrown and provide only small exposures; this is also true of sections in disused railway cuttings.

Those localities where sections are still visible have provided the basic sedimentological and palaeontological data which have been used to recognise lithofacies and lithofacies associations, biofacies, biofacies-lithofacies relationships and rhythmic sedimentation within the upper Great Oolite Group.

1.2.2 Literature

During the course of fieldwork a large number of locations where sections once existed but are now no longer visible have been visited. Published literature and unpublished data, in theses and from other sources, is therefore the only information available on these sections.

These data are of considerable value for unravelling regional facies changes and for improving stratigraphic correlations. A large part of the appendix to this thesis is taken up with a discussion of these data.

1.2.3 Petrographic study

Many hundreds of specimens have been collected for petrographic analysis. Over 300 thin sections have been studied, largely to corroborate field identifications, to aid identifications of minerals and to investigate diagenesis. All thin sections were stained with a combined Alizarin Red-S/Potassium Ferricyanide stain, *following the method developed by Dickson (1965, 1966)*. Micrite and most original allochems stained pink, indicating that they are composed of non-ferroan calcite. The majority of cements stained deep blue, suggesting that they are composed of strongly ferroan calcite. As expected, no dolomite has been encountered in the upper Great Oolite Group of the study area. In addition to thin sections, acetate peels have also been used to provide microfacies data. Point counting has not been employed, for accurate estimates of composition can be made using comparison charts (Flügel, 1982). Lithology, texture and fabric have also been studied using sawn and polished specimens which have the advantage of revealing large scale features not seen with thin sections.

Time has prevented a complete diagenetic study of the upper Great Oolite Group of central and eastern England: this would be a Ph.D topic in itself.* Therefore no cathode luminescence microscopy, trace element geochemistry or stable isotope work has been undertaken; only five samples have been analysed using a scanning electron microscope.

1.2.4 Faunal study

Palaeontological sampling has been undertaken on a bed by bed basis at all localities where detailed sections have been made. Bulk faunal sampling of some beds has been undertaken at many localities so as to provide semi-quantitative information on the composition of a variety of faunal communities. Palaeontological sampling has supplemented the in situ recording of fossils in providing the database for Chapter 6.

A limited amount of taxonomic work has been carried out, since accurate identification of species is essential before palaeoecological or biostratigraphic conclusions can be made. However, taxonomic work has been restricted both by the unsuitability of much of the material collected and by time.

1.3 Lithological nomenclature,

1.3.1 Carbonate lithologies

The carbonate terminology used throughout this thesis is an attempt to marry the different carbonate classification schemes of Folk

* J. Hendry of Liverpool University has recently started a diagenetic study of the White Limestone in the east Midlands.

(1959, 1962) and Dunham (1962). The former has been widely used by academic workers while Dunham's scheme has gained general acceptance in industry. Although Dunham's classification clearly indicates the degree of packing present, it gives little information relating to the composition without becoming cumbersome. Folk's scheme, on the other hand, while very specific with regard to the type of silt/sand grains and the matrix, makes no reference to the packing without the addition of extra epithets. In the scheme adopted here, combined use is made of Folk's allochemical prefixes (oo-, bio-, intra- and pel-) and Dunham's nomenclature; examples of these hybrid names are given below:

<u>This thesis</u>	<u>Dunham (1962)</u>	<u>Folk (1959, 1962)</u>
Oobiograinstone	Ooid, bioclast grainstone	Oobiosparite
Oobiopackstone	Ooid, bioclast packstone	Packed oobiomicrite/ microsparite
Biowackestone	Bioclast wackestone	Sparse biomicrite/ microsparite

The poorly-washed biosparite of Folk terminology is represented by either biograinstone/packstone or biopackstone/grainstone in my terminology: the former is used for a rock in which a small proportion of the intergranular pores contain mud (terrigenous or lime mud), the latter for one in which only some intergranular areas are mud-free. 'Poorly-washed' is considered a poor descriptive term for lithologies where textural inversion is the result of bioturbation rather than incomplete winnowing.

Rocks with under 50% calcium carbonate are not considered as limestones. In limestones with a fine-grained terrigenous content (i.e. undifferentiated clay and silt) of 10-50% by volume (B.V.), the adjective 'argillaceous' is used. For example, a grain-supported oolite with a fine-grained matrix which includes about 20% terrigenous mud is termed an 'argillaceous oolite'. Detrital sand is considered with the allochemical grains with regard to the Dunham name; the adjective quartz-sandy is used preceding the combined Folk/Dunham name when quartz sand is an appreciable component (>10% B.V.); e.g. a 'quartz-sandy biograinstone' is a grain-supported lithology in which the dominant particle type is the bioclast and in which quartz sand typically comprises 10%-35% B.V.. Mount's (1985) recent classification of mixed siliciclastic-carbonate rocks has not been employed.

The major carbonate clast categories (allochems) considered by Folk (1962) were oolites (ooids), intraclasts, fossils (bioclasts) and pellets. Particle nomenclature was revised by R. Wilson (1967), who described eight types of non-organic grain: 'true' ooids, 'superficial' ooids, pellets, 'simple' intraclasts, 'coated shells', botryoidal lumps (grapestones of Illing, 1954), eroded lumps and amorphous lumps.

The 'true' and 'superficial' ooids are end-members of a range of ooid morphologies controlled in part by the size and shape of the ooid nucleus, as well as by turbulence. Small, equant nuclei can typically give rise to well-formed, near-spherical ooids with a well-developed cortex ('true' ooids; Plate 1C); large, equant nuclei can give rise to near-spherical ooids with few laminae (Plate 1A); a large, elongate or irregular nucleus (e.g. shell fragment) can give rise to an irregular ooid with few laminae and with its cortex preferentially developed so that the ooid tends towards spherical (Plate 1D). This largely reflects

the fact that increasing size inhibits ooid growth, the maximum diameter attainable being about 2mm (Carozzi, 1960). Ooids with few laminae have been called 'superficial' ooids, but the difference between these and ooids sensu stricto is artificial. The thickness of the cortex of 'superficial' types is, theoretically, less than half that of the radius of the entire ooid, while that of the 'true' ooid cortex is equal to or greater than half the radius of the grain (Simone, 1981). Ooids of 'superficial' type are encountered more frequently than 'true' ooids in much of the upper Great Oolite Group of the study area.

Most Recent marine ooids have cortical laminae comprising tangentially arranged aragonite needles, as in those described from Bahamian oolite shoals (Illing, 1954; Newell et al., 1960). Ooids with radially orientated aragonite crystals have also been described, notably from the Great Salt Lake (e.g. Sandberg, 1975; Halley, 1977) and also from the Red Sea (Friedman et al., 1973) and the Persian Gulf (Loreau & Purser, 1973). Ooids with radially orientated Mg-calcite, although rare, are known to exist in both Recent (Marshall & Davies, 1975) and early burial environments (Milliman & Barreto, 1975). A third fabric recognisable in ooid cortices comprises concentric layers of microcrystalline Mg-calcite or aragonite (James & Klappa, 1983). Intermediate forms, with alternating laminae of both tangential and radial structure, have been recorded from Laguna Madre (Rusnak, 1960; T. Freeman, 1962), the Yucatan Platform (Logan et al., 1969) and Shark Bay (G. Davies, 1970). Compound ooids, with all three fabrics, are also known (Loreau & Purser, 1973; Land et al., 1979).

It has been suggested that both salinity and turbulence could influence the type of structure developed, with the radial structure developing in sheltered environments; specific organo-carbonate

interactions have also been suggested as a possible control (P. Davies et al., 1978; Ferguson et al., 1978). As with most ancient ooids, the Bathonian ooids encountered during the course of my research have all been calcitic rather than aragonitic. Ooids in the Forest Marble are particularly well preserved and exhibit both radial and tangential structure. Ooids in the White Limestone often comprise concentric laminations of microcrystalline calcite or show a faint radial structure; ooids in the latter formation are often heavily micritised.

Controversy presently surrounds the origin of ancient calcitic ooids with well-preserved radial structure. The uniformitarian argument that they have been diagenetically produced from aragonitic ooids with tangential structure, either by dissolution and recrystallisation utilising an organic template (Shearman et al., 1970) or by inversion (e.g. Bathurst, 1975), has been challenged by those (e.g. Sandberg, 1975; Wilkinson & Landing, 1978; James & Klappa, 1983) who suggest that they were originally formed by calcite, with the radial structure a primary feature. This latter hypothesis has been increasingly accepted in recent literature (see Leeder, 1982; Richter, 1983 and Tucker, 1985 for discussions); it has been suggested that at times in the earth's history, the Ca:Mg ratio of normal sea water was higher than that of the modern oceans, thereby allowing the direct precipitation of low-Mg calcite rather than aragonite. Probably both primary calcite and altered aragonite ooids occur in the rock record. Furthermore, it is now evident that ooids form in a variety of depositional environments, in a range of salinities and in varying degrees of turbulence.

Pellets were described by Folk (1962) as rounded, spherical to elliptical bodies formed from microcrystalline calcite and devoid of internal structure; in any one rock they exhibit a distinctly uniform

shape and size (0.03-0.15mm). They were considered to be invertebrate faecal pellets by Folk, but it is better to ignore this genetic connotation when considering pellets as carbonate silt/sand particles; this does away with the need to call pellets 'pelletoids' (Milliman, 1974) or 'peloids' (e.g. Leeder, 1982) if their genesis cannot be determined. However, it is likely that many of the pellets encountered during this study were of faecal origin, produced by gastropods, bivalves, annelids, crustaceans and other invertebrates living in the shallow marine environments of the study area. In addition to structureless, elliptical or spherical pellets, the microcoprolite Favreina decemlunatus has frequently been encountered; Kennedy et al. (1969) considered this to have been produced by brachyuran crustaceans. Pellets, particularly when partially or fully hardened by rapid interstitial carbonate precipitation, act dynamically as silt and sand grains; however, if still fairly soft they are easily compacted during burial, giving rise to a mottled, unhomogeneous micrite termed 'grumeleuse' by Cayeux (1935). The origin of grumeleuse texture is particularly well illustrated where pellets have locally been protected from compaction by bioclasts or other large grains (Plate 2E).

Large pellets may, in some instances, be difficult to distinguish from R. Wilson's (1967) amorphous lumps, especially when the latter are equant and well-sorted. However, when distinguishable, these amorphous lumps are better grouped under the bucket-term, 'intraclast'. Intraclasts, as defined by Folk (1962), include a broad spectrum of grain types formed by reworking of contemporaneous carbonate sediment; grapestones, lime-mud flakes and 'tidal-flat clasts' were included, but reworked, older limestone fragments (lithoclasts) were not. Problems arise with Folk's definition of intraclasts, however, and Friedman &

Sanders (1978) have argued that grapestones are not strictly intraclasts, being complete grains resulting from an accretionary process rather than from a breaking-down process; this is not accepted by Leeder (1982) who ascribes the origin of grapestones to the ripping-up of subtidal algal mats during storms. In this account, grapestones (botryoidal lumps) are included as intraclasts. Bioclasts or ooids totally micritised by boring algae and/or fungi (Bathurst, 1966) so that all traces of internal structure have been removed are indistinguishable from amorphous lumps formed by reworking of a lime mud/micrite substrate; it is therefore convenient to classify all amorphous lumps, whatever their suspected mode of origin, as intraclasts (e.g. Leeder, 1982).

Similarly, reworked older limestone fragments (lithoclasts) are not necessarily distinguishable from the eroded lumps of R. Wilson (1967), which include reworked fragments of hardgrounds, beach-rock and reef-rock, together with abraded grapestones; they too must be included as intraclasts, unless obviously of exotic origin, along with all other eroded lumps. In this thesis, all eroded lumps, botryoidal lumps (grapestones), coated grains ('simple intraclasts' and 'coated shells' of Wilson, op. cit.) and amorphous lumps have been classified as intraclasts.

1.3.2 Siliciclastic lithologies

Lithologies containing greater than 50% terrigenous mud or sand cannot be considered as limestones, and for such lithologies the hybrid Folk/Dunham terminology is inapplicable. Terrigenous mudstones have been the dominant siliciclastic lithology encountered in the upper Great Oolite Group during the course of my research: these have been variably calcitic and fossiliferous, either thinly laminated, apparently

homogeneous or interlayered with quartz or carbonate sand. Reineck & Singh's (1973) bedding terminology for interlayered sand and mud deposits has been widely used in this thesis. X-ray diffraction studies of terrigenous muds from the Great Oolite Group of Oxfordshire and the east Midlands indicate that illite typically dominates mixed clay mineral assemblages; smectite is locally important (T. Palmer, 1974; Bradshaw, 1975, 1978; Sellwood & Sladen, 1981; J. Andrews, pers. comm.). Terrigenous mudstones with a significant lime mud or microcrystalline calcite cement (10-50% B.V.) have been termed 'calcareous mudstones'. The name 'marl' has not been used; although defined by Sugden & McKerrow (1962), it is felt that 'marl' has been loosely applied in the past and is an imprecise term.

I have not encountered true sandstones in the upper Great Oolite Group. However, variably fossiliferous and calcite-cemented siltstones/sandstones do occur in the northern region (e.g. Bradshaw & Penney, 1982); these are referred to as 'calcitic sandstones', or 'argillaceous sandstones' where there is an appreciable terrigenous mud component (10-75% B.V.; cf. wackes of Dott, 1964), as appropriate. 'Sandy terrigenous mudstones' have also been recognised.

Quartz is the predominant type of siliciclastic sand grain found in upper Great Oolite Group sediments; minor feldspar also occurs. Bradshaw (1978) noted that fine, medium and coarse grained Rutland Formation sands are typically quartz arenites whereas very fine sands and silts tend towards subarkose; this is because abrasion preferentially reduces the size of the less durable feldspar grains, concentrating them in the finer sediments.

CHAPTER 2

THE GENERAL SETTING

2.1 Introduction

Any facies analysis necessitates a full understanding of the background to sedimentation in a given study area. The structural, palaeogeographic and climatic setting of central and eastern England in the Middle Jurassic are reviewed in this chapter, so as to set the scene for the discussions of lithofacies and biofacies distribution, patterns of and controls on sedimentation and detailed palaeogeography which are presented in later chapters.

2.2 Structural setting

In the early to middle Mesozoic, the single 'super continent', Pangaea, was virtually separated by Neo-Tethys into northerly Laurasia (N. America, Greenland, Europe and Asia) and the southern continents group, Gondwanaland (S. America, Africa, India, Antartica and Australia). A.G. Smith et al.'s (1973), A.G. Smith & Briden's (1977) and A.G. Smith et al.'s (1980) reconstructions of the spatial arrangement of the continents during the Jurassic Period are widely accepted; they are, in part, refinements of the earlier work of Bullard et al. (1965) and A.G. Smith & Hallam (1970). The fit of the continents now bordering the Atlantic (in A.G. Smith et al., 1973), based on a 500 fathom contour least-squares fit, is particularly convincing. However, the arrangement of continents along the southern edge of Tethys is open to a number of

interpretations (e.g. Tarling, 1972) and controversy remains over the correct position of various islands and peninsulas of southeast Asia (see Hallam, 1975a, for discussion). More recently, Sengör (1984) has argued that A.G. Smith et al.'s (1980) Jurassic maps have various pieces of his 'Cimmerian Continent' (e.g. Turkey, Iran) incorrectly positioned, and completely fail to show other pieces (e.g. Afghanian fragments, Tibet). Alternative reconstructions, based on the expanding earth hypothesis, have been presented by Owen (1976).

Between the Early Jurassic and today, Pangaea broke up and the continents drifted into their present positions. This change is believed to have occurred largely as a result of accelerated and more extensive sea-floor spreading in the Cretaceous, for which evidence is widespread. The earliest part of the Atlantic to form was probably that part lying between northwest Africa and the eastern seaboard of the United States. Dietz & Holden (1970) put the opening of this sector as far back as the Triassic, based on the occurrence of grabens and basic igneous rocks in eastern U.S.A.. However, although late Triassic graben formation and basic igneous activity is well documented from both eastern North America and northwest Africa (Dewey et al., 1973; Ballard & Uchupi, 1975; Jansa & Wade, 1975; Van Houten & Brown, 1977) and suggests that lithospheric stretching occurred, it does not necessarily signify that the Atlantic had begun to open. Instead it reflects the Late Triassic-Early Jurassic tectonic activity that occurred along the Tethys-Central Atlantic-Gulf of Mexico rift-wrench system (P. Ziegler, 1982b). The fact that the Tethys Ocean at this time stretched westwards only as far as Morocco and the Iberian Peninsula (Hallam, 1971; Van Houten & Brown, 1977) militates against a Triassic opening, and extrapolation of JOIDES data points to a Pliensbachian initiation for the opening of this first sector (A.G.

Smith, 1971, Pitman & Talwani, 1972). Although this coincides with the Pliensbachian/Toarcian collapse of the western Tethyan carbonate platform reported by Bernoulli & Jenkyns (1974), that event may be more closely related to initial sea-floor spreading in western Tethys.

Even though the earliest sea-floor spreading in the North Atlantic was Early to Middle Jurassic (between the Equatorial and Azores Fracture Zones), and while Neocomian sea-floor spreading occurred between the Azores and Charlie Gibbs Fracture Zones, further north the Arctic-North Atlantic Rift, although active throughout the Jurassic and Cretaceous, was not the site of sea-floor spreading (and consequently the site of crustal separation of Greenland from Europe) until the Early Tertiary (P. Ziegler, 1982b). Prior to initial sea-floor spreading in the Arctic-North Atlantic Rift, northwest Europe was subjected to a predominantly tensional stress regime throughout the Permian, Triassic and Jurassic (Eynon, 1981). Extensional stresses caused block-faulting, giving rise to syn-sedimentary grabens and half-grabens which are well documented both on- and offshore. Many of the much discussed onshore Jurassic 'axes of uplift' (S. Buckman, 1901; Arkell, 1933a) or the 'swells and basins' of later authors (Hallam, 1958; Sellwood & Jenkyns, 1975) are related to block-faulting within the pre-Permian basement. The south Mendips, Pewsey and Hog's Back structures (Audley-Charles, 1970; Smalley & Westbrook, 1982; Chadwick *et al.*, 1983) of southern England form a belt that approximately coincides with the Hercynian Front (Lake, 1975; Chadwick *et al.*, 1983); the Hog's Back structure can be taken to mark the southern margin of the Mesozoic London-Brabant Massif. During the Jurassic these structures, which were inverted in the Cretaceous/Early Tertiary, probably acted as growth faults with a southerly downthrow. Other linear structural belts, sub-parallel to the

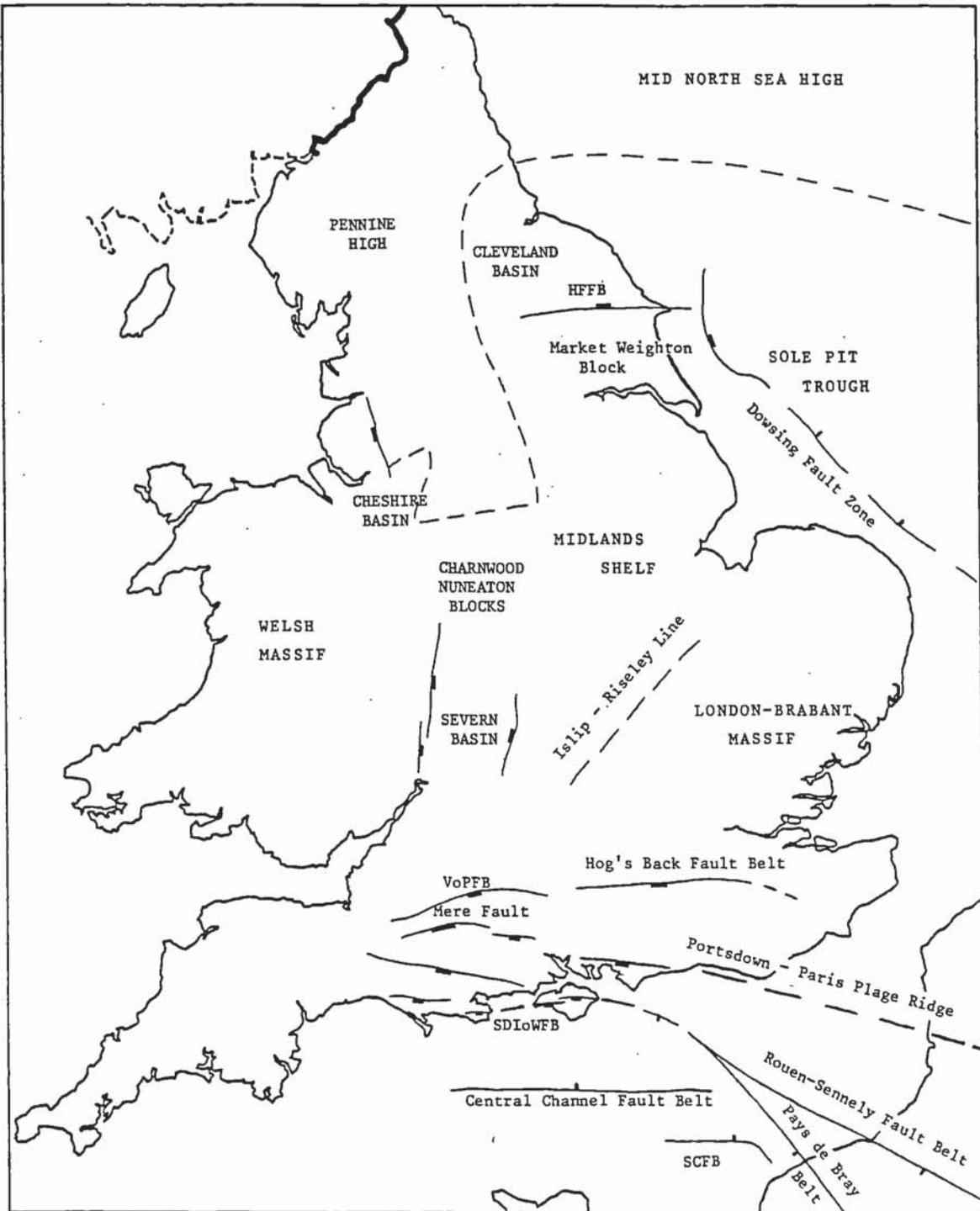


FIGURE 2.1 Major structural elements of Jurassic England and adjacent areas.

(HFFB = Howardian - Flamborough Fault Belt; SDIoWFB = South Dorset - Isle of Wight Fault Belt; VoPFB = Vale of Pewsey Fault Belt; SCFB = South Channel Fault Belt)

Pewsey-Hog's Back Belt, occur further south: the Mere-Wardour and South Dorset-Isle of Wight Belts onshore and the Mid- and South Channel Belts offshore (A.J. Smith & Curry, 1975; Colter & Havard, 1981; Stoneley, 1982). Each of these belts may also have acted as a southerly-downthrowing growth fault during the Jurassic. At its eastern end the South Dorset-I.o.W. Belt probably swings southeastward to join the Pays de Bray and Rouen-Sennely fault systems of the Paris Basin (Colter & Havard, op. cit.; Stoneley, op. cit.). Left-lateral movements along the latter wrench-fault systems in the Middle Jurassic may have compensated for crustal extension across the Celtic Sea, Bristol Channel and Western Approaches grabens (P. Ziegler, 1982a). Stoneley (op. cit.) has speculated that the Mere-Wardour Belt may also trend southeastward to meet the I.o.W. Belt east of the island, but the pattern of folding in the surficial Upper Cretaceous-Palaeogene sequence, related to the sub-Lower Greensand/Gault geology mapped by Chadwick & Kirby (1982), suggests a possible alignment with the Portsdown-Paris Plage feature. This latter, long-recognised structure (Kent, 1949; King, 1949, 1954) was suggested by Terris & Bullerwell (1965) to be a continuation of the shallow basement ridge beneath Paris Plage on the French coast; Sellwood & Sladen's (1981) isopachyte maps suggests that it may be a horst-structure at depth, plunging to the northwest. P. Ziegler (1982a) has depicted the continuation of this structure in northern France as a wrench-fault system. All of these linear structures can be interpreted as lines of relative crustal weakness separating rather rigid basement blocks (Stoneley, 1982).

In the Aalenian and Bajocian, in particular, many of these linear structural belts exerted considerable influence over subsidence rates and facies distributions. Middle Jurassic 'swells', such as the South Dorset

High (=Mid Dorset High of Gatrall, et al., 1972) or the 'Bruton High' (Holloway & Chadwick, 1984), were controlled by these structures, with 'basinal' sequences accumulating on the downthrow side of growth faults and 'swell' sequences on the other. Movement along these growth faults was probably intermittent and at variable rates throughout the Middle Jurassic; they apparently had less influence on sedimentation later in the Epoch.

Fault-controlled depositional highs and basins in the North Sea and adjacent areas are better documented than the southern England structures since large quantities of commercial data from the latter area are, as yet, unreleased. The tectonic development of the North Sea needs to be traced at least as far back as the Permian when the Southern and Northern North Sea Basins formed as post-Hercynian foreland collapse basins, the geometry of which reflects regional crustal downwarping with only minor faulting (P. Ziegler, 1982a). Subsidence in the Triassic continued along the lines established during the Permian, but the basin framework was modified, particularly by development of the Polish - Danish Trough and the North Sea rift system. Subsidence in the Viking and Central Grabens began in the Scythian, these grabens probably forming by fracture propagation of the East Greenland-Western Norway rift following accelerated crustal stretching in the Arctic-N. Atlantic region (P. Ziegler, op. cit.).

The Middle Jurassic history of the North Sea area was dominated by the uplifting of a major rift dome, possibly as a consequence of the emplacement of a low density asthenolith at the crust-mantle interface (P. Ziegler, 1982a), although Dixon et al. (1981) have suggested that rift-flank uplift can be the direct result of lithospheric extension alone (see also McKenzie, 1978). Severe upwarping of the Central North

Sea Rift Dome may have begun in the Late Toarcian, the succeeding sequence of arching, radial basin development and domal collapse occurring over a 10-15Ma period (Eynon, 1981). Domal collapse has been variously dated as Bathonian (P. Ziegler, 1981, 1982a, 1982b), Mid Bathonian (Vail & Todd, 1981) or Late Bathonian (Eynon, op. cit.). As Eynon has shown by the broad concentric distribution of Middle Jurassic facies about the dome, this structure exerted considerable influence on contemporary patterns of sedimentation.

A major tectonic feature of the Southern North Sea, the Sole Pit Trough, was the site of almost continuous sedimentation from the Permian to the Cretaceous, when final structural inversion occurred (Glennie & Boegner, 1981). It was bounded to the southwest by the Dowsing Fault Zone and connected to the northwest with the Cleveland Basin (which also underwent Late Cretaceous structural inversion; Kent, 1980). The relationship between the Sole Pit Trough and the Midlands Shelf/London-Brabant Massif is comparable to that between the Cleveland Basin and the Midlands Shelf. However, Middle Jurassic attenuation adjacent to the Dowsing Fault Zone was not as severe as that over the Market Weighton Block. The Sole Pit Trough passed southeastwards into the Broad Fourteens, West Netherlands and Central Netherlands Basins; together these comprise the so-called Anglo-Dutch Basin.

In the Middle Jurassic the Mid-North Sea High (see Fig. 2.6), rejuvenated by uplift of the Central North Sea Rift Dome, acted as the major source of the siliciclastic sediment deposited in both the Cleveland and Anglo-Dutch Basins (see P. Ziegler, 1982b, Encl. 19); Koch (1983) has suggested that sediment from the dome itself may also have been channelled southwards along the Central Graben. The Mid-North Sea High connected westwards with the Pennine, Southern Uplands and Grampian

Highs, and together these highs largely separated the Midlands Shelf and the Cleveland and Anglo-Dutch Basins from contemporary depositional areas (e.g. the Viking Graben, Moray Firth and Norwegian-Danish Basins) further north.

The Howardian-Flamborough Fault System bounds the Midlands Shelf to the north. The position of this east-west trending fault system, which exerted a major control on subsidence in the Cleveland Basin during the Jurassic, may have been determined by the inferred Caledonian granite present within the basement beneath the Market Weighton Block (Bott et al., 1978; Kent, 1980). Donato & Tully (1982) have similarly shown how the positioning of the fault system at the western edge of the Viking Graben is controlled by a probable granite at the margin of the East Shetlands Platform. The Market Weighton Block itself, long a topic of debate amongst British geologists (e.g. Kendall, 1905; Arkell, 1933a; Kent, 1955, 1974, 1980; Jeans, 1973), is an asymmetric structure, with a steep northerly limb and gently dipping southerly limb, which developed because of a positive-rebound response to the northerly downthrow of the Howardian-Flamborough Fault Belt, perhaps coupled with the buoyant effect of the putative granite. During the Jurassic the Market Weighton Block acted as a swell, characterised by shallow water deposition, non-deposition or erosion; attenuation of the Jurassic succession over the block was accentuated by pre-Cenomanian erosion. The northeastern edge of the Midlands Shelf is delineated by the Dowsing Fault Zone, the positioning of which may also have been controlled by granites; in particular, gravity anomalies from the Wash (Allsop & Jones, 1981; Allsop, 1983) and from East Anglia (Chroston & Sola, 1982) can be interpreted as indicating the presence at depth of low density igneous intrusions. The possible Wash/Norfolk intrusions fall within Kent's

(1968) Complex Basement Ridge, and Caledonian intrusions are well known from the western end of this feature (Le Bas, 1972; Allsop & Arthur, 1983); furthermore, the Wash and northern East Anglia lie within the area of high basement heat flow ($>60\text{mWm}^{-2}$), recognised by Brown et al. (1980), which also encompasses the Lake District, Weardale, Wensleydale and Market Weighton Caledonian intrusions.

Within the study area, acid igneous intrusions are known to occur in the basement at Warboys and in the Bletchley region (Le Bas, 1972; Horton, Shephard-Thorn & Thurrell, 1974; Allsop & Jones, 1981; Allsop, 1985). These intrusions may have controlled the positioning of the northwest margin of the London-Brabant Massif which herein is taken as an essentially linear, SW-NE trending structural belt which passes through the Cornbrash inliers of Islip/Noke, Charlton and Blackthorn Hill in Oxfordshire and Riseley in Bedfordshire, and which can be extrapolated further northeastwards towards Huntingdon. This structural belt is here named the Islip-Riseley Line. The Islip-Riseley Line passes directly to the northwest of both Bletchley and Warboys (Fig. 2.2) and was probably the site of mild northwesterly basement downthrow at times during the Mesozoic. Arkell (1933a, fig. 15) illustrated the southwestern portion of the structure as the 'Islip Axis'. The strike of today's Jurassic and Cretaceous outcrops essentially parallel the Islip-Riseley Line, presumably reflecting Tertiary movement along the structure; the Charlton and Oddington periclinal folds, and other periclinal folds on the same alignment (Arkell, 1944, 1947), were probably also produced by movement along the line at this time. A rapid increase in the thickness of post-Carboniferous/pre-Great Oolite Group sediments northwest of the structure suggests that it was probably active in pre-Bathonian times.

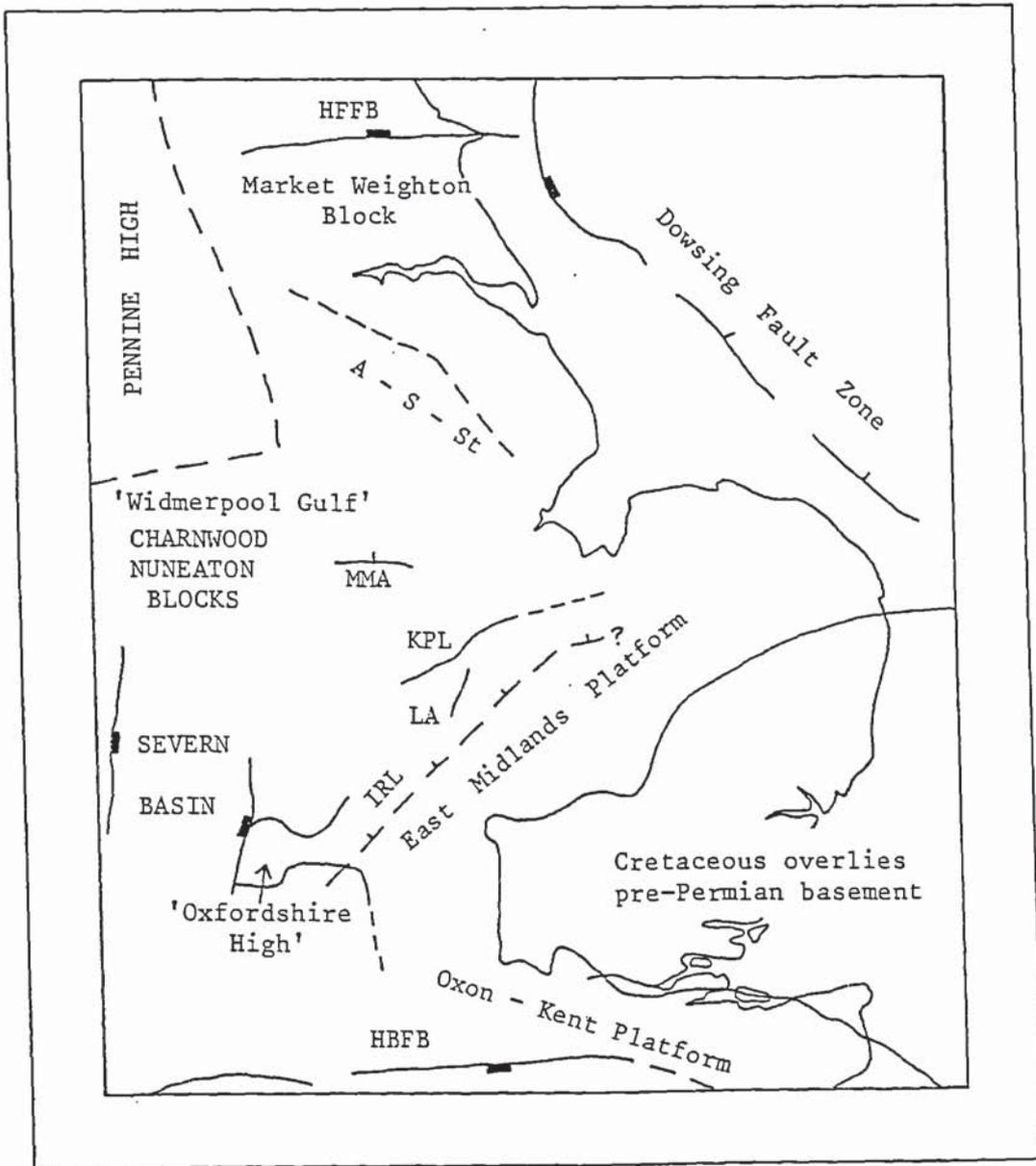


FIGURE 2.2 Major structural elements of Middle Jurassic central England.

(HFFB = Howardian-Flamborough Fault Belt; A - S - St = 'Askern-Spital-Stixwould High'; MMA = Melton Mowbray Axis; KPL = Kettering-Peterborough Line; LA = 'Long Anticline'; IRL = Islip-Riseley Line; HBFB = Hog's Back Fault Belt)

The most positive part of the U.K. onshore sector of the London-Brabant Massif underlies Suffolk, Essex and London; it is delineated by the overstep of the Cretaceous onto the pre-Permian basement. In this work, areas of the massif to the northwest and west/southwest of this highly positive region are termed the East Midlands Platform and the Oxfordshire-Kent Platform respectively. It is not known whether the basement of the London-Brabant Massif contains further low density igneous intrusions which could account for the structural stability and buoyancy of the whole massif; the recent recognition of buried granites within the Mid-North Sea High (Donato et al., 1983) suggests that this is a possibility which should be considered.

The Midlands Shelf, as recognised herein, was bounded by the Pennine High, West Midlands/Charnwood Blocks and the eastern edge of the Severn Basin to the west; by the Howardian-Flamborough and Dowsing Fault Belts to the north and northeast, and by the London-Brabant Platform to the southeast. The shelf was an area characterised by subsidence intermediate between that of the East Midlands Platform and that of adjacent basins (the main exception being the tectonically positive parts of the shelf fringing the Howardian-Flamborough and Dowsing Faults). It should be noted that shelf and platform are here used in a tectonic sense to distinguish these areas from overall more rapidly subsiding basinal areas such as the Cleveland, Severn and Wessex-Weald Basins. All of these 'shelves', 'platforms' and 'basins' were part of the Jurassic continental shelf and that while areas of relatively deeper sea often coincided with tectonic basins, this was not necessarily the case. Where rates of sedimentation, either as a result of input of siliciclastic sediment into the basin or because of autochthonous carbonate sedimentation, kept pace with subsidence, very shallow sea levels or even

emergent conditions could be maintained (e.g. Cleveland, Anglo-Dutch, Viking Graben, Central Graben and Hebridean Basins, etc.). Thus in the Bathonian, similar facies to those developed on the Midlands Shelf occurred in the Cardigan Bay Basin (Penn & Evans, 1976), although subsidence rates in the basin were at least ten-fold greater.

Within the study area, a number of locally-recognised linear features appear to have affected Middle Jurassic facies and depositional patterns. Of these, the most significant is the 'Kettering-Peterborough Line' of Bradshaw (1978). Bradshaw has described the important changes that occur within the Rutland Formation and Inferior Oolite successions across this line, which is actually delineated by the overstep of the Rutland Formation over the Lincolnshire Limestone and Grantham Formation; distinct changes in facies and patterns of sedimentation, outlined in later chapters, can also be recognised within the White Limestone on crossing this line.

The Long Anticline of Thompson (1930), which nearly coincides with the overstep of the Rutland Formation onto the Lias between Rushden and Titchmarsh, was fully discussed by Bradshaw (1978). This feature is marked by a dramatic attenuation of the Rutland Formation, particularly well illustrated by the Raunds Main Street exposure (Loc. 131) where only 0.4m of rootletted, purple mud (Stamford Member) separates the Kallirhynchia sharpi Beds from the Northampton Sand Ironstone. The Rutland Formation undoubtedly thickens both to the west and southeast, so that Arkell's (1933a) dismissal of the structure as "merely the marginal thinning of the Great Oolite Series southeastwards" cannot be accepted.

The east-west orientated 'Melton Mowbray Axis' or 'Anticline' was discussed by Kent (1937). North of this structure, the Jurassic (in particular, the Lias) shows a marked thickening. This area of thickening

largely coincides with a Carboniferous basin, the Widmerpool Gulf (Falcon & Kent, 1960; Kent, 1966), and it is likely that the Jurassic structure was controlled by a reactivated, deep-seated fault belt; the Melton Mowbray 'high' continues westwards into the 'Charnwood-Mountsorrel Block'. As noted by Kent (1937), thickening of the Great Oolite Group occurs north of the 'Melton Mowbray Axis'; in addition, facies study suggests that the line of the Widmerpool Gulf may have acted as a pathway for marine incursions into the east Midlands at times during the Bathonian.

In the southwest of the study area, the Upper Inferior Oolite/Great Oolite overstep over the Lower Inferior Oolite can be mapped so as to delineate a relatively positive area of the Midlands Shelf here informally termed the 'Oxfordshire High'. The Middle Jurassic succession of this region is quite different to that in the areas to the south and northwest. By definition, the Northampton Sand/scissum Beds are absent from the area, the Chipping Norton Formation unconformably overlying Upper Lias across the 'high'. In addition, the Chipping Norton Formation is itself directly overlain, on the 'high', by sediments of the Taynton Limestone/Wellingborough Rhythm, without the intervention of any of the intermediate rhythms which are preserved in the Sharp's Hill/Swalecliffe area (Bradshaw, 1978 & pers. comm.); beds referred to the Sharp's Hill Formation across the 'high' are therefore stratigraphically younger than most of the formation in the type area. While constituent units of the upper Great Oolite Group are continuous across the 'Oxfordshire High', facies changes within some units appear to occur along or close to the southern edge of the 'high', notably within the Ardley and Bladon Members of the White Limestone and within the Forest Marble. These changes are discussed elsewhere.

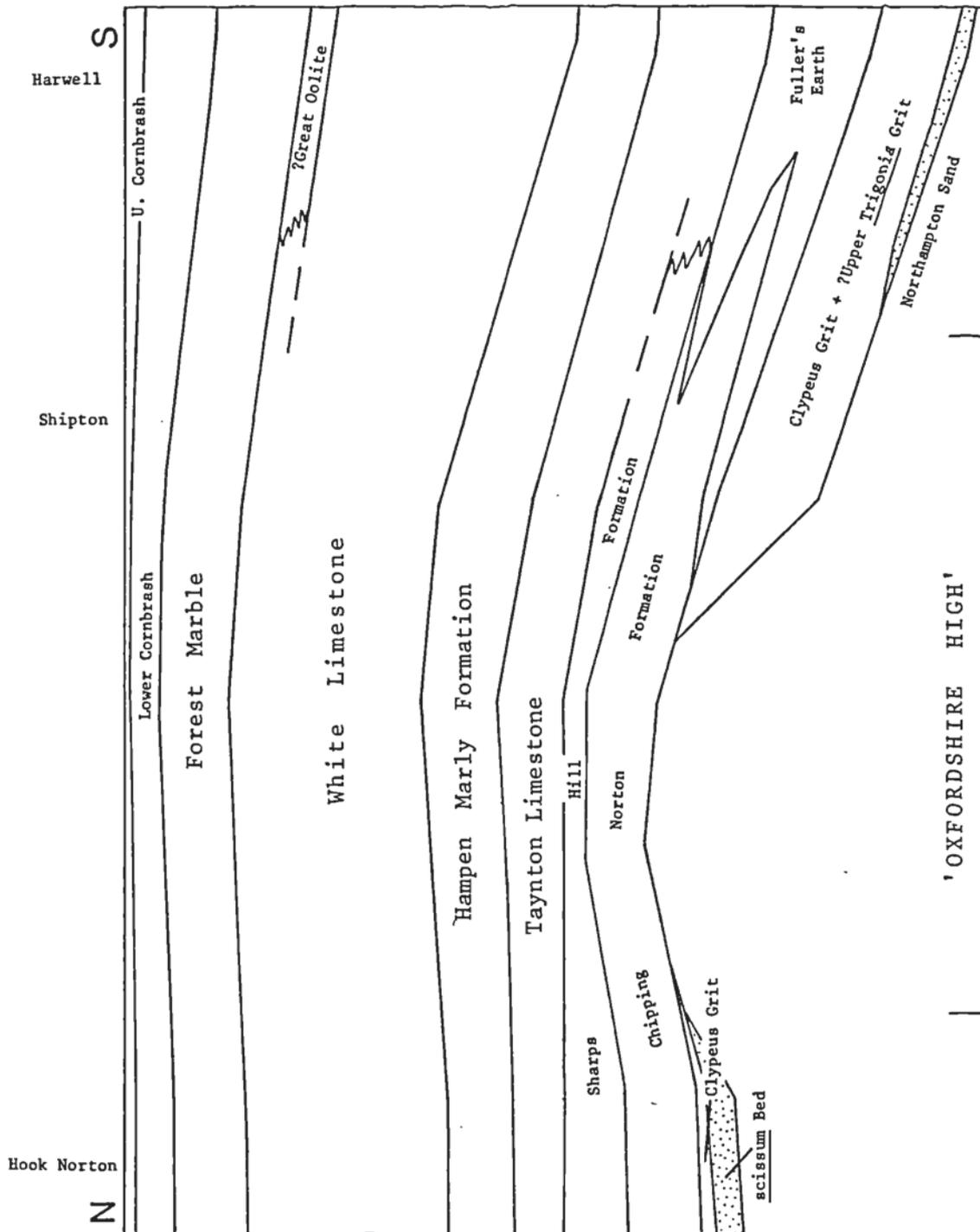


FIGURE 2.3 Stratigraphic cross section across the 'Oxfordshire High'.

2.3 Patterns of subsidence

An isopachyte map for the Bathonian (excluding Lower Cornbrash) of southern England was produced by Martin (1967), essentially based on B.P. and Geological Survey data. While the isopachytes for the western area were subsequently modified by Ponsford (1969) and Green & Donovan (1969), a large amount of recent, mainly hydrocarbon exploration, borehole data are now available and can be incorporated on such a map. Enclosure 2.1 is an attempt to plot an isopachyte map for the Great Oolite Group (i.e. including Lower and Upper Cornbrash) using this enlarged database*. Account has been taken, when constructing this figure, of the linear structural belts, discussed in the previous section, which intermittently acted as growth faults during the Mesozoic. These, while having considerable effect on the thickness of the Great Oolite Group, apparently had little direct effect on facies in the Bathonian; this is in marked contrast to the situation at other times in the Jurassic when both facies and thickness were affected (S. Lake, pers. comm.). Unlike Martin's (1967) map, data from further north, including Norfolk, Lincolnshire and Humberside, have been incorporated in Enclosure 2.1.

Across the Weald and Wessex areas, Enclosure 2.1 clearly illustrates the distribution of Bathonian 'basins' and 'swells', the 'basins' being characterised by greater subsidence rates and thicker Great Oolite Group successions. The absence of major facies changes

* Recent isopachyte maps in Whittaker (1985) and Sellwood et al. (1986) post-date completion of Enclosure 2.1.

between many of the 'basins' and adjacent 'swells' indicates that sedimentation rates in the 'basins' were generally greater than those over the 'swells', thus maintaining a relatively flat sea-floor across areas with very different subsidence histories. Isolated thick 'basinal' sequences, located on the downthrow side of active basement growth faults, have been penetrated at Shrewton, Stalbridge and Winterborne Kingston in the Wessex Basin. However, the thickest Great Oolite Group sequences recorded in this area have been encountered south of the South Dorset-I.o.W. Belt: notably at Kimmeridge, Seabarn Farm and particularly in the Lulworth Banks borehole. At Arreton, although south of the same fault belt, a relatively thin Great Oolite Group succession was encountered, suggesting that the eastern end of this structure was inactive during the Bathonian. Further thick, but incomplete, Great Oolite Group sequences occur at Atworth, Patterdown Farm, Shipton Moyne and Cirencester and also in the surrounding area; these reflect the relatively high subsidence rates of the southern Severn Basin.

Thinner sequences invariably characterise the basement highs ('swells') developed immediately north of the southerly downthrowing growth faults. Similarly, much thinner sequences were developed over regionally positive areas, a gradual thinning onto the London-Brabant Massif being evident. Comparable thinning of the Great Oolite Group towards the Cornubian and Welsh Massifs probably also occurred, although direct evidence for this is lacking. Thinning occurred within individual subdivisions of the group and also as a result of some subdivisions being absent over tectonically positive areas. Regional subsidence trends suggest that a spur of the London-Brabant Massif extended southwestwards to the Reading-Newbury area in the Bathonian. The tectonically positive nature of this area is also suggested by the absence of sediments of

post-Carboniferous/pre-Great Oolite Group age at Sonning Eye and Little Missenden (B181 & B26).

Isopachytes of the Great Oolite Group across the east Midlands reflect the generally stable, tectonically positive nature of the region, with isopachytes locally sub-parallelising the Islip-Riseley Line. Limited data suggests that northwest of the Northamptonshire Middle Jurassic outcrop, between the Nuneaton/Charnwood Blocks and the London-Brabant Massif, an area of slightly greater subsidence existed. In this area, Lower and Middle Inferior Oolite may have been initially preserved beneath the Upper Inferior Oolite/Great Oolite, prior to the removal of all the Middle Jurassic from this area by later erosion.

In Lincolnshire, Cambridgeshire and Norfolk there is a fairly close agreement between Lincolnshire Limestone isopachytes (Fig. 2.4) and those for the Great Oolite Group. The Lincolnshire Limestone is thickest near Grantham, where a thickness of over 40m has been recorded locally (Ashton, 1980). A belt of relatively thick Lincolnshire Limestone initially extends east from Grantham, before swinging southeastward towards Parson Drove. Enclosure 2.1 similarly shows relatively thick Great Oolite Group occurring in the area east of Grantham (notably at Pinchbeck North Fen), and this area of slightly greater Bathonian subsidence also turns southeastwards towards Parson Drove and Denver Sluice. At outcrop this area of increased Middle Jurassic thickness lies just north of the 'Melton Mowbray Axis', and coincides with the Carboniferous basin, the Widmerpool Gulf (see section 2.2). Some borehole evidence suggests that a Bathonian 'high', lying directly to the northeast of this 'basinal' area, extended northwestwards from Wiggshall towards Stixwold. This may have extended further and continued into the Askern-Spital structure of north Lincolnshire. The Askern-Spital

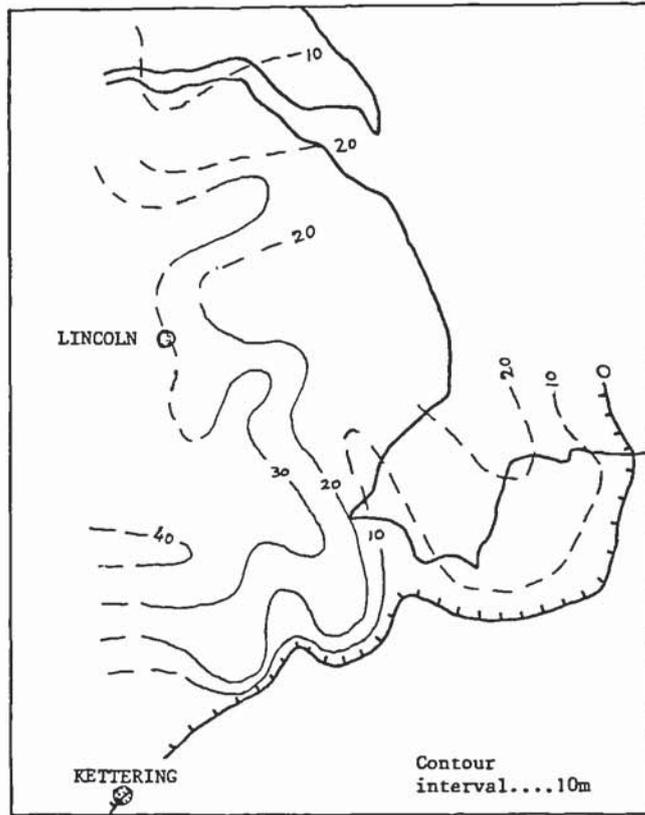


FIGURE 2.4 Lincolnshire Limestone isopach map.

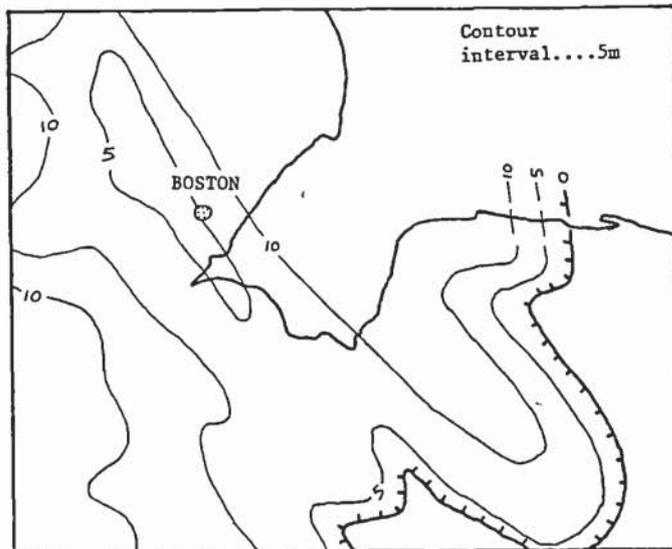


FIGURE 2.5 Rutland Formation isopach map.

structure (Lees & Taitt, 1946; Kent, 1966, 1968) was a positive feature in the Carboniferous, positioned immediately north of the basinal Gainsborough Trough; it, like the 'Melton Mowbray Axis', was probably controlled by basement faulting. Bradshaw (1978) has suggested that rejuvenation of the Askern-Spital structure resulted in the pre-Rutland Formation removal of the upper part of the Lincolnshire Limestone escarpment south of Bishop's Norton (SK9893; Swinnerton & Kent, 1976), and it would appear that the structure acted as a relatively positive feature throughout the Bathonian. That the Stixwold area was a Palaeozoic 'high' is suggested by maps published by Kent (1967, 1968). The region of today's outcrop south of Spital may have been partially separated from the Tetney Lock-Nettleton area of northeast Lincolnshire, and from Humberside, by this putative Askern-Spital/Stixwold/Wiggenhall ridge.

2.4 Palaeogeographic setting

The aim of this section is to briefly describe the Middle/Late Bathonian palaeogeographic setting of central and eastern England. A more detailed appraisal of palaeogeography will be given in a later chapter, after the stratigraphy and depositional history of the upper Great Oolite Group of the study area, and lithofacies/biofacies distributions at different times in the Bathonian, have been discussed.

A large number of generalised palaeogeographic reconstructions of the British area during the Middle Jurassic, or more specifically during the Bathonian, have been published (e.g. Martin, 1967; Donovan, 1972; Sellwood & Hallam, 1974; Hallam, 1975a; Palmer & Jenkyns, 1975; W. Ziegler, 1975; Hallam & Sellwood, 1976; Penn & Evans, 1976; Anderton et

al., 1979; Callomon, 1979; Sellwood & Sladen, 1981; Eynon, 1981; Ware & Windle, 1981; P. Ziegler, 1981, 1982a & b; Cope, 1984; A. Morton, 1985). The majority of published maps show an area of land covering much of East Anglia, variously termed the 'Anglo-Belgian Landmass', 'London Landmass', 'London-Brabant Massif', etc.. This land area essentially coincides with the London-Brabant Massif, a tectonically-positive structural block discussed in section 2.1. While the most positive parts of the London-Brabant Massif were probably emergent throughout the Bathonian, the margins of the land area undoubtedly fluctuated in response to tectonic movements, eustatic sea level changes and coastal progradation. Therefore, so as to distinguish the structural block (the margins of which remained fixed) from the landmass, the term 'Brabantia' is introduced in this thesis for the latter. The upland areas of Brabantia were probably the major source of siliciclastic material incorporated into the Bathonian sediments of the east Midlands. Bradshaw (1978) has argued that during the Middle Jurassic, Old Red Sandstone and marine Devonian shales were the principal rocks cropping out in Brabantia, although Carboniferous, Lower Palaeozoic and Precambrian outcrops may have occurred locally. In addition to these potential sediment sources, Triassic, Lower Jurassic and Early Bathonian terrigenous sediments could have been reworked from the flanks of Brabantia during the Middle and Late Bathonian.

Brabantia is envisaged as a low-lying land in the Bathonian, thickly vegetated by lycopods, pteridophytes, cycadophytes and conifers. Although the predominantly humid climate (section 2.5) might be expected to have encouraged leaching and the development of podzols, in turn leading to the formation of kaolinite (Sladen & Batten, 1984), clay mineralogy studies of Bathonian clays from the east Midlands and

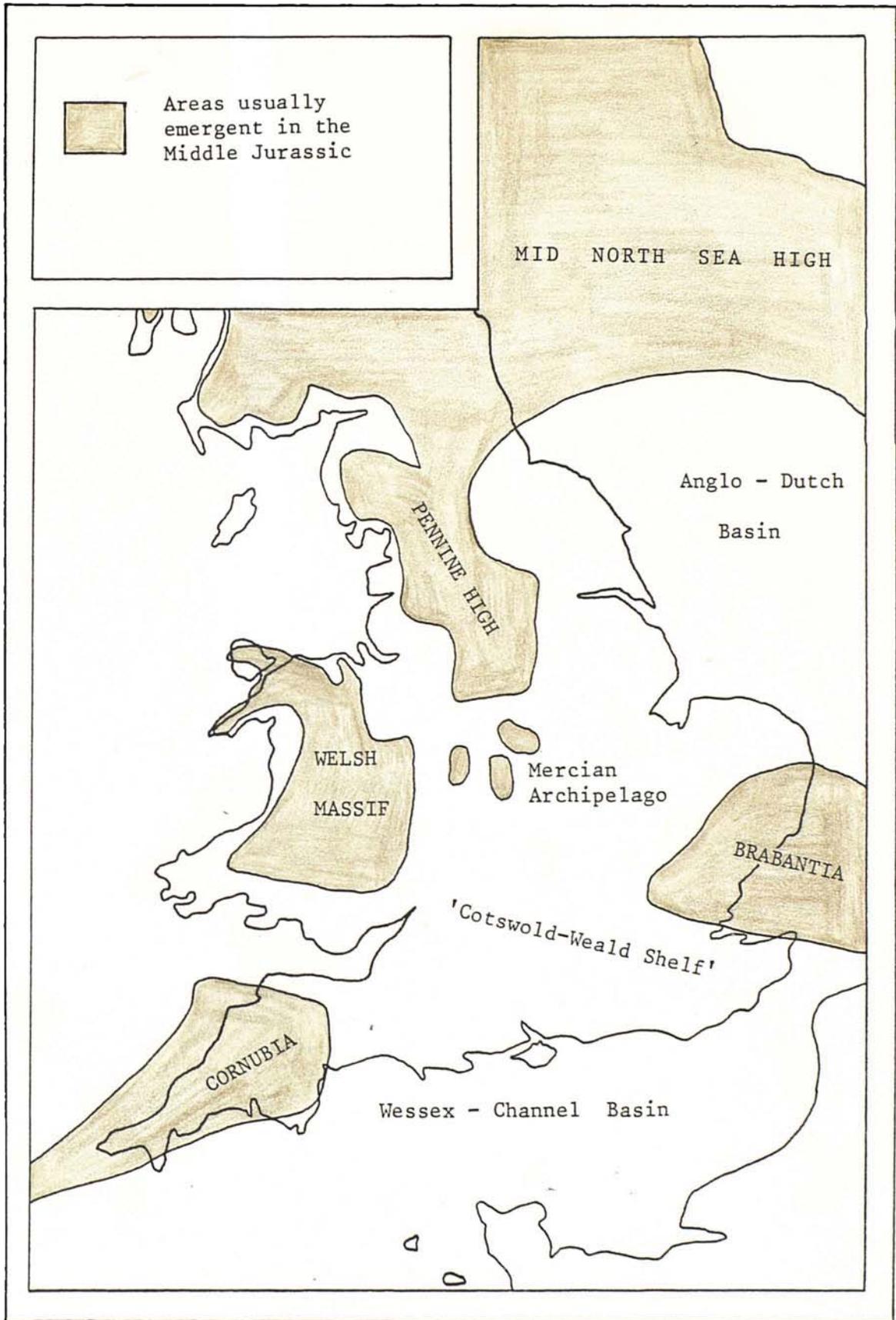


FIGURE 2.6 Major palaeogeographic features of the British area in the Middle Jurassic.

Oxfordshire (T. Palmer, 1974; Bradshaw, 1975, 1978; Sellwood & Sladen, 1981) suggest that illite invariably predominates over kaolinite. However the kaolinite content of British Middle Jurassic clays is generally higher than that of Lower Jurassic clays, perhaps reflecting an increased level of humid, sub-tropical weathering at this time (Sellwood & Sladen, 1981).

While the concept of a Middle Jurassic 'Anglo-Belgian Landmass' is widely accepted, there is less consensus on other features of central England Bathonian palaeogeography. Most published palaeogeographies show the northernmost Pennines as an emergent area in the Middle Jurassic, but few show land extending as far south as the southern Pennines/Peak District region. The fine-grained facies of Lias outliers in the Cheshire and Solway Basins suggests that the Pennine High was submerged during much of the Lower Jurassic, but even then the high probably caused depositional thinning. The high appears to have been an effective faunal barrier during the Late Pliensbachian shallowing (Ager, 1956) and it is here suggested that during the Bathonian sea level low-stand, most of the Pennine/Peak District area was emergent. Leeder & Nami (1979) suggested a Carboniferous source for siliciclastic material derived from the northern Pennines during the Bajocian/Bathonian, but (both in Yorkshire and further south) the major sediment source during the Middle Jurassic may have been the now completely eroded Permian, Triassic and Lower Jurassic (Bradshaw & Cripps, in prep.).

The classic interpretation of the Scalby Formation of the Cleveland Basin is that it represents deposition in a deltaic environment through the Late Bajocian and Bathonian (Black, 1929; Arkell, 1933a; Hemingway, 1974). However, Leeder & Nami (1979) have suggested that the

formation may be wholly alluvial in origin. They employed sedimentological arguments to suggest much higher depositional rates than those calculated by assuming continuous deposition over the approximately 12Ma available. The Moor Grit Member was seen as a sheet of braided channel alluvium, erosively overlying Scarborough Formation facies to which it bore no lateral geographic relationship. The entire Scalby Formation was estimated as having been deposited in (probably) less than a million years, during the latest Bathonian/earliest Callovian, with the succession of facies reflecting an increasing alluviation rate during the eustatic rise in sea level at this time. However, the status of the formation as wholly non-marine has been subsequently questioned on both palynological and sedimentological grounds (Hancock & Fisher, 1981; Livera & Leeder, 1981); Fisher & Hancock (1985) also provide evidence which suggests that not only was the formation deposited in a paralic setting but also that Scalby Formation deposition commenced during Late Bajocian times. The upward change of facies from braided channel complex (Moor Grit Member) to meandering channel deposits cut into finer grained coastal/delta plain sediments (Long Nab Member) may be the result of relative sea level rise during the Bathonian. Sand distribution in the Great Oolite Group in northern Lincolnshire and Humberside suggests a northern siliciclastic source, which may have been the Yorkshire 'delta', with an additional contribution from the Pennine High (Bradshaw & Penney, 1982).

Middle Jurassic facies distribution in the east Midlands and Yorkshire indicate significant siliciclastic supply from the southern Pennines during the Early Aalenian, Late Bajocian and Early Callovian (Bradshaw & Cripps, in prep.). It seems probable that the fault-bounded Precambrian/Palaeozoic inliers of the English Midlands (Charnwood,

Nuneaton, Birmingham) acted as tectonically positive structural blocks in the Middle Jurassic, as they apparently also did in the Triassic (Hains & Horton, 1969; Audley-Charles, 1970); they are thought to have been emergent, at least periodically, during the Bathonian, constituting what is henceforth termed the 'Mercian Archipelago'. These positive blocks probably sourced some of the terrigenous sand which occurs in the western outcrop of the Northampton Sand Ironstone (Hollingworth & Taylor, 1951) and also the sand, and pebbles of quartzite and red sandstone, which occur in northern outcrops of the Chipping Norton Formation; the pebbles of red sandstone in the latter suggest unroofing of Permo-Triassic sediments in the Early Bathonian at no great distance to the north (Bradshaw, 1978; Bradshaw & Cripps, in prep.).

As shown in later chapters, the Mercian Archipelago, together with Brabantia, exerted considerable influence on facies distribution in the east Midlands during the Mid and Late Bathonian. The region between the archipelago and Brabantia was, at this time, frequently occupied by a shallow sea which either closed to the northeast (the 'East Midlands Embayment') or connected the seas of the Wessex and Anglo-Dutch Basins (the 'East Midlands Seaway').

The major palaeogeographic features discussed in this section are illustrated in Figure 2.6.

2.5 Middle Jurassic Climate

Recent reviews of Jurassic climate (Hallam, 1975a, 1981a, 1984, 1985; Frakes, 1979) confirm the widely held view that the Jurassic was characterised by a warm, equable climate. No glacial deposits of Jurassic age exist and it is probable that the poles were ice-free.

Evaporites (indicative of arid and semi-arid conditions), while less abundant than in the Triassic, formed across a latitudinal zone considerably wider than that of the present day. Evaporite deposits in both the Triassic and Jurassic were concentrated in the western part of Pangaea. Coal deposits, suggestive of a more humid climate, are known from higher latitudes and particularly from the eastern sides of Gondwanaland and Laurasia (Hallam, 1975a, 1984). Evaporites became increasingly abundant and coals less widespread from Early through Mid to Late Jurassic times, suggesting an overall increase in aridity through the period.

Evidence from fossil plants (Barnard, 1973; Wesley, 1973) is in general agreement with the concept of a warm, equable climate. This includes the occurrence of rich floras at high latitudes (e.g. the New Siberian Islands) and the considerable spread of cold-sensitive ferns, such as Dictyophyllum, to between 50°-60° on either side of the equator. Plants also suggest some degree of latitudinal variation in climate. In Early Jurassic Laurasia it is possible to distinguish northern and southern floral zones which may be a reflection of climatic differentiation (Vakhrameev, 1964). Cycadophytes were generally restricted to the southern part of Laurasia in the Jurassic, becoming less diverse northwards into Siberia where ginkgophytes dominated. However, Vakhrameev took these floral changes to indicate a latitudinal climate gradient significantly less than that of today. Elliot (1977), on the basis of Middle Jurassic dasycladacean algae distribution, has similarly evoked a latitudinal climate change, speculating on the existence of a possible isocryme at about 30°N (on the reconstruction of Owen, 1976). There is evidence for some degree of seasonality; annual rings have been found in Jurassic coniferous wood from Siberia; a

Bathonian red alga from Gloucestershire, Solenopora jurassica, exhibits distinct growth banding of probable seasonal origin (V. Wright, 1985); further data from the British Bathonian, resulting from Hudson's (1968) work on the finely growth-banded aragonitic shells of Praemytilus from the Great Estuarine Group, are also indicative of climatic seasonality. The fact that these mussel shells are wholly composed of aragonite (Hudson, op. cit.), by comparison with living mussels, suggests a subtropical/tropical environment existing at a Middle Jurassic latitude of about 40°N (on the reconstruction of A.G. Smith et al., 1973).

While broad-brush reviews of the global Jurassic climate give a general indication of the prevailing conditions in the British area during Bathonian times, it is data drawn directly from the Middle Jurassic of northwest Europe which are most enlightening. Most of these data, however, are in accord with the overall picture for the period. Isotope evidence from the Bajocian of eastern England (Marshall & Ashton, 1980) and the Bathonian of western Scotland (Tan & Hudson, 1974; amended by Hudson, 1980) suggest water temperatures of between 17°C and 25°C. Chlorozoan/non-skeletal grain associations, which are well-developed in the shallow marine, pre-Cornbrash Middle Jurassic carbonate deposits of central and southern England, occur today in modern shelf carbonate sediments developed where minimum near-surface water temperature exceeds 14-15°C and the mean exceeds 18°C (Lees, 1975). Such water temperatures today are found only within 30° of the equator, but appear to have extended further north in Middle Jurassic times.

The occurrence of autochthonous humic coals in the British Middle Jurassic (e.g. Ravenscar Group, Yorkshire; Brora Coal Formation, northeast Scotland) points to the widespread development of warm, humid conditions at this time. Plant material from the Middle Bathonian of

Oxfordshire, derived from the western margin of Brabantia, does not suggest an arid climate (T.M. Harris in T. Palmer, 1979), while the large amount of kaolinite generally present within the British Middle Jurassic can be taken to support a substantial degree of humid subtropical/tropical chemical weathering of the principal drainage basin hinterlands (Sellwood & Sladen, 1981). Red bed deposits developed in the Great Estuarine Group (Skudiburgh Formation) of Scotland (Harris & Hudson, 1980; Andrews, 1985) and at a stratigraphically-equivalent level within the Bathonian of Cardigan Bay (Millson, in prep.) may also be the product of a moist, tropical climate (see Besley & Turner, 1983), but the presence of probable calcrete nodules (Harris & Hudson, op. cit.) and traces of anhydrite/gypsum (Millson, op. cit.) suggests, rather, that they were formed in an arid/semi-arid belt temporarily established between the Irish, Welsh and Scottish land areas. Calcite pseudomorphs after gypsum developed in Hebridean stromatolites formed earlier in the Bathonian (Hudson, 1970) bear witness to the occurrence of arid/semi-arid conditions in the same region at other times in the Middle Jurassic. Recently, Julian Andrews (in litt., 1985) has discovered probable calcite pseudomorphs after gypsum in the White Limestone at Croughton, suggesting that the east Midlands area was also subject to at least periodic aridity during the Late Bathonian.

In conclusion, the British Middle Jurassic climate seems to have been primarily a warm, humid one, periodically interrupted by locally-developed aridity; seasonal climatic change is suspected. The shallow epicontinental seas of the region were characterised by minimum near-surface temperatures generally in excess of 15°C and by mean temperatures over 18°-20°C. There is ample sedimentological evidence from the Middle and Upper Bathonian deposits of eastern and central

England studied for this thesis which suggests the occurrence of periodic major storms; however, the pattern of winds which affected the British area during the Bathonian is unknown. Freshwater run-off from hinterland areas was often significant, carrying driftwood considerable distances and creating environmentally important salinity fluctuations in many of the shallow seas (including that of the East Midlands Embayment/Seaway) fringing land areas such as Brabantia or the Welsh Landmass.

2.6 Timescale

In recent years the top of the Jurassic Period has been placed at 144 Ma (Harland et al., 1982; A. Palmer, 1983) and 130 Ma (Odin, 1982), with an intermediate figure of 135 Ma given earlier (Howarth, 1964; Van Hinte, 1976); the base has been variously set at 190-195 Ma (Howarth, 1964; Van Hinte, 1976), 204 Ma (Odin, 1982), 208 Ma (A. Palmer, 1983) and 213 Ma (Harland et al., 1982). Estimates of the length of the period thus vary between 55 Ma and 74 Ma. In the most recent publications, the numerical dates for the upper and lower boundaries of the Bathonian Age have been derived by approaches involving magnetostratigraphy and assumptions of equal duration of stages and zones (Westermann, 1984). Westermann, himself, metered the intra-Jurassic chronostratigraphic scale by assuming that the duration of a subzone was equal to 75% of that of an undivided zone. The use of different methods has led to the Bathonian Age being estimated at between 5 Ma (Westermann, 1984) and 11 Ma (Odin, 1982) in length (Fig. 2.7). Dates for stage boundaries derived by any methods involving assumptions about the relative lengths of Jurassic stages, zones or subzones are obviously inaccurate, even though some methods may appear more refined than others; thus Westermann's low figure

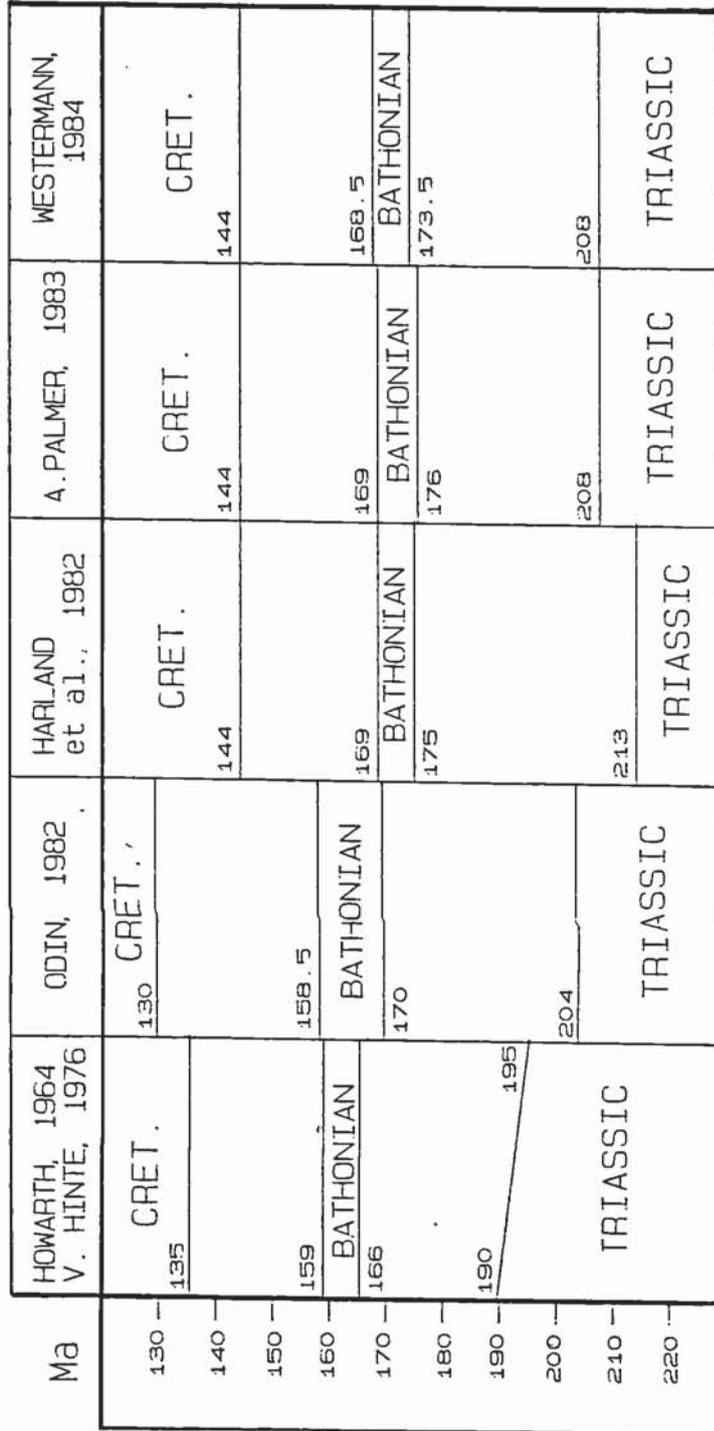


FIGURE 2.7 Recent numerical timescales for the Jurassic showing estimates of the upper and lower limits of the Bathonian.

in part reflects the poor worldwide Bathonian ammonite record, with the consequent lack of refinement of Bathonian zonal schemes compared with those of other Jurassic stages, rather than being a valid estimate of the length of the Bathonian Age. Odin's (1982) figure of 11 Ma for the length of the age is longer than all other estimates of this period of time, but some of the dates on which Odin based his figures, derived from glauconite radiometric dates, are suspect.

Bradshaw (1978) made the reasonable assumption that deposition of the Rutland Formation and its lateral equivalents occupied approximately one third of the duration of the Bathonian Age; if so, deposition of the upper Great Oolite Group occupied roughly two thirds of the age: a period of between 3.3 Ma and 7.3 Ma.

CHAPTER 3

LITHOSTRATIGRAPHY

3.1 The development of the existing lithostratigraphy

3.1.1 Introduction

The rapid lateral and vertical facies changes which characterise the Middle Jurassic deposits of England and the paucity of ammonites useful for correlation, particularly in the Bathonian, largely account for the complex historical development of the modern lithostratigraphy of the English Middle Jurassic. Recent papers (T. Palmer, 1979; Sumbler, 1984; Bradshaw, in prep.) show that this lithostratigraphy is still not entirely resolved. Fluctuations in relative sea level, patterns of deposition and hydrogeography through the Middle Jurassic led to the occurrence of the same lithofacies (and sometimes also biofacies) in different parts of the outcrop at different stratigraphic levels. This, because of poor biostratigraphic control, led to a history of erroneous correlations and mis-classification of sections. An extra complication with Middle Jurassic stratigraphy is the separate development of the lithostratigraphy used in Oxfordshire and that used in the east Midlands. Furthermore, a new lithostratigraphic subdivision of the Aalenian to Bathonian succession of northern Lincolnshire and Humberside recently introduced by the B.G.S. (Sheets 89/Brigg and 80/Kingston-upon-Hull; Riding, 1983) bears little relation to earlier terminology.

The Great Oolite Group ('Series' of Torrens, 1980b) broadly coincides with the Bathonian Stage, although typically also includes rocks of latest Bajocian and earliest Callovian age. The name, 'Great Oolite', like the formational names 'Cornbrash' and 'Forest Marble', was coined by William Smith prior to 1800 (Phillips, 1844). Judd (1875) later introduced the 'Great Oolite Series' as a lithostratigraphic unit encompassing the 'Upper Estuarine Series' (Rutland Formation) up to Cornbrash in eastern England, and Woodward (1894) used the same term to embrace all formations from the Fuller's Earth up to the Cornbrash further south. Following Hedberg (1976), the use of the chronostratigraphic term 'series' in lithostratigraphy has been discontinued; McKerrow & Kennedy (1973) introduced the Great Oolite Group as the correct lithostratigraphic nomenclature. Until publication of the 1:50000 Series Sheet 89 (Brigg) in 1982, the Great Oolite Group had been widely accepted as including strata from Humberside to the Dorset coast. North of the Humber, white sands believed to be the same age as at least part of the Great Oolite Group of further south have recently been named the Drewton Formation (Bradshaw, in prep.); these sands are the most northerly representative of the Great Oolite Group, as the Cornbrash of the Cleveland Basin is not normally included. Rocks north of the Market Weighton Block which may be of similar age to the Great Oolite Group are now referred to the Scalby Formation of the Ravenscar Group (Knox & Hemingway, 1973).

As noted above, the work of those who largely studied the succession of Oxfordshire and Gloucestershire (e.g. Hull, 1857, 1859; Phillips, 1860, 1871; Walford, 1883a, 1883b, 1885, 1906, 1917; Odling, 1913; Arkell, 1931, 1933b, 1947; T. Palmer, 1973, 1974, 1979; Sellwood & McKerrow, 1974; Barker, 1976; Sumbler, 1984) and those who worked in

eastern England (e.g. Sharp, 1870, 1873; Judd, 1875; Thompson, 1891, 1894, 1906, 1921, 1924, 1927, 1930; Aslin, 1965; Pittham, 1970, 1973) led to the development of separate lithostratigraphies for the two regions. These are gradually being reconciled, particularly through the work of those who have studied both areas: Woodward (1894) and Arkell (1933a) in largely compilative works; L. Richardson (e.g. 1910a, 1910b, 1911a, 1911b, 1921, 1922, 1923, 1925, 1929, 1933, 1939a, 1939b, 1940), Bradshaw (1978, in prep.) and myself.

3.1.2 North Gloucestershire and Oxfordshire

Following the early stratigraphical work of W. Smith (reviewed by Phillips, 1844), Townsend (1813), Buckland (1818), Conybeare & Phillips (1822), Murchison (1834), Murchison et al. (1844) and Brodie & Buckman (1845), the main development of the north Gloucestershire/Oxfordshire Great Oolite lithostratigraphy was achieved by Hull (1857, 1859), Phillips (1860, 1871), Woodward (1894) and Walford (1906). Major improvements in the definition of lithostratigraphic units and in correlation were brought about by L. Richardson (e.g. 1929, 1933, 1935) and Arkell (e.g. 1931, 1933a, 1947) and further refinements have been made in the large volume of recent stratigraphic work (Sellwood & McKerrow, 1974; T. Palmer, 1974, 1979; Barker, 1976; Sumbler, 1984).

Hull (1857), working in the Cheltenham area, included in the Great Oolite only those limestone-dominated strata between the Fuller's Earth and the Forest Marble; these beds he believed were the same as the Great Oolite limestones of the type area around Bath (which we now know is not the case, for there they are essentially younger). He separated his Great Oolite of the Old Series Sheet 44 into upper and lower

divisions, with the former comprising what later were to be called the Hampen Marly and White Limestone Formations. What were believed to be laterally equivalent upper and lower zones were also recognised in the area directly north of Bath (Ramsay et al., 1858), but there Hull's upper zone included the Great Oolite sensu stricto and also Cave's (1977) Athelstan Oolite and Tresham Rock. Woodward (1894), compiling work from various sources, formalised the 'White Limestone' and 'Marly Beds' as stratigraphic units, these names being derived from Hull's (1857) descriptive reference to "beds of marl" and his (1859) semi-formal use of "white limestone". The White Limestone and Forest Marble, both included within the Great Oolite Series by Woodward, are taken in this thesis, along with the overlying Cornbrash, to be the constituent formations of the upper Great Oolite across much of my study area; it is the lithostratigraphy of these formations that will be dealt with in detail below. Woodward's 'Marly Beds' became the 'Hampen Marly Beds' of Arkell (1931) and the Hampen Marly Formation of McKerrow & Kennedy (1973). The lithostratigraphy of this and other formations of the Oxfordshire lower Great Oolite has recently been reviewed by Bradshaw (1978, in prep.).

3.1.2.1 Base of the White Limestone Formation

The base of the White Limestone has rarely been exposed in north Gloucestershire/Oxfordshire, and in this area different workers have placed the base of the formation at different levels, even within the same section. Thus, at Stony Furlong (SP063108), Arkell & Donovan (1952) located the base of the formation 3.4m lower than did L. Richardson (1933) and at Ardley (Loc. 28), T. Palmer (1979) defined the Hampen Marly Formation/White Limestone junction at a level 0.6m lower than that suggested by Arkell et al. (1933). While Palmer's (op. cit.) hypothesis,

based on equivocal evidence*, that the base of the White Limestone gets progressively older southwestwards towards Cirencester and beyond may be correct, it should be remembered that the base of the formation, because of the difficulties encountered in placing this lithostratigraphic junction, is likely to be diachronous to some extent between any two exposures.

T. Palmer (1979), who found the passage from the Hampen Marly Formation up into the White Limestone to be lithologically gradational in Oxfordshire, used faunal and floral changes to define the base of the White Limestone. He noted that 'Kallirhynchia' (= Burmihynchia), oysters and rootlets are characteristic of the lower formation, whereas the lowermost White Limestone contains Epithyris, Lopha, Clypeus, Pholadomya, Homomya and nerineid gastropods, and rootlets only in northeast Oxfordshire. In the Ardley-Fritwell Cutting he used these criteria to place the junction between the two formations at the base of Bed 20 of Arkell et al. (1933). However, these faunal changes are of value only within a limited area because of lateral lithofacies/biofacies variability on both local and regional scales; they do not, for example, provide a satisfactory means of defining the base of the White Limestone very far beyond the western limits of Palmer's study area. Here, Sumblar's (1984) recent definition of the base of the formation as the base of the lowest major white or grey limestone overlying the

* It is debatable whether the Hampen Marly Formation, while becoming increasingly calcareous southwestwards, ever becomes indistinguishable from the White Limestone. Palmer's evidence came from sections and boreholes in the Chedworth-Cirencester district which are open to a number of interpretations

characteristic green, grey-green and buff mudstones, calcareous mudstones and sandy, micritic limestones of the Hampen Marly Formation can often usefully be employed.

3.1.2.2 Subdivision of the White Limestone Formation

Early attempts to subdivide the White Limestone in Oxfordshire (Barrow, 1908, 1909; Odling, 1913) and all subsequent attempts (Arkell, 1931, 1947; T. Palmer, 1974, 1979; Barker, 1976; Sumbler, 1984) reflect to some degree the rhythmic pattern of sedimentation which led to the formation of this unit. The White Limestone essentially comprises up to five widely recognisable shallowing-upwards sequences or rhythms (not all are necessarily developed, however) which are fully discussed in Chapter 7. In the past, most subdivisions of the White Limestone in Oxfordshire have had boundaries at, or close to, rhythm junctions. Thus, in Odling's (1913) subdivision, which involved splitting most of the White Limestone into three 'Blocks', 1-3 in descending order, with the lowermost part of the formation classified as 'Fullonian', the junction between his Blocks 1 and 2 coincides with the top of the third White Limestone rhythm in the Cherwell Valley area, while at Ardley the top of his Block 3 is close to the boundary of the second and third rhythms.

Later efforts to subdivide the formation have largely continued to use Odling's mixed lithological/palaeontological approach to the problem. However, whereas L. Richardson (in Richardson *et al.*, 1946) was forced to admit that after many years endeavour he had failed to find fossils of a sufficiently restricted vertical range to be of use in zoning the Great Oolite of the Cotswolds, Arkell (1931, 1947) successfully developed his gastropod-based subdivision of the Oxfordshire White Limestone. Initially (1931), he used both brachiopod and gastropod horizons to make

internal correlations within the formation. He recognised three horizons characterised by abundant terebratulids (his Upper, Middle and Lower Epithyris Beds) and, more importantly, he found that new species of the nerineid, Aphanoptyxis, formed "definite zones of at least local utility" within the White Limestone (his Kemble Beds and White Limestone). His use of Epithyris-rich horizons (following Odling) inevitably led to mis-correlations: not only are epithyrids facies-controlled and common at several irregularly developed horizons, but in small sections it is impossible to tell whether a given horizon is the Upper, Middle or Lower Epithyris Bed. However, Arkell (1947) was able to develop his work on gastropod horizons, using two Aphanoptyxis-rich horizons as the basis for a bipartite subdivision of the White Limestone (into the lowermost Ardley Beds, bounded upwards by the A. ardleyensis 'Bed', and the overlying Bladon Beds, bounded upwards by the A. bladonensis 'Bed'). More recently, Barker (1976) has recognised a third horizon (the A. excavata Bed) which he used to subdivide Arkell's Ardley Beds into the basal Excavata Beds and overlying Ardley Beds.

Errors have resulted from the use of gastropod horizons to lithostratigraphically subdivide the formation because it has been assumed that respective gastropod horizons are isochronous. In fact, as species of Aphanoptyxis occur in particular lithofacies, it is facies distribution rather than time which accounts for the occurrence of Aphanoptyxis at any particular level in a section (although the genus is biostratigraphically important). Where a particular gastropod horizon is missing, because of erosion or the non-development of the necessary facies, it is not only impossible to place the boundary between two gastropod-based 'lithostratigraphic' units, but it is, by definition, impossible to recognise the unit whose capping horizon is missing.

T. Palmer's (1974, 1979) tripartite subdivision of the White Limestone, while having much in common with Barker's (op. cit.) scheme, is based on a mixture of faunal and lithological criteria more refined than those used earlier by Odling (1913). In contrast to Barker's three subdivisions, there is no need for particular fossils to be present before Palmer's members can be recognised; they are, therefore, better potential mapping units.

T. Palmer (1974) originally subdivided the White Limestone into, in ascending order, the Croughton, Ardley and Bladon Members, but later (1979) changed the lower unit to the Shipton Member because of the unsuitability of the original type-section. Each member was considered by Palmer to be a shallowing-upwards unit. Although the vertical sequence of facies within a particular member is not everywhere identical, Palmer has correlated slightly different sequences in the belief that these each represent the same shallowing-upwards unit. As noted above, however, there are more than three shallowing successions developed within the White Limestone so that Palmer's interpretation of his subdivisions is over-simplified. Even so, as lithostratigraphic units, Palmer's members can be consistently recognised and, therefore, must essentially remain valid. The principal features of each member, as described by T. Palmer (1979), can be summarised:

a) Shipton Member. Sparitic, micritic and muddy limestones. A greater proportion of clastic material (both as individual beds and as disseminated quartz sand/silt or clay in limestones) than in the Ardley Member. Limestones less well cemented and therefore less resistant than Ardley Member limestones. Fossils frequently preserved as composite moulds. Typical fauna comprises colonial corals, rhynchonellids, Epithyris, Clypeus, Lopha costatum, Solenopora and Aphanoptyxis excavata.

b) Ardley Member. Three principal lithofacies are developed: well-washed lime sands, pelleted lime muds and 'shelly micrites'. A thin bed of laminated, pelletal and quartz sand is developed at the top of the member locally. The member is frequently capped by a hardground.

c) Bladon Member. Varied lithologies: cryptalgal laminated micrite with birdseyes and dessication cracks; cross-bedded oolite; biopelsparite; unlaminated, fossiliferous micrite; coral-rich biomicrite; terrigenous mudstones. In places the member is capped by a hardground.

Palmer included within the Bladon Member cross-bedded oolites developed between Witney and Burford. Barker (1976), however, showed that these oolites are developed immediately above the horizon of Aphanoptyxis cf. langrunensis at Eton College and above the A. excavata Bed at Sturt Farm; this, and lithological similarities between these cross-bedded oolites and the bioturbated grainstones developed in the basal Ardley Member to the northeast, suggest that these cross-bedded lime sands should be included within the Ardley, rather than Bladon Member. At Eton College, a hardground 0.97m beneath the top of the White Limestone (top of bed 4 of Palmer, 1974) is herein taken to mark the top of the Ardley Member in the Burford area. Elsewhere in this thesis, Palmer & Jenkyns's (1975) incorrect palaeogeographic reconstruction, which resulted from the mis-correlation of these cross-bedded lime sands with supratidal lime muds developed within the Bladon Member to the northeast, is discussed. It is important to note that most of the fossils used by Palmer (1979) to distinguish the Shipton from Ardley Member (colonial corals, Solenopora, Lopha costatum, Clypeus, Epithyris and rhynchonellids) have been found, at various locations within Palmer's study area, in beds placed, on other criteria, within the Ardley Member.

Sumbler's (1984) recent redefinition of the Shipton, Ardley and Bladon Members and his extensive and modified usage of Arkell's 'Upper Epithyris Bed' (the use of epithyrid horizons has already been criticised) and 'Fimbriata - Waltoni Bed' has done little to improve Palmer's lithostratigraphic scheme. Of the changes proposed by Sumbler, the re-definition of the Ardley Member so as to include both the Aphanoptyxis ardleyensis 'Bed' and the A. bladonensis 'Bed' (though neither species is necessarily confined to a single bed), and the consequent exclusion of the main A. bladonensis horizon from the Bladon Member, is particularly nonsensical. This redefinition is clearly at odds with the earlier work of Arkell (1947), T. Palmer (1974, 1979) and Barker (1976), as well as with my own research. Only in the Cherwell Valley, as a result of mis-correlation of sections where A. ardleyensis is absent or occurs well below the top of the Ardley Member, does Sumbler's 'Ardley Member' equate with that of Palmer. Elsewhere, variable proportions of the Bladon Member have been included in the 'Ardley Member' by Sumbler.

Sumbler's redefinition of the Ardley Member is partly based on an assumption that the A. ardleyensis 'Bed' is a correlatable horizon, and that the top of Palmer's original member was related to this gastropod horizon. This is not so; Palmer (1979, p.202) clearly argued against the use of gastropods in making lithostratigraphic correlations.

Two of Arkell's (1931) informal subdivisions of the White Limestone (of this account) have been resurrected by Sumbler (op. cit.): the Fimbriata-Waltoni Bed* and the Upper Epithyris Bed. Not only has Sumbler re-introduced these facies-related subdivisions but he has also

* Renamed the 'fimbriatus-waltoni clays' by McKerrow et al. (1969).

extended their usage far beyond the area in which Arkell originally applied the names. Any correlation over a large area of a particular lithofacies/biofacies of the Great Oolite Group is liable to be wrong, for the same facies is often developed at different stratigraphic levels in different areas. Thus Sumbler's correlation of the 'Fimbriata-Waltoni Bed' of the Cherwell Valley with similar lithologies containing Bakevellia and Eomiodon in the Burford district must be treated with caution. Similarly, while in the Cherwell Valley the 'Upper Epithyris Bed' may be a locally correlatable horizon, attempts to correlate this horizon outside the area have, in the past, invariably met with failure.* Somewhat surprising is Sumbler's inclusion within his 'Upper Epithyris Bed' of limestones which do not contain Epithyris and are of a facies quite unlike the Cherwell Valley coral-brachiopod limestones with which Arkell was familiar. There can be no justification for including laminated and rootletted micrites at the top of the White Limestone at Croughton and Stratton Audley within the 'Upper Epithyris Bed', even though they occupy a similar stratigraphic position. Furthermore, Sumbler has followed Allen & Kaye (1973) in erroneously including within his 'Upper Epithyris Bed' at Shipton, cross-bedded limestones belonging to the Forest Marble; these bear little lithological resemblance to Arkell's original Upper Epithyris Bed.

* For example, Richardson et al. (1946) used the name for a coral bed at Dogslade Quarry (SP336158) developed within the Forest Marble.

3.1.2.3 The Forest Marble - White Limestone boundary

Historically, many of the problems associated with the definition of the White Limestone Forest Marble junction relate to the use of the 'Bradford Clay' to define the base of the Forest Marble. This and the status of the 'Kemble Beds' are discussed in section 3.1.2.4. Within Oxfordshire, however, the definition of this junction has been controversial for purely lithological reasons, particularly in the Cherwell Valley where the 'fimbriatus-waltoni clays' are developed. The latter have been included in the White Limestone (Hull, 1859; Woodward, 1894; Pocock, 1908; Odling, 1913; Arkell, 1947; T. Palmer, 1974, 1979; Barker, 1976; Sumbler, 1984) and in the Forest Marble (Phillips, 1860, 1871; Bayzand in Sollas, 1926; Pringle, 1926; McKerrow et al., 1969), or even considered as a totally autonomous unit (Arkell, 1931). Recent opinion has generally followed Hull (1859) in favouring inclusion in the White Limestone. The coral bed frequently developed above the 'fimbriatus-waltoni clays' in the Cherwell Valley (i.e. Arkell's Upper Epithyris Bed) is lithologically closer to that formation than to the Forest Marble and, locally (e.g. Shipton), A. bladonensis occurs above the same coral bed in a horizon only infrequently preserved beneath the erosive base of the Forest Marble (Barker, 1976).

In another problematic area, around Stratton Audley and Blackthorn Hill, failure to recognise the thinning of Forest Marble towards the London-Brabant Massif and mis-correlation of cryptalgal laminite horizons (developed at two horizons within the Bladon Member; see Chapter 7) across Oxfordshire led T. Palmer (1973, 1974, 1979) to consistently place the White Limestone-Forest Marble junction within the Bladon Member of this area, even after Barker (1976) showed that A.

bladonensis occurred in Palmer's (1973) Bed 10 at Stratton Audley.* This gastropod has not been found in the Forest Marble elsewhere and is herein considered as indicative of the Bladon Member and laterally equivalent strata.

Of the criteria originally suggested by Hull (1857, 1859; see also Barker, 1976) for distinguishing the White Limestone and Forest Marble, the presence of a hardground at the top of the White Limestone (as at Eton College or Temple Mills) is particularly useful. Cross-bedding, which was considered a feature of the Forest Marble by Hull, is also locally well-developed in parts of the White Limestone. The more common occurrence of oysters in the Forest Marble was adopted by McKerrow et al. (1969) as a method of separating the two formations at Kirtlington, but as T. Palmer (1973, 1979) has rightly pointed out, oysters cannot be used to this purpose throughout Oxfordshire; they become increasingly common in the White Limestone northeastwards.

Amongst the distinguishing features of the two formations noted by Palmer (1973) for the area north and northwest of Oxford were that the White Limestone contains abundant micrite and faecal pellets, an extensive infauna and is heavily bioturbated, whereas the Forest Marble is characterised by ripple marks, clay flakes and Gyrochorte. Yet at Kirtlington, micrite occurs within typical Forest Marble limestones and the proportion of micrite within the formation increases northeastwards towards Stratton Audley and beyond into Buckinghamshire. Similarly,

* Further discussion of this aspect of the Stratton Audley and Blackthorn Hill sections can be found in the Appendix (Loc. 43 and 44).

ripple marks and micrite or mud clasts occur within some lithofacies of the White Limestone.

3.1.2.4 Subdivision of the Forest Marble Formation and the status of the 'Kemble Beds'

The 'Bradford Clay' in the type area at Bradford-on-Avon (Wiltshire) is a highly fossiliferous clay which contains abundant brachiopods (particularly Digonella digona, Dictyothyris coarctata and Eudesia cardium) and a hardground-related fauna that includes Apiocrinus and a diverse bryozoan component (Palmer & Fürsich, 1974; P. Taylor, 1977). Prior to the work of Penn & Wyatt (1979), the type 'Bradford Clay' horizon, developed above the Upper Rags, was always believed to occur at the base of the Forest Marble. Woodward (1894) used horizons characterised by 'Bradfordian' faunas throughout southern England to define the base of the Forest Marble. When, on coming to the Kemble area, he found about nine metres of limestones developed between what he took to be the White Limestone and the 'Bradfordian' horizon in the road cutting at Tetbury Road Station (ST982988) he was forced to create the 'Kemble Beds'. Cave (1977) has shown that Woodward's original Kemble Beds comprised a discontinuously developed extension of the Great Oolite of Bath (Cave's ?Great Oolite) together with the lowermost limestones of the Forest Marble in which coral patch reefs are developed. However, Woodward (op. cit.) was far from consistent in his use of the new stratigraphic unit; for example, he included within the Kemble Beds at Hailey Wood Railway Cutting (c. S0962012) a large thickness of

stratigraphically lower Athelstan Oolite/White Limestone (Arkell, MS.*; Cave, in litt.).

Furthermore, in sections in the Cotswolds where 'Bradfordian' faunas are wanting, Woodward found it very difficult to define the base of the Forest Marble. This, however, did not stop Arkell (1931) from utilising what he termed the 'Bradford Fossil-Bed' in Oxfordshire to split the Forest Marble of previous authors into the 'Kemble' and 'Wychwood Beds' and to suggest that 'Forest Marble' should, in general, be dropped from stratigraphical literature.

Arkell's (1931, 1933a, 1947) 'Kemble Beds' comprised a mixture of lithologies including both coral-Epithyris limestones and cross-bedded oolites. These he found to overlay his 'Fimbriata-Waltoni Bed', a stratigraphic unit he originally (1931) regarded as separate from either the 'Kemble Beds' or the underlying White Limestone, but later (1947) included within his Bladon Beds. The lithostratigraphic basis for Arkell's subdivision of the Forest Marble must be challenged, for frequently he was unable to distinguish the 'Kemble Beds' from the 'Wychwood Beds' in the absence of the 'Bradford Fossil Bed', largely because many lithologies of his 'Kemble Beds' were identical to those developed in the overlying 'unit'. However, L. Richardson (1933) followed Arkell's example and used the 'Kemble Beds' as a stratigraphic unit in the Cirencester area. He too included a number of lithologies within the 'Kemble Beds': cross-bedded oolites and cross-bedded

* Arkell, in MS. notes now in Oxford University Museum, wrote: "how he (Woodward) could have come from Kemble (to Hailey Wood) and seen any resemblance to the Kemble Beds passes comprehension"; see also Cox & Arkell (1948-50).

limestones associated with lenticles of clay (both of Forest Marble character) as well as cross-bedded limestones "of Great Oolite facies". Richardson was also forced to acknowledge the difficulty of separating his 'Kemble Beds' of Forest Marble type from what he regarded as true Forest Marble.

Later workers (McKerrow, 1955; Martin, 1958; Worssam & Bisson, 1961; Elliot, 1973) have continued to use 'Bradfordian' horizons to lithostratigraphically subdivide the Forest Marble, believing that these horizons mark a single, isochronous stratigraphic level. This has been shown to be untrue, even in the type area of the 'Bradford Clay' (Green & Donovan, 1969; Cave, 1977; Penn & Wyatt, 1979), although an important corollary of Penn & Wyatt's (1979) inclusion of the Upper Rags within the Forest Marble is that true 'Bradfordian' faunas are now restricted to the Forest Marble Formation. While the Oxfordshire occurrences of 'Bradfordian' faunas may yet be of correlative value if, as is possible, they are related to a single essentially isochronous transgression, their discontinuous development (they occur only sporadically along the southernmost part of the Oxfordshire outcrop; Fig. 7.13) militates against the use of any 'Bradfordian' horizons in the lithostratigraphic subdivision of the Forest Marble in Oxfordshire; I therefore agree with Sumbler (1984) who has stated that "there appears no reliable basis for regional subdivision of the formation".

As the 'Kemble Beds' in the type-area have been shown by Cave (1977) to be a heterogeneous lithostratigraphic unit, there can be no justification for the continued use of Woodward's name. Cave's ?Great Oolite, on the other hand, appears to be distinct from either the Forest Marble or the underlying Athelstan Oolite and Coppice Limestone (laterally equivalent to the upper White Limestone). In the northern

Malmesbury district, Cave (op. cit.) recognised the ?Great Oolite, consisting of a cream to yellow, shelly oolite, as a discontinuously developed unit, probably laterally equivalent to the Combe Down Oolite of the Bath area. This same unit can be recognised further north also. In cuttings north of Cirencester (Loc. 2) it comprises about 3 metres of oolite, attenuating northwards. In this area, most of L. Richardson's (1933) 'Kemble Beds of Great Oolite facies' was probably ?Great Oolite. The ?Great Oolite is further developed in the Burford area (= the Signet Beds of Worssam & Bisson, 1961) where Sumbler (1984) has placed the unit within the White Limestone; this is not followed here, and in this area (e.g. Loc. 7) the ?Great Oolite has been recognised as a distinct, informal lithostratigraphic unit. Between Witney and Bladon, the ?Great Oolite probably passes laterally into the upper part of the Bladon Member.

3.1.2.5 Cornbrash Formation

The Cornbrash Formation is a continuous unit across Gloucestershire and Oxfordshire, the stratigraphy of which has been reviewed in detail by Douglas & Arkell (1928, 1932, 1935). The formalisation of the Cornbrash as a formation follows T. Palmer (1979). The two subdivisions of the formation recognised by Douglas & Arkell on the basis of their very distinct faunas (a separation first noted by William Smith) were formalised as the Lower and Upper Cornbrash Members by Palmer (op. cit.).

3.1.3 East Midlands

Major controversies relating to the Middle Jurassic lithostratigraphy of the east Midlands have involved the Inferior Oolite

and lower Great Oolite, the main problems having been discussed in detail and essentially resolved by Bradshaw (1978, in prep.). Those involving the upper Great Oolite have been minor, relating to the correlation with the Oxfordshire succession, the subdivision of the 'Blisworth Limestone', the placing of the 'Blisworth Limestone'-'Blisworth Clay' junction and the naming of the constituent units. The lithostratigraphic framework for the Great Oolite Group was largely established by Sharp (1870, 1873) and Judd (1875); Judd subdivided the group into the 'Upper Estuarine Series', 'Great Oolite Limestone', 'Great Oolite Clays' and Cornbrash.

3.1.3.1 Nomenclature: White Limestone Formation

The White Limestone Formation in the east Midlands has, in the past, been called the 'Great Oolite Limestone' (e.g. Sharp, 1870, 1873; Judd, 1875; etc.) and more recently the 'Blisworth Limestone' (e.g. Hains & Horton, 1969; most subsequent authors); a few past authors (notably Sharp, 1873, fig. 1; Arkell, 1933a; L. Richardson, 1939b) have used 'White Limestone' in the east Midlands. In addition, Morris (1853, 1869) employed the name 'White Oolite' in works predating those of Judd and Sharp.

The name 'Blisworth Limestone' was conceived by the Geological Survey in 1963 and used during the mapping of the Towcester Sheet from January, 1964 (MS., Keyworth); its conception in literature came in 1969 (Hains & Horton, 1969). However, a type section has never been designated, and justification for the new name was not published until Horton, Shephard-Thorn & Thurrell (1974) stated:

"the term Blisworth Limestone is synonymous with the Great Oolite Limestone of the Northampton Sand Ironstone Field but is preferred to the latter because of uncertainty attending precise correlation with the limestones in the Great Oolite Series of Oxfordshire".

While 'Great Oolite Limestone' is certainly an unsuitable name*, the geographical epithet chosen by Hains & Horton (1969) had already been applied by Sharp (1870) to the overlying formation ('Blisworth Clay'), for which it has been widely used; therefore the introduction of the name 'Blisworth' for the limestone unit is contrary to the recommendations of Hedberg (1976) or Holland et al. (1978), and cannot be supported.

Horton, Shephard-Thorn & Thurrell (1974) noted that the 'Blisworth Limestone' and the White Limestone of Oxfordshire apparently formed a continuous lithological formation and this has been confirmed by my own work. Facies changes that occur within the formation on moving from Oxfordshire into the east Midlands are gradational rather than sudden, and reflect the increasingly restricted nature of the depositional environment in a northeastward direction. Torrens's (1967) claim that the 'Great Oolite Limestone' is faunally quite distinct from the Oxfordshire White Limestone is not true, although gradual faunal changes do accompany northeastward facies changes. The supposition that the greater part of the 'Blisworth Limestone' is considerably younger than much of the White Limestone (Torrens, 1967, 1968) was based on a mis-interpretation of the available ammonite evidence. As was originally

* Not only is much of the formation seldom oolitic but the use of the epithet 'Great Oolite' creates confusion with the younger Great Oolite of the Bath area, which has priority to the name; 'Great Oolite' is also used for the group in which the limestone occurs. Furthermore, 'Great Oolite Limestone' has previously encompassed both the White Limestone and the older Wellingborough Limestone (= 'Upper Estuarine Limestone'), particularly in southwest Northamptonshire (e.g. Woodward, 1897; Thompson, 1927).

suggested by Bradshaw (1978) and subsequently reaffirmed by Torrens (1980b), most of the Shipton Member (containing morrissi and subcontractus Zone ammonites) passes laterally into the Kallirhynchia sharpi Beds (which have apparently not yielded ammonites) while the hodsoni Zone ammonites from the 'Blisworth Limestone' above the K. sharpi Beds allow correlation of these upper beds with the Ardley and Bladon Members of Oxfordshire. Therefore, since the 'Blisworth Limestone' is not only largely lithologically continuous with the Oxfordshire White Limestone, but is now seen as essentially age-equivalent, the usage of the name 'White Limestone' should be (and herein has been) extended to include the east Midlands.

3.1.3.2 Base of the White Limestone Formation

Throughout the east Midlands, the White Limestone overlies the 'Upper Estuarine Series', renamed the Rutland Formation by Bradshaw (1978, in prep.). Many previous workers (e.g. J. Taylor, 1963; Aslin, 1965; Torrens, 1967) encountered difficulty in accurately placing the junction between the White Limestone and the Rutland Formation, with Aslin (1965) opting to create a 'Passage Sequence' at the top of the 'Upper Estuarine Series' to include the beds of uncertain affinity. The problem of defining the base of the White Limestone has been largely resolved by Bradshaw (1978), who defined this junction in the east Midlands as the point where the highest Rutland Formation rootlet bed in a particular section is truncated by the erosive base of the overlying sediments. While this definition may entail assigning a considerable thickness (up to 1.17m at Thompson's Quarry, Ancaster) of siliciclastic sediment below the lowest limestone bed to the White Limestone Formation, the lithostratigraphic/event stratigraphic junction so-defined has been

found to be widely recognisable throughout the east Midlands during the course of my study, doing away with the need for any 'Passage Sequence'. It has therefore been adopted in this thesis. Event stratigraphy indicates that the base of the White Limestone is slightly younger in the east Midlands than in Oxfordshire, and it is even younger in marginal southeastern areas (e.g. Bromham) where the K. sharpi Beds pass into the Rutland Formation and/or are overstepped by Upper Bathonian sediments.

3.1.3.3 Subdivision of the White Limestone Formation

Thompson (1924) presented the first subdivision of the east Midlands White Limestone when he recognised within the formation in Roade Railway Cutting (Loc. 106), in descending order, the Plant Beds, Coral Bed, Terebratula Bed, Nerinea Bed and Rhynchonella/Pholadomya Beds. The latter are equivalent to the Kallirhynchia sharpi Beds recognised in this account. This initial subdivision was palaeontologically-based but Thompson's (1927) subsequent scheme utilised a mixture of faunal and lithological criteria. The essence of this 1927 scheme was that five units (A, B, C, D and E, in descending order, essentially equivalent to the units identified at Roade) were grouped into a tripartite subdivision of the White Limestone comparable to Odling's (1913) subdivision of the formation in Oxfordshire. Units A and B were grouped together as the Upper Division or Pendle Zone; units C and D formed the Middle Division or Terebratula Zone; Unit E constituted the Lower Division or Rhynchonella Zone. As in Odling's work, brachiopod horizons were of considerable importance in making lithostratigraphic correlations and, indeed, have been used for such a purpose ever since (e.g. Torrens, 1967; Pittham, 1970).

Of Thompson's (1927) three divisions, the lowermost Rhynchonella Zone has been most widely used. The zone consists of limestones interbedded with interlayered muds and sands and is characterised by the small, highly variable rhynchonellid, Kallirhynchia sharpi, which is unknown outside of the east Midlands. The species was named by Muir-Wood, in an appendix to Richardson & Kent's (1938) paper in which they introduced the Kallirhynchia sharpi Beds as a lithostratigraphic unit developed at the base of the White Limestone and equivalent to Thompson's 'Rhynchonella Zone'.

The K. sharpi Beds can be traced throughout most of Northamptonshire, south of the Kettering-Peterborough Line. North of this line, however, the index species is sporadically distributed and the lithologies developed at the base of the White Limestone are very variable. In much of this northern area the use of the K. sharpi Beds as a lithostratigraphic unit cannot be justified.

The two units recognised by Thompson (1927) above his Rhynchonella Zone are more problematic. While the tripartite lithostratigraphic subdivision is probably valid for southwest Northamptonshire, in areas southeast, east and northeast of the Blisworth-Roade district, where the coral bed characteristically developed at the base of the uppermost unit is invariably lacking, the White Limestone above the K. sharpi Beds cannot be satisfactorily subdivided. Torrens (1967) and Pittham (1970) both identified a horizon, characterised by Digonella digonoides, which they adopted as an informal lithostratigraphic unit. However, the vertical and lateral distribution of this brachiopod is extremely variable, since it is intimately linked with one lithofacies association, and the species does not characterise a single, laterally-correlatable horizon as Torrens (1967, fig. 2) appears

to have envisaged. Yet, where a tripartite subdivision of the Northamptonshire White Limestone appears tenable, D. digonoides occurs only in the central unit and, in other areas, the species occurs only in the White Limestone above the K. sharpi Beds.

As in the White Limestone of Oxfordshire, the vertical distribution of facies in the formation in the east Midlands was determined by lateral facies migrations during a number of transgressive-regressive episodes of deposition. Not only was the distribution of D. digonoides 'beds' controlled by the rhythmic sedimentation pattern but so also was the development of other, locally traceable, informal lithostratigraphic units (e.g. the 'Epithyris Bed' and 'Trigonia bed' of J. Taylor, 1963; the 'Plant Bed' of Thompson, 1927; Torrens, 1967) which reflect the development of a particular lithofacies and/or biofacies. Most of these facies-based units are too discontinuous to warrant formal status.

The K. sharpi Beds are, similarly, a facies-related unit, herein interpreted as the deposits of a single Middle Bathonian sedimentary rhythm.* Substrates which were extensively colonised by Kallirhynchia became widely established in the outcrop area between Pury End and Twywell during deposition of this rhythm (Rhythm B; see Chapter 7). However, in the area further north, shifting substrates, which the brachiopod could not tolerate, were developed at the same time, thus accounting for the sporadic occurrence of K. sharpi in the lower part of the White Limestone in this area. This explains why the K. sharpi Beds

* K. sharpi also occurs in the underlying rhythm, which is included within the Rutland Formation, in the Cranford-Finedon area.

become largely unusable as a lithostratigraphic unit some distance north of the Kettering-Peterborough Line.

3.1.3.4 Nomenclature: 'Forest Marble' or 'Blisworth Clay'?

In recent literature there has been a tendency to call the mixed limestone and terrigenous mud lithologies developed between the White Limestone and Cornbrash, 'Forest Marble' in Oxfordshire and areas to the west, south and southeast, but 'Blisworth Clay' or 'Great Oolite Clay' in the east Midlands. Different authors (e.g. Woodward, 1894; Arkell, 1933a; Hains & Horton, 1969; Horton, Shephard-Thorn & Thurrell, 1974; T. Palmer, 1974, 1979) have placed the boundary between the regions in which these two names apply in different places, while in the area west of Banbury, Edmonds et al. (1965) were uncertain as to which name they should use. Bradshaw (1978) initially suggested that the county boundary between Oxfordshire and Northamptonshire/Buckinghamshire should be arbitrarily chosen to split the two areas, but has more recently suggested that the name Forest Marble should be used throughout the east Midlands (Bradshaw, in prep.). Certainly in the Blisworth district, and in those parts of Northamptonshire to the west and southwest, the limestones in the 'Blisworth Clay' differ little from oolite grainstones of the classic Oxfordshire Forest Marble, although terrigenous mudstones predominate over these grainstones in Northamptonshire. It is significant that Aveline & Trench (1860) recognised 'Forest Marble' at Grimscoate, while Thomsson (1891, 1902, 1924, 1927) used the name specifically for the limestone beds, at the same time recognising the 'Great Oolite Clay' as a separate lithostratigraphic unit, at many southwest Northamptonshire localities. There can be no justification for using 'Forest Marble' and 'Blisworth Clay' together, so it is here

proposed that all strata between the Cornbrash and White Limestone in that part of southwest Northamptonshire where oobiograinsstones and packstones are interbedded with terrigenous muds should be included within the Forest Marble Formation (see Fig. 3.4).

In the region east and northeast of the Blisworth district, the White Limestone and Cornbrash are separated only by terrigenous muds*. These muds are believed, on event-stratigraphic grounds, to be considerably older than most of the Forest Marble sediments developed to the southwest, and a different name for the formation in this area is probably warranted; this is discussed in section 3.2.4.

In the Stratton Audley-Buckingham-Milton Keynes district, the majority of limestones developed between the White Limestone and Cornbrash are not oobiograinsstones but are instead biomudstones and wackestones, variably pelletal and frequently porcellaneous. Although these represent a more marginal facies than do the limestones of 'typical' Oxfordshire Forest Marble, they can safely be included within the same formation. The margin of Forest Marble usage in this area probably occurs between Great Linford and Newport Pagnell.

3.1.3.5 Top of the White Limestone Formation

In southwest Northamptonshire, the top of the White Limestone can be defined by the same criteria as those which characterise the top of the formation in much of Oxfordshire (section 3.1.2.3); the lowermost bed

* Arkell's (1933a) reference to thick Forest Marble limestones in the Newton Blossomville area was the result of mis-identification of White Limestone; see Locality 65 for discussion.

of the Forest Marble in this area is typically a terrigenous mudstone (e.g. Croughton, Pury End). Furthermore, the top of the formation is easily defined as the top of the uppermost bed of limestone in that part of the outcrop which runs from Bedford, through Irchester and Raunds, northwards to the Thrapston district: here the formation is overlain only by terrigenous muds which extend upwards to the base of the Cornbrash; a layer of ironstone nodules, of diagenetic origin (Bradshaw, 1978), typically overlies the uppermost bed of limestone. However, the top of the formation is less easily defined in the Milton Keynes area and north of the Kettering-Peterborough Line. In the former district, the problem is similar to that encountered at Stratton Audley, where limestones in the Forest Marble are micritic and where clay beds occur in the upper part of the White Limestone Formation. At both Calverton and Great Linford, Horton, Shephard-Thorn & Thurrell (1974) placed the top of the 'Blisworth Limestone' at the top of the uppermost limestone bed, although this appears not to correspond with any event-stratigraphic junction.

Further east, at Newport Pagnell (Loc. 61), Horton et al. (op. cit.) placed the junction at the top of a 0.46m thick, 'shelly, marly limestone', although their section suggests that here there is no sharp lithostratigraphic separation between the 'Blisworth Limestone' and 'Blisworth Clay'. A comparable situation has been found north of the Kettering-Peterborough Line, where the upper part of the White Limestone is dominated by variably calcareous oyster beds which become increasingly argillaceous upwards and eventually grade up into shelly clays. Oyster (oo)biograined stones and packstones in the transition zone, which are lithologically similar to oyster-rich bioo- and oobiograined stones in the Forest Marble of Oxfordshire, were placed in the 'Great Oolite Limestone' by Judd (1875), but also in the 'Blisworth Clay' by Horton, Lake, Bisson

& Coppack (1974). 'Alwalton Marble' was formerly obtained from the transition zone where it crops out along Alwalton Lynch (Loc. 179). Considerable difficulty arises north of the Kettering-Peterborough Line as there is no recognisable event- stratigraphic junction in the crucial transition zone; the problem of defining a suitable lithostratigraphic boundary here is considered in section 3.2.2.7.

3.1.3.6 Cornbrash Formation

The stratigraphy of the Cornbrash in the east Midlands was reviewed by Douglas & Arkell (1932); further important data on this unit were given by J. Taylor (1963), Torrens (1968) and Horton, Lake, Bisson & Coppack (1974). As in Oxfordshire, the Cornbrash in the east Midlands is considered to be a formation, while the Lower and Upper Cornbrash are considered to be members. The Lower Cornbrash is absent at outcrop in a number of areas, particularly in Cambridgeshire and Lincolnshire; the Upper Cornbrash is locally absent, for instance in Buckinghamshire. Subdivision of the formation in the subcrop is often impossible, although a pebble bed frequently encountered at the base of the Upper Cornbrash can be used for this purpose.

3.2 Proposed revision of the lithostratigraphy

3.2.1 Introduction

The revised lithostratigraphy employed throughout the study area (Fig. 1.1) is outlined in subsections 3.2.2 to 3.2.4; the geographic extent of formations and members is detailed and new lithostratigraphic units are formally introduced.

3.2.2 White Limestone Formation

The name 'White Limestone Formation' has been used at outcrop throughout the study area, from Oxfordshire to South Humberside, although in the most northerly parts of the area the formation is as much a calcitic sandstone as a limestone (Bradshaw & Penney, 1982). The formation wedges out northwards between Worlaby and the River Humber, rather than at Appleby, as was suggested by V. Wilson (1948) and Torrens (1967). The names 'Great Oolite Limestone' and 'Blisworth Limestone' have not been used, for reasons outlined in section 3.1.3.1; nor has the 'Snitterby Limestone' of recent B.G.S. terminology.

The formation is widely encountered in the subcrop; the distribution of the formation is shown on Figure 3.3. At outcrop, other than in the northern part of the study area, a number of formal subdivisions of the formation have been recognised. A type section for the White Limestone Formation has not been designated.

3.2.2.1 Shipton Member

The name 'Shipton Member' was introduced by T. Palmer (1979) for the lowermost subdivision of the White Limestone within the confines of his study area in Oxfordshire and parts of adjacent counties; the name supercedes the earlier name, 'Croughton Member' (of Palmer, 1974). The name has been adopted by the Geological Survey (e.g. Sumbler, 1984) and has been used in areas west of Palmer's study area (e.g. Torrens, 1980b). In this thesis the use of Shipton Member has been extended to districts slightly to the northeast of Palmer's study area, but south and southwest of the area in which Kallirhynchia sharpi occurs; however, there are no extant sections through the member in this area. The type section of the member is Shipton Cement Works (SP478175) where it comprises

predominantly bioturbated, quartz-sandy pelbiopackstones and wackestones. The base of the member, contrary to Palmer's (1979) view that the whole member is exposed, is not at present visible in the quarry, although it was encountered in exploratory boreholes (B4). Complete sections through the member have been logged during the course of this study at Ardley (Loc. 30) and Wood Eaton (Loc. 24), where the member was 5.35m and 2.04m thick, respectively; the member is 6.33m thick at Shipton. The upper part of the Shipton Member is considered to pass laterally into the K. sharpi Beds of the east Midlands. The gastropod Aphanoptyxis excavata characterises the upper part of the member, and is not known from the overlying Ardley Member.

Palmer (1979) included terrigenous sediments developed at the junction of the Shipton Member and Ardley Member within the Shipton Member, whereas Sumblar (1984) included the same sediments within the Ardley Member, arguing that they pass "gradually upwards into the Roach Bed but rest disconformably on the A. excavata Bed". However, in so doing, Sumblar was confusing event stratigraphy with lithostratigraphy. Thus, while these fine-grained siliciclastic deposits, at many localities at least, are sedimentologically related to the sediments of the overlying Ardley Member (including the 'Roach Bed'), they can, on lithological grounds, be justifiably included within the underlying Shipton Member. Furthermore, at some localities, some of this terrigenous sediment is genetically related to the sediments of the underlying Shipton Member (e.g. the rootletted muds developed at this horizon at Croughton).

3.2.2.2 Kallirhynchia sharpi Beds

The Kallirhynchia sharpi Beds are herein considered as a formal lithostratigraphic unit, being the lowermost subdivision of the White Limestone Formation throughout a major part of the east Midlands. The southwestern and southern limits of the unit are defined by the distribution of the index species (Fig. 3.1); to the southeast the K. sharpi Beds are probably erosively overstepped by younger strata (e.g. in the Bedford area).

North of the Kettering-Peterborough Line, the distribution of K. sharpi becomes erratic and the unit is recognised with increasing uncertainty. However, it was still possible to identify the K. sharpi Beds at Ketton, Spires Wood and probably also in the Peterborough area, where the unit may be capped locally by a hardground (see Loc. 184). The White Limestone has not been formally subdivided in the area north of Stamford, and in that area the K. sharpi Beds are not recognised; however, K. sharpi still occurs in the basal 1-2m of the White Limestone in Lincolnshire, at least as far north as Spital and Caenby (Kent, 1970; Bradshaw, 1978).

No type section exists for the K. sharpi Beds, but the following sections are considered as representative of the unit:

a) Roade Railway Cutting (Loc. 106)

Here the K. sharpi Beds are 2.99m thick and consist of units of variably argillaceous and often bioturbated biowackestones and packstones interbedded with units of interlayered lime sand and terrigenous mud. The fauna within these lithologies is dominated by K. sharpi, P. hebridica and Modiolus; Globularia, Acrosalenia, Protocardia, Anisocardia, Eocallista and small Pholadomya also occur. A specimen tentatively identified as Aphanoptyxis excavata was collected from just

beneath the top of the K. sharpi Beds; if correctly identified, this specimen adds considerable weight to the correlation of the K. sharpi Beds with the Shipton Member.

b) Irchester North Pit (Loc. 123)

Most of the 2.33m of the K. sharpi Beds at this locality consists of units of variably argillaceous and quartz-sandy, frequently nodular pelbiowackestones and packstones interbedded with units of interlayered terrigenous mud and bioclastic and quartz sand; the fauna is again dominated by K. sharpi, P. hebridica and M. imbricatus, which, at some horizons, are concentrated in thin, moderately winnowed biograinstone/packstone layers. Laterally, however, the interbedded nodular wackestone/packstone and terrigenous mud sequence developed in the upper part of the unit passes into more resistant and massively-bedded biopackstones/wackestones which contain coral (particularly 'Isastraea'), Camptonectes laminatus and other elements of Biofacies 5 (see section 6.4.5). The section here is very similar to those encountered at other quarries in the vicinity. However, it does not display an in situ oyster-rhynchonellid bank such as that exposed at Wellingborough No.5 Pit (Loc. 124).

c) Nene Barge & Lighter Co.'s Quarry, Sibson (Loc. 177)

Over two metres of interbedded, well cemented biopackstones/grainstones and less-resistant argillaceous biowackestones/packstones exposed at Sibson have been assigned to the K. sharpi Beds, although the 'Nerinea Bed' at the top of the section may belong to the overlying lithostratigraphic unit. K. sharpi, along with Pholadomya, ?Falcimytilus, Praeexogyra, Modiolus and Chomatoseris, occur in the wackestones/packstones but the rhynchonellid is not found here in the packstones/grainstones; the fauna of the latter is dominated by

high-spired gastropods, Epithyris and large anomalodesmatans. Two different lithofacies are represented within the unit at Sibson; at the time of deposition, they may have been distributed 'mosaic-fashion'. The higher energy packstones/grainstones probably constituted a periodically shifting sandy substrate, too unstable for Kallirhynchia sharpi, which apparently preferred quieter environments. The interbedding of the two different lithologies seen at Sibson is typical of the K. sharpi Beds in the area north of the Kettering-Peterborough Line.

Lateral lithological and faunal changes within the K. sharpi Beds occur gradually; even the marked change in facies across the Kettering-Peterborough Line is not particularly sharp, for sections in the Cranford-Twywell district contain lithologies and faunas transitional between those of Irchester and Sibson.

The most restricted faunas encountered in the K. sharpi Beds are those of the Irchester-Wellingborough vicinity. Faunal diversity appears to increase both northwards and southwestwards along the outcrop. The increase in faunal diversity appears to correlate with an increase in the proportion of carbonate to siliciclastic sediment, and often with an increase in the occurrence of better-washed lithologies (packstone/grainstones and grainstone/packstones). These changes are believed to reflect increasing distance from the contemporary coastline. To the southwest, these lithological and faunal changes result in the gradual lateral passage into the upper part of the Shipton Member. A southwestward increase in the proportion of carbonate in this lithostratigraphic unit was noted by T. Palmer (1979). However, Palmer suggested that the increase in siliciclastic sediment within the member in the northeast of his study area was associated with an imminent lateral passage into the 'Upper Estuarine Series' (=Rutland Formation).

On event-stratigraphic evidence, this is considered to be largely incorrect.

3.2.2.3 Ardley Member

Ardley Fields Farm Quarry (SP537272) is the type section of the lithologically and faunally variable Ardley Member (T. Palmer, 1974, 1979). Within Palmer's original study area, the member is dominated by oolitic and intraclastic grainstones and packstones, and pel-packstone/wackestones (Lithofacies 2, 3 and 5; see Chapter 5). Lithofacies 1, which comprises cross bedded oograins, occurs in the Burford-Witney area (although here, most cross bedded lime sands were placed by Palmer in the overlying Bladon Member). Cross bedded and bioturbated grainstones, packstones and wackestones belonging to Lithofacies association B are developed at Wood Eaton and in the Cherwell Valley; finely-laminated pelletal limestones belonging to Lithofacies association C occur at the top of the member at Great Rollright, Temple Mills, Whiteways, Croughton and Stratton Audley (T. Palmer, 1979).

As already discussed, Sumbler (1984) used a redefined Ardley Member in Oxfordshire which has not been adopted in this thesis. However, a number of amendments have been made to Palmer's original lithostratigraphic unit. Firstly, cross bedded oograins in the Burford-Witney district, which Palmer included in the Bladon Member, have been transferred to the Ardley Member (section 3.1.2.2). Secondly, the area in which the Ardley Member is recognised has been extended to include southwest Northamptonshire, west of a line joining Wootton, Roade, Pury End and Croughton (Fig. 3.2). The base of the member was seen by Bradshaw at Brackley (Loc. 82) and is presently exposed in Roade Railway Cutting, where the basal 'Nerinea Bed' is a bioturbated oobio-packstone/grainstone, containing high-spined gastropods,

Chomatoseris, Clypeus, pholadomyoids and brachiopods, faunally and lithologically very similar to the lowermost Ardley Member at Croughton. Thompson's (1927) work suggests that this basal Ardley Member 'Nerinea Bed' is well developed in southwest Northamptonshire, where it directly overlies the Kallirhynchia sharpi Beds. Above this horizon, the member in this region is dominated by Lithofacies association B, although Lithofacies association C is prominent in the upper part of the member at Blisworth East, Hartwell and Pury End. The maximum extent of the area in which the Ardley Member can be recognised in Northamptonshire corresponds with the area in which it can be separated from the overlying Bladon Member. The gastropods Aphanoptyxis cf. langrunensis and A. ardleyensis are restricted to the Ardley Member in Oxfordshire. Gastropods provisionally identified as A. ?ardleyensis were found in the member (Lithofacies association C) at Pury End and Blisworth East.

3.2.2.4 Bladon Member

The type section of the Bladon Member, the Old White House Quarry, Bladon (SP448150; Arkell, 1933b; T. Palmer, 1974, 1979), is still extant but has not been personally examined. Here, the Bladon Member consists of c.2.1m of shelly micrite containing corals, biooograstone containing shallow-burrowing bivalves and nerineid gastropods, and argillaceous pelletal biomudstones containing A. bladonensis, Eomiodon and Bakevellia (T. Palmer, 1974). In the Cherwell Valley, the member includes all beds between the base of the 'Middle Epithyris Bed' and the top of the 'Upper Epithyris Bed' (T. Palmer, 1979); the member therefore includes the so-called 'Fimbriata-Waltoni Beds' or 'fimbriatus-waltoni clays' of this district.

T. Palmer (1979) believed that the cryptalgally laminated lime mudstones which occur within the Bladon Member in the northeast of his

study area (Palmer & Jenkyns, 1975) all occur at the top of the White Limestone; but, as discussed elsewhere, this is not always the case. Instead, the laminites are developed at two distinct horizons (at the tops of two shallowing upwards rhythms), although only at Stratton Audley do both laminite horizons appear to occur in a single exposure (Barker, 1976). In Oxfordshire, Aphanoptyxis bladonensis is confined to the Bladon Member.

The Bladon Member in the northeast of Palmer's (1979) study area is very variable. In addition to the cryptalgal laminites, coral beds which pass laterally into oo- and biograinstones (?Lithofacies association B; Biofacies 5), pelletal lime muds containing Bakevella, Eomiodon and Aphanoptyxis (Lithofacies 5; Biofacies 6) and terrigenous muds containing transported representatives of the same fauna (Lithofacies association E) are all developed to varying extents. To the southwest, at the limits of my study area, the upper part of the Bladon Member may pass laterally into what is herein called the ?Great Oolite, in which similar lithofacies and biofacies are developed.

T. Palmer (1974; in Palmer & Jenkyns, 1975; 1979) considered that northeast of his study area, the Bladon Member passed laterally into the 'Blisworth Clay'. This is not strictly the case. The Bladon Member has been recognised, on the basis of lithology and fossil content, in southwest Northamptonshire west of a line drawn from Wootton, through Roade and Pury End to Croughton. In much of this area, the base of the member can be placed at the bottom of an extensively developed coral bed, presently exposed at Blisworth and Roade (Loc. 104, 105, 106 and 108); significantly, the lowest unit of the member at many localities to the southwest (e.g. Ardley, Croughton) is also a coral bed. The fauna of the Bladon Member in Northamptonshire is dominated by elements of Biofacies 5 and 6 (see Chapter 6). Biomudstone/wackestone belonging to Lithofacies 5

and 6 occurs at the top of the member at Pury End, and may also have been developed at Silverstone.

3.2.2.5 ?Great Oolite

At Minster Lovell, a thin unit of white-weathering oolite packstone, containing abundant Epithyris and coral, is developed between the sharp base of the overlying Forest Marble and the sharp top of the underlying White Limestone. This bed is provisionally placed in an informal lithostratigraphic unit, the ?Great Oolite (see section 3.1.2.4), which is included in neither formation. This is largely developed outside my study area and is only briefly considered in this thesis. The ?Great Oolite probably correlates with the upper part of the Bladon Member developed to the northeast (cf. Sumbler, 1984).

The ?Great Oolite is sporadically developed in the area between Witney and Cirencester, beneath the erosive base of the Forest Marble. Beds assigned to this lithostratigraphic unit have previously been called the 'Signet Beds' (Worssam & Bisson, 1961) or 'Kemble Beds of Great Oolite facies' (L. Richardson, 1933). The name '?Great Oolite' is taken from Cave (1977).

3.2.2.6 Irchester Member

In Northamptonshire, Bedfordshire and Buckinghamshire north of Wootton and east of a line running from Wootton to Croughton, it has proved impractical to lithostratigraphically separate strata laterally equivalent to the Ardley Member from those equivalent to the Bladon Member. Therefore, in this area of outcrop, south of Oundle, a new lithostratigraphic subdivision of the White Limestone, the 'Irchester Member', has been recognised. This new unit comprises all of the White

Limestone developed above the K. sharpi Beds in the area so defined and all of the White Limestone at Bromham (Loc. 74) where a thin unit of rootletted interlayered sand and mud correlatable with the K. sharpi Beds must be included in the Rutland Formation on lithostratigraphic grounds.

The type section of the Irchester Member is designated as Irchester Old Lodge Pit, Northamptonshire (Loc. 122; SP914648). The complete member is displayed in the quarry, where it is 6.15m thick. Considerable lateral facies variation is shown, a feature characteristic of the Irchester Member throughout much of Northamptonshire, particularly south of Cranford. At Irchester, as elsewhere, the member is dominated by lithologies of Lithofacies association B and the fauna is predominantly that of Biofacies 4. At the type section, the uppermost bed of the member has yielded locally abundant nerineid gastropods tentatively identified as Aphanoptyxis bladonensis. This suggests that the upper part of the Irchester Member, at Irchester Old Lodge at least, is laterally equivalent to at least the lower part of the Bladon Member of Oxfordshire. However, it is thought that most of the Irchester Member is laterally equivalent to the Ardley Member. At many locations, the White Limestone may not include sediments deposited at the same time as those of the Bladon Member elsewhere.

North of the Cranford-Thrapston district, the Irchester Member becomes increasingly dominated by oyster-rich sediments and is considered to gradually pass into the laterally equivalent Longthorpe Member; the boundary between the areas of outcrop where these different members are recognised has been arbitrarily drawn as an east-west line immediately south of Oundle (Fig. 3.2).

In addition to the extensive development within the member of Lithofacies association B, the upper part of the member in the Milton

Keynes-Bedford area is characterised by the major occurrence of sediments typical of Lithofacies association C. Aphanoptyxis ?ardleyensis has been found in this facies association. The uppermost part of the Irchester Member is rootletted at Great Linford, Weston Underwood, Warrington, Bromham, Bozeat, Irchester, Irthlingborough, Stanwick, Islip and Thrapston.

3.2.2.7 Longthorpe Member

In the area between Oundle and Stamford, where it has been possible to subdivide the White Limestone into two, the upper, oyster-dominated subdivision which overlies the K. sharpi Beds has been termed the Longthorpe Member; Longthorpe Road Cutting, Peterborough (Loc. 182; TL15629859) is designated as the type section. The member, which there consists of over two metres of argillaceous biopackstone/wackestone, with biograinstone intercalations, and thin, shelly clays, containing a fauna dominated by Praeexogyra hebridica and P. hebridica subrugulosa associated with Modiolus, Pseudolimea, Placunopsis, serpulids and locally abundant trioniids, is also exposed at Spires Wood, Fotheringhay, Castor and Ketton. The member was formerly the source of Alwalton Marble, which came from the upper part of the unit. There is a gradual transition upwards from the Longthorpe Member into the overlying clay-dominated formation, and in the absence of an event stratigraphic junction, it is difficult to satisfactorily define the top of the Longthorpe Member. It is here proposed that this lithostratigraphic junction be taken at the top of the uppermost thick limestone bed (approximately greater than 0.20m), although this is, by necessity, a highly subjective definition.

North of Stamford, the White Limestone has not yet been formally split into lithostratigraphic subdivisions, and the Longthorpe Member is

no longer recognised. However, the upper part of the White Limestone is still dominated by increasingly argillaceous oyster beds in this northern region.

3.2.3 Forest Marble Formation

As stated in section 3.1.2.4, the Forest Marble Formation has been recognised in the east Midlands, in Buckinghamshire and Northamptonshire, southwest of a line joining Quinton and Great Linford. Across most of the study area the formation is dominated by interbedded grainstones/packstones and terrigenous mudstones (Lithofacies association A), but in the Bicester-Buckingham-Milton Keynes district the limestones are more lime mud-rich (lime packstones, wackestones and mudstones). At some locations (e.g. Croughton), the basal terrigenous mud of the Forest Marble Formation is more closely related depositionally to the sediments of the immediately underlying White Limestone than to the remainder of the Forest Marble.

In situ developments of the 'Bradfordian' fauna are restricted to the southern fringes of the study area (e.g. Carterton, Witney, Islip) while transported elements of the fauna occur at other southern localities (e.g. Shipton). Only low-diversity faunas occur in the Forest Marble in the east Midlands.

No formal type section exists for the Forest Marble Formation, which can be recognised at outcrop from Northamptonshire to the Dorset coast and in the subcrop from Oxford to Kent. The formation is lithologically very variable and there is probably a need for several exposures to be chosen as representative sections displaying this variation. The type area is the Wychwood Forest, which is now considerably smaller than it was in William Smith's day. In conceiving

the name, Smith may have been influenced by Robert Plot's (1705) description of the 'grey marble, dug in the Parish of Bletchington', used in the eighteenth century for chimney-pieces and pavements, tombstones and millstones; Smith is known to have been familiar with Plot's Natural History of Oxfordshire (Phillips, 1844). The Forest Marble is today excellently displayed in Blue Circle's vast quarry at Shipton-on-Cherwell (Loc. 16), which lies just outside Bletchington parish and no great distance from the eastern limits of the Wychwood Forest of 200 years ago. I therefore support T. Palmer (1974) and Holloway (1981) by suggesting that Shipton should be considered as a type section for the Forest Marble, or at least for the formation as it is typically developed in central England.

3.2.4 Thrapston Clay Formation

The name, 'Blisworth Clay' was introduced into the literature by Sharp (1870). The geographic epithet comes from 'Blisworth Stone Quarries' (Loc. 107) where White Limestone was apparently overlain by 0.61m of clay packed with P. hebridica subrugulosa in Sharp's day. Restudy of the available sections at this location and comparison with the succession at Roade and Pury End suggests that this clay could have been developed within the Bladon Member. Furthermore, in the Blisworth area, the sediments between the White Limestone and Cornbrash differ little from those of the classic Oxfordshire Forest Marble (although clay predominates over lime grainstones and packstones) and have herein been included in that formation. Only further east and northeast (e.g. Bromham, Irchester, Thrapston, etc.), where an entirely clay sequence is developed at this stratigraphic level, does a need exist for a different name. 'Great Oolite Clay', applied to this interval in the east Midlands

by Judd (1875) and many subsequent workers, has largely fallen out of favour since J. Taylor's (1963) work on the Kettering area. Use of this name is militated against by similar arguments to those applied in section 3.1.3.1 against the use of 'Great Oolite Limestone', and it is not re-adopted here. Instead, somewhat reluctantly, the name 'Thrapston Clay Formation' is introduced for the predominantly clay succession developed at this level, east of a line joining Great Linford and Quinton, and in the area to the north, including outcrops in Cambridgeshire, Leicestershire and Lincolnshire. The type section of this new formation is Thrapston L.M.S. Railway Station Quarry (Loc. 148; TL000776). This quarry exhibits one of the few complete sections of this interval in the east Midlands and, following site clearance by the Nature Conservancy Council in 1982, the cleanest section presently available for study. 3.5m of green, blue, turquoise and mauve terrigenous muds are exposed here between the rootletted top of the White Limestone and the erosive base of the Lower Cornbrash.

Although the Thrapston Clay Formation occupies the same stratigraphic position as the Forest Marble, it may not be age-equivalent to most of that formation. Instead, on event-stratigraphic grounds, it is thought to be approximately age-equivalent to the uppermost part of the White Limestone and, in places, to the lowermost part of the Forest Marble to the southwest. The junction between the White Limestone and Thrapston Clay Formations is thought to be diachronous, and probably gets older to the north and in the subcrop to the southeast and east. The Thrapston Clay thins eastward and southeastward from Northamptonshire towards the London-Brabant Massif (cf. J. Taylor, 1963) and is eventually overstepped by the Cornbrash.

The problem of separating the White Limestone from the Thrapston Clay is even more acute in the subcrop than at outcrop. In Lincolnshire, this has resulted in very variable thicknesses being quoted for both formations in boreholes east of the outcrop, although the combined thickness of the two formations exhibits a less random pattern of thickness variation. This was also noted in the Peterborough area by Horton, Lake, Bisson & Coppack (1974) and in the Oundle district by Taylor (op. cit.).

The Thrapston Clay is at present recognised northwards as far as Worlaby.* In the area beyond, where the White Limestone is not developed, the Thrapston Clay and Rutland Formation cannot be separated; in this area, Bradshaw (in prep.) has introduced the 'Drewton Formation', the type section of which is Drewton Railway Cutting (SP916327 to SP919328), to encompass all the terrigenous sediment developed between the Cave Oolite and the Cornbrash/Kellaways. At both Nettleton (Bradshaw & Penney, 1982) and Worlaby (G. Richardson, 1979), however, there is a possibility, based on event-stratigraphic evidence, that strata herein assigned to the Thrapston Clay may be age-equivalent to most of the Forest Marble of further south. A new formational name is perhaps required here for the quartz-sandy beds which G. Richardson (op. cit.) called the 'Upper Sandy Beds' and which Riding (1983) included in the 'Blisworth Clay' at Nettleton; more work must first be done on the succession in this area.

* G. Richardson's (1979) 'Blisworth Clay' in this well (B86) is largely Lower Cornbrash; see also Bradshaw & Penney, 1982.

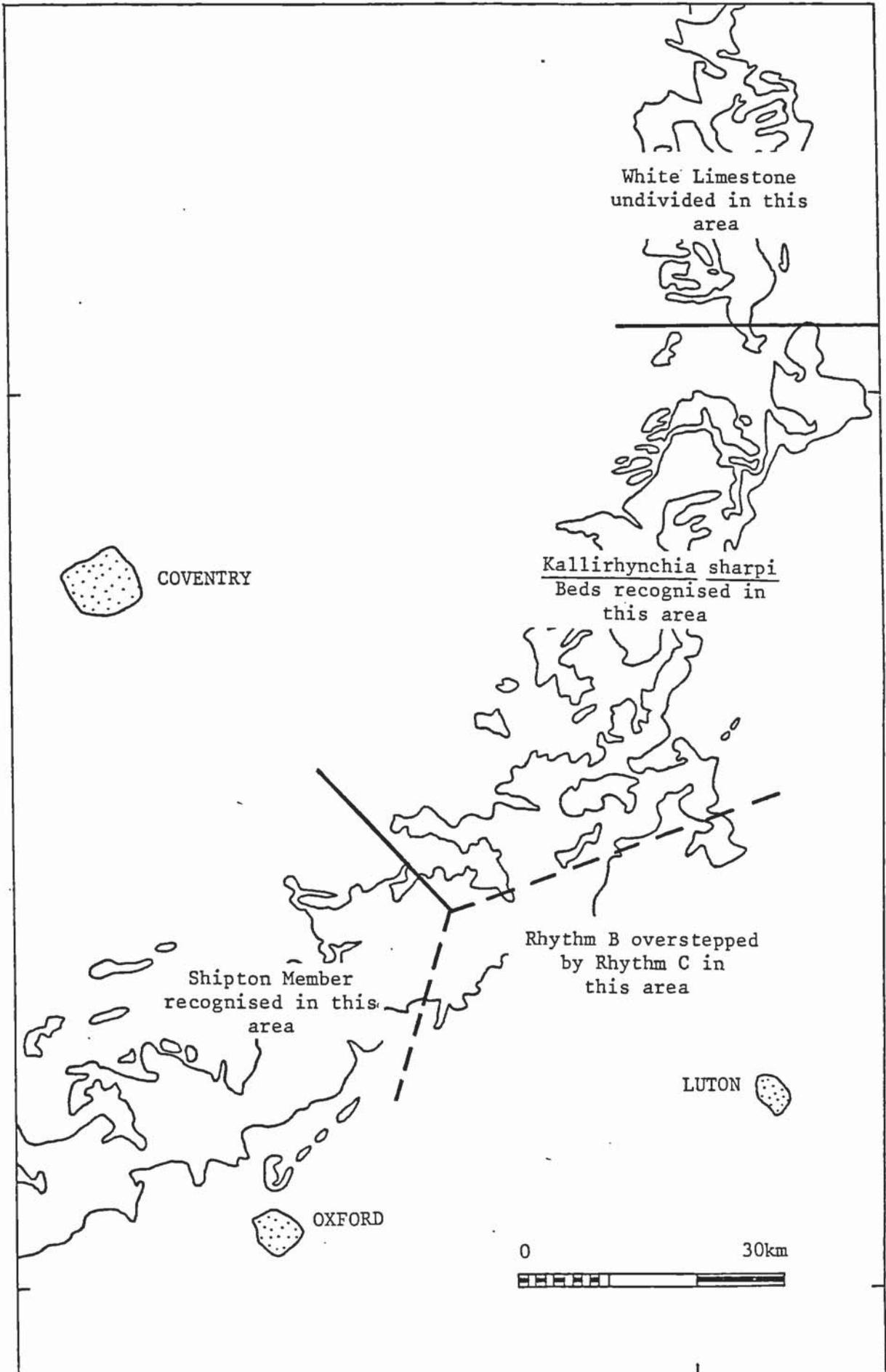


FIGURE 3.1 Area of usage: Kallirhynchia sharpi Beds and Shipton Member.

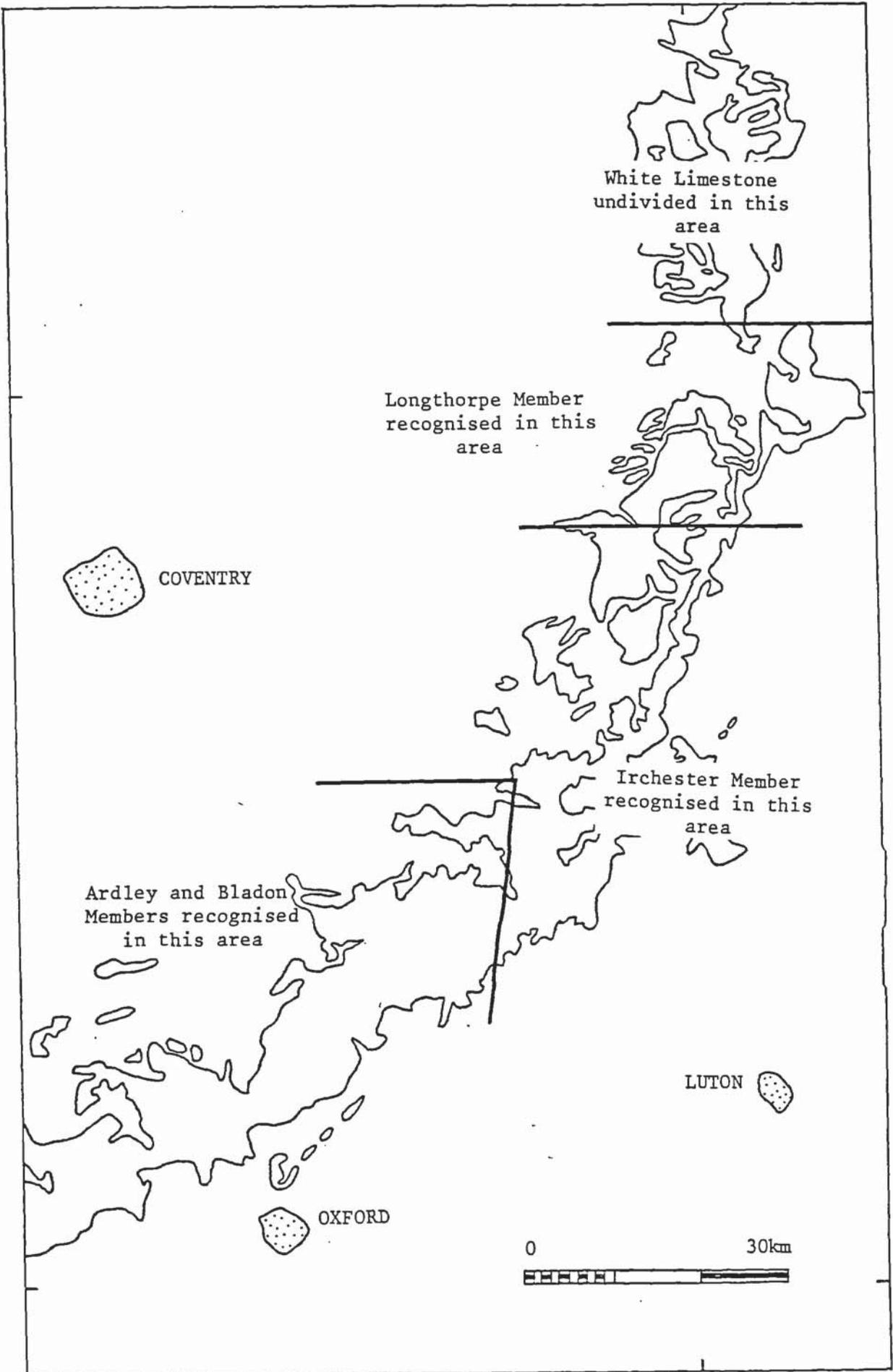


FIGURE 3.2 Area of usage: Ardley, Bladon, Irchester and Longthorpe Members.

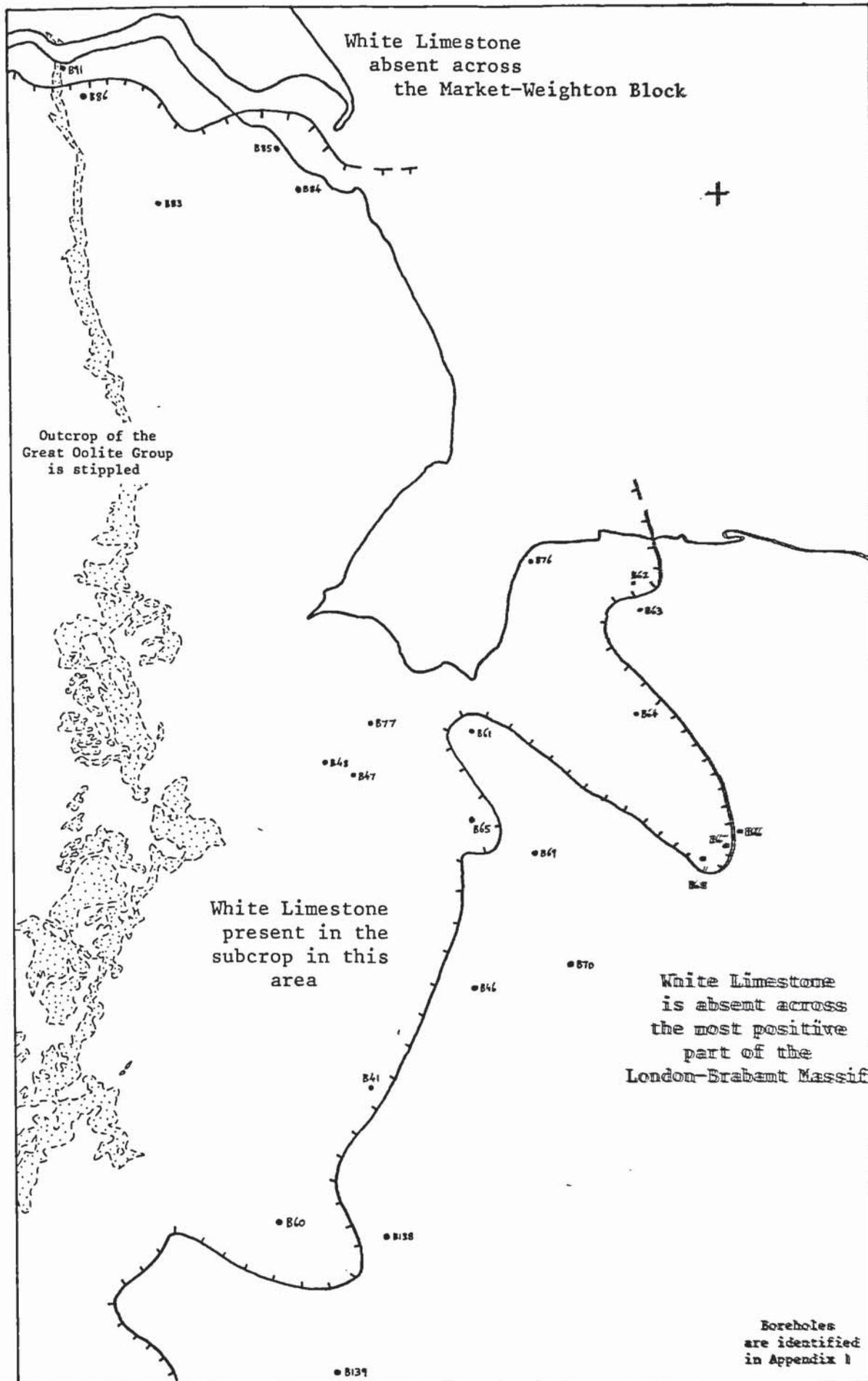


FIGURE 3.3 Maximum extent of the White Limestone Formation.

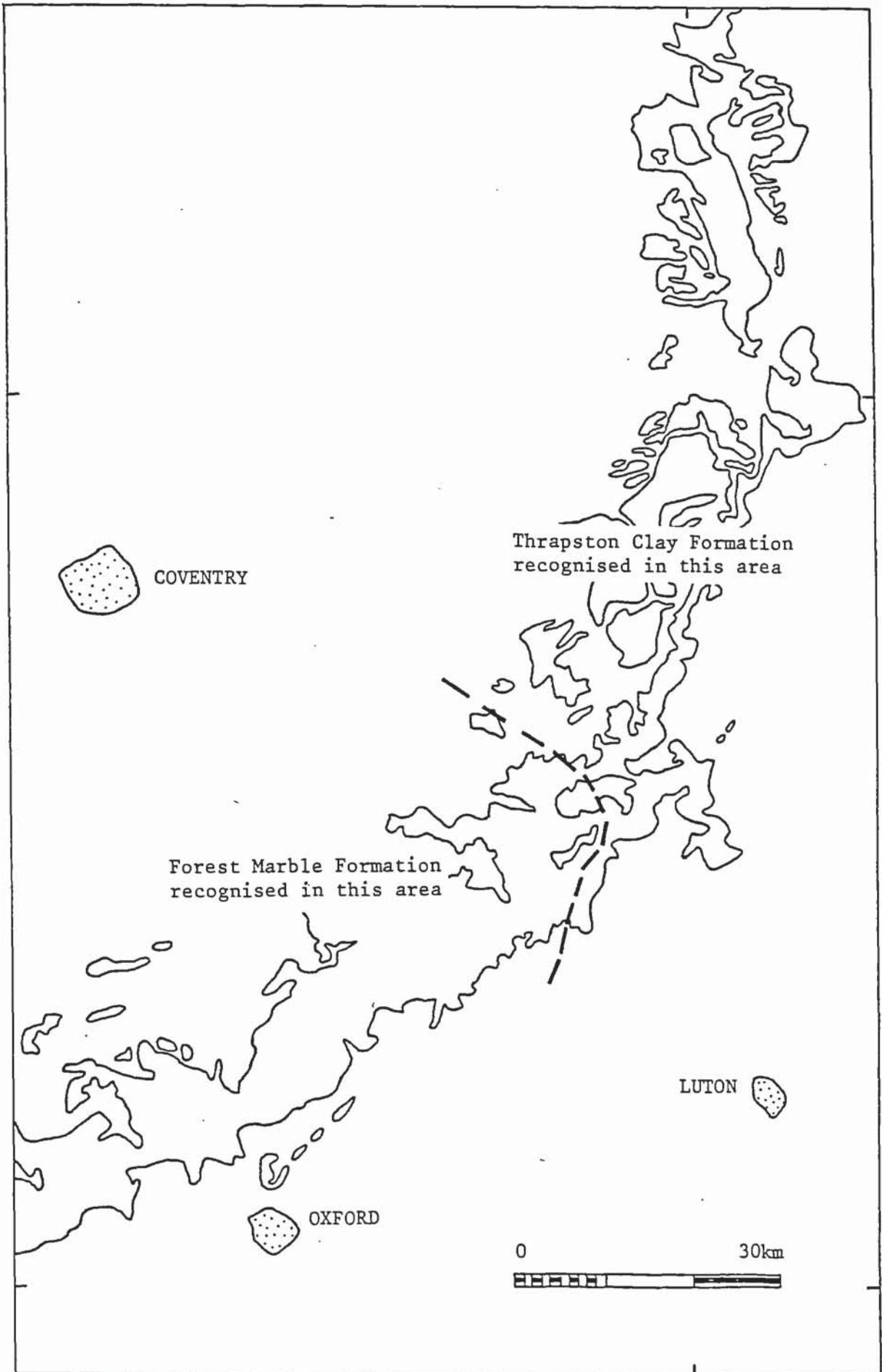


FIGURE 3.4 Area of usage: Forest Marble and Thrapston Clay Formations.

CHAPTER 4

BIOSTRATIGRAPHY

4.1 Introduction

The British Bathonian, which exhibits a diverse range of environments, including such paralic settings as restricted marine embayments, brackish and hypersaline lagoons, paludal, lacustrine and deltaic environments and coastal and alluvial plains, may be of supreme interest to the facies analyst but is a nightmare for the biostratigrapher. The marginal marine to freshwater depositional environments so widely distributed throughout northwest Europe in Bathonian times severely restricted the spread of the highly stenotopic ammonites, the traditional tool of the Jurassic biostratigrapher. The resultant paucity or absence of ammonites in so many Bathonian formations has hampered attempts to erect an ammonite zonal stratigraphy (as Arkell (1951-59, 1956) noted, the Bathonian is the last English Jurassic Stage to yield to ammonite biostratigraphy) and even now, different zonal schemes are used in France (e.g. Mangold et al., 1971; Enay, Mangold et al., 1980) and England (Torrens, 1980b). The English zonal scheme developed by Torrens (1965, 1966, 1974, 1980b), can be applied with increasing confidence, particularly in southern England, when ammonites are present at a given horizon and especially when that horizon's lithostratigraphic position is at least roughly known. However, correlations on the basis of ammonite biostratigraphy obviously cannot be made with any confidence when ammonites are not found. To counter the general lack of ammonites in the British Bathonian, a variety of benthonic organisms, notably gastropods and brachiopods, have been used

with varying degrees of success for biostratigraphic purposes. The impetus the oil industry, with its need for accurate dating of borehole core and chippings, has given to microfossil biostratigraphy is considerable.

Ostracod (Bate, 1978; Sheppard, 1978, 1981; Bate & Sheppard, 1982), foraminifer (Cifelli, 1959, 1960; Coleman, 1982) and dinoflagellate (Woollam & Riding, 1983) zonal schemes for the Bathonian/Jurassic have been presented over recent years, although all remain wholly or partially linked to the ammonite scheme. All of the major taxa used as biostratigraphic tools in the British Bathonian are discussed in this chapter, with particular reference made to their utility in eastern and central England.

4.2 Ammonites

The recent development of the English ammonite zonal scheme is outlined in Figure 4.1. The scheme used in this thesis essentially follows Torrens (1980b), except for the change from aspidoides Zone to orbis Zone. This follows Dietl (1982), who has shown that the lectotype of Oppelia (Oxycerites) aspidoides (Oppel) came from the 'Parkinsonien-Oolith' (parkinsoni/zigzag Zones) of the eastern Swabian Alb (West Germany) while Upper Bathonian Oxycerites formerly called O. (O.) aspidoides can be identified as O. (O.) orbis (Giebel). As these latter forms are retained as the zonal index, the zone's name has had to be corrected.

Although Hedberg (1976) has indicated that biostratigraphy and chronostratigraphy are not synonymous, many Mesozoic ammonite biostratigraphers have come to regard ammonite biozones as tantamount to chronozones (Torrens, 1980a). Certainly, if respective units of

ARKELL (1946)	ARKELL (1956)	ARKELL (1951-59)	TORRENS (1965)	TORRENS (1974)	TORRENS (1980b)	THIS THESIS
discus	discus	discus discus hollandi	discus discus hollandi	discus discus hollandi	discus discus hollandi	discus discus hollandi
	aspidoides	aspidoides	aspidoides	aspidoides	aspidoides	orbis
Not		unnamed zone	'retrocostatum'		hodsoni	hodsoni
	subcontractus	subcontractus	morrisoni	morrisoni	morrisoni	morrisoni
yet		subcontractus	subcontractus	subcontractus	subcontractus	subcontractus
	progracilis	progracilis	progracilis	progracilis	progracilis	progracilis
					tenuiplicatus	tenuiplicatus
				yeovilensis	yeovilensis	yeovilensis
determined	zigzag	zigzag	zigzag	zigzag	zigzag	zigzag
				macrescens	macrescens	macrescens
			convergens	convergens	convergens	convergens

FIGURE 4.1 Development of the English Bathonian ammonite zonation.

chronostratigraphical and biostratigraphical standard are defined at the same location, biozones can then be defined in common with chronozones at points in rock (Torrens, op. cit.). However, it can be argued that the chronozone is an ideal unit, the recognition of which outside the type-section is impossible; ammonite biozones, on the other hand, have been, and for some time yet will continue to be, the working tools of Jurassic correlation.

As stated above, the broad geographic spread of paralic facies in Bathonian northwest Europe inhibited the distribution of ammonites and this, in turn, has led to a paucity of ammonites in the Bathonian rock record. As a result, the English Bathonian ammonite zonal scheme (see Fig. 4.1) has been based on considerably less evidence than that available for the establishment of the zonal schemes of all other northwest European Jurassic Stages.

The possible facies control exerted on certain important ammonites and the consequent apparent limited geographical utility of these types for biostratigraphy has resulted in the validity of two English Middle Bathonian ammonite zones being questioned by some workers. A link between Tullitidae occurring in England, France and Saudi Arabia* and white, 'neritic' limestones was first noted by Arkell (1951-59) and discussed in detail by Torrens (1967). However, evidence from Germany (Hahn, 1971) now suggests that the Tullitidae were not totally restricted to a particular lithofacies. There is also evidence from both southern Germany (Hahn, op. cit.; Dietl, et al., 1979; Dietl & Kapitzke,

* Enay et al. (in prep.) have recently argued that 'tullitid' ammonites described from Saudi Arabia (Arkell et al., 1952) were probably a group of earlier homeomorphs.

1983) and the French Jura (Mangold, 1970) which confirms the faunal sequence Perisphinctidae-Tulitidae-Perisphinctidae worked out in the Middle and Upper Bathonian of southern England (Torrens, 1965, 1969b, 1974). Yet, although not absolutely tied to one lithofacies, the Tulitidae are certainly more common in fine-grained, micritic limestones, possibly as a result of specific predator-prey associations. In France, Torrens's morrиси Zone has not yet been accepted and even in England doubts have been raised over the possible occurrence of Tulites above Morrisiceras in the Fuller's Earth Rock of the Bath area. Such occurrences can apparently be explained away by a combination of landslip and condensed deposition (H. Torrens, pers. comm.).

The exact relationship between the tenuiplicatus and progracilis zonal faunas is still not fully known and only continued work on the relevant faunas throughout Europe will resolve the problem (Torrens, 1980b). As the only ammonite from the British Bathonian characteristic of the tenuiplicatus Zone is the holotype of Asphinctites recinctus S. Buckman, from an unknown stratigraphic horizon, this zone is essentially unusable in England.

While great success has been achieved by Torrens in erecting a Bathonian ammonite zonation, a number of criticisms can still be levelled at the present English scheme: for example, Choffatia, normally indicative of the Upper Bathonian, has been found in situ with Morrisiceras in the Milborne Beds at Shepton Montague (ST686317; Torrens, 1966). The Stonesfield Slate fauna (Arkell, 1951-59; Torrens, 1969a),

the type progracilis Zone fauna, includes genera* (Clydoniceras, Micromphalites) which would not normally be taken to indicate this zone; Clydoniceras, for instance, is restricted to the orbis and discus Zones elsewhere in England. Furthermore, the genus Procerites, used particularly to indicate the presence of either the progracilis or hodsoni Zones, is often difficult to identify to a specific level. Torrens (1980b) notes that contemporary morphological variation amongst the proceritids is often as great as the variation over time and this inevitably leads to suspicion when isolated specimens of Procerites or Choffatia are taken to prove a particular zone. Significantly, Torrens (op. cit.) states only that two specimens of Procerites hodsoni Arkell found in the Combe Down Oolite of Lansdown (Arkell, 1951-59) may have come from the top of the hodsoni Zone and compounds this inconsistency by showing, in column B6 of the correlation chart, the Combe Down Oolite (Great Oolite) as falling entirely within the aspidoides (=orbis) Zone. In defence of the zonal scheme, ammonite-based correlations applied in conjunction with the increasingly sophisticated lithostratigraphy of the Great Oolite Group can usually be made with considerable confidence and Torrens's (1980b) correlations are significantly better than those of earlier workers (e.g. Arkell & Donovan, 1952). Where ammonites are not present, however, Torrens's correlations are at best implied and in some instances are particularly tentative. This is especially the case in the

* The specimen of Tulites in the Oxford University Museum (OUMJB62), labelled as 'Stonesfield Slates, Stonesfield', is either a mislabelled Fuller's Earth Rock specimen (H. Torrens, pers. comm.) or a basal White Limestone specimen from Stonesfield.

east Midlands where very few Bathonian ammonites are known from below the Cornbrash; none have been obtained from the Forest Marble nor from the Rutland Formation. The small number of extant ammonites known from the White Limestone between Gloucestershire and Humberside are listed in Table 4.1; a few further records of White Limestone ammonites, now lost, are given in Table 4.2. All specimens taken by Torrens (1980b) to indicate the hodsoni Zone, where the exact stratigraphic horizon is known, came either from the Ardley Member or from the lower part of the Irchester Member. In Oxfordshire and Gloucestershire, ammonites indicative of both the subcontractus and morrиси Zones have been obtained only from the Shipton Member. No orbis Zone ammonites are known from the Bathonian of north Gloucestershire, Oxfordshire or the east Midlands, save for isolated specimens of 'Oppelia (Oxycerites) aspidoides', and Wagnericeras (suspensites) arbustigerum (d'Orb.) from Minchinhampton (Torrens, 1969a). Torrens's (1967, 1968) early correlations between Northamptonshire and Oxfordshire showed the base of the Great Oolite Limestone (herein White Limestone) in the east Midlands as being younger than the base of the White Limestone in Oxfordshire, since the oldest White Limestone ammonites known from Northamptonshire were hodsoni Zone forms. However, Torrens failed to take into consideration the total absence of ammonites from the Kallirhynchia sharpi Beds in the east Midlands. Bradshaw (1978) subsequently suggested that T. Palmer's (1974) 'Croughton Member' (herein Shipton Member) passes laterally into the K. sharpi Beds, and that both the 'Croughton Member' and K. sharpi Beds were of subcontractus/morrиси Zone age. This correlation, confirmed by my own work, was adopted by Torrens (1980b) although ammonite evidence for the correlation is still absent: no ammonites have, as yet, been conclusively shown to have come from the K. sharpi Beds. The only possible Middle

SPECIMEN	AMMONITE	ZONE	LOCATION	MEMBER
OUMJ30179	<i>Morrisiceras</i> sp.	morrиси	Locality 1	?Shipton
OUMJ29900	<i>Morrisiceras conima</i>	"	"	Shipton
GSM52177	<i>Morrisiceras morrиси</i>	"	Stony Fur long Cutting	?Shipton
Iles colln	<i>Procerites quercinus</i>	hodsoni	Dagham Downs Quarry	Ardley
GSM48482	<i>Tulites mustela</i>	subcontractus	Salperton	?Shipton
OUMJ29901	<i>Morrisiceras</i> cf. <i>morrиси</i>	morrиси	Locality 4	Shipton
OUMJ863	<i>Tulites glabretus</i>	subcontractus	Locality 5	Shipton
OUM	<i>Procerites</i> sp.	hodsoni	Locality 9	?Ardley
OUM	<i>Procerites</i> sp.	"	Locality 15	?Ardley
BMC79345	<i>Procerites</i> sp.	"	Enslow Bridge	?Ardley
GSM31364	<i>Tulites glabretus</i>	subcontractus	Locality 28	Shipton
OUMJ29896	<i>Procerites</i> sp.	hodsoni	Locality 81	Ardley
OUMJ29905	<i>Procerites</i> transitional to <i>Choffatia</i>	"	"	Ardley
OUMJ29166	<i>Procerites</i> sp.	"	Locality 107	?Ardley
BMC3393	<i>Procerites</i> cf. <i>quercinus</i>	?hodsoni	Locality 93	?Ardley
Thompson colln	indet. juvenile perisphinctid	hodsoni	Kingsthorpe	?Irchester
Jesson colln	<i>Choffatia</i> (<i>Subgrossouvria</i>) sp.	"	"	"
BMB2342	<i>Procerites</i> cf. <i>quercinus</i>	"	Kingsthorpe	?Irchester
BMC32424	<i>Choffatia</i> (<i>Subgrossouvria</i>) cf. <i>cerealis</i>	"	Locality 115	?Irchester
Pittham colln	<i>Procerites quercinus</i>	"	Locality 141	Irchester

TABLE 4.1 Extant ammonites from the White Limestone of Gloucestershire, Oxfordshire and the east Midlands.

AMMONITE (as recorded)	AMMONITE (possible identification)	LOCATION	REFERENCE
<i>Ammonites subcontractus</i>	Tulites	Enslow Bridge	Whiteaves, 1861
<i>Teloceras subcontractus</i>	Tulites	Ardley Cutting	Odling, 1913
ammonite	?Procerites	Ardley	Buckman, 1921
<i>Ammonites gracilis</i>	?Procerites	Stamford	Sharp, 1873
<i>Ammonites sp.</i>	?Procerites	Stamford	"
<i>Ammonites macrocephalus</i>	?Morrisiceras	Uffington	"
<i>Ammonites bullatus</i>	?Bullatimorphites	Alwalton	"

TABLE 4.2 Non-extant ammonites from the White Limestone of Oxfordshire and the east Midlands.

Bathonian ammonite which may have come from the east Midlands is the 'Ammonites macrocephalus' noted by Sharp (1873) as coming from the 'Great Oolite' of Uffington*. Torrens (1969a; in litt., 1982) believes that this was a Morrisiceras from the White Limestone but, alternatively, it could have been a Macrocephalites from the Upper Cornbrash (M. Bradshaw, pers. comm.). Torrens's opinion is perhaps supported by Sharp's (op. cit.) separate record of A. macrocephalus in the Cornbrash of Uffington; furthermore, the fauna of the K. sharpi Beds (of presumed subcontractus/morrisi Zone age) in this area shows an increased marine influence when compared with that of further south, and rare cephalopods might be expected to occur in the K. sharpi Beds about Stamford.

4.3 Gastropods

Sohl (1977) has stated that in 'nearshore sand', 'reefal' and 'lagoonal' Mesozoic facies in which ammonites are scarce, gastropods are often common and may be useful as tools of correlation; this appears to be the case within the White Limestone. Arkell (1931) first recognised that, in Oxfordshire, certain nerineid gastropods maintain fairly constant positions within the White Limestone and the overlying 'Fimbriata-Waltoni Beds' (which he had erected in the same paper; see Chapter 3). In particular, he noted that three gastropod beds, characterised in ascending order by 'Nerinaea eudesii', Aphanoptyxis ardleyensis and A. bladonensis, could be widely recognised. In the following years this early gastropod sequence was employed without

* The specimen is presently unlocated; it may be amongst Sharp's material at Birmingham University (Torrens, in litt.).

revision in other parts of Oxfordshire and east Gloucestershire (Whitehead & Arkell, 1946; Richardson et al., 1946; Worssam & Bisson, 1961). Although the N. eudesii horizon was subsequently abandoned by Arkell (1947), the Aphanoptyxis horizons were used to define the uppermost limits of two new lithostratigraphic subdivisions of the White Limestone (now including the 'Fimbriata-Waltoni Beds'); Arkell's Ardley Beds were capped by the 'A. ardleyensis bed', his Bladon Beds by the 'A. bladonensis bed'. In the same work, Arkell suggested that 'Ptygmatis (Bactroptyxis) bacillus (d'Orbigny)' (= B. implicata (d'Orbigny) in Barker, 1976) was almost as important as a subzonal index as A. ardleyensis, but Barker (1976) strongly refuted this on account of the species' occurrence at three separate horizons within the White Limestone and also at horizons within the Bajocian, and its sporadic distribution in parts of Oxfordshire.

Barker (op. cit.) advocated the occurrence within the White Limestone of four correlatable gastropod horizons: the 'A. excavata bed', the 'A. cf. langrunensis-Eunerinea arduennensis-Nerinella cf. pseudocylindrica horizon', the 'A. ardleyensis beds', and the 'A. bladonensis bed'. The lowermost horizon, characterised by the newly recognised species Aphanoptyxis excavata, was used to subdivide Arkell's (1947) Ardley Beds into the Excavata Beds and overlying, re-defined Ardley Beds; the Excavata Beds were defined upwards by the 'A. excavata bed'.

The main argument which can be used against the biostratigraphic utility of nerineid gastropods is one of facies control. While Bathonian nerineids, by analogy with present-day gastropods (most of which undergo a pelagic larval stage long enough in the right circumstances to allow even transoceanic dispersal; Sohl, 1977), could feasibly have been

dispersed as widely as ammonites, they could only settle and colonise a substrate where the environment was favourable. Judging by the persistent occurrence of large numbers of Aphanoptyxis (except where obviously transported) only in quiet-water environments dominated by pelleted lime mud, this genus was very conservative with regard to the facies in which it prospered. The result of this facies control is that bed to bed correlations of the sort made by Arkell (1931, 1947), Barker (1976) and Sumbler (1984) must be treated with great suspicion. However, Barker's (op. cit.) important work has suggested that A. excavata, A. cf. langrunensis and A. ardleyensis form an evolutionary lineage. In addition, McKerrow et al. (1969) suggested that A. bladonensis evolved from A. ardleyensis, although this was not confirmed by Barker. Significantly, there have been no proved occurrences of these species in a single section other than in the upwards order: A. excavata, A. cf. langrunensis, A. ardleyensis and A. bladonensis; records of two species occurring in the same bed at some sections (T. Palmer, 1974, 1979) were not confirmed by Barker (1976) when he studied the same sections.

If White Limestone Aphanoptyxis are truly part of an evolutionary succession, as the evidence suggests, they are of considerable biostratigraphic value, whatever the control exerted by facies. As will be discussed later, the occurrences of different species of Aphanoptyxis tie in closely with particular regressive sedimentary events that can be recognised in the White Limestone. The regressive nature of these events in turn appears to account for the development of the distinct gastropod horizons, these typically occurring in the upper part of the regressive sequences, where quiet water facies are best developed.

4.4 Ostracods

The first published attempt to erect an ostracod zonal scheme for the Bathonian, to rival the ammonite zonal scheme of Torrens (1980b), was Bate's (1978; revised in the same volume by Sheppard, 1978). This scheme, founded on the detailed study of three boreholes near Bath, has appeared subsequently in B.G.S. publications (Bate, in Penn et al., 1979; Bate & Sheppard, 1982) and has been used by other ostracod workers (e.g. Ware & Windle, 1981); recently Sheppard (1981) has given names to these zones (see Fig. 4.2).

Bate's (1978) scheme came in for strong criticism from Torrens (1980a), although Bate had admitted that the scheme was only 'provisional'. Certainly Torrens's criticisms that ostracods are benthonic, facies-bound to some degree and associated with particular sediments, either directly or because the distribution of the plants on which they lived was controlled by substrate-type, are valid; however, Torrens's condemnation of Bate for stating that Glyptocythere penni Bate & Mayes appears totally restricted to Zone 8 (falcata Zone) except for rare occurrences at the top of Zone 5 (blakeana Zone) is ironic when one considers Torrens's (1980b, p.40) own statements on the distribution and significance of Choffatia (Subgrossouvria) sp..

It is undeniable that the lithostratigraphic correlations presented by Bate (1978) between eastern England and the Oxford area are not compatible with those of either Torrens (1980b) or Bradshaw (1978). Since the ostracod-based correlations conflict to such an extent with correlations made elsewhere using reasonably good ammonite data (e.g. between Oxfordshire and the Bath area), and also with correlations made using palynostratigraphic data, it seems likely that because of the occurrence of highly heterogenous environments in Oxfordshire and the

Ammonite zonation in Bate (1978)	Bate (1978)	Sheppard (1978)	Penn et al. (1979)	Bate & Sheppard (1982)	Sheppard (1981)	Ammonite zonation in Sheppard (1981)
<i>discus</i>	ZONE 8	ZONE 6	/	ZONE 6	<i>falcata</i> Zone	<i>discus</i>
	ZONE 7					
	ZONE 6					
<i>aspidoides</i>	ZONE 5	ZONE 5	ZONE 5	ZONE 5	<i>blakeana</i> Zone	<i>aspidoides</i>
<i>hodsoni</i>	ZONE 4	ZONE 4	ZONE 4	ZONE 4	<i>polonica</i> Zone	<i>hodsoni</i>
	ZONE 3	ZONE 3	ZONE 3	ZONE 3	<i>confossa</i> Zone	<i>morrisoni</i> & <i>subcontractus</i>
						<i>progracilis</i>
<i>morrisoni</i>	ZONE 2	ZONE 1	ZONE 2	ZONE 1	<i>rimosa</i> Zone	<i>zigzag</i>
<i>subcontractus</i>						
<i>progracilis</i>						
<i>tenuiplicatus</i>	ZONE 1		ZONE 1			
<i>zigzag</i>						
<i>parkinsoni</i>						<i>parkinsoni</i>

FIGURE 4.2 Development of the English Bathonian ostracod zonation.

east Midlands region in the Middle Jurassic, the over-riding facies control has militated against any effective use later being made of ostracods for time-correlative purposes.

4.5 Brachiopods

Brachiopods are a common to abundant, often very obvious, constituent of many English Bathonian biofacies, and thus it is not surprising that attempts have been made in the past to use these sedentary benthonic organisms for biostratigraphic purposes. These attempts have met with varying degrees of success.

Within the Cornbrash, brachiopods were used to erect four biozones by Douglas & Arkell (1932), these brachiopod zones being stratigraphically equivalent to less than two ammonite subzones. However, at some localities, the index species characterising the two Lower Cornbrash zones occur in inverted positions. This suggests that the distribution of these species is controlled by facies (Torrens, 1980b) and abnormal faunal sequences reflect reversals in the usual sequence of Lower Cornbrash depositional environments. The underlying facies control therefore means that these brachiopod zones are invalid as formal biostratigraphic units.

Although the distribution of brachiopods is closely related to the distribution of particular lithofacies/biofacies, as with high-spired gastropods, if a particular facies was extensively developed at a particular period of time, then brachiopods may be useful for intra-regional correlations.

In the Oxfordshire White Limestone, Arkell (1931) recognised three brachiopod beds (the Lower, Middle and Upper Epithyris Beds) which

he used to make local correlations. Many of Arkell's correlations have subsequently been found to be inaccurate: thus his 'Middle Epithyrus Bed' at Eton College Quarry is within the Ardley Member whereas at most other localities the 'Middle Epithyrus Bed' falls within the Bladon Member. Within the Cherwell Valley some of the Epithyrus beds may be essentially isochronous, since their vertical distribution was controlled by the small scale transgressive-regressive events which characterise the top of the White Limestone in this area; however, one cannot use Epithyrus alone to make stratigraphic correlations.

In Northamptonshire, two other important brachiopods, besides the terebratulid 'Avonothyris cranfordensis' (probably the same species as the Oxfordshire Epithyrus, and herein referred to only as Epithyrus sp.), occur in large numbers. The zeillerid Digonella digonoides, although sporadic in its distribution, is only found in the central division of the White Limestone. The small rhynchonellid Kallirhynchia sharpi characterises the lower part of the White Limestone over a large area, from Pury End, near Paulerspury, as far as the Cranford-Twywell district. It still occurs, often commonly, further north, but its distribution becomes complicated beyond the 'Kettering-Peterborough Line' (Bradshaw, 1978).

Brachiopods were used to subdivide the White Limestone of Northamptonshire by Thompson (1927), Torrens (1967) and Pittham (1970). Thompson and Torrens both used Digonella digonoides and Kallirhynchia sharpi for correlative purposes while Pittham, in addition to these two species, also used Epithyrus sp. to recognise a third, upper horizon within the formation, 'characterised by yielding only terebratulid brachiopods, frequently very large specimens' (Pittham, 1970). In reality, just as with many of Arkell's Epithyrus beds, the presence of

these large terebratulids is linked to the occurrence of coral beds (e.g. at Blisworth Rectory Farm). In fact, terebratulids occur at all levels within the White Limestone of Northamptonshire and, on their own, are of little use in correlation.

Kallirhynchia sharpi and Digonella digonoides, on the other hand, are never found together, and the latter, where present, always occur in beds above those containing the rhynchonellid. Bradshaw (1978) and Torrens (1980b) have both suggested correlations of the K. sharpi Beds with the Shipton Member and it seems probable that K. sharpi thrived in environmental conditions prevalent over a large part of the east Midlands while the sediments of at least the upper part of the Shipton Member were being deposited in Oxfordshire. Undoubtedly, K. sharpi is important for local correlations; the species may be a valid sub-zonal index within the relatively limited area in which it occurs, but this is difficult to prove. Alternatively, the distribution of this species may have been controlled by facies alone.

Digonella digonoides, when present in the east Midlands, can be taken as indicative of the central part of the White Limestone. It is highly facies-bound in its distribution, but it appears to occur in beds which correlate with the Ardley Member, as defined by T. Palmer (1979). Indeed, T. Palmer (1973, 1974, 1979) recorded this brachiopod locally within the Ardley Member in Oxfordshire, in sections where facies similar to those commonly encountered in the central part of the Northamptonshire White Limestone are developed. Although of local utility for correlation, D. digonoides cannot be used for formal biostratigraphic correlation, since outside the study area, the species apparently occurs in the Forest Marble (e.g. Cave, 1977).

The 'Bradfordian' facies fauna, in which brachiopods are the most distinctive elements, has long been used for biostratigraphic and lithostratigraphic correlations; Eudesia cardium, Dictyothyris coarctata, Digonella digona and Goniorhynchia boueti (southern England and France only) are the most diagnostic species. Woodward (1894) used 'Bradfordian' faunas as the most reliable indicator of the base of the Forest Marble, and the acceptance that in England 'Bradfordian' faunas occur at only one horizon was followed by many subsequent workers (e.g. Arkell, 1931, 1933a, 1947; L. Richardson, 1933; McKerrow, 1955; Martin, 1958), although not by all (e.g. Engelheart, c.1925). It has now been shown that 'Bradfordian' faunas are not restricted to a single horizon (Green & Donovan, 1969; T. Palmer, 1974; Cave, 1977), although following Penn & Wyatt's (1979) inclusion of the Upper Rags within the Forest Marble, 'Bradfordian' faunas are restricted to the Forest Marble.

'Bradfordian' faunas are dominated by highly stenotopic species, and occurrences of the fauna suggest the development of normal marine, possibly offshore shelf, conditions. The association of a number of the few ammonites found in the Forest Marble with 'Bradfordian' faunas, and the frequent development of these faunas at specific horizons (in many cases directly above hardgrounds) suggest that many occurrences of 'Bradfordian' faunas may be directly related to relative rises in sea level; if so, and if these rises were eustatically induced, occurrences of 'Bradfordian' faunas may still be of considerable correlative importance.

In the Bath area, 'Bradfordian' faunas occur throughout the Upper Rags, and also throughout laterally equivalent strata to the north and south (Green & Donovan, 1969; Cave, 1977; Penn & Wyatt, 1979). However,

the faunas are particularly well-developed at two horizons: at the base of the Upper Rags (=base of the Forest Marble) and at the top of the Upper Rags (=former base of the Forest Marble). Penn (1982) has correlated these two horizons southwards, the lower one with the basal Forest Marble boueti Bed of Somerset and Dorset and the upper horizon with the sporadically developed digona Bed of Dorset.* The possibility exists that horizons with in situ 'Bradfordian' faunas in Oxfordshire and Gloucestershire could be similarly correlatable with one of the two principal 'Bradfordian' horizons in the Bath area; even if not, it is probable that Oxfordshire 'Bradfordian' faunas are no older than the basal Forest Marble 'Bradfordian' fauna of southern England, and perhaps no younger than the 'Bradford Clay' developed above the Upper Rags in the Bath district.

In southern England, 'Bradfordian' faunas occur only in the lower part of the Forest Marble, due to the regressive nature of the upper part of the formation. In Oxfordshire, 'Bradfordian' faunas are developed not far beneath the base of the Cornbrash; this probably results from pre-Cornbrash erosion of the upper most regressive deposits of the Forest Marble in the Oxfordshire area.

This review suggests that, as with Aphanoptyxis, certain species of brachiopod fulfill a useful role in correlation of upper Great Oolite Group strata, at least within the confines of the study area, even though

* This second correlation was first presented by Sylvester-Bradley (1957), who correlated the 'Bradford Clay' at Bradford-on-Avon with the digona Bed of the Weymouth Anticline.

the distribution of any given species was controlled by facies. This is because the occurrence of some species is closely related to particular transgressive-regressive sedimentary rhythms, which are believed to be broadly isochronous in character. Problems may arise over the use of brachiopods for correlative purposes because the taxonomy of Bathonian brachiopods has not been fully worked out. This point is discussed further in Chapter 6.

4.6 Dinoflagellates

Palynostratigraphy in the Jurassic (which primarily utilises dinocysts for time-correlative purposes), as far as is suggested by published work, is still in its infancy and closely tied to the Standard Ammonite Zones. Considerable palynostratigraphic work has been done on the northwest European Jurassic in recent years in relation to hydrocarbon exploration in the North Sea and elsewhere, but much of this work remains confidential. In the recently published B.G.S. dinocyst zonation of the English Jurassic (Woollam & Riding, 1983), the Bathonian is contained entirely within a single zone, within which only two subzones are recognised (Fig. 4.3). Clearly this zonation can add little to the detailed correlation of most Bathonian strata at outcrop. Dinocysts have, however, proved to be useful in distinguishing certain Bathonian paralic deposits from earlier deposits of a similar facies: notably for showing that the Oxfordshire 'White Sands' of Horton (1977) are late Bajocian/Bathonian rather than Aalenian (Fenton, 1980), thereby confirming Bradshaw's (1978) view that these deposits belong to the Swerford Member (Chipping Norton Formation). Similarly, palynostratigraphy has recently been used to show that the so-called 'Raasay Cornbrash' in the Hebrides is of Bajocian age (Bradshaw & Fenton,

Stage	Ammonite zone	Dinocyst zone (Woollam & Riding, 1983)
CALLOVIAN	macrocephalus	-----
		Subzone b
BATHONIAN	discus	
	orbis	
	hodsoni	
	morrisoni	Ctenidodinium combazii -
	subcontractus	Ctenidodinium sellwoodii
	progracilis	
	tenuiplicatus	
	zigzag	

BAJOCIAN	parkinsoni	

Figure 4.3 Comparison of the Bathonian ammonite and dinocyst zonation

1982), a fact which has subsequently been confirmed by the discovery of a specimen of Garantiana sp. (T. White, 1984).

4.7 Foraminifers

Foraminifer biostratigraphical work has been undertaken on the Bathonian outcrop and adjacent subcrop of southern England (Cifelli, 1959, 1960; Coleman, 1982) but the 'zones' recognised in the Fuller's Earth province of the Wessex Basin appear to be unworkable further north. Furthermore, foraminifer-based correlation of the wattonensis Beds of Dorset with the lower 'smithi' limestone of the Bath/Frome area (Penn, 1982) apparently conflicts with the ammonite evidence (H. Torrens, pers. comm.) which supports Torrens's (1980b) correlation of the wattonensis Beds with the Rugitela Beds of the Fuller's Earth Rock. The true value of Bathonian foraminifer biostratigraphy, even outside my study area, is therefore difficult to assess.

4.8 Time-correlative methods adopted in this thesis

Time-correlation of the upper Great Oolite Group of the study area has been achieved primarily using event-stratigraphic methods coupled with the ammonite, brachiopod and gastropod biostratigraphic data reviewed above. Stacked, laterally-extensive, shallowing-upwards sedimentary rhythms recognised through much of, or the whole of, the study area are here regarded as having been initiated by geologically-instantaneous relative rises in sea level (although within each rhythm, facies are diachronous); biostratigraphic data, where available, are mostly compatible with such an assumption. Further discussion of the nature of the rhythmic events and the resultant sediments can be found in Chapter 7; the origin of the relative sea level

rises which induced each rhythm, whether caused by subsidence or by eustatic sea level change, at least within the limited confines of the study area, is not considered to prejudice the use of rhythms for correlative purposes. Beyond the limits of the study area, rhythmic events are only likely to be of correlative value if they were of eustatic origin.

The stratigraphic distribution of certain brachiopods and aphanoptyxid gastropods within the rhythms recognised in the upper Great Oolite Group of Oxfordshire and Northamptonshire is illustrated in Figure 4.4.

ZONE		RHYTHM	Ammonite indicative of zone	Lithostrat.	
discus	discus	LOWER CORNBRASH	*	A. excavata	LOWER CORNBRASH
	hollandi	FOREST MARBLE		A. ardleyensis	FOREST MARBLE
orbis				A. bladonensis	
hodsoni	E			K. sharpi	
	D			D. digonoides	
	C		*	O. thrapstonensis	
morrisi	B		*	D. digona, E. cardium D. coarctata	
	A		*	C. intermedia, O. obovata	
subcontractus	A		*		
?	CRANFORD		*		
progracilis	WELLING-BOROUGH		*		
					TAYNTON LIME-STONE
					HAMPEN MARLY FMN
					WHITE LIMESTONE
					THRAP CLAY
					WHITE LIMESTONE
					RUTLAND FMN

THRAP CLAY = THRAPSTON CLAY

FM = FOREST MARBLE

FIGURE 4.4 Vertical distribution within the study area of selected faunal elements, related to ammonite zones and rhythmic units

CHAPTER 5

SEDIMENTOLOGY OF THE UPPER GREAT OOLITE GROUP

5.1 Introduction

The upper Great Oolite Group of central and eastern England comprises a mixed siliciclastic-carbonate sequence interpreted as having been deposited in a variety of shallow marine and coastal environments. For the most part, these environments were developed on, or in close proximity to, the western and northwestern flanks of the London-Brabant Massif, the core of which was emergent throughout the Middle and Upper Bathonian (see section 2.2).

Extensive study of most extant sections through the succession in the field area, coupled with a standard petrographical analysis of several hundreds of specimens (thin sections, acetate peels, polished slabs) has enabled the confident recognition not only of basic lithology types but also of recurring lithofacies and lithofacies associations.

Study of further Bathonian sections beyond the confines of the field area (notably in the Cotswolds, and southwards to the Dorset coast) has allowed the lithofacies recognised in central and eastern England to be fitted into a larger-scale depositional model.

5.2 The general setting of Middle and Late Bathonian sedimentation in southern and central England

Consideration of facies distributions within the Great Oolite Group as a whole suggests that the gross two-dimensional morphology of the Bathonian carbonate platform of southern and central England was, in part at least, that of Read's (1985) 'homoclinal ramp with a barrier

oid/pellet shoal complex'. The ramp may have flattened out in the east Midlands. However, the Bathonian 'platform' differs from Read's modern example of such a facies model (the Trucial Coast, Persian Gulf; see Purser & Evans, 1973) in a number of ways: i) the humid Bathonian climate and consequent high freshwater run-off from the hinterland did not encourage the formation of evaporites in intertidal and supratidal/sabkha environments; ii) intertidal flats are well developed in the Persian Gulf but lagoons/protected subtidal environments are not geographically extensive; the reverse is true of the English Bathonian; iii) the ooid shoals of the Cotswold-Weald Shelf occupied a broader area than do today's ooid tidal-deltas of the Trucial Coast; iv) finally, the Bathonian carbonate 'platform' as a whole covers a greater area than does the Trucial Coast carbonate regime.

The Bathonian carbonate environments of central and eastern England were themselves set within the European epeiric sea, which surrounded lands of predominantly modest or low relief.* The idealised distribution of carbonate facies in an epicontinental sea has been considered by Shaw (1964) and Irwin (1965), and the latter's ideas have been expanded particularly by J. Wilson (1975; see also Flugel, 1982, for a discussion). The facies transitions encountered in passing (in the Bathonian) from the Fuller's Earth/Frome Clay province of the Channel and Wessex Basins (offshore, open shelf) onto the Cotswold-Weald carbonate

* In the British area, the areas of highest relief were probably the Scottish Highlands and the flanks of the Central North Sea Rift, which may have reached 500m above sea level; the height of Brabantia may rarely have exceeded 150m throughout the Bathonian (Bradshaw & Cripps, in prep.).

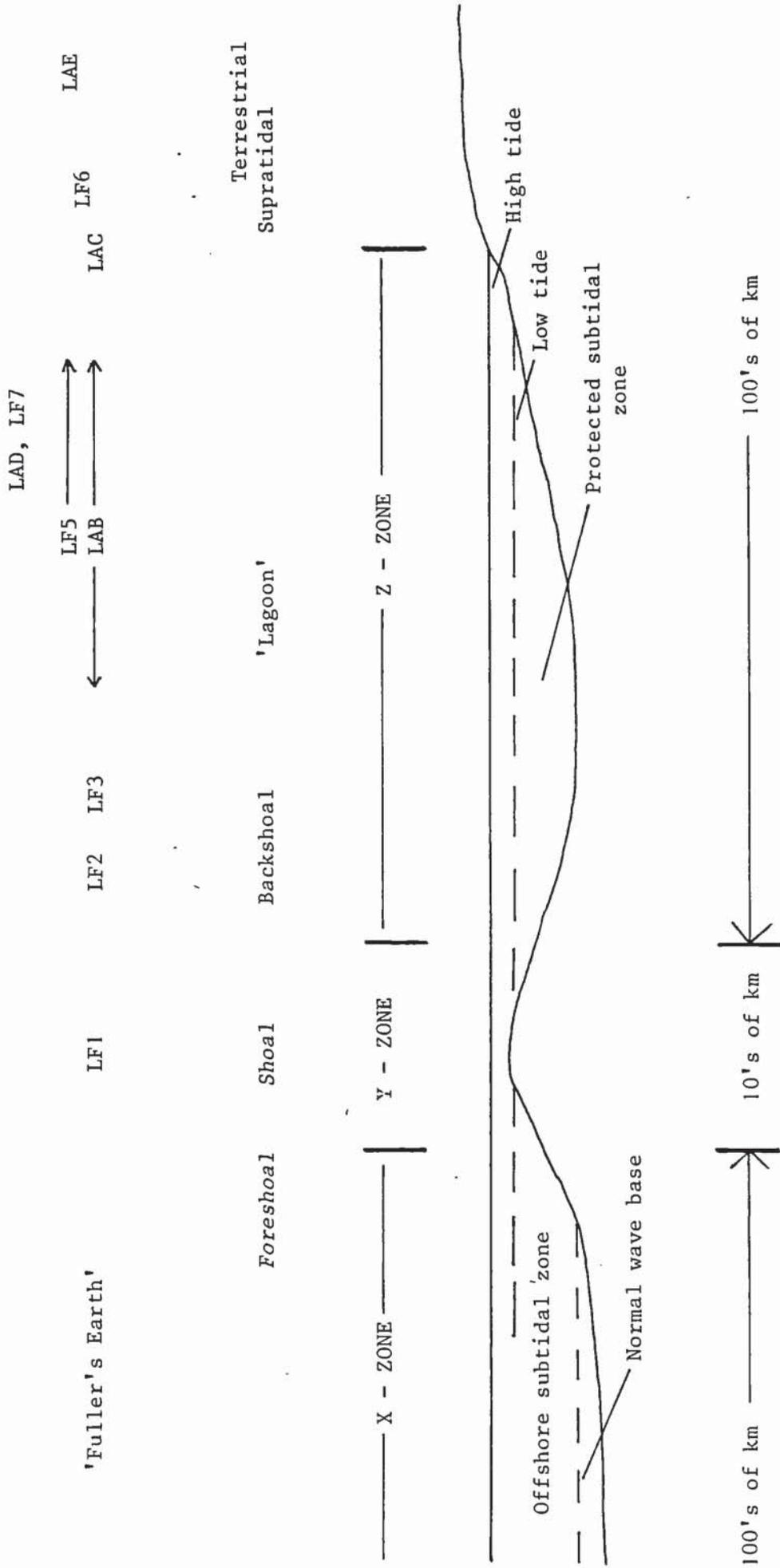


FIGURE 5.1 Bathonian deposition in southern and central England related to Irwin's (1965) model for carbonate sedimentation in an epeiric sea. (See subsection 5.3 for identification of lithofacies mnemonics)

'platform' and thence into the more protected environments of the east Midlands correspond closely with those predicted by Irwin's (1965) theoretical model (although Irwin did not consider siliciclastic input to the depositional system). The Fuller's Earth/Frome Clay province equates with Irwin's Zone X, an extensive zone up to hundreds of miles across where deposition occurred below normal wave-base. The predominantly oolitic limestones of the Cotswolds-Weald region in the Middle and Upper Bathonian correspond with Irwin's high energy Zone Y, although the Bathonian shoal complexes apparently comprise a belt considerably broader than the 'tens of miles' predicted for the zone by Irwin (although this may partially reflect lateral migration of the active oolite shoals). Lastly, Irwin's Zone Z, the lagoonal or protected subtidal to supratidal environment, is represented particularly by the upper Great Oolite Group of Oxfordshire and the east Midlands; for the most part, the limestones studied during the course of my research have been those which might typically be associated with Zone Z.

Shoaling-upwards sequences are characteristic of shelf carbonates (James, 1979; Tucker, 1985). However, the shallowing-upwards sequences of the study area differ from those discussed by James (op. cit.) in that they lack a distinctive intertidal unit (which James believed was fundamental to such sequences); instead, in slightly offshore settings, the shallowing-upwards units consist only of subtidal deposits (usually capped by a hardground or erosion surface), while in settings closer to contemporary land areas (e.g. Brabantia), sequences typically exhibit a rapid change from subtidal into supratidal and terrestrial environments (when preserved). The lack of obvious intertidal deposits was noted within the White Limestone of Oxfordshire (T. Palmer, 1974, 1979) and within the siliciclastic-dominated Rutland Formation of the east Midlands

by Bradshaw (1978). The negligible influence diurnal tides exerted on sedimentation in environments of Zone Z type, such as those in the English Bathonian, was predicted by Irwin (1965). In the broad expanses of the European epeiric sea, tidal and wave energy was probably greatly reduced by friction with the sea-floor (cf. Keulegan & Krumbein, 1950). Furthermore, any tidal currents generated in the Channel Basin/Wessex Basin open shelf setting (=Zone X) were largely dissipated across the ooid-dominated shoal complexes of the 'Cotswold-Weald Shelf' (=Zone Y); they thus had little effect on deposition in the protected subtidal environments of Oxfordshire and the east Midlands (=Zone Z). On the other hand, wind-driven tides may have been important in very shallow water depositional environments. Besides being responsible for sediment transport, meteorological tides could also have rendered large areas of the very shallow subtidal environment temporarily emergent or could have periodically submerged supratidal areas.

The geological effects of storms and hurricanes in modern and ancient shallow marine carbonate environments have been extensively discussed in recent literature (e.g. Ball *et al.*, 1967; Perkins & Enos, 1968; Hardie & Ginsburg, 1977; Einsele & Seilacher, 1982; Aigner, 1985). They are herein believed to have exerted an important control on deposition in many of the Bathonian lithofacies of the study area. In the very shallow environments of the east Midlands, onshore wind drift currents may have been the dominant influence on sedimentation during storms; in addition, coastal set-up in response to cyclonic depressions may have had an important effect on deposition in nearshore settings (Aigner, 1985).

5.3 Lithofacies and lithofacies associations

Nine lithofacies types and five lithofacies associations have been recognised in the upper Great Oolite Group of the study area, although not all lithologies encountered can be satisfactorily pigeon-holed. The vertical distribution within the group of these lithofacies and lithofacies associations, which are described in sections 5.3.1 to 5.3.14, is shown in Enclosures A-1 to A-16, using the following codes:

Lithofacies 1: Cross bedded, offshore lime sands	LF1
Lithofacies 2: Winnowed, shifting lime sands	LF2
Lithofacies 3: Muddy, stable lime sands	LF3
Lithofacies association A: Cross bedded lime sands and terrigenous muds	LAA
Lithofacies association B: Cross bedded lime sands; interlayered lime sands and lime muds; bioclastic/oolitic lime muds	LAB
Lithofacies 4: Pelletal lime sands	LF4
Lithofacies 5: Bioturbated, pelletal lime muds	LF5
Lithofacies association C: Pelletal lime sands/lime muds and oolitic/bioclastic lime sands	LAC
Lithofacies 6: Lime muds	LF6
Lithofacies 7: Oyster reefs	LF7
Lithofacies 8: Hardgrounds and pebble beds	LF8
Lithofacies 9: Interlayered sands and terrigenous muds	LF9
Lithofacies association D: Interbedded argillaceous, bioclastic lime muds and interlayered sands and terrigenous muds	LAD

Lithofacies association E: Homogeneous terrigenous muds
and 'swirl-based', fossiliferous
terrigenous muds

LAE

5.3.1 Lithofacies 1: Cross bedded, offshore lime sands

Thick units of oolitic, intraclastic and bioclastic lime-sand, typically exhibiting large-scale cross stratification (frequently trough cross bedding), are developed within the White Limestone of central-west Oxfordshire (around Burford) and further west in Gloucestershire. However, although representing an important and widespread lithofacies, these limestones occur only at the very limits of my study area and have not yet been examined in great detail. T. Palmer (1974, 1979) included these cross bedded limestones within the Bladon Member, but they are herein included in the Ardley Member (see Chapter 3). The Athelstan Oolite (Cave, 1977), essentially the lateral equivalent of the upper part of the White Limestone south and south-west of Cirencester, largely consists of these cross bedded 'oolites', as is the case at Veizey's Quarry, Tetbury (ST88119435; pers. obs.). In both formations, well-developed ooids are common in this lithofacies, although these may be subordinate to intraclasts and rounded bioclasts at some horizons. The lime sands of the Minchinhampton area, west of Cirencester, developed at both this and a slightly lower stratigraphic level (Torrens, 1980b), differ in that they contain abundant eroded lumps and, more significantly, an abundant molluscan fauna, renowned through the work of Lycett (1848, 1857, 1863) and Morris & Lycett (1850-53), which includes elements that may have been locally derived from a rocky shoreline (Barker, 1976).

Unlike the cross bedded lime sands of the Irchester Member, most of the cross bedded 'oolites' of west Oxfordshire and Gloucestershire are not intimately associated with large amounts of lime-mud; instead they were well-washed at the time of deposition and are now invariably well-cemented by ferroan calcite. It is believed that these sands represent mobile oolite sand shoals developed along the Cotswolds-Weald Shelf (those of Minchinhampton may have been associated with a local 'swell' within the Severn Basin). Texturally-graded, fining-upwards intrasets locally developed within these 'oolites' may be storm settle-outs (Klein, 1965); migration of the shoals was probably periodic, at a maximum during storms. However the restricted nature of the autochthonous fauna (see Chapter 6) and the general absence of bioturbation suggests that these oolites constituted a permanently shifting substrate. It is not known whether individual oolite shoals coalesced into a tidal-bar belt or a marine sand belt (see Ball, 1967; Halley et al., 1983) but palaeogeographic considerations suggest that individual shoals may have belonged to an extensive marine sand belt, albeit one considerably wider than modern examples (the active parts of which are typically only a few kilometres across). Some of the cross bedded lime sands of Lithofacies 1 may represent spill-over lobes or submarine tidal deltas associated with such a sand belt. T. Palmer (1974) noted that cross bedding within this facies consistently dips towards the SSE octant and my own observations at Sturt Farm (Loc. 4) are in general agreement. Bimodal, diametrically opposite dip azimuths, often taken to indicate tidal currents, were not recorded by Palmer but, in approximately contemporaneous lime sands within the Great Oolite Group of Humbly Grove (Sellwood et al., 1985), cross bedding dips were found to

be bi- and multi-modal; at least local tidal influence on the Cotswolds-Weald Shelf is therefore suggested.

In terms of Irwin's (1965) epeiric sea model, these oolitic sands equate with the well-winnowed, chemically-formed lime-sands of his high-energy Zone Y. Comparable lime-sands have been frequently described from the fringes of both the Great Bahamas Bank (Illing, 1954; Newell et al., 1960; Imbrie & Buchanan, 1965; Ball, 1967; Bathurst, 1975; Harris, 1979; Halley et al., 1983) and Little Bahamas Bank (Hine, 1977; Hine & Neumann, 1977) but the general setting of the Bahamian sands at the edge of an isolated platform (Read, 1985) is very different to that of the Bathonian lime-sands of southern and central England, which formed on a ramp. The oolitic 'tidal deltas' of the Persian Gulf (e.g. Kinsman, 1964) are also developed on a ramp (Read, op. cit.), but they are sited much closer to land than were the Bathonian shoals.

5.3.2 Lithofacies 2: Winnowed, shifting lime sands

This lithofacies consists of extensively bioturbated, oolitic, intraclastic and particularly bioclastic lime sands, now typically cemented by blocky ferroan calcite into massive beds of biooo-, oobio- and intrabiograine. Skeletal grains are usually abraded (as a result of both bioerosion and mechanical erosion) and often rounded; brachiopod, echinoderm and foraminiferan debris occurs but bivalve and gastropod material predominates in most examples of this lithofacies. The intraclasts are dominated by coated grains and amorphous lumps; botryoidal lumps and eroded lumps are relatively uncommon.

Primary sedimentary structures within this lithofacies have invariably been destroyed by the activity of an infauna dominated by rapid-burrowing bivalves such as Eocallista, more sluggish burrowers such

as Vaugonia and infaunal nerineid gastropods. This is essentially the 'clean washed lime sands' facies of T. Palmer (1979) or the lithofacies associated with Sellwood's (1978) 'low diversity, temporarily stable calcarenite community'. The associated biota contains few epifaunal species, and as Palmer (op. cit.) suggests, this is probably a reflection of a substrate affected by scouring bottom currents. A periodically shifting, loose sediment is envisaged for this lithofacies. It can be interpreted as a 'backshoal' facies, developed shoreward of Lithofacies 1. The sediments of Lithofacies 2 can be compared with the relatively stable lime sands of inactive parts of today's Bahamian shoals, such as have been described from Joulter's Cay by Harris (1979). These lime sands were probably deposited initially in active parts of an extensive sand body (following an initial relative rise in sea level) but contraction of the active part of the shoal (in response to changing sea level; cf. Hine, 1983) left them as a sheet of lime sand affected by only periodic current activity.

In the Bathonian, non-organic allochems may have been washed landward from shoal complexes, particularly during periods of high current activity (e.g. onshore storms), thereby supplementing the supply of locally derived bioclastic material incorporated in the sands of Lithofacies 2. Botryoidal lumps may have developed in this backshoal environment during quieter episodes, the product of localised early cementation. A relatively slow sedimentation rate and long-residence time of grains in the photic zone is suggested by the common occurrence of heavily micritised grains. Intermittent to fairly persistent background current activity continually removed fines from the sand and killed off any faunal elements intolerant of a periodically shifting substrate.

Typically, this lithofacies becomes increasingly muddy in a landward direction as a result of the decreasing ability of wind or tidal driven waves to completely winnow out fine-grained material.

Consequently Lithofacies 2 is found, in places, to grade laterally or vertically into the muddy, stable lime sand lithofacies.

Lithofacies 2 is particularly developed within the Ardley Member in the Oxfordshire part of my study area, where its distribution has been discussed by T. Palmer (1974, 1979)*. The same lithofacies also occurs at a lower stratigraphic level, within the Shipton Member and laterally equivalent strata, to the south and west of my study area. Similar well-washed lime sands (consisting mainly of skeletal grains with rare pellets) occur in the Cornbrash in the east Midlands, but they are neither associated with ooid shoals nor contain the same burrowing gastropod-bivalve fauna. These bioclastic grainstones probably accumulated in a different depositional environment and may, therefore, represent another lithofacies.

5.3.3 Lithofacies 3: Muddy, stable lime sands

Although this lithofacies is closely comparable to the winnowed, unstable lime sand lithofacies, the distinct changes in the associated biofacies indicate that quite subtle differences in the proportion of admixed lime mud were of considerable environmental importance. In thin

* Locally, at the base of the Ardley Member in Oxfordshire, this lithofacies exhibits conspicuous biomouldic porosity (Arkell *et al.*'s (1933) 'Roach Bed'), which T. Palmer (1973) attributed to the presence of an underlying clay horizon that prevented the passage of pore water through the immediately overlying limestone, thus preventing secondary cementation.

section, lithologies of this facies are seen to comprise ooids, skeletal grains (particularly molluscan), amorphous lumps and subordinate pellets, botryoidal lumps and coated grains. The proportions of each allochem present in a given example of the lithofacies varies considerably, as does the degree of micritisation of the grains. Siliciclastic sand/silt (principally detrital quartz) may be common locally. Intergranular areas are either partially or totally filled by lime mud (micrite/microsparite).

Thorough bioturbation invariably completely admixed the lime mud and lime sand components of this lithology. The resultant muddy lime sand substrate was firmer than the winnowed sands described above, and supported faunal elements (notably brachiopods and deep-burrowing anamolodesmatans) unable to colonise a shifting sea floor. Mixed mud-sand lithologies of this sort can arise in two ways, as outlined in Figure 5.2. They can arise simply from a consistent inability of bottom currents to completely winnow out fines; secondly they can develop from an alternation of periods of slack-water mud accumulation and periods of high current activity, winnowed sand accumulation when these alternating conditions are followed by a period of extensive burrowing. Plate 6A illustrates an intermediate stage in this latter process. In reality, this lithofacies probably arose from a combination of both methods.

The stability of the substrate may have been enhanced by the development of a subtidal algal mat of the sort described by Bathurst (1967, 1975), Scoffin (1970) and Neumann et al. (1970). Algal mats, consisting of an interlocking mesh of filamentous blue-green algae, with subordinate green and red algae, diatoms and animal-built grain tubes, are capable of protecting the substrate from currents at least twice as great as those that would normally erode comparable unbound sediments

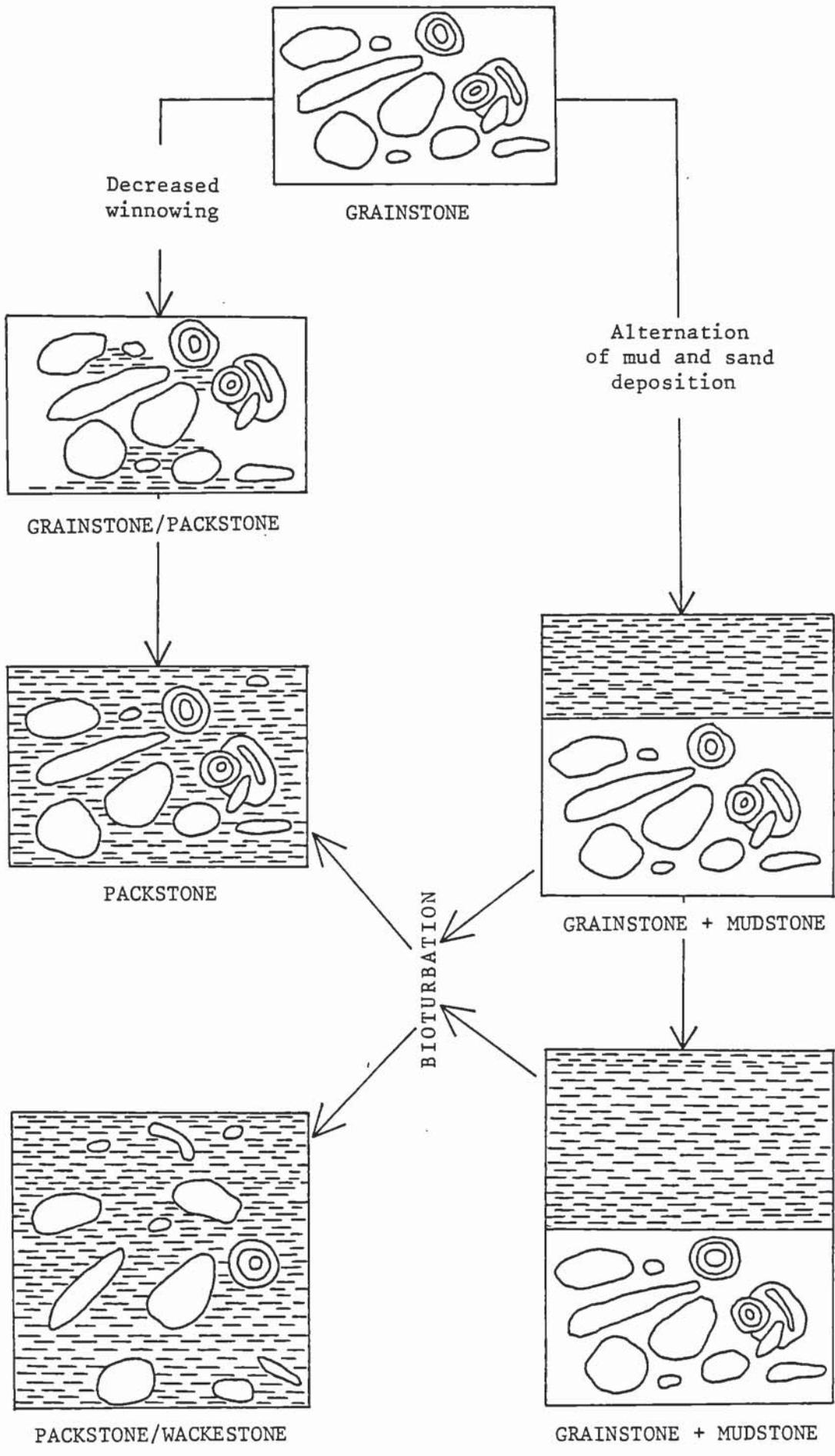


FIGURE 5.2 Production of muddy lime sand and sandy lime mud substrates.

(Scoffin, 1968). Thus, although this facies probably accumulated in more sheltered areas than the winnowed lime sands of Lithofacies 2, this need not be the case.

Lithologies representing this lithofacies are well developed in the Ardley Member of northeast Oxfordshire and, to a lesser extent, southwest Northamptonshire. They are also common within the K. sharpi Beds in the Ketton-Peterborough-Nassington district and have been seen in the lower part of the White Limestone further north, at Clipsham and Ancaster. At Shipton and elsewhere in Oxfordshire, packstones belonging to this lithofacies occur at a number of horizons within the Shipton Member. Comparable grainstones/packstones and packstone/grainstones to those of the White Limestone have been encountered within both members of the Cornbrash, but in that formation oolitic lime sand is absent. The bioclastic grainstone/packstones of the Cornbrash are thought to have accumulated in a more offshore, open shelf environment than did the oolitic, intraclastic and bioclastic grainstone/packstones of the White Limestone, and they represent a more condensed deposit.

5.3.4 Lithofacies association A: Cross bedded lime sands and terrigenous muds

This lithofacies association is characteristic of the Forest Marble, both in the study area and in areas to the south and west. It essentially comprises thick units of biooo- and oobiograins, with subordinate packstones, interbedded and interdigitated with units dominated by terrigenous mudstone. Exposures of this lithofacies association are frequently of poor quality and at all but a few localities (i.e. working quarries such as Shipton or Wood Eaton) the mudstones are very overgrown; quarry exposures also under-represent the

importance of terrigenous mudstones within the facies association since it has always been uneconomic to work the Forest Marble where it is dominated by that lithology.

The facies association is best exposed in Blue Circle's quarry at Shipton where it has been studied in detail by Allen & Kaye (1973); this exposure can be used as a basis for interpreting less significant exposures of the facies association elsewhere.

The oobio- and biooograinsstones ("Forest Marble" in the strictest sense) occur in units up to 6.5m thick at Shipton, but laterally the lime sands thin out almost completely (particularly southeastwards along the east and south faces of the quarry), and are replaced by thick units of terrigenous mudstone. Wedges of lime sand extend out from the main mass of lime sand into the mudstone. Cross bedding is well developed in the main body of calcarenite, but is less well developed in these wedges. Allen & Kaye found that most foresets are inclined towards the southwest, with a small number dipping in a diametrically opposite direction. Individual intrasets usually exhibit textural grading normal to bedding, with skeletal debris concentrated in the coarser, lower part of intrasets, becoming subordinate to ooids upwards. Foreset surfaces may be rippled (asymmetrical current, round-crested wave-current and interference ripples) and are frequently draped by thin layers of terrigenous mudstone (Allen & Kaye, op. cit.). Allen & Kaye observed lime sand-filled polygonal dessication cracks amongst the muddy bottomset beds and mud-drapes of the cross bedded grainstones but I, like T. Palmer (1974), have not seen these desiccation cracks.

In addition to ooids and skeletal grains, the grainstones contain pellets, peloids, botryoidal lumps, lithoclasts, coated grains and frequent clay galls. The major skeletal grains are of bivalve,

echinoderm and brachiopod origin; gastropod, serpulid, bryozoan, coral, foraminiferan and vertebrate debris is also invariably present (cf. Allen & Kaye, 1973).

From the distribution of lime sands in the quarry, and from the sedimentary structures observed, Allen & Kaye interpreted the main body of calcarenite at Shipton as an elongate sand shoal about 0.5km wide and over 0.7km in length, which probably trended southwest-northeast; the bar probably never had a relief greater than two metres. Their interpretation of these calcarenites differs markedly from the earlier belief (e.g. Klein, 1965) that they represent the deposits of meandering tidal channels (i.e. features of negative relief); however, their view is preferred here. Terrigenous mud is thought to have been deposited in troughs between adjacent sand bars. The edge of another sand bar, possibly developed on the same trend as the Shipton bar, may have been encountered in Forest Marble exposures at Bladon and Hanborough to the southwest (Arkell, 1931, 1933b, 1947; T. Palmer, 1974).

The cross bedding seen in Forest Marble sand bodies is thought to have been produced by long-crested dunes which migrated along the sand bars (Allen & Kaye, 1973). The graded intrasets, rippled foreset surfaces and mudstone drapes suggest that current energy fluctuated; as the flow weakened, waves and currents draining the shoal fashioned ripples on the leeward side of the immobilised dunes, while mud later accumulated on the rippled sides of the dunes during periods of slack-water. Allen & Kaye (op. cit.) suggested that this variation in current strength may have been related to tidal activity. The desiccation cracks they observed in this lithofacies association could have developed while the top of the shoal at Shipton was exposed at low tide and, furthermore, the bimodal distribution of cross bedding dip

azimuths might also reflect tidal influence. Certainly there are many similarities between the sand bars of present-day tidal bar belts in the Bahamas area and those of the Forest Marble. At Joulter's Cay, for example, individual bars within the belt are between 0.5-1.0km wide, up to 15km in length and have a relief 1-3m; water depths over the bar vary between 0-3m. Megaripples, with an amplitude of 1-1.5m are commonly developed on bar crests, orientated obliquely to the long axis of the bar. Sand or muddy sand accumulates in the channels between bars (Harris, 1979). Other examples of tidal bar belts with which a comparison can be drawn fringe the Tongue of the Ocean at its southern end, and also occur at Lily Bank, Schooner Cays and Frazers Hog Cay (Purdy, 1961; Ball, 1967; Harris, *op. cit.*; Halley *et al.*, 1983).

However, with the Bathonian sand bars, there is no unequivocal evidence to suggest that tides, if involved, were diurnal, astronomical tides; wind-driven tides would have produced similar sedimentary structures in a very shallow setting. If tides were not involved in the genesis of this facies association, it is possible that an alternation of storm and fairweather conditions could also have produced the sedimentary features observed (T. Palmer, 1974). In this case, most lime sand transport would have occurred during short-lived, high-energy events. The wedges of lime sand which extend out from the main mass of calcarenite at Shipton may represent small lobes of oolitic and bioclastic sand washed off the sand bar during storms. In the longer periods of fairweather, terrigenous muds would have accumulated, particularly in the inter-bar troughs, but at times over the sand bars, thereby producing the frequently observed clay drapes.

Infaunal bivalves and other taxa are uncommon in this facies association, perhaps because the depositional environment was hostile for

most filter-feeding organisms not raised above the sediment-water interface. Relatively little bioturbation has affected the constituent lithologies of the association, with terrigenous mud and lime sand seldom admixed to any great extent as a result of burrowing. Gyrochorte is frequently preserved, probably because the sediment has not been completely churned up; it was particularly encountered in thin calcarenite beds interbedded within units of terrigenous mud. Gyrochorte was probably produced by a deposit-feeding organism which tunnelled through the sediment just beneath the sea floor (Hallam, 1970); the progenitor may have been vermiform, possibly a polychaete (Seilacher, 1953; Heinberg, 1973).

5.3.5 Lithofacies association B: Cross bedded lime sands; interlayered lime sands and lime muds; bioclastic/oolitic lime muds

The dominant lithofacies association encountered in the Irchester Member comprises four separate lithology types, as outlined below. The facies association is very similar to Lithofacies association A; it is essentially T. Palmer's (1974, 1979) 'shelly micrite', which he described from the Ardley Member of Wood Eaton and the Cherwell Valley.

A relatively minor component of the facies association consists of white-weathering lime mud containing thin interlayers of lime sand, ranging from stringers a few grains thick to laminae 10-20mm thick. Planolites occurs frequently in this lithology, but the horizontal lamination has not been destroyed by more extensive bioturbation.

A more conspicuous lithology developed within this facies association comprises cross bedded oobio-grainstones, very similar to those developed in Lithofacies association A; both tabular and trough cross bedding occur. Intrasetts show well-developed textural grading

normal to bedding and foreset surfaces are often ripple-marked (e.g. Torrens, 1967; Pittham, 1970); lime mud drapes up to 5mm thick are present on many foreset surfaces. Extremely coarse clasts of lime mud are frequently incorporated into the basal layers of graded intrasets. At some localities, elements of the most commonly associated biofacies (Biofacies 4), such as Digonella or Nucleolites, have also been observed concentrated in the coarser parts of intrasets; these organisms are usually unabraded, articulated and either partially or completely filled by calcite spar, implying that they were transported only short distances before being rapidly buried. Gyrochorte occurs rarely within these cross bedded limestones; other trace fossils have not been recorded.

As petrographic analysis shows, the grainstones of this association are dominated by rounded skeletal grains (bivalves and echinoderms predominate; also serpulids, brachiopods, foraminiferans, bryozoans, gastropods and fish debris) and oolitically coated skeletal grains, frequently referred to as pseudo-ooliths or false ooliths (e.g. J. Taylor, 1963). Ooids are variably micritised, and in extreme examples have been altered to coated grains or amorphous lumps, probably as a result of algal or fungal boring (Bathurst, 1966); bioclasts usually have thick micrite envelopes. Scattered quartz grains occur throughout these grainstones and form the nuclei of a small proportion of ooids; detrital feldspar grains are rare. Pellets are a persistent but generally minor component of these rocks, and amorphous lumps or peloids also occur. Botryoidal lumps and eroded lumps are apparently uncommon but not absent from this lithofacies association in the east Midlands (cf. J. Taylor, 1963) and are also encountered in Oxfordshire. Elongated skeletal grains are commonly well bedded in these grainstones.

In many quarries, the cross bedded grainstones pass laterally into highly fossiliferous, bioturbated oobio- and bioo-packstones and wackestones which constitute the third major lithology of this facies association. At Kirtlington, relict large scale cross bed foresets have been preserved within these bioturbated limestones, but elsewhere bedding features have usually been destroyed. These bioturbated packstones and wackestones commonly occur interbedded with other lithologies of this association. Thalassinoides may sometimes be recognised within bioturbated packstone/wackestones, and the crustacean microcoprolite Favreina (see Kennedy et al., 1969) is often present, either concentrated in burrows or dispersed. Terebelloid worm tubes also occur in these lithologies, being particularly conspicuous at Kirtlington (McKerrow et al., 1969; T. Palmer, 1974). Biofacies 4 (the sandy mud community) is typically associated with this lithofacies association, and in particular with the bioturbated packstone/wackestones: the sandy mud and muddy sand substrates represented by these lithologies are believed to have been particularly stable, supporting a diverse epifauna and both a shallow and deep burrowing endobenthos. Biofacies 5 (the coral bed community) may also have been supported by the same sandy mud/muddy sand substrate at some localities.

Petrographically the limestones of the bioturbated horizons resemble those of the cross bedded units, except that lime mud (with minor amounts of terrigenous mud in some instances) is present in most intergranular areas in the packstones and, by definition, supports the grains in the wackestones. Bioclasts, ooids and coated grains predominate; botryoidal lumps, peloids and terrigenous grains are rare or absent.

The fourth lithology of this association has been seen in the Irchester quarries and consists of interbedded units of interlayered lime sand and terrigenous mud and units of interlayered lime sand and lime mud; it therefore resembles the first lithology described, but includes a higher proportion of terrigenous mud. It is suggested that these predominantly fine grained sediments infilled troughs between adjacent sand bars, just as the terrigenous muds of Lithofacies association A are thought to have done.

The interpretation of the cross bedded sands of this facies as the deposits of bars with positive relief contrasts with Klein's (1965) suggestion that they were deposited by migrating tidal channels, or T. Palmer's (1979) belief that they infilled extensive deep areas between stable muddy mounds. However, such is the similarity between this lithofacies association and Lithofacies association A that this interpretation is preferred to that of either Palmer or Klein. As in the Forest Marble, the cross bedding of this association may have been produced by dunes (both straight- and curve-crested) which periodically migrated along the tops of the sand bars. Unfortunately, exposures of this lithofacies association do not allow the orientation or geometry of the sand bars to be worked out with any certainty. Furthermore, the geometry is often obscured by bioturbation, which in places has destroyed cross bedding and admixed lime sand with the lime mud of foreset drapes, thereby producing packstones; elsewhere it has disrupted the horizontal bedding of interlayered mud and sand lithologies, mixing the sediment to produce wackestones. Only at Irchester, and perhaps also at Whitehill Farm Quarry, Gibraltar, can the edges of sand bars be recognised.

As with the Forest Marble sand bars, the movement of lime sand on the Irchester/Ardley Member sand bars was periodic and controlled either by tidal or storm currents; ripples again formed on the sides of dunes as current energy waned; mud-grade sediment was deposited thinly over the dunes and more thickly in the troughs between sand bars during quiet-water periods, but in this instance was mainly lime mud rather than terrigenous mud. The sediment was often completely bioturbated by a shallow and deep burrowing infauna during the quiet-water (?fairweather) periods, at least in those parts of the sand bar complex where an endobenthos was able to establish itself. The stable substrate produced by burrowing was usually colonised by a diverse epifauna, elements of which are typically incorporated into nearby cross bedded grainstones. The diversity of this fauna strongly suggests that the sand bars of this facies association were not developed in an intertidal setting; rather, current activity is thought to have been associated with storms and these bars are believed to have developed in a shallow subtidal setting. As with the sand bars of Lithofacies association A, comparison can be made with the tidal bars of the Bahamas. However, comparison may also be made with the Safety Valve skeletal bank complex of the Florida area (Aigner, 1985). This complex, about 3km by 8km, consists of numerous elongate 'bars' aligned perpendicular to its axis. Each bar has a core comprising predominantly bioturbated pelletal and bioclastic wackestones, similar to the bioclastic/oolitic lime muds of Lithofacies association B; skeletal sands extend about 1km onto the banks at their seaward end. Like the lime sands in Lithofacies association B, these bioclastic sands often occur as sharp-based layers or as vertically graded, fining-upwards units; however, cross bedding was not recorded by Aigner at Safety Valve. The bioclastic sands have been interpreted as subaqueous sand lobes which

were winnowed and accreted onto 'mudbanks' by storm-related, onshore directed wind-drifted currents. In addition to wedge-shaped onbank sand lobes, offbank spillover lobes (also wedge-shaped) are developed at the seaward ends of inter-bar channels within the bank complex. Storms are the major influence on deposition in the Safety Valve complex, as they are thought to have been on the Lithofacies association B sand bars.

In the Bladon Member and ?Great Oolite in Oxfordshire, bioturbated, oolitic and bioclastic packstones and wackestones, containing a fauna dominated by corals, epifaunal bivalves and Epithyris, have been seen to pass laterally into locally cross bedded biooo- and oobiograinsstones (e.g. Shipton, Kirtlington). While this may be a further occurrence of Lithofacies association B, I have not been able to examine enough exposures to confirm this. Similarly, the facies association may be developed in the lower part of the White Limestone in the Little Bytham area (Loc. 193 and 194) but the quality of sections in that district is too poor to warrant further comment.

5.3.6 Lithofacies 4: Pelletal lime sands

This minor lithofacies has only been separately identified in the Forest Marble at Croughton, where a 0.7m thick unit of ripple-cross laminated pelgrainstone is developed. In thin section, this lithology comprises equal proportions of well-sorted, extremely fine to very fine grained comminuted skeletal grain debris and pellets with subordinate quartz sand and silt. Micrite occurs in some intergranular pores in minor amounts, but for the most part intergranular areas are occluded wholly by a ferroan calcite cement. This was deposited as a winnowed, pelletal sand. Similar, locally rippled, pelletal sands today carpet the floor of the lagoon in the Abu Dhabi complex of the Persian Gulf in areas

where waves, driven by both the shamal wind and afternoon onshore winds, winnow mud away from intergranular areas (Bathurst, 1975). In the Forest Marble facies, waves or currents which were strong enough to generate ripples may also have been wind-driven. The general setting of this lithofacies is believed to have been more sheltered than that in which the sand shoals of Lithofacies association A developed; the pelletal sands probably accumulated in a more nearshore, but wholly subtidal, depositional environment. Other pelletal grainstones recognised in the upper Great Oolite Group of the study area belong in Lithofacies association C, and are described in subsection 5.3.8.

5.3.7 Lithofacies 5: Bioturbated, pelletal lime muds

This is the 'pelletal lime mud' lithofacies of T. Palmer (1974, 1979). It is characterised by pale-grey and white weathering micritic limestones containing an unabraded, whole macrofauna (high-spired gastropods and bivalves). In thin section, lithologies of this facies consist of well-defined to poorly defined, regular, spherical to elliptical pellets set in a micrite/microsparite matrix and associated with mainly very fine to fine bioclastic sand. The matrix exhibits grumeleuse texture (Cayeux, 1935) and probably much of it has been derived by compaction from uncemented pellets; this is suggested by numerous instances where large skeletal grains have protected pellets from compaction. The complete bioturbation of this lithology was achieved by the burrowing fauna associated with the lithofacies; distinct trace fossils have not been recognised.

Comparisons can be made between the pellet muds of Lithofacies 5 and those of the 'mud and pellet mud' facies of the Great Bahama Bank (Purdy, 1963; Bathurst, 1975). The Recent pellet muds typically contain

40% pellets (presumed to be of faecal origin), 10% bioclasts and about 45% lime mud; similar proportions are found in the Bathonian lithofacies, although skeletal grains are often more abundant in the latter. On the Great Bahama Bank, the pellet muds represent essentially undiluted authochthonous carbonate accumulation in a low-energy environment. Unlike the pelletal sands of Lithofacies 4, the pelletal lime muds of this facies formed on areas of the sea floor unaffected by major wave and current activity. Modern examples of similar lithofacies are essentially lagoonal/peritidal in origin. The substrate formed by these bioturbated, pelletal muds was, as T. Palmer (1979) envisaged, probably thixotropic. This undoubtedly exerted an important control on the composition of the fauna most commonly associated with this lithofacies (Biofacies 6).

The origin of the lime mud within Recent carbonate environments has been the subject of considerable discussion (e.g. Milliman, 1974; Bathurst, 1975). Following the work of Stockman et al. (1967), it is now widely accepted that the lime mud accumulating today in Florida Bay is derived largely from calcareous algae (Penicillus and other genera) which disintegrate after death to produce fine crystals (<15 μ m) of aragonite and calcite. However, as noted earlier by Matthews (1966), mud-grade skeletal debris can also be produced both by physical and biological processes of particle-size reduction, in agitated and quiet-water environments respectively. In many modern environments (e.g. Great Bahama Bank, Florida Bay, Belize Shelf) lime-mud has been produced by a combination of particle-size reduction and algal disintegration. By analogy, Bathonian lime-mud may have had a similar heterogeneous origin. However, since traces of calcareous green algae are rare in the English Middle Jurassic (T. Palmer, 1979; Elliot, 1982a), possibly, as suggested by Elliot (1977), because of unfavourable climate, the role of algae in

producing lime-mud in the Bathonian needs to be discussed. At the present-day, the udoteacean Halimeda breaks down in such a way that it produces recognisable skeletal debris, whereas Penicillus and Rhizocephalus, which have different calcification, leave little evidence of their existence in the sediment. The possibility exists, therefore, that abundant udoteaceans, comparable to Penicillus and Rhizocephalus, flourished on the Cotswold-Weald Shelf in the Bathonian, sourcing large quantities of lime-mud but leaving no recognisable fossil debris (Elliot, 1982a). Yet, if the one type of udoteacean algae were abundant, it is to be expected that Halimeda-type algae might be at least moderately common. Instead, fossilised udoteacean debris is particularly uncommon in the English Middle Jurassic, being limited to occurrences of Lekhamptonella in the Lower Inferior Oolite (Elliot, 1982b) and Arabicodium in the White Limestone near Cirencester (Elliot, 1975). Thus, since traces of dasycladacean algae are also rare, it is possible that calcareous algae played only a minor role in generating the mud-grade carbonate sediment of the English Bathonian, in striking contrast to the situation in Recent environments.

Inorganic precipitation of aragonite needles from waters of abnormally high salinity and carbonate saturation has been presented as a method of lime mud production in some modern settings (Cloud, 1962; Wells & Illing, 1964), but while this process may occur in the Persian Gulf or in Coorong lagoons, it is unlikely to have been the method of large-scale lime mud production in the Bathonian seas of the east Midlands; faunal evidence suggests the common development of reduced salinities, and the general absence of evaporites militates against arid conditions and high evaporation rates. Perhaps, however, if the composition of Jurassic seas was truly different from that of today's oceans (section 1.3.1), the

inorganic, or bacterially-catalysed, precipitation of magnesian calcite muds could have occurred, as it apparently does today at Coorong (Milliman, 1974).

The pelletal lime muds of Lithofacies 5 are developed in all members of the Oxfordshire White Limestone, but are particularly well-developed in the Ardley and Bladon Members. The lithofacies is also locally encountered in the Irchester Member in the east Midlands.

5.3.8 Lithofacies association C: Pelletal lime sands/lime muds and oolitic/bioclastic lime sands

Finely laminated pelletal lime sands are particularly well-developed within the Irchester Member between Bedford, Milton Keynes and Hartwell, but are also thinly developed at the top of the Ardley Member in north and northeast Oxfordshire, and at a lower level within the member about Burford. These laminated pelletal sands are invariably associated with coarser lime sands in the east Midlands, although this association is less evident in Oxfordshire. Where the facies association is best developed, these deposits consist of stacked, erosionally-based couplets of oolitic and bioclastic lime sand overlain by laminated pelletal sands. Such couplets are reminiscent of deposits described by Kreisa (1981) from the Ordovician of S.W. Virginia, which he interpreted as storm-generated shelf sediments. Figure 5.3 shows the idealised couplet from this facies (cf. fig. 3 of Kreisa); close comparison can be made with the A to C divisions of the Bouma sequence (Bouma, 1962; Rupke, 1978) and, like the Bouma sequence, these couplets were probably deposited under waning flow conditions. Just as complete Bouma sequences are relatively rare, so these couplets are often not fully developed. Frequently either the lower oobiograstone unit or the finely laminated

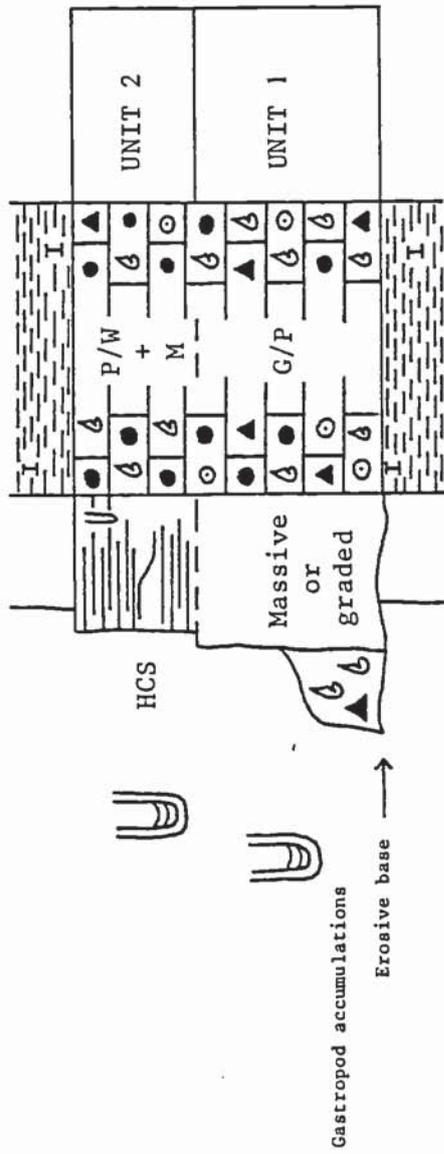


FIGURE 5.3 Idealised storm couplet of Lithofacies association C.

pel-packstone/grainstones are developed in isolation. In describing this facies association, however, it is convenient to refer to the idealised couplet.

Couplets are everywhere characterised by a sharp, erosive base. This may either be planar or show the development of undulating scours. Post-depositional load structures are commonly present where couplets are developed above beds of interlayered mud and sand. Prod and bounce marks have been recorded from the base of these units, but flutes and grooves have not yet been noted; this perhaps reflects the limited exposure of bedding surfaces at the appropriate horizon.

The basal part of the fully developed couplet (unit 1) comprises fine to coarse grained oobio- and biograinstone, either massively bedded or exhibiting vertical grading of the coarsest allochems. Often, large micrite rip-up clasts occur at the base of unit 1; concentrations of whole fossils, notably nerineid gastropods, similarly occur (Plate 9C). The clasts are generally angular to slightly rounded and up to 60mm across. They were presumably consolidated and partially cemented prior to their erosion and re-deposition. The sands are dominated by skeletal grains, rounded and often heavily micritised; bivalve and echinoderm material proliferates. In addition, variably micritised ooids and ooid-derived coated grains may be common; eroded and botryoidal lumps, pellets, peloids and detrital quartz can also be present.

Beside graded bedding, unit 1 may also exhibit hummocky cross stratification (HCS). This bedform was so-named by Harms et al. (1975), although it was first described by Gilbert (1899) and later by Campbell (1966); it has been the subject of considerable recent work (e.g. Hamblin et al., 1979; Hunter & Clifton, 1982; Mount, 1982; Dott & Bourgeois, 1982; Walker et al., 1983; Marsaglia & Klein, 1983; Duke, 1985). Harms

et al. (op. cit.), who described HCS from the Upper Cretaceous Gallup Sandstone of New Mexico, noted as its essential characteristics:

i) Erosional lower bounding surfaces to sets, typically sloping at angles of less than 10° ; may have tool marks at contacts with underlying clay beds.

ii) Laminae above an erosional set base parallel or nearly parallel to that surface.

iii) Laminae thickening laterally within a set, producing a fan-like trace on vertical faces, with dip diminishing regularly.

iv) Scattered dip directions of erosional set bases and the overlying laminae.

The above features have all been recognised within the medium to coarse grained lime sands of unit 1, both where these occur as isolated units and in stacked sequences, providing weathering has been favourable. Often only the low-angle, multi-directional dipping erosive bases of sets are clearly visible within a stacked sequence of sands, with internal laminations poorly developed; at other exposures, sets exhibiting complete hummocks and swales, together with clearly visible internal lamination, have been seen (Plate 8D; cf. fig. 1B of Duke, 1985).

HCS was interpreted by Harms et al. (op. cit.) as the product of particularly strong wave action (with surges of displacement and velocity greater than those needed to produce wave ripples). Initial scouring of the sea floor produced poorly orientated, low hummocks with shallow, intervening swales, subsequently mantled by laminae of silt or sand grade material which was swept over this undulating topography.

Unit 1 passes gradually or, more often, sharply up into parallel laminated pelletal and bioclastic, fine grained sand to silt (unit 2) in

the idealised couplet. Associated subordinate bedforms, notably ripple cross lamination and HCS, many also be developed within unit 2.

In this laminated unit, dark pel-and pelbiograinsstone/packstone layers typically alternate with paler weathering laminae which, in the field, appear to be micritic; in thin section they can be seen to comprise pel-packstone/wackestone in which the pellets are less well defined than in the better-washed layers. The matrix in the packstone/wackestone laminae typically exhibits *grumuleuse* texture.

Laminations vary from 10mm to <1mm in thickness. Occasional coarser laminae, consisting of fine and medium grained bioclastic and oolitic lime sand, may be developed. Laminae dominated by small, but complete nerineid gastropods have been recorded, but are uncommon. Small-scale structures characteristic of HCS (Plate 9A & B; cf. fig. 7 & 8 of Mount, 1982) occur within unit 2, intimately associated with the even-parallel lamination. Furthermore, isolated developments of unit 2 within this facies association often possess a hummocky, erosive base; the fine laminae of pelletal sand lie parallel or nearly parallel to this lower bounding surface and may thicken into troughs in a manner characteristic of HCS. Thin beds of ripple lamination occur infrequently.

A number of trace fossils are found in this lithofacies association, of which locally abundant Diplocraterion are the most noticeable (Plate 5B; Plate VIIIA of Hains & Horton, 1969). Vertically retrusive and protrusive forms occur, up to 0.5m in height. Gyrochorte, Imbrichnus and Pelecypodichnus have been recorded from thinly-bedded biograinsstones of unit 1, a trace fossil assemblage similar to that found in flaggy, sandy limestones in the Forest Marble of southern England

(Hallam, 1970; Holloway, 1981). The association of Pelecypodichnus and Imbrichnus was also recorded by Bandel (1967) in the Carboniferous of Kansas. Holloway (1981) found Pelecypodichnus at the end of an Imbrichnus trace in the Forest Marble at Watton Cliff and suggested that they were made by one individual; a burrowing bivalve is believed to have been responsible. Narrow, often calcite spar-filled, vertical burrows, 1mm in diameter and up to 10mm in height, occur within unit 2; T. Palmer (1979) suggested that these were worm burrows. Larger burrows within the same unit at Croughton, filled by fine to medium grained oolitic sand, may be of crustacean origin. Rupturing of the parallel laminations of unit 2 which is sometimes seen (Plate 10A & B) may represent invertebrate escape structures rather than features produced by downward burrowing.

No definite in situ macrofauna has been found within this facies association. However, transported accumulations of nerineid gastropods occur in both units 1 and 2 (Plate 9C & 10D). Valvata occurs within unit 2 at the top of the Ardley Member at Croughton. Small procerithid gastropods have been washed from argillaceous sediments associated with the dominant carbonates of the association in Buckinghamshire (G. Osborn, pers. comm.). Non-gastropod faunal elements occur only sporadically and are always allochthonous.

A number of authors (T. Palmer, 1974, 1979; Barker, 1976; Sumbler, 1984) have suggested possible algal involvement when explaining the fine laminations developed within unit 2 of this facies association, where it is developed as thin beds in the Ardley Member. However, both the bedforms found in unit 2 and the close association with the coarser lime sands of unit 1 suggest that the lamination of unit 2 was largely mechanically produced. Similar finely laminated pelletal limestones

developed at the tops of shallowing-upwards sequences within the Lincolnshire Limestone have also been interpreted as having been mechanically deposited (Ashton, 1981). 'Micrite' layers within these Bajocian laminites were interpreted by Ashton as having been deposited from suspension as lime mud. He therefore compared this interlaminated 'micrite' and pellet sand lithology with interlayered terrigenous mud and sand deposits described from siliciclastic intertidal flats developed around the North Sea (Reineck & Singh, 1973). Ashton suggested that the pelletal layers were deposited by tidal currents whereas the lime mud settled from suspension at still-stand. In this thesis, however, both the pelgrainstone/packstone and pelpackstone/wackestone layers present in the White Limestone laminites of Lithofacies association C are believed to have been mechanically deposited; the apparent mud grade of some laminae is the result of compaction of soft pellets rather than a true reflection of original grain size. This being so, the development of HCS within this facies-association strongly suggests that storm currents, rather than tidal activity, were largely responsible for producing both the laminated horizons and the couplets, where developed. A storm origin for HCS is now widely accepted and a storm genesis for the couplets of this facies association is in accord with Kreisa's (1981) work mentioned earlier. Duke (1985) has suggested that both intense winter storms or hurricanes could produce HCS. A storm origin for the laminites need not totally rule out algal involvement; algae may have colonised the sediment surface during fairweather. However, algal colonisation could not have occurred between the deposition of individual laminae, which mark passing storm surges, only between the deposition of individual sets (a number of which might be present in a single laminite bed).

Laminated pelletal sands have been documented from modern beach environments (Hardie & Ginsburg, 1977; Inden & Moore, 1983) and the occurrence of Diplocraterion within Lithofacies association C would be compatible with such a high energy intertidal setting. However, the lithofacies association lacks many features characteristic of beach sediments, such as keystone vugs, beachrock clasts or marine vadose isopachous rim cements. For this reason, most of the sediments of Lithofacies association C are thought to have been deposited by storms in a very shallow, but perhaps largely subtidal environment. Comparison can perhaps be made with the Late Devonian Baggy Formation sands of southwest England, which contain Diplocraterion (Goldring, 1971), apparently exhibit HCS (Duke, 1985), and have been interpreted as storm-deposited shallow subtidal sediments (Goldring & Bridges, 1973).

The presence of the freshwater gastropod Valvata in unit 2 sediments at Croughton (T. Palmer, 1974, 1979) implies either that the environment was flooded for lengthy periods by freshwater, thus allowing Valvata to become established here, or that these gastropods were washed in from nearby freshwater environments (such as ponds on adjacent supratidal marsh flats). In the same laminated sediments at the top of the Ardley Member at Croughton, J. Andrews (in litt.) has recently discovered calcite pseudomorphs after gypsum. While the presence of gypsum could be taken to indicate deposition in an intertidal environment, it could also have developed if these sediments were subaerially exposed during the end of the Ardley Member regression.

5.3.9 Lithofacies 6: Lime muds

Lime mudstones, frequently laminated and containing a preponderance of open-space structures, were described from the upper

part of the White Limestone by Palmer & Jenkyns (1975). While these authors' supposition that their 'vuggy micrite' formed the uppermost bed of the White Limestone at all localities at which it occurred is not accepted (see Chapters 3 and 7) and while evidence from both Oxfordshire and Northamptonshire does not support their palaeogeographic conclusions (Palmer & Jenkyns, op. cit., fig. 3), their description and basic interpretation of this lithofacies is very valuable.

Within my study area, the lime mud of this lithofacies is usually found in the upper part of vertically graded, fining-upwards sequences. For example, at Croughton, pelletal biograinstone/packstones pass up through finer-grained biowackestones and mudstones into laminated lime mudstone; similar fining-upwards sequences are well-developed elsewhere. Barker (1976) described the same fining-upwards trend, ascribing it to a combination of increasing micritisation upwards and a vertical decrease in grain size; Sumbler (1984) re-iterated this view, stating that the micritisation of the upper layers occurred during hardground formation. While I agree that the upwards decrease in grain size was of primary origin, I cannot accept their opinion that micritisation of the upper layers occurred, and particularly not during hardground formation: this would not account for increases in the proportion of micrite in cases where the lithofacies is not hardground-capped. Instead, I believe that both the decreasing allochem size and the increasing proportions of micrite (deposited as lime mud) reflect a reduction in energy conditions, brought about by gradual shallowing.

The lower parts of these graded sequences (typically Lithofacies 5) often contain a low diversity fauna in which Aphanoptyxis is conspicuous, but in the pure lime mudstones of the upper parts of these

sequences, particularly in more proximal settings, macrofauna is generally absent. The micrite in this lithofacies is usually well-cemented, thus producing a hard, splintery, white to pale grey weathering limestone, often described as 'porcellaneous' or 'sub-lithographic'. In thin section, the micrite has a comparatively homogeneous texture, unlike the grumeleuse micrites of Lithofacies 5 and Lithofacies association C which are interpreted as ex-pelletal; this suggests that the micrite of Lithofacies 6 may have been deposited from suspension as original mud-grade sediment.

Lithofacies 6 is characterised by a combination of some of the following distinctive structures:

- i) Fenestrae.
- ii) Laminae.
- iii) Mudcracks and intraclasts.
- iv) Rootlets.

Palmer & Jenkyns (1975) noted the common occurrence of open-space structures in the lime mudstones of this lithofacies; both millimetre-scale, ellipsoid birdseyes and anastomosing cracks up to 1mm across and a few centimetres in length occur (Plate 2G). The birdseyes frequently occur in stringers parallel to the bedding, with their longest axis orientated in that direction (Plate 2H). All the birdseyes studied have been infilled by pore-filling ferroan calcite. While most of the anastomosing cracks examined were also filled only by ferroan calcite, some examples of geopetal clay partial-infills were seen. The vertical and sub-vertical, calcite-filled tubular cavities observed by Palmer & Jenkyns (op. cit.) in this lithofacies are interpreted as worm burrows; they are not true fenestrae.

Very fine to coarse, horizontal or slightly undulating cryptalgal laminae are locally developed in Lithofacies 6, very often accentuated by alternating dark and light layers. However, unlike fenestrae, laminae have not been recorded in this lithofacies, within the White Limestone, northeast of Croughton. Palmer & Jenkyns (op. cit.) recorded both V-shaped cracks which wedge downwards and delineate polygons on horizontal surfaces and small (20mm), polygonal, micritic intraclasts within this lithofacies at a number of localities. Rootlets are sometimes present in Lithofacies 6, notably at Croughton, Stratton Audley, Pury End and Stanwick.

Each of these structures has been listed by Shinn (1983a) as a diagnostic feature of modern, lime mud-dominated carbonate supratidal marsh flats. Both organically and inorganically produced laminations have a high preservation potential in such environments. The redeposition of micrite intraclasts produced by the dessication, early cementation and subsequent erosion of the uppermost laminae of sediment is a commonplace event, particularly when the supratidal environment is affected by storm tides. Mudcracks within this environment form as a result of dessication of the upper layers of the substrate; syneresis cracks have not been reported from carbonate substrates (Shinn, 1983a). Birdseyes are the ancient counterparts of modern vugs, which are universally present in modern supratidal and upper intertidal carbonate sediment (Shinn, 1968, 1983b); such vugs are formed when air bubbles are trapped within the sediment. The anastomosing cracks seen in Lithofacies 6 may result from dessication and shrinkage of the substrate, as suggested by Palmer & Jenkyns (op. cit.), but it should be noted that Brewer (1964) has illustrated comparable fenestrae from modern soils. Plant colonisation occurs on both carbonate and terrigenous supratidal

marsh flats at the present day; plants (and therefore rootlets) become more common in a landward direction.

Clearly the lime mudstones of Lithofacies 6 were deposited in a supratidal environment. Palmer & Jenkyns (1975) used the mud-flat islands of Florida Bay (particularly Crane Key) as analogues for these limestones, but comparable sediments and sedimentary structures have been widely described, particularly from the Persian Gulf, the Bahamas and Florida Bay. The sediments of the essentially freshwater inland algal marsh developed in the Three Creeks area of Andros (Hardie & Garrett, 1977) appear to be very similar to those of Lithofacies 6, although nothing like the Scytonema algal tufa (Hardie & Ginsburg, 1977) occurs in the sediments of Lithofacies 6. The supratidal lime muds of Crane Key were described by Ginsburg et al. (1954). At both Three Creeks and Crane Key, lime mud is swept onto the supratidal flats during periodic storms.

Unlike intertidal/supratidal algal stromatolites of the essentially contemporary Great Estuarine Group of the Hebrides (Hudson, 1970), supratidal carbonates within the White Limestone have not been found to contain either dolomite or evaporite minerals; this suggests that there is a closer parallel with the humid supratidal marshes of Florida and the Bahamas than with the arid sabkhas of the Persian Gulf.

In their environmental reconstruction, Palmer & Jenkyns (op. cit.) interpreted supratidal carbonates in the upper part of the White Limestone as the deposits of an emergent carbonate island, thought to have separated open sea to the southwest from an area of brackish lagoons to the northeast. I believe, instead, that they represent the deposits of supratidal carbonate marshes, developed at the fringes of Brabantia, which, during certain regressions, prograded across the east Midlands and northeast Oxfordshire. The progradation of these supratidal marshes

across very shallow subtidal pelletal and bioclastic sands and muds produced the fining-upwards sequences which have been observed in the White Limestone. In some cases, terrigenous coastal marshes, developed landward of the carbonate supratidal marshes, prograded over the lime mudstones of Lithofacies 6 during the same regressions; these siliciclastic deposits are described in section 5.3.14. The present-day supratidal carbonate marshes around Andros are 3-4km wide (Shinn et al., 1969; Hardie & Garrett, 1977); the Bathonian marshes may, at times, have been considerably broader.

5.3.10 Lithofacies 7: Oyster 'reefs'

In this thesis, lithologies containing an overwhelming preponderance of whole and abraded oyster shells have been recognised as a separate lithofacies, regardless of the nature of the matrix. The lithofacies is widely developed in the Great Oolite Group of the study area; in the upper Great Oolite Group, oyster 'reefs' are particularly well developed in the Forest Marble Formation, in the Longthorpe Member and in the Kallirhynchia sharpi Beds. The palaeontology of these beds is discussed in section 6.4.7.

The oyster Praeexogyra hebridica dominates this lithofacies. Other bivalve material and rhynchonellid debris usually also form a major component of oyster 'reef' lithologies; echinoderm and serpulid debris may also occur. Most lithologies belonging to Lithofacies 7 are packstones, with either terrigenous or lime mud present in intergranular areas. Ooids and other allochemical grain-types may be present in addition to the bioclastic material in the matrix. Oyster-dominated biograined stones and biograined stone/packstones occur locally.

Oyster beds are seldom biohermal in character; more often, oyster debris is well-bedded and the original reef morphology cannot be discerned. However, most of the packstones, and particularly those containing abundant articulated oysters, are considered to have been deposited fairly close to the site of reef development. Oyster material in the winnowed lithologies may have been transported further; storm currents were probably responsible for carrying shell debris away from reef sites.

By comparison with modern oyster reefs, the Bathonian oyster reefs probably resembled low mounds with a high centre, with living oysters and associated organisms concentrated on the flanks of the reef (Ladd et al., 1957). Mud-grade sediment may have been trapped within the reefs because of the baffling effect they exerted. It has also been suggested that by converting suspended inorganic material into faecal or pseudofaecal pellets, oysters can greatly influence sedimentation in the immediate neighbourhood of a reef (Lund, 1957; T. Palmer, 1979); the pellets are usually deposited about the reef which may, therefore, act as a centre of rapid sedimentation.

Present-day reefs are mostly confined to shallow (intertidal to 30m), often slightly brackish environments (Milliman, 1974). Comparison may be made (Hudson, 1963b; Hudson & Palmer, 1976) between P. hebridica reefs and the Crassostrea virginica reefs of the Texas Gulf Coast, which form at reduced salinities (12-25⁰/oo), in enclosed bays developed behind a string of sandy barrier islands (Ladd et al., 1957; Parker, 1960). However, while reefs in the Great Oolite Group probably also developed at reduced salinities, it is not thought that brackish conditions in eastern and central England were maintained by emergent physical barriers (Bradshaw, 1978).

Oyster 'reefs' in the upper Great Oolite Group do not seem to be confined to any single substrate type, although T. Palmer (1979) only found 'reefs' in the Hampen Marly Formation developed directly above limestones. While the initial settlement of oyster larvae could only have occurred where there was a hard substrate, this need have been nothing more than scattered shell debris. Once a few oysters were established, they could act as a nucleus for further settlement.

5.3.11 Lithofacies 8: Hardgrounds and pebble-beds

Intraformational hardgrounds are developed at numerous levels within the White Limestone in Oxfordshire and Gloucestershire; however there is only one confirmed record of a hardground within the White Limestone of the east Midlands (Bretton; Loc. 184). Occasional hardgrounds have been recorded within the Cornbrash of the east Midlands, but pebble-beds are more common in that formation; the latter also occur in the White Limestone, ?Great Oolite and Forest Marble in Oxfordshire.

Hardgrounds represent areas of cemented carbonate sediment exposed on the sea floor; the required intergranular cementation can either have occurred during episodes of emersion, when the sediment was exposed to the action of meteoric freshwater, or else in the subtidal environment, during periods of negligible sedimentation and erosion. Both sand- and mud-grade sediment can be cemented to form hardground surfaces (Goldring & Kazmierczak, 1974) and both types occur in the upper Great Oolite Group of the study area. Hardgrounds within this succession are invariably encrusted by oysters and often riddled with Trypanites and/or 'Lithophaga' borings. Frequently, Bathonian hardgrounds, irrespective of substrate-type, contain burrows, especially of the Thalassinoides-Spongeliomorpha variety (e.g. Fürsich & Palmer, 1975); in

cases where the original substrate can be interpreted as having been unstable (e.g. well-washed lime sand) or 'soupy' (e.g. pelletal lime mud), these burrows may have been excavated when the substrate was partially cemented in the subtidal environment, and thus rendered firm (cf. Holloway, 1981). Burrows within hardgrounds provide a niche for encrusting taxa intolerant of the exposed regime of the upper surface, particularly bryozoans, serpulids, calcisponges and thecideacean brachiopods (Palmer & Fürsich, 1974); this can be demonstrated using Ardley Member hardgrounds from Foss Cross (Loc. 1) and Ardley (Loc. 30).

The upper surfaces of most hardgrounds within the study area are planar and, often, polished; Goldring & Kazmierczak (1974) have suggested that corrasion (a temporary, mobile cover of coarse sediment acting as the corrasive agent) was generally the dominant factor giving rise to such surfaces, although bioerosion may have been a contributory factor. A close comparison can be made with Recent Persian Gulf examples of subtidally-cemented 'hard layers' exposed at the sediment/water interface, the upper surfaces of which are typically smooth, grey-black and abraded (Shinn, 1969; Bathurst, 1975). Shinn (op. cit.) believed that the grey to black zone surrounding borings and vugs within cemented layers in the Persian Gulf, as well as covering the upper surface, may have had an organic origin and was probably the result of a process which took place on rock surfaces exposed for long periods to sea water. Analogous crusts are associated with some Bathonian hardgrounds: the hardgrounds capping the Ardley Member at Shipton (Loc. 16) and Eton College (Loc. 5) exhibit black coatings of limonite and, at Shipton, oyster-encrusted pebbles at the base of the Bladon Member are similarly coated by limonite; limonite lining Thalassinoides burrows developed within the Eton College hardground contains relict oxidised pyrite.

Elsewhere, hardgrounds capping the Ardley Member are extensively reddened, reflecting the pronounced iron-enrichment of the lithified surface. Mineralisation of the sea floor is usually indicative of prolonged phases of non-deposition or very slow sedimentation (Fürsich, 1979): iron hydroxide crusts are characteristic of shallow shelf hardgrounds; pyritisation of hiatus concretions or hardgrounds usually occurs only after burial (Hallam, 1969a; Fürsich, op. cit.), although pyrite can also form in the microenvironment of burrows prior to burial.

The majority of hardgrounds within the upper Great Oolite Group of the study area are located at the tops of shallowing-upwards sequences; similar occurrences of hardgrounds at the tops of regressive cycles have been noted elsewhere (e.g. Purser, 1969; Fürsich, 1979). The timing of the lithification of the hardgrounds studied is uncertain: cementation could have occurred in the intertidal/supratidal zone, when the regression was at its height; subtidally, either during the regression or early in the following transgression (but before the initiation of deeper-water sedimentation); or it may have occurred both subtidally and subaerially, and at both times. Purser (1969) argued that early lithification of Middle Jurassic carbonates in the Paris Basin occurred largely in a subtidal setting during the periods of slow sedimentation which preceded the onset of 'deep-water' mud accumulation, when rising sea level inhibited the deposition of carbonates. In the same paper, however, he also noted the association of microstalactitic cements (indicative of early lithification in the intertidal/supratidal zone) with hardgrounds capping the Comblanchien Formation (in sediments containing birdseyes and algal laminae; see Purser, 1975).

Microstalactitic cements have not been observed in any of the hardgrounds examined petrographically during the course of this study, perhaps because most hardgrounds have been wackestones or packstones. However, Sellwood et al. (1985) have recently recognised some hardgrounds within essentially contemporaneous limestones at Humbly Grove which exhibit vadose silts and meniscus cements, characteristic of the freshwater vadose diagenetic zone. Furthermore, Palmer & Fürsich (1975) argued from textural evidence that intra-Ardley Member hardgrounds at Dagham (SP 003060) underwent both marine and subaerial cementation, prior to the encrustation of the hardgrounds. While there is therefore evidence which suggests that at least some upper Great Oolite Group resulted from freshwater cementation during periods of emersion, the absence of emergence features in most hardground-capped beds and the more common occurrence of hardgrounds in offshore rather than marginal settings suggests that subtidally-cemented hardgrounds may predominate overall in the English Bathonian. Further work is necessary to confirm this hypothesis; Marshall & Ashton (1980) were able to demonstrate, using isotopic evidence, that three hardgrounds within the Lincolnshire Limestone were subtidally cemented and this method of research might yield important results if undertaken on Bathonian hardgrounds.

Both the development of open burrow systems and the incomplete coalescing of patches of a particular early-cemented layer probably facilitated reworking, during strong phases of erosion, of hardgrounds into bored and encrusted limestone pebbles. Pebble-beds so-produced are developed locally in Oxfordshire/Gloucestershire (particularly at the bases of sedimentary rhythms) in the Ardley and Bladon Members and in the ?Great Oolite; they are especially common at the base of the Upper Cornbrash in the east Midlands. The pebbles in such beds are typically

irregular in shape, bored and encrusted. In some cases, pebble-beds pass laterally into hardgrounds; as noted by Fürsich (1979), pebbles may also rest on the very hardgrounds from which, elsewhere, they were derived.

The general absence of hardgrounds within the White Limestone of eastern England requires some explanation, in view of their frequent occurrence in Oxfordshire/Gloucestershire. One possibility is that the lime mud and pelletal lime mud sediments developed at the tops of sedimentary rhythms in Northamptonshire (where hardgrounds might be expected) contain too much clay; Zankl (1969) has suggested that early lithification does not occur in lime mud containing over 2% (by weight) of insoluble residue (in particular clay minerals). A further factor may be that high freshwater run-off into the "East Midlands Embayment" may have sufficiently lowered the level of CaCO_3 supersaturation to prevent subtidal interparticle cementation. Lastly, across the tectonically positive east Midlands area, a rapid transition from subtidal to emergent conditions, followed by a subsequent high rate of erosion may also have militated against hardground formation and/or preservation.

5.3.12 Lithofacies 9: Interlayered sands and terrigenous muds

Very finely interlaminated silt and clay through to more coarsely interlayered sand and terrigenous mud has been described from the Rutland Formation (Bradshaw, 1978), where such lithologies are essentially restricted to the lower parts of sedimentary rhythms developed above the Stamford Member. Within units of interlayered sand and mud the sand layers, which average 3mm in thickness but locally are up to 15mm thick, are predominantly siliciclastic but always contain a high bioclastic component. Internally, most sand layers are structureless but they

frequently possess wave-rippled tops, giving rise to lenticular or wavy bedding.

Upper Great Oolite examples of the interlayered sand and mud lithofacies are not restricted to the lower parts of rhythms, although the lithofacies is particularly common there. Furthermore, while sand layers are of comparable dimensions to those in the Rutland Formation and occur both as layers with rippled tops and as discrete ripples, they are dominated by bioclastic sand, with or without oolitic or intraclastic sand but with only a subordinate siliciclastic component (principally quartz sand/silt). The bioclasts comprise largely bivalve debris, although echinoderm (echinoid spine and plate fragments; crinoid ossicles), brachiopod and gastropod material also commonly occurs, in varying proportions. Large shell fragments or complete valves (particularly of Praeexogyra) are invariably associated with medium and coarse-grained sand, and are typically orientated in convex-up positions. Where the lithofacies is developed at the base of rhythms, vertebrate material (fish teeth and scales) and terrestrial plant debris (carbonaceous fragments, stems, occasional logs, etc.) may be associated with sandy layers.

Besides the lenticular, and wavy bedding characteristic of this lithofacies, Bradshaw (1978) recorded the presence of prod and bounce marks on the bases of some sand layers. Within some thicker sand units developed in this lithofacies in the Wellingborough Rhythm of the east Midlands he also recognised most of the essential features of HCS. This sedimentary structure has not yet been observed within sand layers of this lithofacies developed in the upper Great Oolite, but sand exhibiting even-parallel lamination has been encountered.

The interlayered sands and muds of Lithofacies 7 resemble the tidal rhythmites described by Reineck & Singh (1973) in which the sand layers are deposited by tidal current activity while the mud settles from suspension during still-stand phases at high or low water. However, thin, erosively-based, often vertically graded sand layers exhibiting coquinas, parallel lamination, HCS and sole marks have been widely interpreted as storm-sand layers (e.g. Reineck & Singh, 1972; Brenner & Davies, 1974; Hamblin & Walker, 1979; Brenchley et al., 1979; Benton & Gray, 1981; Kreisa, 1981; Mount, 1982; Nelson, 1982). Similarly, Bradshaw (1978) interpreted the sand layers of Lithofacies 7 as products of storm activity, comparing the lithofacies with sequences of laminated, storm-generated sands interlayered with bioturbated offshore muds described from the North Sea (Gadow & Reineck, 1969) and the Gulf of Gaeta (Reineck & Singh, 1971).

Deposition of storm-sand layers has been related to both wind-drift currents (e.g. Allen, 1982) and to density or traction currents generated by the storm-surge ebb (e.g. Mount, 1982). Nelson (1982) has recently suggested that both mechanisms act to varying degrees, depending on the strength of the storm; the storm-surge ebb is a feature of relatively rare but particularly strong storms. Storm-sand layers may also be deposited from storm-generated suspension clouds (Reineck & Singh, 1972; Kreisa, 1981). Any single sand layer may be the product of several storm events.

If, as seems most probable, the sand layers of Lithofacies 7 are storm products, then the mud layers were presumably deposited from suspension during fairweather. In instances where Lithofacies 7 is developed at the base of rhythms, some of the mud may have been reworked (perhaps during storms) from the uppermost terrigenous sediments of the

previous rhythm: this is suggested particularly by the occurrence of abundant comminuted plant material and a reworked palynoflora in interlayered sands and muds developed at the bases of many rhythms (Bradshaw, 1978; Fenton, 1980); Bradshaw's (1975, 1978) clay mineralogy studies also suggest reworking of sediment.

The lack of siliciclastic sand in sand-layers within this lithofacies in the Ardley and Irchester Members, in particular, reflects the reduced input of sand-grade terrigenous material into the east Midlands outcrop area during the hodsoni Zone. This was because the extensive transgression which initiated Rhythm C had largely drowned local source areas of sand-grade siliciclastics. Quartzose sand occurring within the lithofacies at the base of Rhythm C was probably reworked from earlier siliciclastic deposits, exposed around the margins of Brabantia, during this transgression.

In many instances the separate sand and mud layers of Lithofacies 7 were admixed by burrowing organisms. By comparison with similarly admixed lime sand/lime mud sediments, this bioturbation probably produced a substrate of increased stability which could be colonised by a greater variety of both burrowing and epifaunal invertebrates.

5.3.13 Lithofacies association D: Interbedded argillaceous, bioclastic lime muds and interlayered sands and terrigenous muds

Units of interlayered bioclastic sand and variably calcareous, terrigenous mud interbedded with units of argillaceous, often silty, biomudstone and biowackestone are characteristic of the Kallirhynchia sharpi Beds of eastern Northamptonshire, south of the Kettering-Peterborough Line. The interbedded units are typically between 0.10-0.40m thick and, at outcrop, weather from blue-grey to brown and

yellowish-grey to pale grey respectively; contacts between the limestones and the mudstones ('marls' of many authors) are usually gradational. The fauna of these beds is dominated by Kallirhynchia sharpi, Praeexogyra hebridica and Modiolus imbricatus; individuals are often articulated and unabraded. At some localities, a number of 'marl' and limestone beds may be seen to pass laterally into locally developed units of well-cemented, bioturbated and variably argillaceous pelbiopackstone or wackestone; these usually contain small coral colonies and other elements of Biofacies 5.

The argillaceous limestone units of this Lithofacies association are usually slightly nodular and, in thin section, are seen to be variably microsparitic. Bivalve and rhynchonellid debris predominates, but echinoderm and rare fish debris are usually also present; besides skeletal grains, rare to frequent pellets occur, and quartz silt and very fine grained sand may form up to 10%, by volume, of the whole rock. Ooids have not been observed in this facies association.

A large proportion of the limestone units within this facies association have been extensively bioturbated and, in these, both lime and siliciclastic sand have been thoroughly admixed with the lime mud matrix. Discrete trace fossils are usually not developed, the exception being Teichichnus, which has frequently been observed in these limestone units. Where burrowing has not completely destroyed primary depositional textures, thin layers of biopackstone and biograinstone/packstone may be visible within the limestones. Such layers are usually sharp-based and up to a few millimetres thick; they are usually dominated by extremely coarse grained rhynchonellid and oyster material.

The units of interlayered sand and terrigenous mud developed within this facies association are closely comparable to the interlayered

sand and mud of Lithofacies 9. They differ from the limestone units in containing predominantly terrigenous rather than lime mud and in being generally less bioturbated.

Lithofacies association D is an example of Hallam's (1975a) 'marl-limestone' sequences. As noted by Hallam, such sequences usually reflect both initial alternations in the pattern of sedimentation and also subsequent diagenetic modifications to the sequence. In this case, both 'marls' and limestones are predominantly fine-grained lithologies, deposited in a protected setting. The facies association probably resulted from an interdigitation of nearshore terrigenous muds with slightly more offshore lime muds and pelleted lime muds. The environment of deposition is envisaged as having been wholly subtidal: there is a lack of sedimentary structures (birdseyes, mudcracks, rootlets, etc.) indicative of intertidal or supratidal deposition and the fauna, although moderately restricted, contains organisms (rhynchonellids, rare corals) which could not have colonised intertidal flats. While mud deposition probably occurred most of the time, periodically the environment was affected by high energy events, thought to have been storms; these storms gave rise to the shell-dominated sand layers which are interlayered with both the lime and terrigenous mud. Shell debris was derived mainly from a local source. Locally, the lime sand and mud layers were admixed by burrowing organisms, thus producing a more stable sandy mud substrate readily colonised by epifaunal brachiopods and bivalves. Bioturbation is generally more extensive in the limestone layers. The Teichichnus encountered in this lithofacies association was probably produced by deposit-feeding organisms. This trace fossil is characteristic of subtidal areas of reduced turbulence/current activity, including quiet water lagoons (Fürsich, 1975).

5.3.14 Lithofacies association E: Homogeneous, terrigenous muds and fossiliferous, terrigenous muds

Apparently homogeneous, often carbonaceous, unfossiliferous muds and clays which dominate the upper parts of Rutland Formation rhythms (Bradshaw, 1978) characterise a lithofacies association rarely encountered within most of the White Limestone Formation but one which is locally important at the base of the Forest Marble Formation and is particularly evident within the Thrapston Clay Formation.

Often these clays are extensively rootletted (the abundance of Equisetites rootlets suggests a sphenopsid-dominated marsh flora) and contain a palynoflora consisting principally of pteridophyte miospores with Botryococcus, associated with abundant cuticle and vitrinite; microplankton is rare to absent (Fenton, 1980). These homogeneous muds were probably deposited on a widely established coastal marsh flat, perhaps comparable to the present day salt and brackish marine marshes which occupy a 50-65km wide belt parallel to the coast in the East Mississippi Embayment area (Treadwell, 1955). The sediments of most modern coastal plains are predominantly fine-grained, suspended load deposits (Reineck & Singh, 1973).

Both in the upper part of some Rutland Formation rhythms and within the Bladon Member in Oxfordshire, these rootletted, homogeneous muds are intercalated with erosively-based deposits of fossiliferous mud which invariably contain a mixture of freshwater and brackish floral and faunal elements. Shell material is typically broken and there may be winnowing, particularly associated with basal shell lags. The bases of these fossiliferous intercalations are frequently seen to be deeply scoured or swirled, and 'flames' of homogeneous mud may locally extend upwards into the fossiliferous mud. Any rootlets present in the

underlying muds are truncated at the erosive contact. Such contacts must be contemporary with deposition of the fossiliferous muds and, as suggested by Bradshaw (1978), they were probably a product of turbulent flow conditions. A storm-related origin is considered likely for the fossiliferous muds of this lithofacies association. The coastal marsh setting postulated for the homogeneous muds was probably flooded either from a seaward direction, perhaps when exceptionally strong onshore winds coincided with spring high tides, or from the adjacent hinterland when torrential rainfall may have induced an exceptionally high run-off. Mixing of water from both sources could account for the mixed salinity floral/faunal assemblages that are often found. This was the conclusion reached by Bradshaw (1978), who has interpreted the fossiliferous mud intercalations found towards the top of several Rutland Formation rhythms as storm-induced flash flood deposits.

Within the Bladon Member of the Cherwell Valley, a number of fossiliferous mud intercalations of the type described above are developed within the so-called 'fimbriatus-waltoni clays'. Mixed salinity floral/faunal assemblages occur in most of these deposits. At Kirtlington (Loc. 26), for example, these fossiliferous muds have yielded charophytes, brackish-freshwater ostracods (particularly Theriosynoecum kirtlingtonense and Timiriasevia mackerrowi), Valvata and large amounts of wood debris together with marginal marine bivalves such as Bakevellia waltoni, Eomiodon angulatus and Protocardia sp. (Bate, 1965; T. Palmer, 1974). The succession of fossiliferous muds and rootletted homogeneous muds at both Kirtlington and Shipton (Loc. 16) suggests that once each flood had subsided the marsh was once again colonised by horsetails, and further unfossiliferous muds accumulated.

Bright green clays (said to contain over 90% illite; T. Palmer, 1974) with swirled, erosive bases have been seen within the Bladon Member at both Shipton and Stratton Audley (Loc. 44). Although they contain abundant terrestrial plant material (including conifer logs) and Valvata, they lack a marine macrofauna in both instances. Therefore it is thought that these illite-rich clays represent flash-flood deposits involving no input of water from a seaward direction.

The absence of rootlets in the Thrapston Clay between Thrapston and Irchester suggests that here the homogeneous muds were not colonised by Equisetites; they may, therefore, represent coastal lake rather than marsh deposits. J. Taylor (1963) suggested that the brightly coloured clays of the formation in the Corby-Oundle region were fluvial in origin, and were perhaps deposited in "some enclosed basin or lagoon".

At a number of localities in Oxfordshire and southwest Northamptonshire, channels encountered at the tops of sedimentary rhythms have been filled by terrigenous muds assignable to this lithofacies association (Plate 13). The channels typically have a basal lag of logs, while rootlets are frequently present towards the top of the channel fill. Dinosaur remains, particularly bones of the giant sauropod Cetiosaurus, have, in the past, been found at the base of such channels. These channels were probably cut during the late stages of regression by streams or tidal channels which dissected the coastal plain. Usually they are up to about 1m deep; apparent widths range up to 15m, but this figure depends on the angle of section through the channel. Often channels are seen to cut down only as far as the top of an underlying limestone bed. Such limestone beds were probably already lithified when the channel was eroded. Modern tidal channels of the peritidal belt

around Andros similarly cut down only to the top of the underlying lithified Pleistocene limestone (Shinn et al., 1969).

It is thought that these mud-filled channels were passively infilled following abandonment, which possibly occurred as a result of either chute cut-off or neck cut-off (Reineck & Singh, 1973). By comparison with present day siliciclastic channel fills, initial sedimentation in the abandoned channels was probably rapid, but is likely to have slowed later. The channel fills may have been thinly laminated originally, but laminations are not visible in the weathered sections which have been examined. Channel filling may have been largely the result of overbank flows (Reineck & Singh, op. cit.). Channels of this type have been seen only at the top of the Ardley Member, within the Bladon Member and at the White Limestone/Forest Marble junction.

CHAPTER 6

FAUNA OF THE UPPER GREAT OOLITE GROUP

6.1 Introduction

A variety of shallow marine through to freshwater environments are represented within Bathonian sediments cropping out in northern France, England and Scotland. Within these sediments a broad pattern of faunal change related to the transition from 'normal' marine through increasingly less marine environments into brackish, hypersaline and freshwater conditions can be recognised. The faunal changes do not relate only to salinity changes but to increasing environmental stress (see sub-section 6.2.3).

The most diverse Bathonian faunas are found in sediments deposited in 'normal' marine environments where the sea floor provided a firm substrate (firmgrounds and hardgrounds; sandy muds and muddy sands): in Middle and Upper Bathonian shelf carbonates of Normandy and, to a lesser extent, in the Cornbrash, Fuller's Earth Rock and parts of the Forest Marble of southern England. The Upper Bathonian limestones of Normandy, in particular, contain a rich diversity of stenotopic benthic taxa such as sponges, brachiopods, bryozoans and echinoderms (T. Palmer, 1974; Palmer & Fürsich, 1981). Similar, but less diverse, faunas occur locally within the Forest Marble of southern England ('Bradfordian' faunas).

At the restricted end of the marine spectrum (brackish or hypersaline environments such as those represented within the Great Estuarine Group, Brora Coal Formation and Rutland Formation), abundant, but low diversity, macrofaunas (dominated by bivalves and subordinate

gastropods) are found. Where environmental stress is thought to have been greatest, faunas may be reduced to only a few of the most eurytopic species of bivalve, or even to monospecific bivalve assemblages (e.g. Bradshaw, 1978).

The majority of faunas encountered within the upper Great Oolite Group of the east Midlands, with the exception of those found in the Cornbrash, are those of intermediate stress, less than 'normal' marine environments. They are typified by moderate species diversity, are dominated by molluscs, and contain only hardy representatives of stenotopic, benthic taxa such as brachiopods, bryozoans and echinoderms. Ammonites and belemnites are largely absent from the upper Great Oolite Group, beneath the Cornbrash, in eastern and central England.

In this chapter the fauna of the upper Great Oolite Group of the study area is discussed. The palaeoautecology of different elements of the fauna is outlined in subsection 6.3, following a discussion of the environmental controls on faunal distribution in section 6.2. Relevant taxonomic comments are also made in section 6.3. Finally the main faunal associations or biofacies encountered during the course of this study are described in section 6.4.

6.2 Environmental controls on faunal distribution

6.2.1 Physical controls

6.2.1.1 Temperature

Water temperature is an important limiting factor controlling the distribution of some organisms in today's seas, and may also have been a control on faunal and floral distribution in the Jurassic; certainly

Elliot (1977) related the paucity of calcareous algae in English Middle Jurassic limestones to northwards cooling. Generally, however, it is difficult to ascertain the degree to which temperature affected Bathonian faunal distribution within the confines of my study area. Temperature variation through the area is more likely to have been related to water depth rather than to climatic changes. Both Hallam (1976) and Hudson (1980) have indicated that water temperature was unlikely to have been a significant control on local faunal distributions in the Jurassic.

6.2.1.2 Salinity

At the present day, both the mean salinity and range of salinities tolerated by different taxa vary considerably; those taxa with a narrow tolerance range are termed 'stenohaline', those tolerant of a broad range are 'euryhaline' (Raup & Stanley, 1971). The majority of marine species are stenohaline and live in offshore areas, where they are never subjected to major variations of salinity. Species diversity decreases in areas where salinities higher or lower than 'normal marine' (c.35⁰/oo) are developed, since relatively few species are adapted to live in either hypersaline or brackish water.

It is generally accepted that most corals, cephalopods, bryozoans, articulate brachiopods and echinoderms have always been stenohaline marine organisms, whereas ostracods, bivalves and gastropods have long inhabited a wide spectrum of environments, from fully marine, through brackish to freshwater; many species of the latter are thought to have been euryhaline in the past, as at the present.

Salinity was undoubtedly an important limiting factor in the Bathonian seas of the British area and, in the Great Estuarine Group of the Hebrides, was probably the major control on faunal distribution and

diversity (Hudson, 1963a, 1980). The control exerted by salinity in the Great Oolite Group of the area studied is discussed further in section 6.2.3.

6.2.1.3 Substrate

The work of Newell et al. (1959) and Purdy (1963) on the Great Bahamas Bank shows us how closely the distribution of benthic faunal communities may be tied to the occurrence of particular carbonate sediment types. T. Palmer's (1979) faunal study of the White Limestone in Oxfordshire and my own research confirm this is the case in the Bathonian of central and eastern England. Many of the biofacies identified in this study are closely associated with specific lithofacies, although the exact composition of a given community also reflects the effect of limiting factors such as salinity. This indicates an important link between the distribution of benthic communities and the combined effect of substrate and turbulence.

Substrate is important in relation to the method of attachment and locomotion of benthonic animals, and there is a close connection between sediment-type and different feeding mechanisms employed by organisms (Sanders, 1956; Raup & Stanley, 1971). For example, Rhoads & Young (1970) suggested that soft, soupy substrates are severely limiting to most suspension feeders, while Hallam (1976) noted that the dominant Jurassic bivalves occurring in non-silty, mud-grade sediment are ones adapted to resist sinking into the mud and deposit-feeding protobranches.

The firmness of the substrate appears to have been a particularly important factor controlling the distribution of biofacies in the upper Great Oolite Group. The least stable substrates were the shifting, winnowed sands of high energy settings and the thixotropic muds and

pelletal muds of low energy environments. Sands were rendered increasingly stable by an admixture of mud (often by bioturbation) or, less commonly, as a result of intergranular cementation; muds were made firmer by admixture of silt or sand-grade sediment or, occasionally, by interstitial cementation. In general, the most diverse faunas were associated with firm substrates: a shallow and deep burrowing infauna and varied epifauna usually colonised firm sandy muds/muddy sands, provided that other environmental controls were favourable. In addition to the communities adapted to firm, soft or shifting substrates, certain organisms were restricted to, or most frequently associated with, hard substrates.

6.2.1.4 Other physical controls

Turbidity, turbulence, and light intensity are among the other physical factors which may have exerted an influence on the distribution of the Bathonian fauna/flora of the study area. Of these, the effects of turbulence and turbidity are usually difficult to disentangle from those of substrate (Hallam, 1976). However, an abundance of clay in suspension appears to have produced an environment unsuitable for bryozoans (e.g. P. Taylor, 1977) and perhaps also for most corals. Light intensity may have affected the distribution of photosynthesising algae and organisms, such as corals, which had a symbiotic association with such algae, but in the shallow Bathonian seas of the study area, variations in light intensity would have been a function of turbidity rather than water depth. The oxygen content of the water is not thought to have exerted an influence on fauna/flora distribution: both the sea floor and the sediment immediately below the sediment-water interface are believed to have been permanently oxygenated.

6.2.2 Biotic controls

6.2.2.1 Food availability

It is unlikely that in the shallow Bathonian seas of the east Midlands, populations were food-limited, for they appear not to be in modern shallow water regimes. However, in any given environment, one species would frequently have been out-competed for food and/or other resources (e.g. space, light) by another species. This would have been the case particularly in low stress environments in which populations were biologically-accommodated. This may explain the virtual absence of many eurytopic species from high-diversity assemblages, although the same species occur in large numbers in high-stress, restricted assemblages.

6.2.2.2 Predation

While predation plays an important role in determining the composition of present day benthonic communities, it is impossible to estimate how predation shaped Bathonian communities in the east Midlands. The fossil record of predatory taxa is very variable: thus carnivorous gastropods occur relatively frequently, but rays and asteroids, which may have been the most important predators in the restricted seas of the east Midlands, have a poor or patchy fossil record. It seems unwise to speculate on precise predator-prey relationships, as did T. Palmer (1973) with Pholadomya and Globularia in the White Limestone at Ardley, when the fossil record is so incomplete.

6.2.3 Environmental stress

In recent years emphasis has been placed on the control exerted on restricted marine faunas by the instability of the physical environment rather than on the effect of an individual limiting factor. The degree of stability of the physical factors controlling an environment is termed 'environmental stress', with high stress environments characterised by less stability than low stress environments (e.g. Sanders, 1968).

The physically-controlled populations of high stress environments, unlike stable, biologically-accommodated populations, frequently do not fully exploit the available food and space resources. Thus those eurytopic organisms which are able to survive in stressful environments proliferate, even to the extent of forming dense populations dominated by a single species. The almost monotypic shell beds which occur in the Rutland Formation (Bradshaw, 1978) and Great Estuarine Group (Hudson, 1980) are examples of such populations. The eurytopic organisms which occur in these shell beds are 'opportunists', comparable to those described by Levinton (1970). Invariably they are non-specific feeders which have high reproductive rates. In the upper Great Oolite, opportunistic behaviour appears to have been exhibited to varying degrees by Kallirhynchia sharpi, Praeexogyra hebridica and Modiolus imbricatus in the Kallirhynchia sharpi Beds, by Bakevellia waltoni and Eomiodon angulatus in the Bladon Member and by P. hebridica and Placunopsis socialis in the Forest Marble and Longthorpe Member. In general terms, however, the high stress environments of the upper Great Oolite Group were apparently less stressful than those of the lower part of the group (Bradshaw, op. cit.); populations are therefore slightly more diverse and characterised to a lesser degree by opportunistic species. As suggested

by Hudson (1980), fluctuations in salinity were probably the major feature of high stress, restricted, brackish-marine Bathonian environments.

6.3 Life habits and taxonomic comments

In the following section, the palaeoautecology of the most important elements of the upper Great Oolite Group fauna are discussed; taxonomic comments are made where deemed appropriate. In some cases, brief comments are made on the life habits and distribution of a particular group of organisms rather than on individual species within that group.

6.3.1 Corals

Only a few genera of corals occur in the upper Great Oolite Group of the study area; they are largely absent from the Forest Marble or Cornbrash, unknown in the Thrapston Clay, and only sporadically distributed in the White Limestone.

Chomatoseris orbulites (Lamoureux)

This small, solitary microsolenid is common in bioturbated grainstones and packstones within the White Limestone (particularly in Lithofacies 2 and 3). It occurs less frequently in more micritic lithologies, although Chomatoseris is occasionally found in packstone/wackestones of Lithofacies association B.

Chomatoseris has been compared with the Recent, free-living fungiids, Diaseris distorta (T. Palmer, 1974) and Cycloseris (Gill & Coates, 1977), both of which can migrate, unbury and right themselves (e.g. Hubbard, 1972). Chomatoseris, which is morphologically very similar to Cycloseris, is envisaged as having been 'auto-mobile' and

therefore able to colonise shifting lime sands (Gill & Coates, op. cit.); however, an active burrowing existence (cf. Sellwood, 1978) is thought unlikely. The close similarity of the sediments in which Chomatoseris and Cycloseris are found further indicates that their life habits are comparable.

'Isastraea' sp.

In view of McKerrow et al.'s (1969) discovery that corallites of both 'Thamnasteria' and 'Isastraea' sometimes occur together on the same specimen, no attempt has been made here to separate corals with thamnasteroid corallites from the more common 'Isastraea'; the two genera are kept separate by Jurassic coral workers (e.g. Negus, 1983). Specific identification of 'Isastraea' has not been undertaken. Colonies of 'Isastraea' exhibiting both branching and massive growth forms have been found within the upper Great Oolite of the study area. Branching colonies usually dominate Biofacies 5, whereas the massive growth form is more characteristic of higher energy environments and is, therefore, more normally associated with better-washed, coarser-grained sediments.

6.3.2 Bryozoa

Modern cyclostomate ectoprocts are stenohaline animals and Middle Jurassic ectoprocts were probably also stenotopic; bryozoans occur only in the most marine Bathonian sediments (particularly limestones) of eastern and central England. While the 'normal' marine Upper Bathonian limestones of Normandy or the 'Bradfordian' faunas of the Forest Marble of southern England contain a rich diversity of bryozoans (the 'Bradford Clay' of Canal Pit, Bradford-on-Avon has yielded at least 16 different species; P. Taylor, 1977 & in litt., 1983), only a very small number of species occur in the White Limestone or Forest Marble (other than in

'Bradfordian' faunas) of the Midlands. Most common in the White Limestone of Oxfordshire and Northamptonshire are bereniciform bryozoans generally referred to 'Berenicea' but invariably belonging to the genus Hyporosopora (P. Taylor, in litt.). The relatively common occurrence of H. parvipora (Canu & Bassler), together with H. sauvagei (Gregory), not only in the White Limestone but also in the Hampen Marly Formation (T. Palmer, 1974) and Wellingborough Rhythm of the Rutland Formation (Bradshaw, 1978), suggests that this genus was the most eurytopic of Bathonian ectoprocts. Within the White Limestone of the east Midlands, Hyporosopora has been found particularly with other stenotopic taxa in Biofacies 4 in the Irchester Member; it is considerably less common in the Kallirhynchia sharpi Beds. In addition to bereniciform types, T. Palmer (1974) recorded Stomatopora within his study area, in sheltered environments such as amongst coral rubble. I have found the same genus encrusting the sides of a burrow within the hardground which caps the Ardley Member at Ardley (Loc. 30).

6.3.3 Echinoids

Acrosalenia sp.

Acrosalenia may have been the most eurytopic Bathonian echinoid, for it is the only genus found in Rutland Formation rhythms in the east Midlands (Bradshaw, 1978). It was an epifaunal, mobile algal grazer, believed to have been responsible for the stellate trace Gnathichnus pentax (Bromley, 1975) found on shells in a number of environments in both the White Limestone and Forest Marble.

Frequently, Acrosalenia is represented only by disarticulated spines, but complete specimens have been encountered in a number of different lithologies/biofacies, in particular in Lithofacies association

B. Thin horizons packed with whole Acrosalenia have been recorded from the White Limestone (T. Palmer, 1974) and the Wellingborough Member (Aslin, 1968). Rather than reflecting opportunistic behaviour, these occurrences probably reflect the tendency of echinoderms to 'swarm'. In both instances, the Acrosalenia are thought to have been buried and killed by a sudden influx of sediment.

Separate species of Acrosalenia (A. hemicidaroides, A. pustulata) have not been identified in this account.

Nucleolites sp.

Nucleolites was an early and fairly primitive cassiduloid which occurs commonly in the White Limestone and Cornbrash in eastern England, but is unknown in either the Rutland Formation or Forest Marble; it was, with Clypeus, one of the least stenotopic of Bathonian irregular echinoids, although probably less tolerant of environmental stress than the regular echinoid Acrosalenia. Scurry (1979) recorded three species of Nucleolites in the Bathonian of the Cotswolds and eastern England; however, as all three species occur in similar faunal associations and probably had comparable life habits, separate species have not been distinguished in this account.

The living cassiduloid 'Apatopygus recens, known from the shelf seas around New Zealand (Higgins, 1974), can be used as an analogue for Jurassic Nucleolites (Scurry, op. cit.). This species is a shallow burrowing deposit feeder which typically lives in coarse, gravelly sediments. The species is able to burrow completely beneath the surface of the substrate without maintaining any apparent connection with the overlying water column, presumably because the porous nature of the substrate obviates the need for the animal to construct a respiratory burrow; thus Kier's (1962) hypothesis that cassiduloids, because they

lack tube feet, can only partly burrow, up to the edge of their petals, appears to be inaccurate. However, Nucleolites in the White Limestone occurs most frequently in wackestones, packstones and grainstones/packstones; since such substrates may not have been porous enough to allow Nucleolites to completely burrow, T. Palmer's (1974) suggestion that the genus ploughed through the surface layers of the sediment with its ambulacra exposed above the sediment-water interface may be partially correct. In the Cornbrash, Nucleolites occurs in a variety of lithologies, including medium to coarse grained lime sands into which the genus may have been able to burrow deeper.

Clypeus muelleri Wright

Clypeus muelleri occurs most frequently in muddy lime sands (grainstone/packstones and packstones) in the White Limestone; it has not been recorded in the Thrapston Clay, Forest Marble or Cornbrash. T. Palmer (1979) compared Clypeus with the present-day 'sand dollar' Clypeaster rosaceus and suggested that it was a detritus-feeder which ploughed through the soft sediment, either just below or at the sediment-water contact. The flattened test was useful in that it enabled the echinoid to more easily cover itself with sediment. This not only acted as camouflage, but also as a source of food: modern 'sand dollars' have thousands of accessory tube feet which collect the organic material from the sand as it passes over the test (Kier, 1974).

Holactypus depressus (Leske)

The palaeobiology of this irregular echinoid, which occurs frequently in the Cornbrash but more rarely within the White Limestone in Northamptonshire and Oxfordshire, has recently been reviewed by A. Smith (1984). Smith concluded that H. depressus was a fairly unselective deposit feeder which used only its Aristotle's lantern to gather in

sediment. It had relatively few tube feet (none of which specialised in gas exchange) and therefore probably a low metabolic rate. Unlike either Clypeus or Nucleolites, which probably constantly ploughed through the sediment, H. depressus, by comparison with the similar, extant holotypoid Echinoneus, may have been nocturnal: sedentary within the sediment during the day and active at the substrate/water interface in the cool of night. Holactypus was apparently more stenotopic than Clypeus and Nucleolites, although when present it appears to have colonised the same substrates as the latter: particularly bioturbated muddy lime sands and sandy lime muds.

6.3.4 Brachiopods

Epithyris sp.

Prior to Pittham's (1970) work in Northamptonshire, the terebratulids of the White Limestone in the east Midlands had been assigned to at least five different genera (Terebratula, Epithyris, Kutchithyris, Avonothyris, Stiphrothyris). However, although they exhibit considerable external variation, they were found by Pittham to have consistent internal features and he ascribed them all to a single new species, 'Avonothyris cranfordensis'. Pittham (op. cit.) stated that none of the Northamptonshire terebratulids he studied showed hinge plates or cardinal processes which could be regarded as epithyrid, but instead they had avonothyrid hinge plates, crura, musculature and brachidia. Pittham did note, however, that some specimens also possessed features characteristic of Cererithyris.

In the Oxfordshire White Limestone, terebratulids exhibiting what appears to be the same range of external morphologies as 'A. cranfordensis' are usually referred to 'Epithyris oxonica', less

frequently to 'Stiphrothyris capillata'. It is probable that the latter two 'species' are, in reality, end-members of a single, highly variable species. Further work is required on the Oxfordshire terebratulids, and particularly on their internal characteristics, to demonstrate whether or not they belong to the same species as Pittham's terebratulids.

Details of the hinge structure of either 'E. oxonica' or 'S. capillata' have not, as yet, been published. However, Bradshaw (1978) noted that some sectioned terebratulids in the McKerrow collection have the generic characteristics of both Epithyris and Avonothyris. The true status of the genera Epithyris, Cererithyris, Stiphrothyris and Avonothyris may, therefore, be in doubt.

In view of the uncertainty surrounding the validity of the species 'S. capillata', 'E. oxonica' and 'A. cranfordensis', terebratulids encountered in the White Limestone and Forest Marble of the study area have not been identified down to a specific level; they have, somewhat arbitrarily, been assigned to Epithyris, pending further research.

Epithyris sp. occurs most frequently in Biofacies 4 and 5, associated with muddy sand and sandy mud lithologies (which formed stable substrates). Juvenile Epithyris may have initially attached themselves to hard substrates (shell debris, coral, other Epithyris). Bradshaw (1978) suggested that the transapical foramen and reinforced pedicle opening of Epithyris indicates that they were well adapted to moderate energy conditions. Locally, Epithyris occurs in nests in the White Limestone (T. Palmer, 1974; Bradshaw, 1978); in these nests, both juveniles and mature adults usually occur together; they appear to represent in situ colonies. A fine example of such an Epithyris nest occurs in the Ardley Member (Lithofacies association B) at Wood Eaton.

More often, however, Epithyris occurs more evenly distributed throughout a particular bed, probably reflecting some degree of current dispersal (cf. Ager, 1965).

Cererithyris intermedia (J. Sowerby)

C. intermedia is restricted to the Lower Cornbrash, where it is associated with muddy lime sands and sandy lime muds; transported specimens occur in better washed sands (grainstones/packstones). Although nests of C. intermedia have not been observed, the species probably had similar life habits to the Epithyris sp. of the White Limestone and Forest Marble; it too was probably well adapted to moderate energy conditions.

Ornithella thrapstonensis Pittham MS.

In Northamptonshire, ornithellids occur sporadically in the Kallirhynchia sharpi Beds, from Irchester northwards, and less commonly at certain horizons within the Irchester Member, particularly about Cranford and Twywell. Pittham (1970) found that these belong to a single species, which he named Ornithella thrapstonensis, using a specific name coined in MS. by Helen Muir-Wood. Ornithellids obtained from the White Limestone at Ancaster (Torrens, 1967) and Lincoln (Batters, 1939) probably belong to the same species.

O. thrapstonensis is known only from the White Limestone of the east Midlands, where it is usually associated with predominantly fine-grained sediments, particularly with variably argillaceous, sandy lime muds. It was probably intolerant of both high energy environments and unstable substrates; certainly this is suggested by its small pedicle opening. Its absence from the Oxfordshire White Limestone may have been largely the result of increased turbulence and the widespread development

of unfavourable substrates (e.g. soupy muds or shifting sands) further southwest.

Obovothyris obovata (J. Sowerby)

I agree with Douglas & Arkell (1928) in considering that the ornithellids named 'O. grandobovata' by Buckman (1927) were, in reality, gerontic specimens of O. obovata. This species is restricted to the Lower Cornbrash and it was undoubtedly stenotopic. Its distribution suggests that it colonised different environments to C. intermedia: possibly more protected parts of the sea floor.

Digonella digonoides (S. Buckman)

Digonella digonoides has only been found in the study area in the White Limestone, in Lithofacies association B and related sediments developed in the Ardley and Irchester Members. This restricted distribution suggests that the species was stenotopic; it, like other Bathonian articulate brachiopods, was probably restricted to stable substrates.

D. digonoides may have colonised the flanks of the sand bars represented in Lithofacies association B (see 5.3.5), particularly where sand and mud-grade sediment had been admixed by bioturbation; this was probably a periodically moderate to high energy environment. The local occurrence of clumps of undamaged, cement-filled specimens in the cross bedded lime sands of this facies association (e.g. Pittham, 1970) suggests that occasional storm events of greater than usual strength sometimes dislodged populations of D. digonoides and brought about their rapid burial nearby. The axiniform morphology which D. digonoides possesses was thought by Ager (1965) to be an adaptation to increase oxygen absorption in species living on a poorly oxygenated, very quiet sea

floor; however, the distribution of the species in the White Limestone suggests that this hypothesis may be incorrect.

Kallirhynchia sharpi Muir-Wood

The highly variable, small and widely distributed rhynchonellids found in the lower part of the east Midlands White Limestone, particularly in Northamptonshire, were shown to be a single species by both Muir-Wood (1938) and Pittham (1970). This species, Kallirhynchia sharpi, is not known outside the east Midlands. It appears to have favoured relatively low energy and possibly slightly less than normal marine environments; Bradshaw (1978) has even suggested that it was something of an environmental opportunist.

For the most part, K. sharpi occurs scattered throughout individual beds, dispersed by gentle current activity. Sometimes, however, in situ clumps of K. sharpi occur in which a number of generations are present. At Wellingborough No. 5 Pit (Loc. 124), K. sharpi occurs together with Praeexogyra hebridica in an in situ oyster-rhynchonellid bank. The rhynchonellids in this bank may have been pedically-attached to both oysters and modiolids, in the same way that Terebratulina living today off northwest Scotland attach themselves to large Modiolus (G.B. Curry, pers. comm.). There is no way of knowing if, elsewhere, K. sharpi also attached themselves to soft, non-preserved organic material (cf. Rudwick, 1970) or to shell debris, as Bradshaw (1978) suggested.

North of the Kettering-Peterborough Line, K. sharpi is patchily distributed due to the local development of higher-energy environments (represented by grainstone/packstone lithologies) in the lower part of the White Limestone. It is not certain whether the rhynchonellids found the increased levels of turbulence or the less stable substrates more

inhospitable. The absence of K. sharpi from the White Limestone southwest of Pury End was probably related both to higher levels of turbulence and to increased competition from a more diverse collection of epifaunal species, including Epithyris and Burmirhynchia.

Kallirhynchia yaxleyensis (Davidson)

K. yaxleyensis occurs only rarely in the Lower Cornbrash of Oxfordshire and the east Midlands, although it is abundant in the member in southwest England (Douglas & Arkell, 1932). This northeastwards decrease in abundance may reflect a relative stress gradient of the sort Bradshaw (1978) described in the Wellingborough Rhythm; however, it may equally be related to changes of lithofacies, degree of turbulence or of some other environmental control.

Burmirhynchia sp.

Large rhynchonellids in the Great Oolite Group of Oxfordshire and the east Midlands have been assigned either to Burmirhynchia or to Kallirhynchia since the work of Buckman (1918): T. Palmer (1979) adopted Buckman's name 'Kallirhynchia concinna' for forms occurring in the White Limestone in Oxfordshire; similar forms occurring in the Northamptonshire White Limestone (which belong to a single species) were named 'Burmirhynchia beebyi' by Pittham (1970). Although the holotype of 'K. concinna' came from the Wellingborough Member of Aynho, Bradshaw (1978) preferred to include Wellingborough Member rhynchonellids in Burmirhynchia, following Pittham (op. cit.), who had included rhynchonellids from the Wellingborough Member at Hopping Hill in his new species, and Buckman (op. cit.), who had named Wellingborough Member species from Roade as 'Burmirhynchia dromio'. A comprehensive review of these large rhynchonellids and the status of Kallirhynchia and Burmirhynchia is long overdue (Bradshaw, 1978). However, without

undertaking this taxonomic work, it is extremely difficult to separate 'B. beebyi' or 'B. dromio' from 'K. concinna'; they may all belong to the same species and have therefore not been separately identified in this thesis. I have followed Pittham by identifying large upper Great Oolite Group rhynchonellids as Burmihynchia, but have not identified them to a specific level.

Burmihynchia sp. (including K. concinna of some authors) is, like K. sharpi, frequently associated with oyster reefs and oyster-rich sediments, particularly in the lower Great Oolite Group, in the Forest Marble and in the Duntulm Formation of the Inner Hebrides (e.g. T. Palmer, 1974, 1979; Hudson, 1963b, 1980; Bradshaw, 1978). It was apparently tolerant of minor reductions or variations in salinity (cf. Ager, 1965).

6.3.5 Bivalves

Arca (Eonavicula) subminuta (J. de C. Sowerby)

Stanley's (1970) suggestion that, prior to the Cretaceous development of free-burrowing arcoids, all forms led an epifaunal, byssally-attached, filter-feeding existence and the elongated, flattened ventral margin of A. (E.) subminuta (Bradshaw, 1978) support T. Palmer's (1979) conclusion that this species led an 'adpressed, byssate' mode of life. Within the White Limestone, A. (E.) subminuta has been found most commonly in coral beds; there, the species occupied a sheltered habitat amongst the coral branches (T. Palmer, 1974, 1979; Hallam, 1976).

A. (E.) subminuta is apparently uncommon in the Northamptonshire White Limestone, even in coral beds, but this may be the result of collection failure. The restriction of the species within the Rutland Formation to the southern outcrop of the Wellingborough Rhythm (Bradshaw,

1978) probably resulted at least as much from the lack of suitable niches (i.e. coral beds) further northwest as to an environmental stress gradient.

T. Palmer (1979) recorded Barbatia pratti (Morris & Lycett) from the Shipton Member at Croughton, but without the evidence of well-preserved hinge teeth it has not proved possible to separate this species from A. (E.) subminuta on the grounds of external morphology alone.

Parallelodon hirsonensis (d'Archiac)

The extreme elongation and rostrate posterior extremity of P. hirsonensis have led to this species being interpreted as having lived tightly pressed against the substrate, held by a strong byssus (e.g. T. Palmer, 1979). The species occurs particularly in grainstones and grainstone/packstones; in life it probably byssally-attached to shell debris (cf. Sellwood, 1978). As Bradshaw (1978) noted, the thick shell of P. hirsonensis provided the species with protection in a high-energy environment. Parallelodon bynei Cox & Arkell, which T. Palmer (1979) recognised in the Ardley Member in Oxfordshire, has not been separately identified in this account.

Arcomytilus asper (J. Sowerby)

This stenotopic mytilid, which is common in 'Bradfordian' faunas, was recorded from an oyster bed supposedly developed at the top of the 'Blisworth Clay' (=Thrapston Clay) at Sudbrooke, Lincolnshire (Loc. 204; Douglas & Arkell, 1932); however, regional facies considerations suggest that this bed must belong to the Lower Cornbrash (i.e. is of discus Subzone age), despite Cox & Arkell's (1948-50) comments that nowhere had they found this species in the Cornbrash. The top of the Thrapston Clay

elsewhere in this area is markedly regressive, typically comprising rootletted, unfossiliferous clays.

Cox & Arkell (op. cit.) noted that A. asper occurs in the White Limestone at Felmersham, Wymington and Blisworth; all of these occurrences were probably in Biofacies 4/Lithofacies association B. The reduced anterior and low point of maximum width characteristic of Arcomytilus suggests that the genus was epifaunal, probably a byssally-attached filter feeder (T. Palmer, 1974). However, Arcomytilus retained a rudimentary anterior extension (less pronounced than in Modiolus) and this anterior lobe may have been partially buried in the substrate (Seilacher, 1984).

Falcimytilus sublaevis (J. de C. Sowerby)

F. sublaevis is another stenotopic mytilid occasionally found in the White Limestone of the study area. It, like A. asper, was probably an epibyssate suspension feeder.

Modiolus (Modiolus) imbricatus J. Sowerby

M. (M.) imbricatus is common in most British Bathonian marine formations, except in lithologies interpreted as representing unstable, shifting lime sand substrates. Its widespread occurrence in Rutland Formation rhythms (Bradshaw, 1978) suggests that it was a relatively eurytopic species. Hudson (1963b) collected small 'M. cf. imbricatus' from three horizons in the Great Estuarine Group; while these horizons were among the most marine horizons encountered by Hudson in the Great Estuarine Group, they probably represent environments of greater physical stress than are generally found within the White Limestone. This may account for the small size (typically 30mm in length; Hudson, 1980) of the Great Estuarine forms.

McKerrow et al. (1969) referred M. (M.) imbricatus to an epifaunal mode of life; however, the high position of maximum shell width and inflated anterior suggest a semi-infaunal existence (cf. Stanley, 1970, 1972; Seilacher, 1984). M. (M.) imbricatus occurs commonly to abundantly in oyster reefs and oyster-rich sediments in the Hampen Marly Formation (T. Palmer, 1979), in the Rutland Formation (Bradshaw, 1978) and in the K. sharpi Beds. However, the largest examples of the species have been collected from Biofacies 4, particularly from the Ardley and Irchester Member: specimens up to 60mm in length were collected at Roade (Loc. 104).

Inoperna plicatus (J. Sowerby)

Like M. (M.) imbricatus, I. plicatus was probably endobyssate; its anterior end is likely to have been buried deeper. The species was certainly stenotopic, for it appears to be largely restricted to Biofacies 4/Lithofacies association B, developed within the Ardley/Irchester Member. Bradshaw (1978) reported I. plicatus to be entirely absent from the Rutland Formation.

'Lithophaga' sp.

T. Palmer (1974, 1979) has noted that many of the boring bivalves in Middle Jurassic hard substrates, called Lithophaga in the past, are actually a myoid, Gastrochaenopsis. However, for simplicity's sake, Lithophaga and Gastrochaenopsis have not been separated in this work; as frequently only the crypts remain, either hollow or filled by terrigenous or lime mud, it is often not possible to recognise whether the borers responsible were mytilids or myoids.

'Lithophaga' was restricted to hard substrates of either inorganic (hardgrounds, pebbles) or organic origin. Coral rubble and

areas of dead coral were particularly colonised, although use was also made of thick-shelled bivalves (e.g. Lopha marshii).

Pinna sp.

P. odlingi Arkell, P. subcancellata Lissajous and P. cuneata Phillips have not been distinguished in this account. Like Recent Pinna, the Bathonian examples were probably semi-infaunal, byssally-attached filter feeders (cf. Stanley, 1970; T. Palmer, 1974, 1979; Bradshaw, 1978). The genus occurs sporadically in the White Limestone (frequently in life-position, orientated with its longest dimension sub-vertical), particularly in Bladon Member coral bed communities. Exhumed and transported examples occur infrequently in the 'fimbriatus-waltoni clays' of the Cherwell Valley (McKerrow et al., 1969; T. Palmer, 1979).

Stegoconcha ampla (J. Sowerby)

This large pinnid was recorded by Cox & Arkell (1948-50) in the White Limestone of Farthingstone, Wellingborough and Bedford. During the course of my study several specimens were found in life-position in a bioturbated biointrapackstone developed towards the base of the Irchester Member at Twywell (Loc. 141) and a further specimen was recorded in situ in the Irchester Member at Irchester (Loc. 122). The species appears to be an uncommon member of Biofacies 4; it may have been endobysate rather than, as Seilacher (1984) suggested, an epibysate 'edgewise recliner'.

Bakevellia (Bakevellia) waltoni (Lycett)

Within the White Limestone, B. (B.) waltoni is particularly common in the Bladon Member, occurring both as transported individuals in the 'fimbriatus-waltoni clays' and as autochthonous specimens in Lithofacies 5. The species also occurs in the latter lithofacies in the Ardley and Irchester Members in the study area (e.g. T. Palmer, 1974; Cox & Arkell, 1948-50), and in the upper Forest Marble in Wiltshire (Lycett,

1863; Cox & Arkell, op. cit.; Holloway, 1981). That the species was eurytopic is indicated by its widespread occurrence in all rhythms of the Rutland Formation (Bradshaw, 1978). Bakevellia appears to have been adapted to hostile environments at least as far back as the Permian for, in Co. Durham, the genus occurs in restricted faunas in the Zechstein I (D. Southwood, pers. comm.).

T. Palmer (1979) interpreted B. (B.) waltoni as a free-swinging, byssate bivalve. It may have attached itself to soft-bodied organisms, just as Recent species of Pteria often live byssally-attached to alcyonarian sea whips (Stanley, 1972). However, Bradshaw (1978) suggested that the greater weight of B. (B.) waltoni would have militated against such a life habit.

Costigervillia crassicosta (Morris & Lycett)

C. crassicosta was said to be widely distributed within the White Limestone of Oxfordshire and Northamptonshire by Cox & Arkell (1948-50), although I have not found it to be common in the east Midlands. Where it does occur, it shows a marked preference for firm substrates, being most common in Biofacies 4 (cf. T. Palmer, 1979). While the left valve of this species exhibits a rather feeble convexity, the right valve is flat; comparable highly inequivalve, Recent pteriaceans are typically byssate and pleurothetic (Stanley, 1970) and it is likely that C. crassicosta similarly reclined with its commissure parallel to the substrate. The strongly sculptured right valve probably increased adhesion to the substrate (Seilacher, 1984). Bradshaw (1978), on the basis of its restricted distribution within the Rutland Formation, considered this species to have had a low tolerance of environmental stress.

'Gervillella' ovata (J. de C. Sowerby)

Bradshaw (1978) has questioned the generic affinities of this species and has suggested that it belongs to neither Gervillella nor to Frenaix's (1965) Virgellia. Whatever its true taxonomic position, it was both eurytopic and opportunistic (Bradshaw, op. cit.). The species is uncommon in the White Limestone, although T. Palmer (1979) recorded it in non-coraliferous sediments of the Shipton Member at Croughton. It was probably epibyssate, orientated with its saggital plane at less than 45° to the substrate.

Pulvinites mackerrowi Palmer

This species has recently been described by T. Palmer (1984). It was a stenotopic, byssate bivalve, apparently restricted, in the White Limestone, to examples of Biofacies 4 and 5 developed in the Ardley, Bladon and Irchester Members. Bradshaw (1978) recorded the same species (as 'Hypotrema') in Lithofacies association B sediments developed in the Wellingborough Member at Helmdon. P. mackerrowi lived closely adpressed either to corals or to the shells of other organisms, as does the present-day Australian pulvinitid, P. exempla (T. Palmer, 1974; Bradshaw, op. cit.)

Isognomon (Isognomon) promytiloides Arkell.

Bradshaw (1978) suggested that both I. (I.) isognomonoides (Stahl) and I. (I.) oolithicus (Rollier) are synonymous with I. (I.) promytiloides and I have followed him in this thesis. The species has been encountered particularly in Shipton Member coral beds, and it probably lived byssally-attached to dead branches of coral (T. Palmer, 1979). Both Bradshaw (1978) and T. Palmer (1974) have noted the tendency of Isognomon to occur in clumps; in such instances they were presumably byssally-attached to shell debris on the sea floor. However, banks of

Isognomon, such as those described from the restricted marine Upper Jurassic sediments of Santa Cruz, Portugal (Fürsich, 1981); have not been encountered in the Great Oolite Group.

Isognomon (Mytiloperna) sp.

In this thesis, I. (M.) bathonicus (Morris & Lycett) and I. (M.) murchisonii (Forbes) have not been separated. Using the criteria of Stanley (1970, 1972), this mytiliform bivalve can be interpreted as having led a byssally-attached, epifaunal mode of life, tightly adpressed against the substrate (cf. T. Palmer, 1979). Isognomon (Mytiloperna) sp. was eurytopic and tolerant of salinity fluctuations (T. Palmer, 1974; Bradshaw, 1978; Hudson, 1980); this is also suggested by occurrences of the subgenus, with Neomiodon, in the restricted marine Brora Coal Formation of eastern Scotland (pers. obs.; Hurst, 1981).

Camptonectes (Camptonectes) laminatus (J. Sowerby)

The synonymy and functional morphology of this species have been fully discussed by Johnson (1984). Its presence in restricted Bajocian limestones and shales in the U.S. Western Interior (Imlay, 1964), its rare occurrence in the marginal marine Duntulm Formation of the Inner Hebrides (Hudson, 1980) and its distribution in the Rutland Formation (Bradshaw, 1978) suggest that it was the most euryhaline Middle Jurassic pectinid, although it was probably only able to withstand relatively slight fluctuations in salinity.

Johnson (op. cit.) noted the frequent association of C. (C.) laminatus with oysters, and suggested that the species may have byssally-attached itself to these bivalves. Both Johnson and Bradshaw (1978) believed that the species was byssally-attached early in its ontogeny, but accepted that large adults could have been free living.

Camptonectes (Camptochlamys) obscurus (J. Sowerby)

Johnson (1984) placed Camptonectes annulatus (J. de C. Sowerby) into synonymy with C. (Cc.) obscurus, in marked contrast to Bradshaw (1978), who had regarded C. annulatus as synonymous with C. laminatus; I have followed Johnson in this thesis. C. (Cc.) obscurus has been encountered most commonly, in the upper Great Oolite of the study area, in coral beds (Biofacies 5) and in the diverse epifaunas associated with sandy mud substrates (Biofacies 4). Johnson (op. cit.) considered the species to have had a juvenile byssate followed by an adult reclining mode of life. The distribution of the species may have been controlled by the availability of potential byssal-attachment sites for the juvenile, perhaps provided by coral, oysters or Epithyris.

Radulopecten vagans (J. de C. Sowerby)

The promotion of Radulopecten to generic level follows Johnson (1984). Johnson placed into synonymy with R. vagans a number of pectinid 'species' originally described by Lycett (1863) from the White Limestone and Cornbrash of the east Midlands: Pecten Wollastonensis, Pecten Griesbachi and Pecten Rushdenensis.

R. vagans is apparently restricted, in the White Limestone, to Lithofacies association B; it is also associated with muddy sand and sandy mud substrates in the Cornbrash. The distribution of this species suggests that it was a stenotopic organism, intolerant of reductions or fluctuations in salinity (cf. Bradshaw, 1978). Most of its occurrences in the Bathonian (reviewed by Johnson, op. cit.) suggest that it was usually associated with abundant epifaunas, which probably provided essential sites for byssal-attachment.

Meleagrinnella echinata (W. Smith)

This small, highly equivalve, byssate oxytomid, a predominantly Lower Cornbrash species, is interpreted as having been a stenotopic, epifaunal filter-feeder which lived closely adpressed to the substrate. Frequently M. echinata appears to have been associated with muddy sand substrates. Duff (1978) noted the tendency of Meleagrinnella to occur in clusters in the Lower Oxford Clay and this certainly appears to be the case with M. echinata in the Lower Cornbrash. He also suggested that the Callovian species, M. braamburiensis (Phillips), may have led a 'pendent' mode of life, attached to organic material rooted to the sea floor. This seems unlikely to be the case with M. echinata, which probably byssally-attached to shell debris within the sediment.

Placunopsis socialis Morris & Lycett

The distribution of this species in the Bathonian of the east Midlands and the Inner Hebrides (Bradshaw, 1978; Hudson, 1963b, 1980) suggests that it was eurytopic and adapted to marine-brackish environments; it was almost certainly opportunistic. T. Palmer (1979) described it as a cemented species but, as other authors have noted, only the free left valves of P. socialis have ever been encountered, so that this cemented mode of life cannot be confirmed. The species is particularly common, in the upper Great Oolite of the study area, in the Forest Marble.

Plagiostoma cardiiformis J. Sowerby

P. cardiiformis has the distinctive mytiliform morphology which characterises epibyssate limids (Stanley, 1970). The species is found most commonly, in the White Limestone (as well as elsewhere in the English Bathonian), in coral beds; its preferred habitat was probably

amongst the branches of colonial corals, such as 'Isastraea' (cf. T. Palmer, 1974, 1979).

Pseudolimea duplicata (J. de C. Sowerby)

P. duplicata occurs commonly in the Irchester Member in Northamptonshire, in Lithofacies association B; T. Palmer (1979) has described its occurrence in the same facies association in the Ardley Member in Oxfordshire. Cox & Arkell (1948-50) recorded this species as "common throughout the Great Oolite Series, especially the Cornbrash". It was compared to Recent Lima lima Linne by Bradshaw (1978), the latter being an epibyssate suspension feeder which occurs particularly within crevices in the undersides of coral colonies (Stanley, 1970). However, Bradshaw also speculated that P. duplicata may have been a nest-building species, comparable to other Recent limids (see Tebble, 1976) which construct nests in sand or gravel by meshing such material together with their byssal threads (presumably to protect exposed soft parts). Like many other Bathonian epifaunal bivalves, P. duplicata appears to have been restricted to relatively firm, sandy substrates. Its absence from the Rutland Formation and the K. sharpi Beds may reflect an intolerance of variable or reduced salinity.

Praeexogyra hebridica, (Forbes)

The commonest Bathonian oyster found in the east Midlands, which was placed in the genus 'Praeexogyra' by Hudson & Palmer (1976), has recently been named 'Aeostrea hebridica' by Brannan (1983). However, as Brannan's work has not yet been published, I have continued to use Hudson & Palmer's name in this thesis. P. hebridica was a eurytopic oyster which is widely distributed in the upper Great Oolite Group of the study area. In the Irchester and Longthorpe Members in central and northern Northamptonshire, locally in the K. sharpi Beds north of Cranford and in

the White Limestone and Thrapston Clay in Lincolnshire, a small, ribbed variety of P. hebridica, Praeexogyra hebridica subrugulosa, occurs commonly, and in some instances is the dominant form present. While this variety is not restricted to the east Midlands (rare rugulose P. hebridica have been encountered in the Duntulm Formation of the Inner Hebrides), it is certainly most common there.

Lopha marshii (J. Sowerby)

Following an extended encrusting stage, L. marshii adopted a reclining life habit (Seilacher, 1984). The zig-zag folding of the commissure, which characterises this species, is probably an adaption to this mode of life: it reduces the danger of sediment intake (cf. Rudwick, 1964), guarantees that one side of the commissure is always well above the sediment and may even result in anchoring ribs (Seilacher, op. cit.). L. marshii, which has only been encountered in the Upper Cornbrash in the study area, is likely to have been a stenotopic organism; certainly Recent Lopha are not found in restricted marine environments.

Myophorella scarburgensis Lycett

Trigonia (Trigonia) costata J. Sowerby

Vaugonia (Vaugonia) impressa (Broderip)

The only living member of the Trigonacea, Neotrigonia, is a shallow-burrowing suspension feeder (McAlester, 1965). The three trigoniids recognised in this thesis (in part, following Bradshaw, 1978) are thought to have had the same mode of life. M. scarburgensis, a stenotopic species, is relatively rare in the upper Great Oolite of the study area, common only in the Upper Cornbrash (Cox & Arkell, 1948-50; Bradshaw, 1978). Both T. (T.) costata and V. (V.) impressa are more widely distributed and were probably more tolerant of environmental stress. V. (V.) impressa is found both in clean and muddy lime sands in

the White Limestone: its heavy ornament is an adaption to shifting substrates, where it would have imparted considerable stability. T. (T.) costata is found in similar lithologies, and also, more rarely, in pelleted lime muds (T. Palmer, 1979); it is less common than Vaugonia within the study area. That Vaugonia was relatively eurytopic is suggested by its widespread occurrence in the oyster reefs of the Longthorpe Member, as well as by its distribution in the Wellingborough Rhythm (Bradshaw, 1978), its occurrence in the restricted faunas of the Staffin Bay Formation of Skye and its presence in the marginal-marine Bajocian of the U.S. Western Interior (Imlay, 1964).

Sphaeriola oolithica (Rollier)

Cox & Arkell (1948-50) did not record this species in the Great Oolite Group of the east Midlands, but it has been found to be a common member of Biofacies 4, associated with developments of Lithofacies association B in the Ardley, Bladon and Irchester Members of the study area (cf. T. Palmer, 1979). Bradshaw (1978) found it in the same lithofacies in the Wellingborough Member at Helmdon, but its general rarity in the Rutland Formation suggests that it was a stenotopic species. The concentric ribbing and inflated morphology of S. oolithica implies that it was a slow moving, shallow burrower.

Protocardia stricklandi (Morris & Lycett)

Separate species of Protocardia, other than P. stricklandi, have not been identified in this thesis. The latter species can be recognised by its distinctive comarginal ribbing.

Protocardia, by comparison with modern cardiids of similar external morphology, was probably a moderately rapid burrowing, shallow infaunal, suspension feeder. The comarginal ribbing of P. stricklandi

may have improved its stability within the sediment, although it may have been a slower burrower than forms with less external sculpture.

Bradshaw (1978) has suggested that P. stricklandi was a relatively stenotopic species, whereas other 'species' of Protocardia were probably more stress-tolerant. For example, the forms identified by Bradshaw (op. cit.) as 'Protocardia sp. A' are widely distributed in most Rutland Formation rhythms and are thought to have displayed opportunistic tendencies. These eurytopic Protocardia are uncommon in the White Limestone, probably because of unfavourable competition from Anisocardia and other more stenotopic, shallow-burrowing genera.

Tancredia spp.

Tancredia is presumed to have been an active burrowing suspension feeder (Wright, 1974; Hallam, 1976; Bradshaw, 1978; T. Palmer, 1979). Species of this genus may have ranged from eurytopic to relatively stenotopic in the Bathonian, although taxonomic reclassification of Middle Jurassic tancrediids (recommended by Bradshaw, op. cit.) may show that the most stress-tolerant form, T. (T.) gibbosa Lycett, belongs to a genus different to that of the more stenotopic species. Tancrediids are extremely rare in the upper Great Oolite of the study area.

Anisocardia (Anisocardia) beaumonti (d'Archiac)

Forms comparable to Anisocardia truncata (Morris), A. rostrata (J. Sowerby) and A. caudata (Lycett) have all been identified in this thesis as A. (A.) beaumonti (cf. Cox, 1947; Fischer, 1969; Bradshaw, 1978). The species was probably a moderately sluggish, shallow burrower.

Anisocardia (Antiquicyprina) loweana (Morris & Lycett)

I have followed Bradshaw (1978) by relegating Anisocardia islipensis (Lycett) into synonymy with A. (Antiq.) loweana. The species

was probably another slightly sluggish, shallow burrower. It is common throughout the study area, in a number of facies in both the White Limestone and Cornbrash, but it has not been encountered in the Forest Marble.

Rollierella minima (J. Sowerby)

Duff (1978), following a study of the hinges of well preserved Upper Callovian 'Anisocardia' minima from Poland, was able to confirm Cox's (1947) view that these globose Anisocardia-like forms belong to Rollierella. During this study, R. minima has been encountered most commonly in Biofacies 4. The inflated morphology, very fine cancellate ornament and absence of a pallial sinus suggests that R. minima was a slow burrower which, like Recent Arcticacea, lived just below the sediment surface. Its distribution suggests that it was a stenotopic species.

Eomiodon angulatus (Morris & Lycett)

Bradshaw (1978) regarded E. angulatus and E. fimbriatus (Lycett) as two end members of a single species, in which case E. fimbriatus is the junior synonym; I have adopted this taxonomic revision here. The ornament of this species would have made it a slow burrower; as T. Palmer (1974) suggested, the ornament and small size may have given buoyancy in the soupy pelletal lime muds and terrigenous muds of the Bladon Member, in which the species has most commonly been found during this study.

Judging by its occurrence in almost all Rutland Formation rhythms (Bradshaw, 1978) and by its association in the Bladon Member with eurytopic species such as Bakevellia (B.) waltoni, E. angulatus is likely to have been a euryhaline, stress-tolerant species. The genus Eomiodon is known to preferentially occur in reduced salinity environments in both

the Jurassic and Lower Cretaceous (e.g. Casey, 1955a; Huckriede, 1967; Fürsich, 1981).

Eocallista antiopa (Thevenin)

E. antiopa can be interpreted as a rapid burrowing suspension feeder which lived just below the sediment-water interface (cf. T. Palmer, 1974, 1979; Bradshaw, 1978). A number of authors have suggested that Eocallista was tolerant of less than normal marine salinities (e.g. Casey, 1955b; Hallam, 1976; Bradshaw, 1978).

Corbulomima sp.

I have not, because of taxonomic uncertainties expressed by Bradshaw (1978), generally identified separate species of Corbulomima. An exception has been made for the distinctive specimens from the Irchester Member of Cranford North Pit identified as C. cf. attenuata (Lycett). The majority of specimens from the upper Great Oolite Group of the study area, identified as Corbulomima sp., have been associated with both terrigenous and lime mud substrates (e.g. in the Forest Marble); Bradshaw (op. cit.) noted that Corbulomima in the Rutland Formation display a similar preference for very fine-grained sediments (see also Duff, 1978).

Corbulomima was probably a sluggish, relatively shallow-burrowing, siphonate suspension feeder. The genus is particularly common in the 'fimbriatus-waltoni clays' of the Oxfordshire Bladon Member; T. Palmer (1979) also recorded 'Corbula hulliana' (= Corbulomima sp.) in 'shelly micrites' (=Lithofacies association B) in the Ardley Member. In addition, Corbulomima is commonly encountered in pelleted lime muds in the Ardley, Bladon and Irchester Members (in Lithofacies 5).

Corbulomima is thought to have been tolerant of considerable salinity variation (Bradshaw, 1978); it may have been most successful in brachyhaline salinity regimes (cf. Hallam, 1976; Fürsich, 1981).

Ceratomya concentrica (J. de C. Sowerby)

The absence of a siphonal gape and the shallow pallial sinus which characterise this species suggest that C. concentrica did not burrow quite as deeply as its relatives, Pholadomya and Homomya, with which it is often found; as Bradshaw (1978) noted, it is less frequently found in situ. This bivalve commonly occurs in bioturbated packstones and wackestones in both the White Limestone and Cornbrash.

Homomya gibbosa (J. Sowerby)

Pholadomya (Bucardiomya) lirata (J. Sowerby)

These two anamolodesmatans are frequently found together, often in life position, particularly in muddy sand and sandy mud substrates (e.g. Lithofacies 3; Lithofacies association B); both were deep-burrowing species which possessed a wide posterior siphonal gape and a deep to moderately deep pallial sinus. Comparison has been made between these species and the Recent deep burrower, Mya (Arenomya) arenaria (e.g. T. Palmer, 1979; Bradshaw, 1978).

Pleuromya uniformis (J. Sowerby)

Pleuromya alduini (Brongniart)

Pleuromya calceiformis (Phillips)

All three species of Pleuromya recognised in the upper Great Oolite of the study area can be interpreted as deep-burrowing suspension feeders (cf. Duff, 1978). They, like the larger pholadomyoids, are most often found in the White Limestone and Cornbrash, in muddy sands/sandy muds believed to have constituted relatively stable substrates at the

time of deposition. Different species of Pleuromya have generally not been separately identified in this thesis.

'Cuspidaria' ibbetsoni (Morris)

The taxonomic affinities of this species have been questioned by numerous workers (e.g. Cox, 1960; Hudson, 1963b; Bradshaw, 1978; T. Palmer, 1979); it was perhaps a corbulid. The species was eurytopic and apparently exhibited opportunistic behaviour in the lower Great Oolite Group (Bradshaw, op. cit.). 'C. ibbetsoni was probably a sluggish, shallow-burrowing suspension feeder (T. Palmer, 1979).

6.3.6 Gastropods

A major taxonomic revision of the gastropods of the Great Oolite, which is beyond the scope of this work, is required before they can be constructively used for detailed palaeoecological work; an exception are the Nerineacea, which have been thoroughly studied by Barker (1976).

Identifications of non-nerineacean gastropods have followed Cox & Arkell's (1948-50) revision of the works of Morris & Lycett (1851-55), Lycett (1863) and Blake (1905-07), but they have often not been pursued beyond a generic level. Of the non-nerineacean most frequently encountered during this study, Globularia occurs sporadically throughout the White Limestone; it was probably an infaunal carnivore (T. Palmer, 1979); a large number of other genera have been encountered (e.g. Amberleya, Neridomus, Trochotoma, Dicroloma, Naricopsina), most of which were 'vagile grazers' (Palmer, op. cit.). Epifaunal Pleurotomaria may have been a scavenger; it is found particularly in coral beds in the White Limestone. Viviparus (= Bathonella of some authors), and Valvata

were also scavengers, according to Palmer; they inhabited freshwater but were occasionally transported into marginal marine environments.

Barker (1976) considered that the nerineids, Eunerinea arduennensis, Aphanoptyxis spp. and Endiaplocus munieri were all epifaunal species; Aphanoptyxis, at least, may have been an algal grazer. E. munieri and Eu. arduennensis are both found in the relatively high-energy lime sands and muddy lime sands of Lithofacies 2 and 3, whereas Aphanoptyxis occurs most commonly in pelleted lime muds, undoubtedly deposited in a more sheltered environment. Eunerinea and Aphanoptyxis may have been ecologically competitive (Barker, op. cit.) or may just have occupied the same niche in different environments.

The elongate high-spired genera, Nerinella and Bactroptyxis were probably infaunal, either deposit feeders (Barker, op. cit.) or, perhaps more likely, suspension feeders (cf. T. Palmer, 1974, 1979). Both genera occur most frequently in well-winnowed grainstones in the White Limestone.

6.3.7 'Vermes'

The serpulid genera Dorsoserpula, Tetraserpula and Cycloserpula have not been separated in this account; all were encrusting suspension feeders. Colonial Sarcinella socialis was likewise a filter feeder, as were the tube dwelling terebelloid worms found in Lithofacies association B in the White Limestone of the Cherwell Valley (T. Palmer, 1979). Deposit feeding 'worms' may have produced the trace fossils Planolites and Gyrochorte, found in several lithofacies.

6.4 Fossil assemblages

During the course of my research, I have been able to recognise a number of recurring faunal associations within the upper Great Oolite Group; these fossil 'communities' often appear to be closely related to particular lithofacies/substrates. Similar faunal associations have already been described by T. Palmer (1974, 1979) and Sellwood (1978). The composition and character of these associations are discussed briefly in sections 6.4.1 to 6.4.9; the term 'biofacies' has been used to compliment the use of 'lithofacies' in Chapter 5.

The exact make-up of a given biofacies can vary both stratigraphically and geographically (on both a local and regional scale), in part because of the control exerted on community composition by variations in salinity/environmental stress. On a more local scale, spatfall in a restricted area or micro-environmental variations may have affected the composition of a particular biofacies at a given point in space and time (cf. T. Palmer, 1979).

Often faunal associations intermediate in composition between two or more biofacies are encountered: closely related biofacies grade into one another. Furthermore, in some instances, faunal associations have been found which cannot satisfactorily be placed in any of the biofacies discussed in this chapter.

6.4.1 Biofacies 1: Shifting lime sand communities

The indigenous fauna which characterises the shifting oolitic lime sands of Lithofacies 1, developed particularly within the Ardley Member around Burford, constitutes Biofacies 1 of this account; it essentially consists of rare Purpuroidea (a large, thick-shelled, herbivorous gastropod) and pectinids (T. Palmer, 1979); smooth, infaunal

bivalves and the elongate nerineid, Bactroptyxis, occur infrequently. The pectinid was, as Palmer noted, probably able to swim away from encroaching sediment. This biofacies is essentially the 'oolitic limestone community' described by Sellwood (1978).

Biofacies 1 is, like the communities associated with modern active oolite shoals, typified by a low species diversity; this is because of the substrate instability inherent in such environments. Comparison can be made between Biofacies 1 and the Tivela and Strombus samba communities described from unstable lime sand environments developed at the margins of the Andros platform (Newell et al., 1959). The latter community, which is particularly restricted, is dominated by the rapid-burrowing bivalve, Tivela abaconis; the echinoid Mellita and the starfish Oreaster also occur. The S. samba community is slightly more diverse; the 'black conch', Strombus samba, which dominates the fauna, is morphologically similar to Purpuroidea. Other elements of the fauna include pectinids (Chlamys, Aequipecten), the arcid, Anadara, a number of rapid-burrowing bivalves and Mellita.

6.4.2 Biofacies 2: Unstable lime sand communities

T. Palmer (1974, 1979) has described the principal components of this biofacies, which is particularly well established in bioturbated grainstones developed in the lower Ardley Member of Oxfordshire (=Lithofacies 2). The fauna is dominated by infaunal molluscs, particularly shallow-burrowing bivalves (Eocallista, Protocardia, Mesomiltha, Vaugonia) and elongate nerineids (Cossmanea, Nerinella, Bactroptyxis). In addition, the infaunal bivalves Anisocardia, Pleuromya and Trigonia and semi-infaunal Modiolus also occur, though less commonly.

The less abundant epifauna is relatively specialised and includes Chomatoseris, which probably had the ability to exhume itself if buried; Parallelodon hirsonensis (cf. Anadara in the Strombus samba community of Newell et al., 1959), which may also have been able to unbury itself if covered by sediment (Sellwood, 1978); and the presumed epifaunal nerineids, Eunerinea and Endiaplocus.

Biofacies 2 is characterised by organisms adapted to an unstable substrate, periodically affected by current activity (albeit gentle, effecting winnowing of fines without causing excessive current scour; T. Palmer, 1979). The paucity of the epifauna in this biofacies particularly reflects the instability of the sediment surface.

6.4.3 Biofacies 3: Stable lime sand communities

Developments of Biofacies 3 in the White Limestone are usually associated with the muddy lime sands of Lithofacies 3. Since the winnowed lime sands of Lithofacies 2 usually grade both vertically and laterally into muddy lime sands of Lithofacies 3, it is not surprising that faunas intermediate between Biofacies 2 and Biofacies 3 often occur; furthermore, the two communities contain a number of elements common to both. In particular, Eocallista, Anisocardia, Protocardia, Vaugonia, Trigonia, Pleuromya, Modiolus, Nerinella, Eunerinea, Endiaplocus and Chomatoseris may all be found in Biofacies 3, although often in different proportions to those in which they occur in Biofacies 2.

Biofacies 3 has much in common with both the 'diverse calcarenite' and the 'muddy lime sand' communities described by Sellwood (1978). The differences between Sellwood's two communities are perhaps related to different prevailing environmental stress/salinity regimes, the 'diverse calcarenite community' being an open marine expression of

Biofacies 3 (as found in the Cornbrash) and the 'muddy lime sand community' being a more restricted Biofacies 3 fauna (as found in the White Limestone).

Like Biofacies 2, stable lime sand communities are dominated by infaunal species, while, at the same time, also containing a more diverse epifauna (especially in open marine settings). In contrast to Biofacies 2, large deep-burrowing anomalodesmatans (Pholadomya, Homomya, Ceratomya) occur in this biofacies. Pholadomya and Homomya can both be compared with Recent, slow-burrowing Mya (Arenomya) arenaria, a species which cannot clear away material which clogs up its siphons and which is often unable to reburrow, if exposed, before predatory attack (Weymouth, 1920; Yonge, 1966). Like Mya, Homomya and Pholadomya would probably have been intolerant of strong wave and current activity; they required a degree of sediment stability not found in the winnowed lime sands of Lithofacies 2. Crustaceans such as Glyphaea were able to excavate open burrow systems (Thalassinoides) in the stable substrates associated with this biofacies.

The semi-infaunal echinoid Clypeus occurs frequently in Biofacies 3 in the White Limestone; Nucleolites occurs more commonly in the Cornbrash. In addition to molluscs the epifauna of the biofacies includes both rhynchonellid and terebratulid brachiopods. In the Lower Cornbrash, Kallirhynchia yaxleyensis, Cererithyris intermedia and Ornithella obovata are frequently found in association with muddy lime sand sediments. In the White Limestone, Epithyris and, less commonly, Burmihynchia, are found in Biofacies 3. Amongst the epifaunal bivalves sometimes moderately common in stable lime sand communities are Praeexogyra hebridica, Isognomon (I.) promytiloides, 'Gervillella' ovata and Costigervillia crassicosta; Meleagrinnella echinata is common in this

biofacies in the Lower Cornbrash; Limatula gibbosa occurs frequently in the Cornbrash but less commonly in the White Limestone.

6.4.4 Biofacies 4: Stable sandy lime mud communities

This biofacies is best developed in the Ardley, Bladon and Irchester Members, where it is particularly associated with bioturbated shelly and oolitic lime muds within Lithofacies association B. The biofacies is also developed in the Forest Marble; transported elements of the community are common in the limestones of Lithofacies association A in Oxfordshire. The biofacies has features in common with Biofacies 3, 5 and 7, all of which are also associated with stable or relatively stable substrates. The predominant fauna of the Kallirhynchia sharpi Beds (K. sharpi; Praeexogyra hebridica; Modiolus (M.) imbricatus; smooth-shelled, shallow-burrowing bivalves such as Anisocardia (A.) beaumonti and Eocallista antiopa; serpulids) is an example of a relatively restricted fossil assemblage; intermediate between that of Biofacies 3, 4 and 7, typically associated with sandy muds.

Typical examples of Biofacies 4 developed in the Middle Jurassic have been described by T. Palmer (1979) as the 'shelly micrite community' and by Sellwood (1978) as the 'shelly lime mud community'. The biofacies, in the White Limestone, is typified both by a diverse epifauna and a diverse endobenthos. Often the fauna is dominated by Epithyris which, locally (e.g. at Wood Eaton or Bromham), may constitute over 90% of the fossil assemblage. Other brachiopods which occur in this biofacies in the Ardley and Irchester Members are Ornithella thrapstonensis, Burmihynchia sp. and Digonella digonoides. The latter species, which is apparently restricted to Biofacies 4, is often the most conspicuous element of the biofacies in Northamptonshire.

The epifaunal bivalves typical of Biofacies 4 in both the Ardley and Irchester Members are Pseudolimea duplicata, Radulopecten vagans and Praeexogyra hebridica (also P. hebridica subrugulosa in the east Midlands); less common are Pulvinites mackerrowi, Costigervillia crassicosta, C. (Camptochlamys) obscurus, Ctenostreon rugosum, Arcomytilus asper and Falcimytilus sublaevis. Semi-infaunal species are represented by common Modiolus, with Inoperna plicatus and rare Stegoconcha ampla. Especially large examples of both Praeexogyra and Modiolus are sometimes found in Biofacies 4 in the Irchester Member, suggesting (as does the general diversity of the fauna) a very stable environment.

In addition to bivalves and brachiopods, the epifauna also includes bryozoans (e.g. Hyporosopora), serpulids, gastropods, and echinoids, particularly Acrosalenia and, rarely, Holcotypus. The semi-infaunal echinoid Nucleolites also occurs; both Acrosalenia and Nucleolites may occur locally in great numbers within this biofacies.

Within the Ardley/Irchester Members the infauna of Biofacies 4 includes numerous species of bivalve, both shallow burrowers and deep-burrowing pholadomyoids: E. antiopa, Anisocardia (Antiqui.) loweana, Anisocardia (A.) beaumonti, Sphaeriola oolithica, Protocardia, Vaugonia, Trigonia, Ceratomya, Homomya and Pholadomya are all common to moderately common; Rollierella minima, 'Cuspidaria' ibbetsoni, Corbulomima and Pleuromya also occur. Firm, sandy mud sediments also provided a suitable substrate in which crustaceans could excavate open burrow systems. Occasionally, as at Kirtlington (Sellwood, 1971), crustaceans are actually preserved together with the more common elements of Biofacies 4. The crustacean microcoprolite Favreina is frequently associated with the

biofacies. In the Ardley Member in Oxfordshire, terebelloid worm tubes are also encountered (T. Palmer, 1979).

A more restricted occurrence of Biofacies 4 was studied by Bradshaw (1978) in the Wellingborough Member of the Helmdon area. Here too, the biofacies is associated with sediments of Lithofacies association B, but the fauna at Helmdon lacks a number of the more stenotopic elements of the biofacies, notably Digonella, Ornithella, Nucleolites, Holectypus, Arcomytilus and Stegoconcha.

6.4.5 Biofacies 5: Coral bed communities

Bathonian coral bed communities have been fully discussed by T. Palmer (1974, 1979). In typical Bladon Member coral beds (well developed between Witney and Ardley and in the Blisworth-Roade-Wooton district), in situ stands of branching 'Isastraea', with abundant coral debris, are found within bioturbated oolite/wackestones; Cladophyllia and Lochmaeosmia also occur. Epithyris and byssally-attached epifaunal bivalves (Plagiostoma, Isognomon, Camptonectes, Eonavicula) are invariably intimately associated with the corals; boring organisms ('Lithophaga', ?polychaetes) and encrusters (bryozoans, calcisponges, serpulids), which utilised dead branches of the coral stands and coral rubble as hard substrates, are typically present. This association of corals, brachiopods and epibyssate bivalves (in Bathonian examples, particularly Plagiostoma), borers and encrusters has been recorded at many stratigraphic levels in the Jurassic: in coral beds in the ?Great Oolite, in the Shipton and Ardley Members of Oxfordshire and southwest Northamptonshire and in the K. sharpi Beds and Irchester Member in the east Midlands; in the basal Forest Marble patch reefs developed between Bath and Kemble (Green & Donovan, 1969; Cave, 1977; pers. obs.) and in

patch reefs in the Aalenian of the Severn Basin (Mudge, 1978; pers. obs.), the Bajocian of the Lorraine (Hallam, 1975b) and in the Corallian of eastern Oxfordshire (Arkell, 1935) and Yorkshire (pers. obs.).

Bladon Member coral bed communities were described as transported assemblages of McKerrow et al. (1969) and have been compared with Florida back-reefs by Allen & Kaye (1973). Yet the corals did not form rigid, unbedded structures exhibiting positive relief, like either the fringing reefs or patch reefs of modern tropical seas (T. Palmer, 1979). In contrast to the examples of biohermal patch reefs mentioned above, which usually occur as discrete units with positive relief separated from each other by bedded, often cross-stratified, high energy, inter-reefal detrital sediments, the Bladon Member and other White Limestone coral beds are biostromal in nature. The delicate nature of the coral's branching habit suggests a relatively low energy depositional environment, as does the abundant lime mud in the enclosing sediment. Palmer's (op. cit.) use of the inshore Porites shoals found along the seaward edge of the Florida Keys (Ginsburg, 1964; Turmel & Swanson, 1976) as an analogue for White Limestone coral beds is followed here, although the absence of green and red calcareous algae and probably the very different morphology of the Bathonian shoals should be borne in mind. The Florida coral shoals occur in quiet waters of less than 3m depth; the common branching habit of the Porites (e.g. James, 1983, fig. 49) is comparable to the ramose morphology of White Limestone 'Isastraea'. Furthermore, the Porites shoals contain Lima scabra, Barbatia, Isognomon radiata and Pinctada radiata which today respectively fill the same niches occupied in the Middle Jurassic by Plagiostoma, Eonavicula and Isognomon promytiloides (T. Palmer, 1979).

Other elements of the Bladon Member coral bed faunas (e.g. Acrosalenia, Clypeus, Pholadomya, Modiolus, Globularia) are not ubiquitous; they were not restricted to Biofacies 5 and for them the presence of corals was not a life requirement.

Developments of Biofacies 5 outside the Bladon Member are essentially similar, but some differences can be noted; for instance Burmirhynchia occurs together with Epithyris in many Shipton Member coral beds, while in contemporaneous coral beds developed in the east Midlands, Kallirhynchia sharpi is often present. In both cases the epifauna usually also includes Praeexogyra hebridica. Camptonectes is common in Biofacies 5 in the K. sharpi Beds.

6.4.6 Biofacies 6: Aphanoptyxis bed communities

The different species of Aphanoptyxis found in the White Limestone are usually associated with pelletal lime mud sediments, belonging to Lithofacies 5. These gastropods, and the fauna most commonly associated with them, constitute Biofacies 6. The fauna is low in diversity, in part because many organisms were not suited to the soupy substrate formed by the pelleted lime muds and perhaps, in part, because of salinity fluctuations in a very shallow water environment. The fauna of Biofacies 6 comprises only molluscs.

The epifauna of the biofacies is particularly restricted. In addition to Aphanoptyxis, which was probably epifaunal (Barker, 1976), gastropods such as Neridomus, Naricopsina and Amberleya occur in small numbers. The only epifaunal bivalve was Bakevellia (B.) waltoni, which may have byssally-attached itself to soft-bodied organisms (e.g. gorgonians) and may, therefore, have been raised above the sediment-water interface.

The infaunal bivalves found in the biofacies are all shallow-burrowing forms; Eomiodon angulatus and Corbulomima are particularly common; Protocardia and 'Cuspidaria' ibbetsoni are often also present. Occurring more sporadically in the biofacies are Trigonia (T.) costata, Mesomiltha bellona and 'Mactromya'. The infaunal gastropod Nerinea is sometimes present in this biofacies, particularly in association with Aphanoptyxis cf. langrunensis in the Ardley Member.

Mollusc-dominated faunal assemblages of similar composition occur in terrigenous muds in the Rutland Formation (Bradshaw, 1978) where, again, both high environmental stress and a thixotropic substrate may have limited the faunal diversity; in this instance, the former was considered to have been the dominant controlling factor (Bradshaw, op. cit.). It is significant that of the species found in Biofacies 6, the majority are inferred to have been eurytopic (see section 6.3.5).

6.4.7 Biofacies 7: Oyster bed communities

In Bathonian nearshore environments, only Praeexogyra hebridica formed oyster lumachelles (e.g. in the Great Estuarine Group, Hampen Marly Formation and Rutland Formation; Hudson, 1963b; T. Palmer, 1979; Bradshaw, 1978), although P. acuminata and Catinula knorri also formed lumachelles in more offshore, open shelf environments (such as are represented within the Fuller's Earth/Frome Clay). Within the upper Great Oolite Group of the study area, nearshore oyster lumachelles comprised of Praeexogyra hebridica are encountered within the Forest Marble in Oxfordshire and within the K. sharpi Beds, the Irchester and Longthorpe Members and the Thrapston Clay in the east Midlands.

Upper Great Oolite oyster lumachelles in the study area are usually dominated by disarticulated and broken shells, with the deposits

exhibiting variable degrees of winnowing. Both terrigenous mud and lime mud may be associated with poorly winnowed lumachelles, whereas well-winnowed lumachelles are typically calcite-cemented, very coarse-grained biograinstones and subordinate biopackstones.

P. hebridica is a ubiquitous member of the fauna of the K. sharpi Beds of central Northamptonshire, but is usually not present in lumachelle proportions. However, at Wellingborough (Loc. 124; Plate 11), a 0.26m thick lumachelle is well displayed, flanked by biowackestone/packstone containing coral, Camptonectes and other elements of Biofacies 5. Within the oyster lumachelle, P. hebridica and K. sharpi are particularly abundant, while Modiolus occurs commonly, but in lesser numbers. This lumachelle represents an in situ oyster-rhynchonellid bank; the fauna is largely articulated and all growth-stages of the three above species occur.

The occurrence of rhynchonellids within oyster banks is a recurring association: Burmihynchia, for example, occurs abundantly in oyster lumachelles within the Hampen Marly Formation (T. Palmer, 1979) and more rarely within the oyster reefs of the Duntulm Formation (Hudson, 1980). However, there is no modern analogue for such an association, for brachiopods no longer colonise the same shallow marine environments. On the other hand, the association of Modiolus and Praeexogyra is comparable with the association in the Recent oyster banks of the Texas Gulf coastal lagoons of Crassostrea and Brachidontes (Parker, 1960).

In addition to rhynchonellids, oysters and Modiolus, serpulids and Placunopsis socialis are also frequently found in Biofacies 7. Oyster shells may exhibit echinoid grazing traces (Gnathichnus).

6.4.8 Biofacies 8: Firm and hard substrate communities

Hardground faunas have been discussed by Palmer & Fürsich (1974), Fürsich & Palmer (1975), Fürsich (1979) and T. Palmer (1982).

Intra-Ardley Member hardgrounds west of the study area (e.g. at Foss Cross) exhibit moderately diverse crevice faunas (Moorellina, bryozoans, serpulids, calcisponges) and the upper surfaces are typically encrusted by oysters, ?Atreta, serpulids and rare Apiocrinus (Fürsich & Palmer, op. cit.). Cavity faunas are generally lacking further east, but at Ardley (Loc. 30), occasional bryozoans encrust the sides of burrows in the hardground capping the Ardley Member.

For the most part, in Oxfordshire and the east Midlands, the commonest encrusters associated with hardgrounds/firmgrounds in the upper Great Oolite are oysters, usually identified as Exogyra. In addition, the larger Liostrea wiltonensis was recorded by T. Palmer (1974) at Sturt Farm and Great Rollright (Loc. 4 & 33); Lopha marshii and ?Nanogyra nana encrust pebbles and hardground surfaces within the Cornbrash. Exogyra encrusting a hardground 1.95m above the base of the Ardley Member at Foss Cross are clustered and show signs of intra-specific competition (S. Kershaw, pers. comm.); similar clumping of various taxa on other Jurassic hardgrounds has been noted by Fürsich (1979).

Apiocrinus holdfasts have not been encountered on hardgrounds in Oxfordshire or the east Midlands, probably, as Fürsich & Palmer (1975) suggested, because these areas were too hostile for this stenotopic crinoid. Serpulids are perhaps more common within intra-hardground burrows but examples of serpulids encrusting the upper surfaces of hardgrounds have been seen at Eton College, Shipton and Ardley. Serpulids are common on pebbles at the base of the Upper Cornbrash at Thrapston, but are less abundant on pebbles in the Wood Eaton

intra-Ardley Member pebble bed. Serpulids exhibited a preference for the undersides of hiatus concretions in the Cretaceous of South Africa (Kennedy & Klinger, 1972) and this is apparently true also for Upper Cornbrash pebbles collected at Thrapston. Bryozoans have been most frequently encountered in the study area encrusting bivalve and brachiopod shells rather than associated with hardgrounds.

'Lithophaga' and/or Trypanites borings are invariably found in hardgrounds, limestone pebbles, coral rubble and even in large bivalve shells within the Great Oolite Group. Trypanites, however, is also known to occur in firmgrounds (Goldring & Kazmierczak, 1974). These vertical to sub-vertical, cylindrical borings of 1-3mm diameter are generally interpreted as worm borings (?polychaetes) although modern endoliths of a number of different phyletic groups produce comparable borings (Nield, 1984 and references therein).

6.4.9 Biofacies 9: Freshwater communities

The typical Middle Jurassic freshwater community has been described by Sellwood (1978) and need only be summarised here. The most important elements of the fauna are the freshwater gastropods Viviparus and Valvata; the bivalve Unio occurs in some Bathonian freshwater communities but has not been recorded in the upper Great Oolite Group of the study area. In addition to gastropods, freshwater to brackish ostracods (e.g. Theriosynoecum; Timiriasevia; see Bate, 1965) are also found in Biofacies 9. More rarely, reptilian and mammalian teeth and bones occur (e.g. Ware, 1978; E. Freeman, 1979). Plant debris, buried roots and stems of horsetails and charophytes (the oogonia of freshwater calcareous algae) are also characteristic of this biofacies.

In the upper Great Oolite Group, elements of Biofacies 9 have been found in situ in terrigenous muds of Lithofacies association E (e.g. in the Thrapston Clay, in the 'fimbriatus-waltoni clays' of the Bladon Member or in passive infills of channels developed at the tops of several sedimentary rhythms); transported elements of the biofacies also occur in other lithofacies, notably in Lithofacies association A and C, in both the White Limestone and Forest Marble. Very often, where elements of Biofacies 9 have been transported, they occur mixed with brackish water organisms. It should be noted that freshwater communities are better developed in the Rutland Formation, in the Ravenscar Group of the Cleveland Basin and in the Great Estuarine Group of western Scotland than they are in the White Limestone and overlying formations in the study area.

CHAPTER 7

RHYTHMIC SEDIMENTATION

7.1 Introduction

Rhythmic sedimentation within the Great Oolite Group was first recognised within the lower part of the group in eastern England (Aslin, 1965; Ferguson, 1970; Bradshaw, 1978). Bradshaw (op. cit.) described the rhythmic nature of the Rutland Formation in considerable detail. Above the essentially non-marine sediments of the Stamford Member, six rhythmic sedimentary units were recognised within the formation north of the Kettering-Peterborough Line. Southeast of the Kettering-Peterborough Line, moving towards the London-Brabant Massif, the lowermost three rhythms (the Ketton, Clipsham and Casterton Rhythms of Bradshaw) were found to be overstepped by the fourth rhythm (the widely recognisable Wellingborough Rhythm). The simplest Rutland Formation rhythms were found to exhibit the following characteristics:

- a) interlayered sands and muds (Lithofacies 9) sharply truncating rootletted muds of the underlying rhythm;
- b) an upward-decreasing prominence of interlayered texture and, hence, an upward trend towards apparent homogeneity;
- c) an upward-increasing abundance of plant debris and thus a trend towards carbonaceous muds;
- d) an upward-decreasing abundance of calcareous macrofossils;
- e) the rootletted upper parts of rhythms are sharply truncated by interlayered sands and muds at the base of the succeeding rhythm.

Unlike the simple rhythms, throughout much of the east Midlands the Wellingborough Rhythm contains a well-developed central carbonate unit. This particular rhythm was initiated by a marine transgression more extensive than those which generated the lowermost three rhythms; one which drowned greater areas of Brabantia, the Pennine High and the Mercian Archipelago. As a consequence there was a reduction in the volume of siliciclastic sediment washed into the East Midlands Seaway from these sources and carbonates were allowed to accumulate in place of terrigenous sediment across a wide area.

Within all Rutland Formation rhythms and their lateral equivalents, there is an increase in the proportion of carbonate towards the southwest, reflecting the increasingly offshore setting in this direction. In Oxfordshire and north Gloucestershire, therefore, the lateral equivalents of even the simple Rutland Formation rhythms are more complex and also have a central carbonate unit.

The pattern of sedimentation which produced the rhythms so evident in the Rutland Formation continued during deposition of the White Limestone sediments. Within the White Limestone, rhythms are most easily identified in northeast Oxfordshire, probably because that region was close enough to land in the Bathonian to be affected by coastal progradation and was an area where subsidence was sufficient to allow rhythm tops to generally be preserved rather than removed by erosion during periods of emergence. The rhythms developed within the White Limestone are comparable to the Wellingborough Rhythm in that they are dominated by carbonate sediments. T. Palmer (1974, 1979) recognised only three shallowing-upwards units within the White Limestone whereas Sumbler (1984) has recognised five or six phases of shallowing, of which he believed only two were of widespread extent. There are, in fact, five

LOWER CORNBRASH 'RHYTHM'
FOREST MARBLE 'RHYTHM'
RHYTHM E
RHYTHM D
RHYTHM C
RHYTHM B
RHYTHM A
CRANFORD RHYTHM
WELLINGBOROUGH RHYTHM
CASTERTON RHYTHM
CLIPSHAM RHYTHM
KETTON RHYTHM
CHIPPING NORTON/STAMFORD 'RHYTHM'

FIGURE 7.1 Sedimentary rhythms recognised within the study area.

widely recognisable rhythmic units developed largely between the upper and lower limits of the Oxfordshire White Limestone; a sixth phase of shallowing has been recognised more locally. The lowermost rhythm of the Oxfordshire White Limestone is believed to be laterally equivalent to the locally developed sixth rhythm of the Rutland Formation (the Finedon/Nassington Rhythm of Bradshaw, 1978). In the southwest of the study area and beyond, the sediments of the fifth rhythm are lithostratigraphically classified as ?Great Oolite rather than White Limestone.

The five 'White Limestone' rhythms are herein referred to as Rhythms A to E; geographical epithets may be attached to each rhythm at a later date. They are described in turn in the rest of this chapter. In addition, two further 'rhythms', the Forest Marble and Lower Cornbrash depositional units, are also described. Each rhythm was initiated by a relative rise in sea level. The underlying control on rhythmic sedimentation is discussed in subsection 7.10.

7.2 Rhythm A

7.2.1 Introduction

During his study of the Rutland Formation, Bradshaw (1978) recognised rhythms locally developed between the top of the Cranford Rhythm and the base of the White Limestone in the area around Finedon and in the area around Nassington. He named these rhythms the Finedon and Nassington Rhythms respectively. While recognising the probable contemporaneity of these rhythms, he suggested that the Finedon Rhythm may have accumulated as a localised lobe of clastic sediment built out from a nearby land area into the early White Limestone sea; he therefore

implied a belief that the 'Finedon Rhythm regression' was of only limited geographic extent, temporarily interrupting the White Limestone sea's transgression across the Finedon area. This interpretation is not accepted here. Neither the Finedon nor the Nassington Rhythms were related by Bradshaw to the 'First White Limestone Rhythm' which he had recognised in Oxfordshire. In sharp contrast, it is my belief that Bradshaw's Nassington, Finedon and First White Limestone Rhythms are not only contemporaneous but were the product of a single marine transgression, post-dating the transgression which initiated deposition of the Cranford Rhythm, but earlier than the one which generally initiated White Limestone deposition in Northamptonshire. Together Bradshaw's three rhythms constitute Rhythm A of this account. The geographic isolation of the 'Nassington' and 'Finedon' Rhythms results from the Rhythm A sea lying largely to the northwest of today's Great Oolite outcrop, with the consequent non-deposition of the rhythm over much of the study area. Bradshaw's (op. cit.) Rhythm 3 at Roade (Loc. 106) also belongs to Rhythm A; on the other hand, his Rhythm 3 at Bromham (Loc. 74) is my Rhythm B, close to its depositional margin. The apparent absence of Rhythm A along the outcrop to the northwest and southwest of Roade is probably due to a lack of extant sections exposing the relevant stratigraphic interval, rather than to the rhythm not being developed.

In Oxfordshire, Rhythm A is largely contained within the White Limestone Formation, although the lower part typically extends down into the underlying Hampen Marly Formation. The rhythm in the east Midlands is included in the Rutland Formation on lithological grounds.

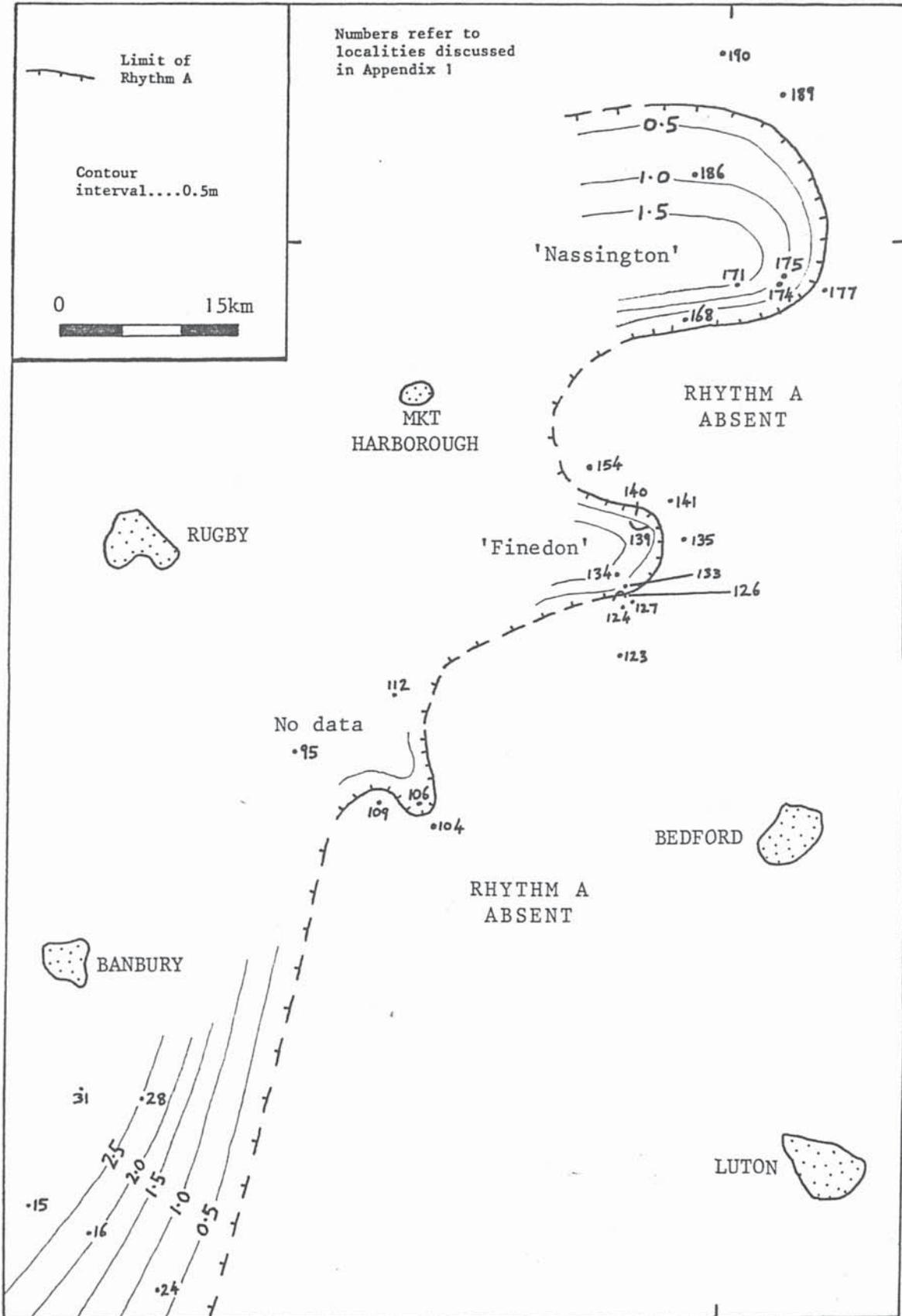


FIGURE 7.2 Rhythm A: geographical limits and isopachs.

7.2.2 Regional variation and facies distribution

Rhythm A is not well-exposed in Oxfordshire. The best exposure is in the Ardley-Fritwell Railway Cutting (Loc. 28) where the whole rhythm (c.2.5m) is still visible; the entire rhythm can also be seen at Wood Eaton (Loc. 24) and has been logged in the Shipton Borehole (B4). The rhythm thins southeastwards from Shipton and Ardley and is only 0.5m thick at Wood Eaton. In Oxfordshire the rhythm is dominated by interlayered sands and muds in the lower part and by bioturbated, variably argillaceous biowackestones to calcareous mudstones in the upper part. The faunas in the more carbonate-rich facies are moderately diverse and include some stenotopic elements, notably 'Isastraea', Epithyris, Burmihynchia and nerineid gastropods.

The exact distribution of the rhythm and any facies changes which occur within the rhythm northwest of Oxfordshire are difficult to ascertain due to insufficient data. The rhythm could have been developed at Hopping Hill (SP72456213) and Moulton Park (SP77586435), even though Bradshaw (1978) interpreted Thompson's (1930) borehole data as showing the White Limestone immediately overlying the Cranford Rhythm at both locations; Rhythm A may have been classified with the White Limestone by Bradshaw, who admits that he did not personally inspect samples from the upper part of the Rutland Formation in these boreholes. However, the presence of limestone immediately overlying rootletted green clay at Moulton Park suggests that there, at least, Rhythm B directly overlies the Cranford Rhythm. Rhythm A is undoubtedly present at Roade, where it comprises 0.45m of rootletted, interlayered sand and sandy mud with a stress-tolerant fauna of oysters, B. waltoni and P. socialis, but it is known to be absent at Blisworth, Roade, Hartwell and Irchester (Loc. 109, 104, 101; 121, 122 & 123), respectively to the west, south, southeast and

northeast. The terrigenous lithofacies and low-diversity fauna of the rhythm at Roade could indicate a general change from a predominantly carbonate lithofacies in Oxfordshire northeastwards into a non-carbonate, restricted marine depositional environment. However, it is perhaps more likely that the marginal facies developed at Roade reflects the proximity of the rhythm's southeastern depositional margin.

Rhythm A is moderately well exposed between Irthlingborough, Cranford and Burton Latimer. In this area, the distributional limits of the rhythm are well known (Fig. 7.3). The northern, eastern and southern limits of the rhythm have been controlled by pre-Rhythm B erosion, but they may also, in part, reflect the original maximum extent of the Rhythm A marine transgression.

The only limestone seen within Rhythm A in Northamptonshire occurs at the northwestern end of Cranford South Pit (Loc. 139; see Fig. 7.4). As was first described by Bradshaw (1978), when the exposure was better than today's, the upper part of a succession of interlayered silty sand and mud passes northwestward into a sandy biowackestone in which rootlets are initially less common than in the sand and mud, and eventually disappear. Further to the northwest the limestone passes back into interlayered sand and mud, now non-rootletted; the rhythm is here only 0.26m thick. The local absence of rootletting at the northwest end of Cranford South Pit is probably not as significant as Bradshaw (op. cit.) believed, and does not mark the maximum northward extent of marsh progradation; rootlets reappear in the attenuated Rhythm A to the north, at Cranford North (Loc. 140). The local absence of rootlets may simply be the consequence of pre-Rhythm B erosion.

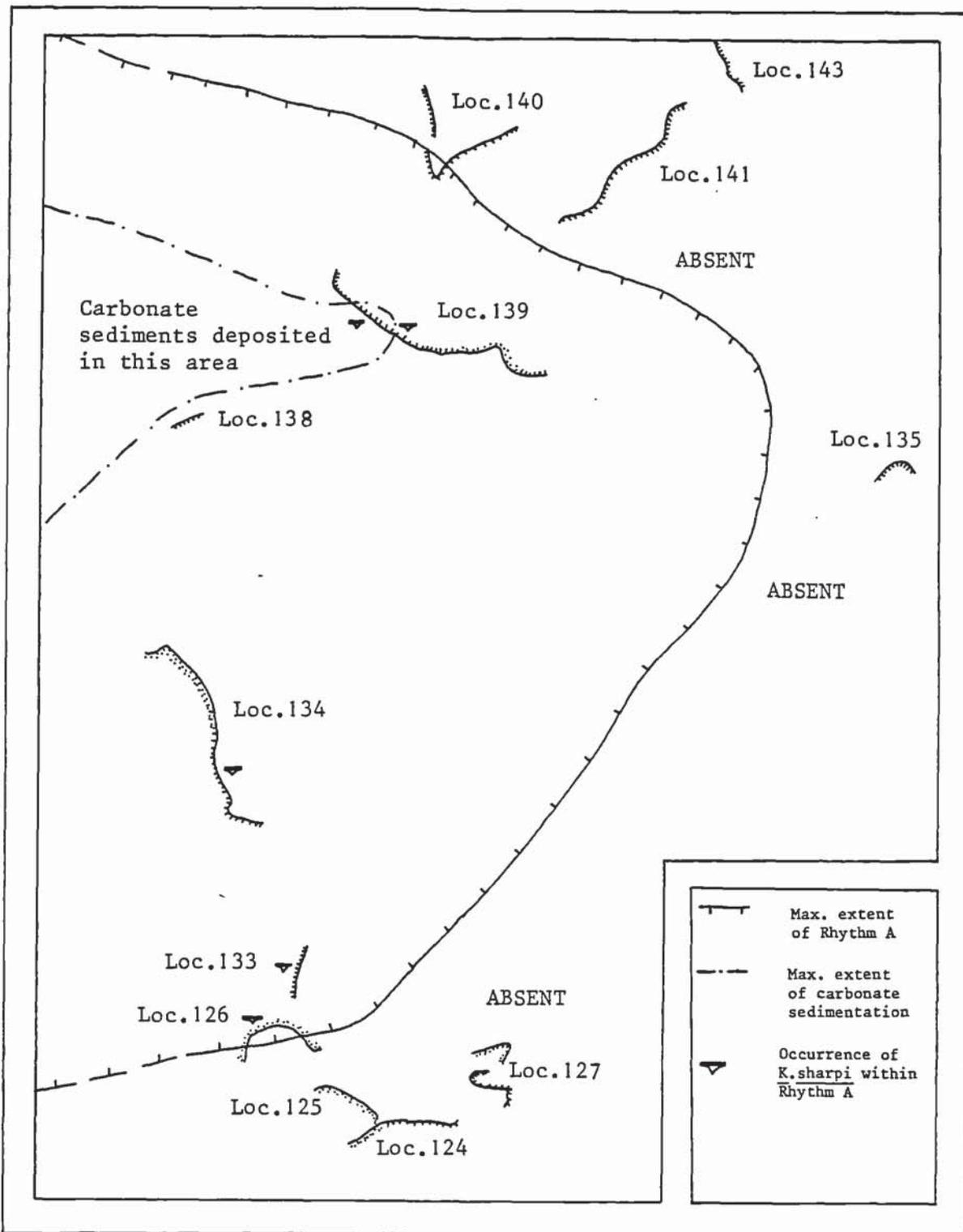
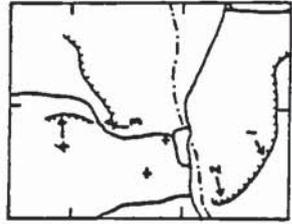
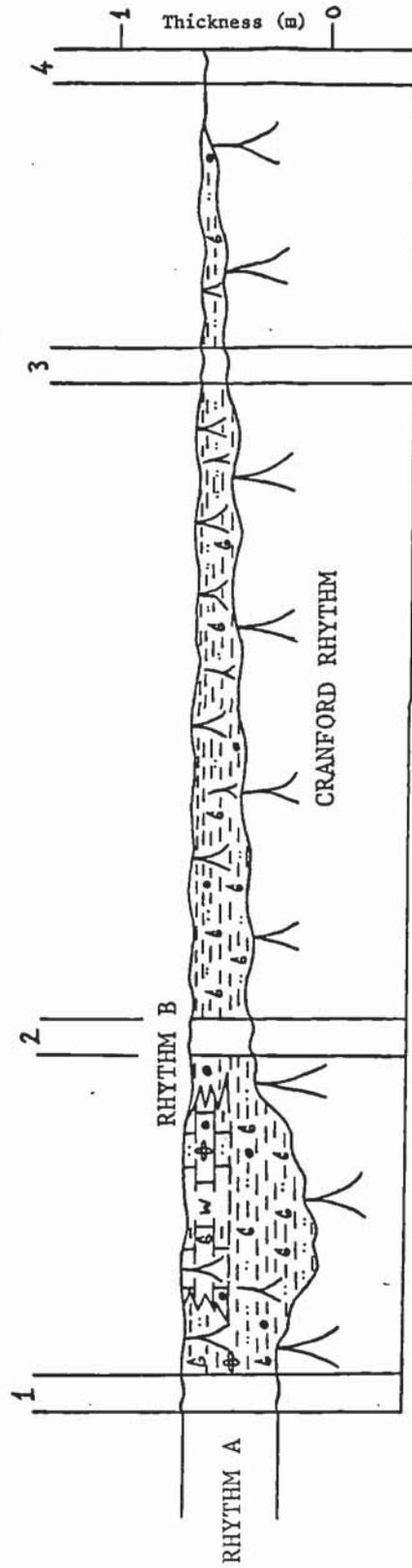


FIGURE 7.3 Distribution of Rhythm A sediments in quarries in the Cranford-Finedon district.



500m

FIGURE 7.4 Lateral facies and thickness variation within Rhythm A in Cranford North and South Pits.

The most marine faunas encountered in Rhythm A in the east Midlands (including Costigervillia crassicosta and Pinna sp.) are associated with the local development of limestone at Cranford South. This carbonate facies was probably originally more extensively developed west of today's outcrop. Kallirhynchia sharpi occurs in both interlayered sand and mud and in biowackestone at Cranford. Unlike Bradshaw (1978), I encountered K. sharpi in Rhythm A around Finedon (Loc. 133 & 134); therefore Bradshaw's argument, based on K. sharpi distribution, for a local southward increase in environmental stress from Cranford to Finedon, was based on incorrect data. Occurrences of K. sharpi in Rhythm A at Cranford and Finedon constitute the earliest appearance of this east Midlands brachiopod. Ornithella thrapstonensis, which occurs at the base of Rhythm B at Cranford, has not been found in Rhythm A sediments.

Rhythm A is not developed at Geddington (Loc. 154), but reappears between Ketton (Loc. 186) and Bulwick (Loc. 168; where it is only 0.15m thick and probably close to its depositional/erosional limit). Throughout the Nassington-Kingscliffe-Ketton area, Rhythm A again consists of interlayered silts, muds and sands in which sand becomes less important upwards. At Kingscliffe (Loc. 171) the rhythm is capped by a dark green, homogeneous, rootletted clay, but elsewhere this marsh/swamp deposit has been removed by pre-Rhythm B erosion. The rhythm does not extend as far east as Sibson (Loc. 177) nor as far northeast as Essendine and Clipsham New Quarry (Loc. 189 & 190). The fauna of the rhythm in this area is comparable to that seen at Roade, although Bradshaw (1978) recorded an indeterminate rhynchonellid and large Acrosalenia in the rhythm at Ketton; these are relatively stenotopic organisms not present

at Roade. An in situ oyster clump was seen in this rhythm in Spire's Wood Railway Cutting (Loc. 174) by Bradshaw.

7.3 Rhythm B

7.3.1 Introduction

The distribution of Rhythm B is illustrated in Figure 7.5. In Oxfordshire the rhythm is contained within the upper part of the Shipton Member, while throughout the east Midlands outcrop the rhythm essentially coincides with the Kallirhynchia sharpi Beds. The rhythm has been recognised by a combination of sedimentological and faunal criteria, and by consideration of likely regional facies changes. The northern, eastern and southeastern limits of Rhythm B are difficult to determine; however, occurrences of thin units of rootletted, interlayered sand and clay at the top of the Rutland Formation at Bromham (Loc. 74) and Timberland (B81) probably belong to this rhythm, with both localities sited close to its depositional/erosional margin. Away from its depositional margin, in Northamptonshire and adjacent counties, the rhythm is characterised by Kallirhynchia sharpi. This brachiopod, apart from its occurrences in Rhythm A discussed above, is believed to be restricted to Rhythm B. However, it is a facies-controlled species and does not occur where unfavourable facies prevailed. This is believed to explain the absence of K. sharpi from exposures of Rhythm B at Kingscliffe, in the Peterborough area and localities further north; it also explains the absence of K. sharpi from Rhythm B, southwest of a line joining Greens Norton and Pury End (Fig. 7.5). In Oxfordshire, the nerineid Aphanoptyxis excavata is commonly present at the top of the

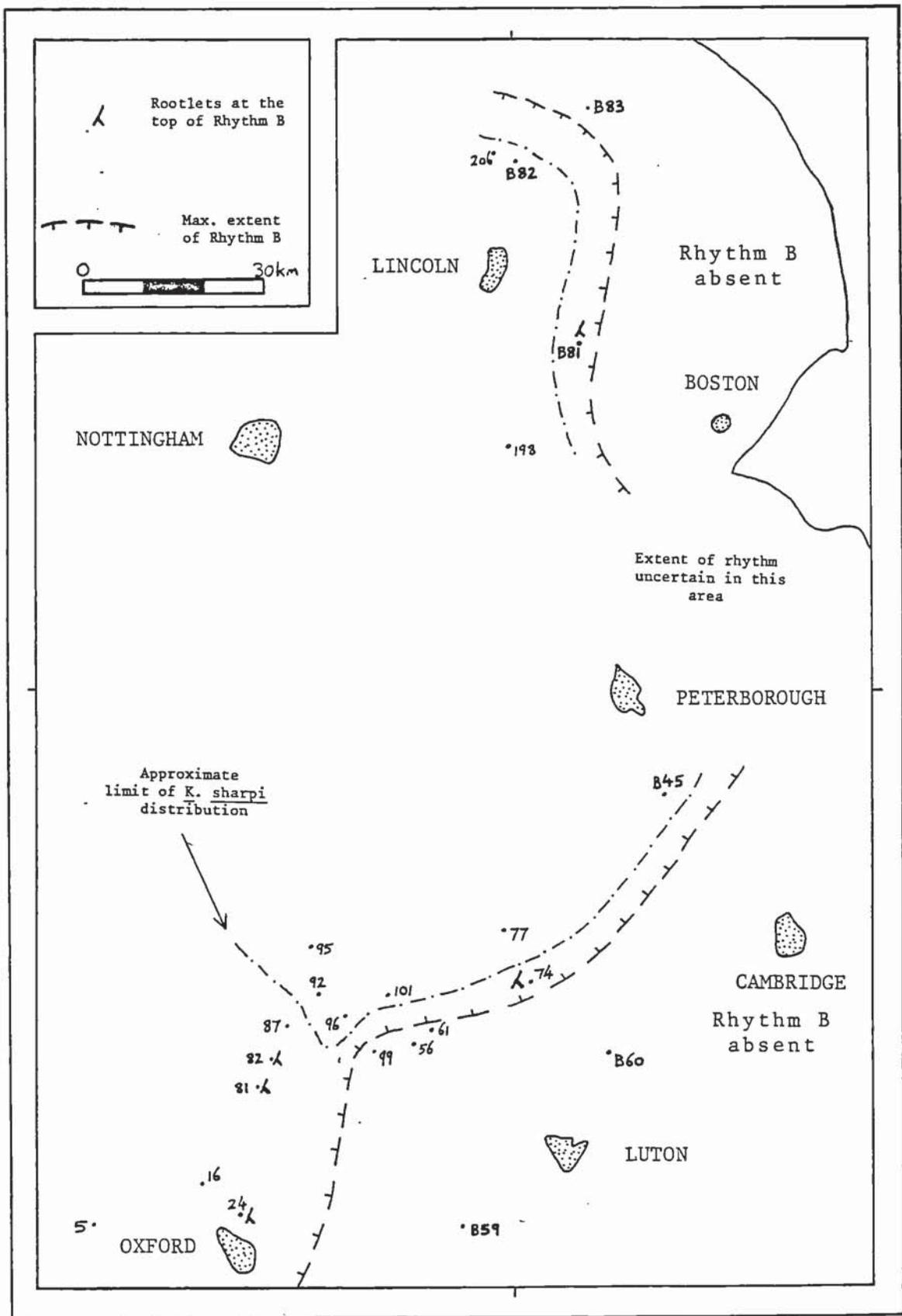


FIGURE 7.5 Rhythm B : geographical limits and distribution of *Kallirhynchia sharpi*.

rhythm. This gastropod may also be present in the uppermost sediments of the rhythm in the Roade area.

Over most of the study area the top of Rhythm B is not marked by the rootletting which characterises the top of Rhythm A or the tops of earlier Bathonian rhythms. Rootlets have been observed at the top of Rhythm B only at Wood Eaton, Croughton and Brackley (in addition to at Bromham and Timberland, where thin examples of a marginal facies are developed). At Ardley, a putative dinosaur trackway occurs at the top of the rhythm (T. Palmer, 1979). Beyond the southwestern limit of the study area a hardground sometimes caps the rhythm. However, supposed 'hardgrounds' recognised at this stratigraphic level at Shipton and Croughton (Barker, 1976; Sumbler, 1984) are not believed to be true hardground surfaces; Barker's 'hardground' at Croughton occurs immediately beneath the rootletted clay which caps Rhythm B there. In the Peterborough district (Loc. 184), in an area where relatively offshore lime sands (Lithofacies 3) are developed in Rhythm B, the rhythm is locally capped by an oyster-encrusted hardground. It is probable that coastal progradation did not extend as far as Bretton at the end of Rhythm B times; the hardground may have formed as a result of marine cementation during a prolonged pause in sedimentation at the close of the rhythm. North of Peterborough and Stamford the top of the rhythm does not appear to be sharply defined; however, there is a paucity of suitable data from this northern region.

The absence of rootlets at the top of the rhythm throughout much of the east Midlands is surprising in view of the relatively marginal nature of the Kallirhynchia sharpi Beds in areas such as Irchester and Wellingborough. However, throughout Northamptonshire the base of the overlying Rhythm C is sharply erosive; indeed, in the Irchester area,

this erosive surface nearly cuts down to the base of Rhythm B (e.g. Loc. 121). It therefore seems likely that while the uppermost sediments of Rhythm B, across much of Northamptonshire and adjacent areas, were originally penetrated by Equisetites rootlets, these rootletted sediments were subsequently removed by extensive erosion prior to the deposition of the first Rhythm C sediments. Comparable erosion of rootletted sediments from the tops of rhythms has been observed, on a more localised scale, within the Rutland Formation (Bradshaw, 1978) and in the Bladon Member in Oxfordshire. The abundance of reworked carbonaceous and lignitic material in the basal sediments of Rhythm C at many Oxfordshire and Northamptonshire localities adds further support to this hypothesis.

The base of Rhythm B is everywhere erosive. In Oxfordshire, Rhythm B sharply overlies Rhythm A sediments in the few sections where the base is seen. In the east Midlands, at most localities beyond the maximum extent of Rhythm A, the rhythm overlies Cranford Rhythm sediments. At relatively few exposures at outcrop, Rhythm B oversteps onto the Wellingborough Rhythm. Locally (e.g. Raunds) it directly overlies the Upper Bajocian/Lower Bathonian Stamford Member.

7.3.2 Regional variation and facies distribution

The most offshore sediments encountered during this study in Rhythm B are found in the southwest part of my study area and beyond. They comprise the clean and muddy lime sands, belonging to Lithofacies 2 and 3, which occur in the Shipton Member at Sturt Farm and elsewhere around Burford. Biofacies 2 and 3 are well developed in these sediments, Mesomiltha bellona being particularly common locally. Rare ammonites (belonging to both the subcontractus and morrisoni Zones) have been found in Rhythm B in Oxfordshire.

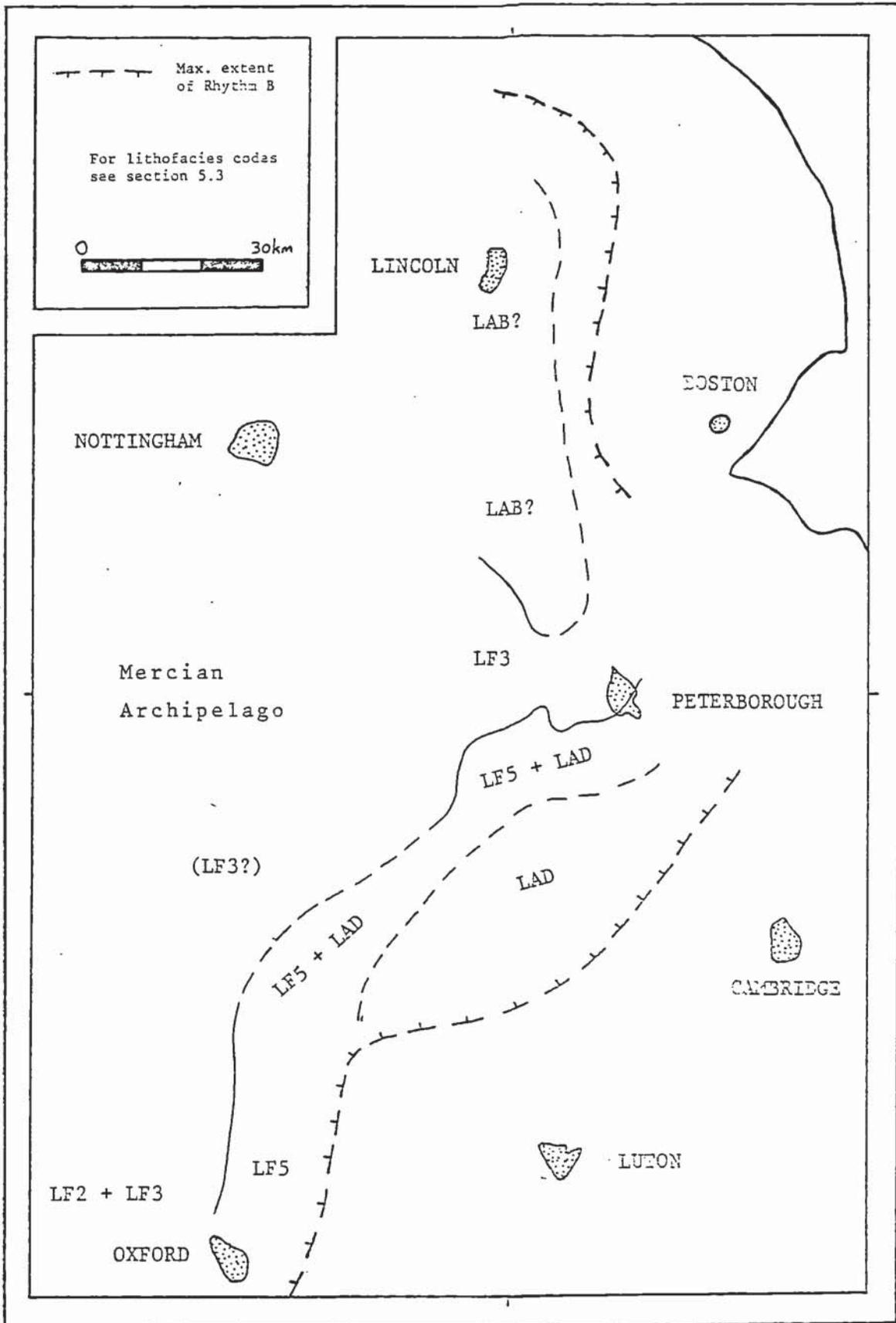


FIGURE 7.6 Rhythm B : facies distribution in mid-Rhythm B times.

In general, the winnowed lime sands of Lithofacies 2 pass northeastwards into more muddy lime sands (Lithofacies 3). In northeast Oxfordshire, siliciclastic sand/silt and terrigenous mud become increasingly common in Rhythm B; so, too, do oolitic and shelly lime muds in which Biofacies 5 (i.e. corals and their associated fauna) is especially well developed. The proportion of siliciclastic sediment in Rhythm B increases even more on following the rhythm further northeastwards into the east Midlands; this reflects the increasingly nearshore nature of the environment and the greater influence of adjacent land areas (particularly Brabantia) on passing into the 'East Midlands Embayment'. However, facies distributions within Rhythm B suggest that there was not a simple northeastward trend along the outcrop towards more restricted depositional settings. Instead, relatively offshore facies occur in Lincolnshire and in Northamptonshire north of the Kettering-Peterborough Line. This is probably because the most marine part of the 'East Midlands Embayment', during Rhythm B times, generally lay to the west of today's outcrop; however, the axis of the embayment must have swung eastwards or southeastwards, perhaps near Grantham, to introduce the relatively offshore facies into the northern outcrop area (see Fig. 7.6).

Muddy lime sands of Lithofacies 3 are patchily developed in Rhythm B in the Peterborough-Kingscliffe-Ketton region; once again the muddy lime sands are interbedded with muddier limestones (packstones and wackestones) that are intermediate in character between the typical sediments of Lithofacies association D and bioturbated sandy lime muds developed in Lithofacies association B.

To the south and southeast of the Kettering-Peterborough Line, Rhythm B is dominated by sediments of Lithofacies association D; a

relatively restricted fauna is dominated by Kallirhynchia sharpi, Praeexogyra hebridica and Modiolus (M.) imbricatus, particularly in the Irchester-Finedon district; faunal diversity within the rhythm increases gradually both to the southwest and north of this area of outcrop. At Wellingborough No. 5 Pit (Loc. 124), an in situ oyster-rhynchonellid bank is developed within Rhythm B (Lithofacies 7/Biofacies 7).

North of Stamford, as already noted, the top of Rhythm B is neither well-defined nor well exposed. At Little Bytham (Loc. 193, 194) cross bedded lime sands of Lithofacies association B occur in the rhythm. Both here and at Ancaster (Loc. 198) stenotopic faunas of Biofacies 4 type are well developed in Rhythm B.

7.4 Rhythm C

7.4.1 Introduction

Rhythm C can be biostratigraphically dated, on the basis of limited ammonite data (summarised in Chapter 4), as being of basal hodsoni Zone age. In Oxfordshire and southwest Northamptonshire the rhythm largely coincides with the Ardley Member. In the east Midlands most or all of the Irchester Member, all of the Longthorpe Member and, in many places, the lower part of the Thrapston Clay Formation are thought to belong within Rhythm C.

Rhythm C has been interpreted as the product of the most extensive pre-discus Subzone transgressive event recognisable within the Great Oolite Group. The initiating relative rise in sea level in the east Midlands was sufficient to introduce rare ammonites and more common nautiloids into the region; carbonate sedimentation spread further onto

the London-Brabant Massif than at any time previously in the Bathonian, a direct consequence of more extensive coastline retreat.

Throughout much of the study area the top of Rhythm C is poorly defined. This is not the case in Oxfordshire, however, where the iron-enriched, oyster-encrusted and bored hardground frequently capping the Ardley Member also marks the top of Rhythm C. At many Oxfordshire and southwest Northamptonshire localities, Aphanoptyxis ardleyensis occurs abundantly in pelletal lime muds at or near the top of Rhythm C.

In the Milton Keynes-Bedford area and at Irchester, the top of Rhythm C is not marked by a hardground, and cannot be located with certainty. At Irchester Old Lodge (Loc. 122), Aphanoptyxis bladonensis occurs in the top bed of the White Limestone. Since, elsewhere, this species is only found in Rhythms D and E, it seems likely that here, at least, the uppermost part of the Irchester Member belongs within Rhythm D. Here too, the overlying Thrapston Clay is thought to belong within Rhythm D. The rootlets at the top of the White Limestone at Irchester (e.g. Torrens, 1967) belong to a phase of coastal progradation associated with Rhythm D, not with Rhythm C. Bearing this in mind, the rootlets found in the uppermost White Limestone at Weston Underwood, Bromham and elsewhere in this district must be interpreted carefully. At Weston Underwood the rootlets occur in Lithofacies association C sediments identical to those developed in the upper part of Rhythm C at Pury End. However, it is here believed that the rootlets penetrated these sediments, while they were still soft, during Rhythm D times. The carbonate sediments themselves belong to Rhythm C; the overlying Thrapston Clay again belongs to Rhythm D.

A similar situation exists at Thrapston (Loc. 148). Here, all of the Irchester Member belongs within Rhythm C, the top of the rhythm

coinciding with the top of the White Limestone Formation. The uppermost sediments of Rhythm C are again thought to have been rootletted, prior to lithification, during Rhythm D coastal progradation; however, this cannot be proved, and alternative hypotheses are also viable.

North of the Kettering-Peterborough Line it is even harder to place the junction between Rhythms C and D. In this northern region, the junction between the White Limestone and Thrapston Clay is gradational; the oyster-rich limestones and 'marls' of the Longthorpe Member gradually give way upwards to oyster-rich terrigenous muds with thin oyster biograinstone/packstone layers; these, in turn, pass upwards into unfossiliferous, rootletted, terrigenous muds. It seems likely that in this area the lower part of the Thrapston Clay belongs within Rhythm C. The upper, unfossiliferous part of the formation may belong within Rhythm D; there is, unfortunately, no biostratigraphic data available to confirm this.

Reference should be made to the numerous relevant localities from the east Midlands discussed in the appendix for further details relating to the placement of the Rhythm C/Rhythm D junction. It should be noted that sections through the critical Thrapston Clay interval north of the Kettering-Peterborough Line have not been examined personally; I do not know of any extant sections through the formation in this northerly part of my study area. The top of Rhythm C in boreholes in north Lincolnshire and Humberside is discussed in the appendix.

The maximum known distribution of Rhythm C sediments in the study area, particularly about the flanks of Brabantia, is illustrated in Figure 7.7.

7.4.2 Regional variation and facies distribution

Rhythm C in the southwest part of my study area, at Eton College Quarry (Loc. 5), is 5.52m thick. In the Burford area, a distinct intra-Rhythm C shallowing event can be recognised, marked by the development of a pelletal laminite (Lithofacies association C) and/or a hardground surface directly above the horizon of Aphanoptyxis cf. langrunensis. This shallowing event cannot be recognised further northeast, although an intra-Rhythm C hardground/pebble bed has been observed at Wood Eaton. Beneath the laminite at Eton College the rhythm consists of oolitic and bioclastic grainstones and packstones of Lithofacies 2 and 3 which contain a fauna of nerineid gastropods and infaunal bivalves. In the north quarry at nearby Sturt Farm (Loc. 4), much of this lower part of Rhythm C appears to have been removed by erosion (Sumbler, in prep.).

Well developed in Rhythm C above this intra-rhythm shallowing event at both Sturt Farm and Eton College are cross bedded oograins and oobiograins which belong to Lithofacies 1. These sediments are interpreted as the sediments of an active oolite shoal which extended, at this time, southeastwards towards Sussex and southwestwards towards the Tetbury district of Gloucestershire. Northeast of the Burford area, bioturbated oobio- and intrabiograins (Lithofacies 2) and grainstone/packstones (Lithofacies 3) dominate the lower part of Rhythm C, particularly in the area between Bladon and Ardley. These lime sands, which have been interpreted as backshoal sediments, become increasingly muddy in a northeast direction, towards Croughton and beyond. At Roade, sediments of Lithofacies 3 only form the lowermost 0.56m of Rhythm C.

In the area between Shipton and Croughton, where Rhythm C is between 5.6m and 5.1m thick, clean and muddy lime sands pass upwards (in

response to regional shallowing) either into pelletal lime muds (Lithofacies 5) or into the complex sediments of Lithofacies association B. It is probable that the sediments of these two facies were distributed 'mosaic fashion', landward or lagoonward of the shoal/backshoal environments. The bioturbated pelletal muds of Lithofacies 5 are interpreted as a particularly shallow water subtidal facies; Aphanoptyxis ardleyensis and other elements of Biofacies 6 are commonly found in these sediments.

Lithofacies association B dominates most of Rhythm C in Northamptonshire, but sediments of this facies association are developed only sporadically in the upper or central part of the rhythm in Oxfordshire (Cherwell Valley) and Gloucestershire (e.g. Foss Cross). The great extent to which the facies association is developed in Northamptonshire suggests that sand bar complexes (section 5.3.5) were very widely distributed in the east Midlands area at this time. The fauna usually associated with the sediments of Lithofacies association B across much of Northamptonshire is a particularly diverse one (Biofacies 4), characterised particularly by Digonella digonoides. Northwards, oysters become increasingly more common in Rhythm C, and north of the Kettering-Peterborough Line, oyster reefs and their associated sediments (Lithofacies 7, Biofacies 7) dominate the rhythm.

In the area between Blisworth, Milton Keynes and Bedford, the upper part of Rhythm C is composed predominantly of sediments of Lithofacies association C. These sediments overlies deposits of Lithofacies association B and represent an extremely shallow subtidal/intertidal facies. These sediments are particularly well developed in the uppermost 1.4m of Rhythm C at Pury End (Loc. 96) where they comprise laminated beds of pelgrainstone and pelpackstone and massive beds of

oobiograins/packstone in which Diplocraterion is conspicuous. Transported accumulations of Aphanoptyxis ?ardleyensis occur in the facies association at Pury End, Weston Underwood (Loc. 62) and Blisworth (Loc. 107); generally, however, these beds contain only a sparse macrofauna. Towards the close of Rhythm C times, as regression resulted in extremely shallow water conditions becoming more widely developed, sediments of Lithofacies association C (particularly finely laminated pelletal sands and muds) were deposited in northern Oxfordshire. These pelletal laminites occur at the top of the Ardley Member at Stratton Audley, Croughton, Great Rollright, Temple Mills and Whiteways (T. Palmer, 1979). They have been interpreted as algal laminites by some authors, but are herein believed to be storm-deposited sediments (section 5.3.8).

North of the Kettering-Peterborough Line, a rapid change of facies occurs within Rhythm C. As already mentioned, the sand bars of Lithofacies association B give way northwards to oyster reefs and associated sediments mainly belonging to Lithofacies 7; this change in lithofacies is accompanied by a sharp reduction in faunal diversity, with the fauna of Rhythm C north of the Kettering-Peterborough Line being dominated by Praeexogyra hebridica. The brachiopods (Burmirhynchia, Epithyris, Ornithella, Digonella), echinoids (Nucleolites, Acrosalenia, Holactypus) bryozoans and stenotopic bivalves (e.g. Radulopecten) found in Rhythm C sediments in the Cranford-Twywell area are rare or absent further north. This suggests the existence, during Rhythm C times, of an environmental stress gradient, similar to that described within the Wellingborough Rhythm by Bradshaw (1978); environmental stress is thought to have increased passing north or northeast from Cranford towards Stamford and Peterborough.

Further north still, in Lincolnshire, there is an increase in the proportion of terrigenous mud present within Rhythm C. This siliciclastic sediment may have been derived from the southern Pennines and the Yorkshire area. Oysters continue to dominate the fauna, with eurytopic molluscs becoming increasingly important. The absence of any apparent marine influence from the northeast or east suggests that there was only a limited marine connection with the Anglo-Dutch Basin at this time.

Similar changes in facies to those encountered on passing northwards from Cranford are believed to also occur within Rhythm C on passing eastwards from Irchester towards Brabantia. These facies changes can be recognised in the subcrop, particularly in boreholes at Roxton, Wyboston and Cambridge (B36, B37 and B41). A sand bar complex (Lithofacies association B) was well developed in the Irchester district, where Rhythm C is about 5.8m thick. Further east, the rhythm thins and is dominated by shelly mudstone and argillaceous limestone containing locally abundant oysters. At Cambridge, the rhythm is only 1.22m thick (?reflecting pre-Upper Cornbrash erosion) and comprises interbedded oyster-rich, shelly, argillaceous limestone and shale. Beyond Cambridge, the rhythm is overstepped by the Cornbrash.

There is little evidence of widespread emergence at the close of Rhythm C times, particularly if the rootlets which penetrate the uppermost Rhythm C sediments at several localities in Northamptonshire/Buckinghamshire are, as already suggested, the product of Rhythm D regression and emergence. In much of the study area it is very difficult, if not impossible, to recognise the top of the rhythm. In Oxfordshire, however, at numerous localities, the rhythm is capped by a well-marked hardground. Prior to full lithification, the uppermost

sediments of Rhythm C (typically pel-packstones and wackestones of Lithofacies 5, containing A. ardleyensis) were often burrowed by crustaceans (producing Thalassinoides open burrow systems). This hardground surface is believed to mark a major pause in sedimentation, during which early cementation of the sediment occurred. This cementation could have occurred in either a submarine or a vadose setting; the former is considered more plausible since emergence indicators (rootlets, birdseyes, shrinkage cracks, etc.) are usually absent from the lithology immediately beneath the hardground surface.

There is localised evidence, other than the widespread development of Lithofacies association C sediments, which marks the close of Rhythm C. At Stratton Audley and Temple Mills, channels were cut through the uppermost carbonate sediments of Rhythm C, probably by streams which, draining a land area at no great distance to the north and east, traversed an emergent ?intertidal/supratidal flat. The channels were subsequently infilled after abandonment by terrigenous muds of Lithofacies association E. At Croughton, calcite pseudomorphs after gypsum have been discovered in the uppermost, laminated sediments of Rhythm C (J. Andrews, pers. comm.). This is clear evidence of at least patchy emergence at the close of the rhythm.

Unlike most earlier Bathonian rhythms, where the axis along which most facies changes occur lies to the west of today's outcrop, this axis for Rhythm C essentially follows the outcrop. It is thought that this is because the main transgressive thrust which initiated Rhythm C came into the 'East Midlands Seaway' largely along the line of the outcrop. Preceding transgressive thrusts were offset to the west of the outcrop, mainly because transgression southeastward onto the London-Brabant Massif was less extensive in the earlier rhythms.

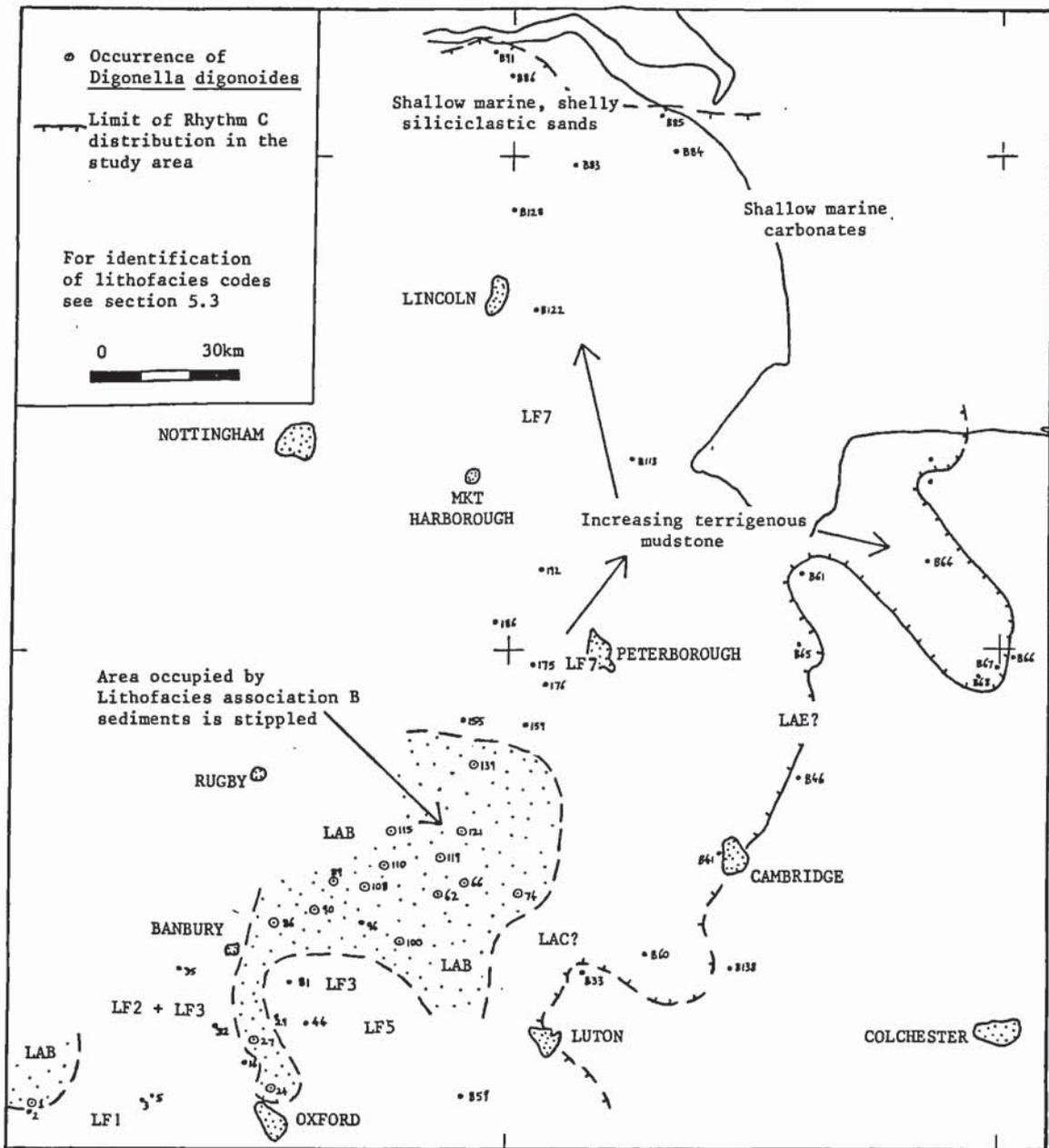


FIGURE 7.8 Rhythm C: facies distribution in early Rhythm C times.

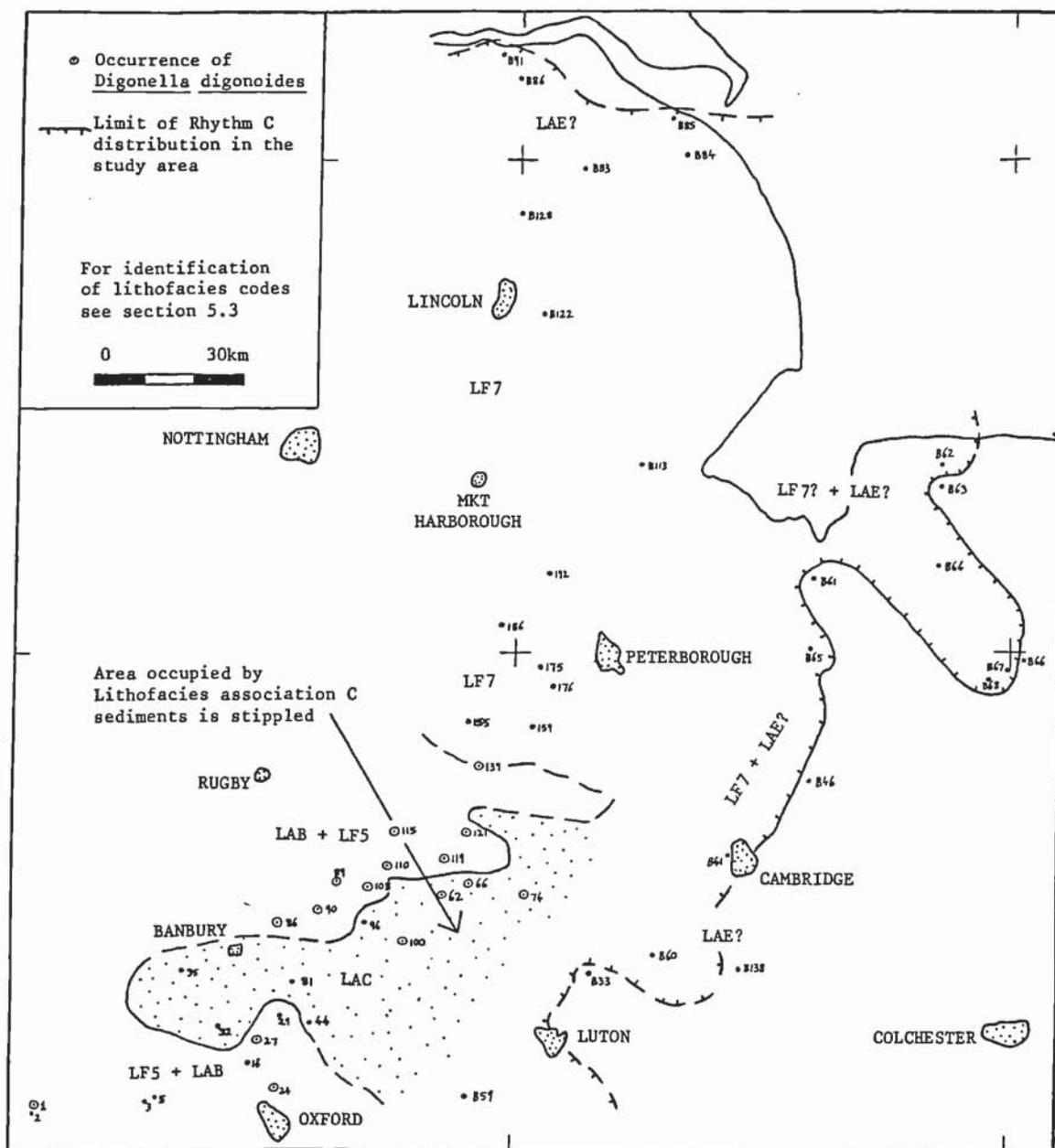


FIGURE 7.9 Rhythm C: facies distribution in late Rhythm C times.

7.5 Rhythm D

7.5.1 Introduction

In Oxfordshire, Rhythm D is usually contained wholly within the Bladon Member; in the east Midlands, Rhythm D sediments are included within the Bladon and Irchester Members, and occasionally within the Forest Marble Formation; they are believed to be extensively developed within the Thrapston Clay Formation. Rhythm D sediments are probably of hodsoni Zone age, but the ammonite evidence to confirm this is lacking.

Rhythm D was initiated by a marine transgression considerably less extensive than that which began Rhythm C. The probable maximum extent of the Rhythm D marine transgression is indicated in Figure 7.10. Beyond the probable limits of the marine transgression, Rhythm D sediments are believed to be of wholly freshwater origin (e.g. in areas where the only Rhythm D sediments are terrigenous muds within the Thrapston Clay which have yielded only non-marine palynofloras; e.g. Fenton, 1980). The regression which ended the rhythm is believed to have led to very widespread emergence and to the extensive spread of nearshore carbonate facies in regions beyond my field area. The Coppice Limestone of the Malmesbury district (Cave, 1977), and similar lithologies around Minchinhampton may belong within Rhythm D; so too may the porcellaneous limestone developed at the top of the 'White Limestone' in the Warlingham borehole (Worssam & Ivimey-Cook, 1971).

The most important element of the Rhythm D fauna found within the study area is Aphanoptyxis bladonensis. This species is not found in lower rhythms, but does, in addition, occur in the overlying Rhythm E in Oxfordshire and southwest Northamptonshire. Besides the well-documented occurrences of the species in the Bladon Member in Oxfordshire, specimens

of A. bladonensis have been collected from lowermost Rhythm D sediments at Irchester Old Lodge.

Rootletted sediments characterise the upper part of Rhythm D in the east Midlands and at numerous localities in northeast Oxfordshire. At some localities in the latter area, supratidal marsh carbonates (Lithofacies 6) are developed in the upper part of the rhythm. These carbonates were described in detail by Palmer & Jenkyns (1975) who, incorrectly in my opinion, identified them as sediments deposited on an emergent carbonate island. Similar supratidal marsh lime mudstones also occur in the upper part of Rhythm E. At some localities in Oxfordshire, particularly in the southwest part of my study area and also beyond, in Gloucestershire, Rhythm D is capped by a hardground.

The terrigenous muds and associated sediments of the so-called 'Fimbriata-Waltoni Beds' or 'fimbriatus-waltoni clays', where they occur in the Cherwell Valley district, largely belong within Rhythm D.

7.5.2 Regional variation and facies distribution

The earliest Rhythm D sediments deposited across much of northeast Oxfordshire and southwest Northamptonshire were oolite packstones and wackestones containing stands of 'Isastraea', and the associated fauna which typifies Biofacies 5. These are thought to be the deposits of a relatively protected, shallow, normal marine, subtidal environment. Oolitic sand within these lithologies may have been derived from areas of high-energy shoal, developed to the south of both my study area and the Oxfordshire outcrop; ooids may have been washed northwards by onshore storm waves. The lime sand has usually been totally admixed with lime mud, as a result of bioturbation, in the Rhythm D coral beds. The coral bed facies dies out east of Croughton and Roade, in a region where

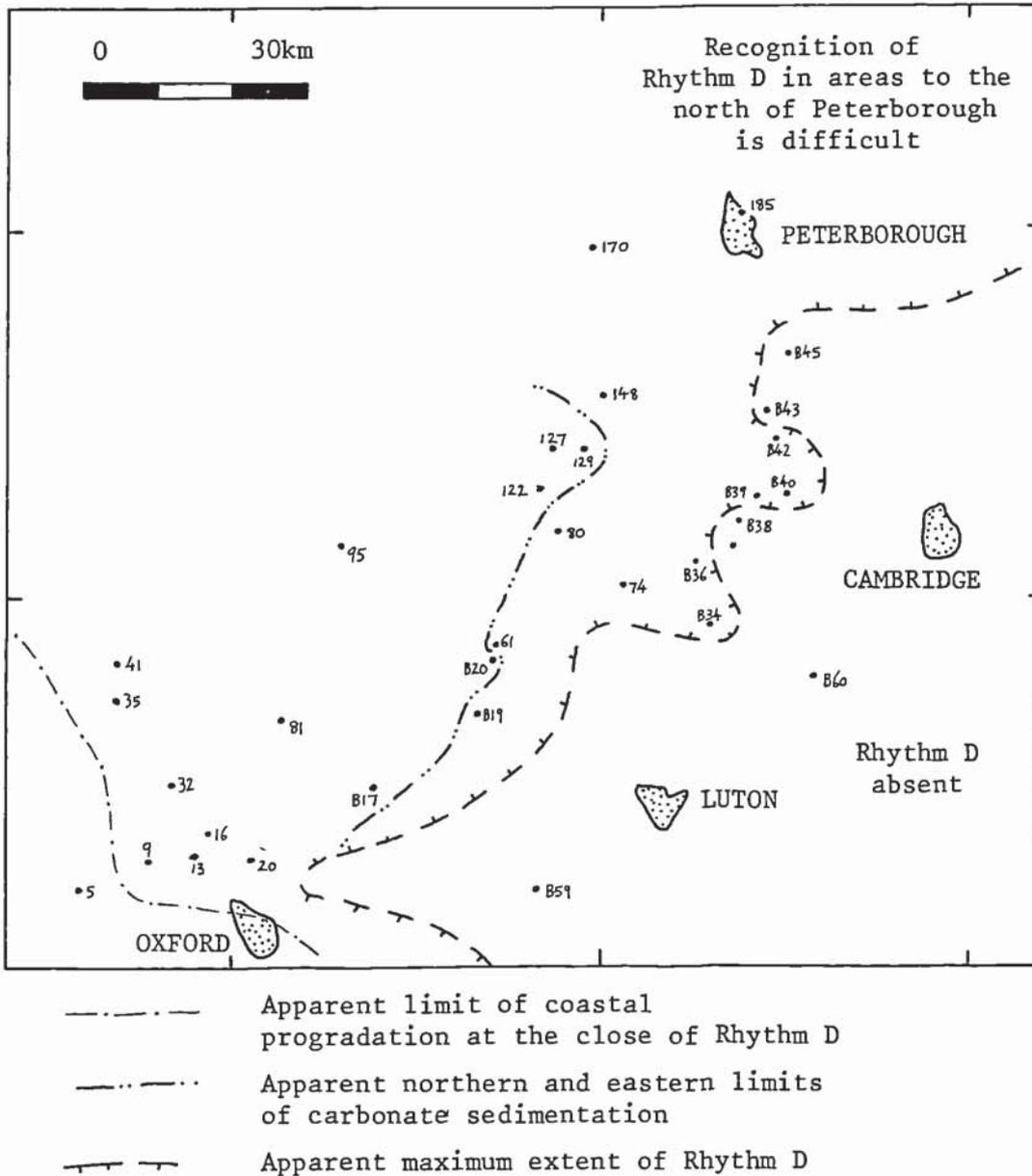


FIGURE 7.10 Rhythm D: geographical limits and maximum southwestward extent of coastal progradation.

carbonates are less well developed within Rhythm D. The absence of Biofacies 5 in this region is believed to be due largely to increasing environmental stress in an east/northeast direction, but perhaps also to the absence of stable substrates which corals could readily colonise.

Locally in the Cherwell Valley, coral beds appear to pass laterally into poorly fossiliferous (bio)oograinstones and packstones, the deposits of less protected areas of the sea floor. Often these sediments, or the basal Rhythm D coral bed, are overlain by terrigenous muds, the 'fimbriatus-waltoni clays'. These sediments mark an important episode of coastal progradation during the regressive phase of Rhythm D. The 'fimbriatus-waltoni clays' are essentially sediments of Lithofacies association E. Coastal progradation is indicated by the common occurrence of Equisetites rootlets in these sediments. These rootlets are truncated not only at the erosive base of the overlying rhythm (Rhythm E or the Forest Marble 'Rhythm') but also at the base of 'swirl-based' fossiliferous clays (often containing B. waltoni, E. angulatus and other bivalves of Biofacies 6) which are interpreted as storm deposits washed landward onto the coastal plain. The regressive phase of Rhythm D also witnessed the development of a supratidal carbonate marsh across part of Oxfordshire and some areas of Northamptonshire. Lime mudstones (often containing rootlets, birdseyes and/or shrinkage cracks) belonging to Lithofacies 6 are developed in the upper part of Rhythm D at North Leigh, Slape Hill, Ardley, Temple Mills, Pest House Railway Cutting, Stratton Audley, Pury End and Stanwick. Across much of the east Midlands, the uppermost Rhythm D carbonate sediments (Lithofacies association 5, Lithofacies 6 or oyster beds of Lithofacies 7) are overlain by predominantly freshwater terrigenous muds of Lithofacies association E, believed to have been deposited in a widely

established swamp and lake coastal plain complex during the Rhythm D regression. In many parts of the east Midlands, particularly north of Irchester and southeast of Milton Keynes and Roade, Rhythm D consists wholly of these marginal marine to freshwater, non-carbonate sediments.

A channel, passively infilled by non-marine, terrigenous mud after abandonment, occurs at the top of Rhythm D at Croughton (Plate 13C). This was cut through the pelleted lime mud sediment of the underlying 'A. bladonensis Bed' while still soft.

7.6 Rhythm E

7.6.1 Introduction

Rhythm E is the least extensively developed rhythm recognised within the upper Great Oolite Group of the study area. It has not been identified to the northeast of Croughton and Stratton Audley and is only sporadically developed to the southwest of these localities. The absence of the rhythm in the east Midlands could be because:

- i) Northeast of Croughton the rhythm has been overstepped by the Forest Marble and, further northeast, by the Cornbrash. Certainly the rhythm has been removed by pre-Forest Marble erosion at many Oxfordshire localities to the south and southwest of Croughton, notably in the Cherwell Valley and in the Burford area.
- ii) The marine transgression which initiated Rhythm E did not extend far northeast of Croughton, and sediments contemporaneous with those of Rhythm E were never deposited in this area, which remained emergent from the end of Rhythm D times until inundated by the Forest Marble transgression.

iii) The marine transgression which initiated Rhythm E did not extend far northeast of Croughton, and the Rhythm D regression continued without interruption in the east Midlands; in this case, the uppermost Rhythm D sediments in the east Midlands will be contemporary with the Rhythm E sediments of further southwest.

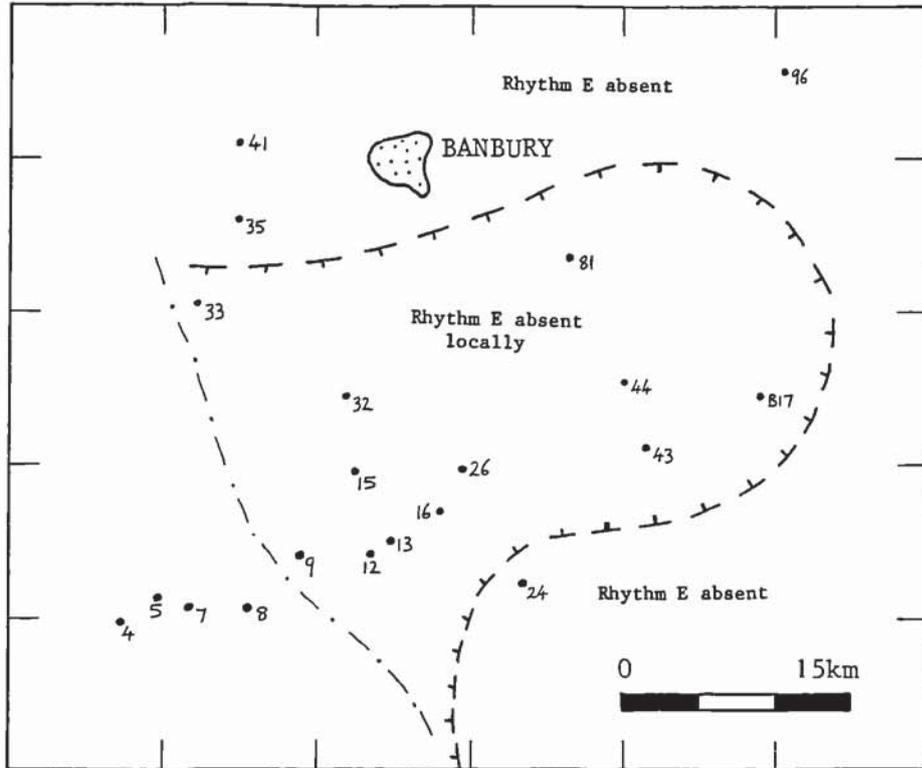
iv) A combination of any two or all three of the above possibilities occurred.

In the study area, Rhythm E sediments are contained within the ?Great Oolite, within the upper part of the Bladon Member and, locally (e.g. Croughton), within the lowermost portion of the Forest Marble Formation. Many of the sediments found in Rhythm E are similar to those found in the underlying Rhythm D. Aphanoptyxis bladonensis occurs in Rhythm E as well as in Rhythm D.

7.6.2 Regional variation and facies distribution

The most offshore sediments encountered within Rhythm E are oobiopackstones and wackestones containing corals and other elements of Biofacies 5. The 'Upper Epithyris Bed' of the Cherwell Valley, the lowermost unit of Rhythm E in that area, is characteristic of this facies. Locally (e.g. Kirtlington), coral beds pass laterally into relatively unfossiliferous, oobiopackstones/grainstones, the sediments of periodically current-scoured, less protected areas of the sea floor.

At Croughton, a biopelpackstone is present at the base of the rhythm. This grades up into unfossiliferous, cryptalgally laminated lime mudstone which contains birdseyes and other fenestrae and is locally rootletted; these are the sediments of a supratidal carbonate marsh. Similar sediments are developed in the rhythm at Stratton Audley and Blackthorn Hill. At Croughton, these lime mudstones are overlain by



- · — Apparent limit of coastal progradation at the close of Rhythm E
- · - Apparent maximum extent of Rhythm E

FIGURE 7.11 Rhythm E: geographical limits and maximum southwestward extent of coastal progradation.

rootletted terrigenous mudstones which bear witness to the progradation of a siliciclastic-dominated marsh over the carbonate marsh during the late stages of Rhythm E. As during the final phase of both Rhythms C and D, streams draining the hinterland to the east or northeast cut channels in the uppermost sediments of Rhythm E in the Oxfordshire area. These channels were subsequently abandoned and infilled with freshwater terrigenous mudstones which are often rootletted and typically contain abundant plant debris, freshwater ostracods, charophytes and rare dinosaur, crocodile and even mammal remains. The 'Kirtlington Mammal Bed' (E. Freeman, 1979; Loc. 26) is believed to be the basal part of such a channel-fill. Another channel-fill developed at this stratigraphic level occurs at Stratton Audley (Plate 13B).

Following the Rhythm E regression, sedimentation did not resume in the study area until the earliest Forest Marble transgression. In the intervening period, widespread erosion occurred.

7.7 Forest Marble 'Rhythm'

7.7.1 Introduction

The distribution of the Forest Marble 'Rhythm' in the study area is illustrated in Figure 7.12. Throughout most of the study area the 'rhythm' is contained entirely within the Forest Marble Formation, although at some locations (e.g. Croughton, Ardley, Roade) the lowest part of that formation is comprised of sediments belonging to earlier rhythms. Most of the sediments of the Thrapston Clay Formation also belong to earlier rhythms. However, in northern Lincolnshire/South Humberside (e.g. Nettleton) sediments which are possibly correlatable

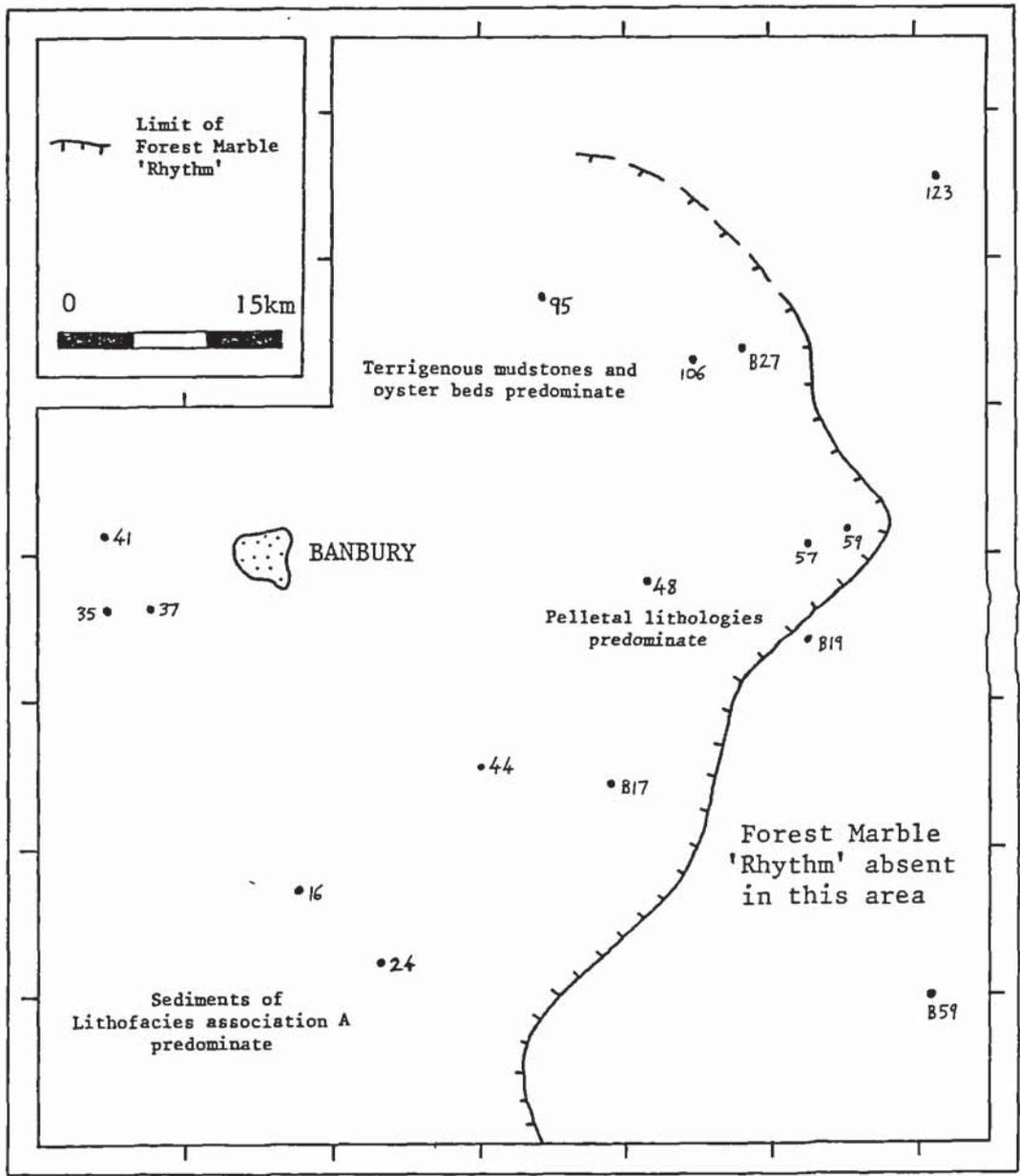


FIGURE 7.12 Forest Marble 'Rhythm': geographical limits.

with those of the Forest Marble 'Rhythm' have not been separated from the Thrapston Clay.

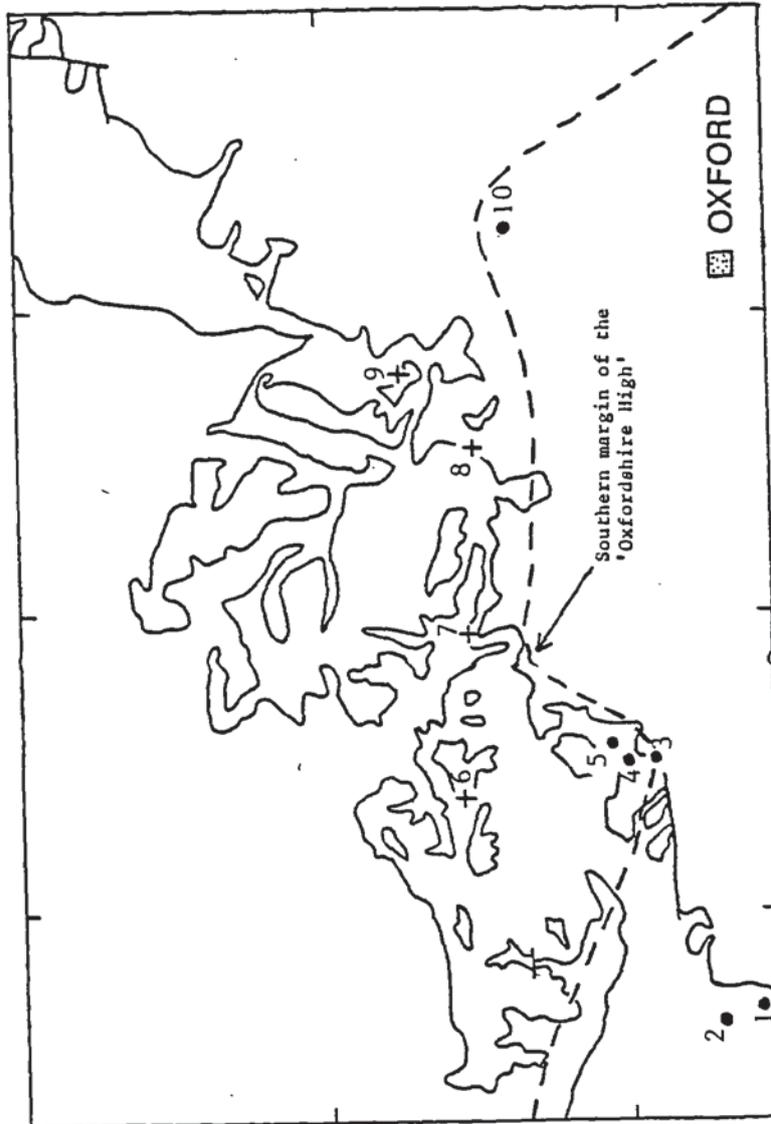
The Forest Marble 'Rhythm' was initiated by a relative rise in sea level, poorly dated but thought to have been of hollandi Subzone age. Everywhere in the study area the base of the 'rhythm' is sharply erosive and, in places, the 'rhythm' base cuts down through underlying rhythms. The erosive nature of the base of the Forest Marble in Oxfordshire and Gloucestershire has frequently been commented on (e.g. Woodward, 1894; Odling, 1913; L. Richardson, 1933; Worssam & Bisson, 1961; Barker, 1976; Sumbler, 1984). Deposition of Forest Marble 'Rhythm' sediments followed a period of extensive emergence which closed White Limestone/Thrapston Clay deposition. The basal sediments typically contain large amounts of woody debris and, frequently, concentrations of vertebrate material.

The existing exposures of the Forest Marble 'Rhythm' in the study area are not sufficient to allow subdivision into more than a single depositional unit. However, evidence from the Forest Marble developed to the southwest suggests that this may be an over-simplification. In particular, in southern England, it is possible to recognise a lower and an upper depositional event, each with, at its base, a horizon in which characteristic 'Bradfordian' faunas are developed. The boueti Bed of Dorset/Somerset and the 'Bradfordian' horizon developed at the base of the Upper Rags in the Bath district are examples of the lowest 'Bradfordian' horizon, found at the bottom of the lower 'rhythm'. The digona Bed of the Weymouth Anticline and the type horizon of the 'Bradford Clay' in Wiltshire (which occurs directly above the Upper Rags) are examples of the 'Bradfordian' horizon at the base of the upper

'rhythm'.* Both the 'Bradfordian' horizons and the firmgrounds or hardgrounds above which they typically occur probably relate to two relative rises in sea level which affected the whole of southern England. If so, then the so-called 'Bradford Fossil Bed' of central England (Arkell, 1931) may be related to the second sea level rise, believed to have initiated the upper depositional event. However, such a hypothesis is difficult to prove in the absence of convincing biostratigraphic evidence. Certainly it is not the view of many; T. Palmer (1974), for example, has stated that the development of 'Bradfordian' faunas in the Oxfordshire Forest Marble was merely the result of the local occurrence at any given moment in time of suitable ecological conditions and he did not believe that these conditions need be developed everywhere at the same time, as is implied by my own argument.

The 'Bradfordian' fauna is a facies fauna comprising stenotopic organisms which flourished on a stable substrate in offshore, open and well-circulated sea-water (T. Palmer, 1974). It is a fauna considerably more common in southern England than in Oxfordshire, where occurrences of the fauna at outcrop are restricted to the southern fringes of the 'Oxfordshire High' (Fig. 7.13). Indeed, northerly occurrences of Arkell's 'Bradford Fossil Bed' lack the most distinctive elements of the 'Bradfordian' fauna (Eudesia, Dictyothyris, Digonella). Thus the

* This argument is based on correlations initially proposed by Sylvester-Bradley (1957), albeit unintentionally, and more recently suggested by the B.G.S. (Penn & Wyatt, 1979; Penn, 1982). These correlations are not, however, universally accepted (e.g. Torrens, 1980b; Holloway, 1981, 1983); ammonite evidence is equivocal.



- Occurrences of 'Bradfordian' faunas
- + Poorly developed
 - Well developed
1. S.W. of Carterton crossroads
 2. Alvescot Down
 3. Ducklington Lane Quarry, Witney
 4. Witney Cemetery Quarry, Witney
 5. Crawley Road Quarry, Witney
 6. Dogslade Quarry
 7. Breakpear's Quarry, East End
 8. Bladon Spinney Quarry
 9. Shipton Cement Works
 10. Grange Quarry, Islip

FIGURE 7.13 Map illustrating the distribution of 'Bradfordian' faunas in the Oxfordshire Forest Marble.

'Bradford Fossil Bed' of Sunhill (Elliot, 1973), Carterton (Arkell, 1931) and Islip (T. Palmer, 1974) contains well-developed 'Bradfordian' faunas, though less diverse than those of the Bath area and Dorset; at Witney, the presence of 'Bradfordian' faunas is indicated only by Digonella digona, rhynchonellids, cidarid spines and occasional bryozoans; at Bladon and East End, the supposed 'Bradfordian' fauna is reduced to a single species of rhynchonellid, cidarid spines and bored corals.

The regression which closed the Forest Marble 'Rhythm' can be recognised beyond the limits of my study area, notably in the Cirencester area, where freshwater faunal and floral elements have been obtained from the upper part of the Forest Marble Formation (Ware & Windle, 1981; Ware et al., 1983), and in the Wessex Basin, where brackish-water faunas occur beneath the Cornbrash and where the lithofacies and trace fossils of the upper Forest Marble suggest shallow-water conditions (Holloway, 1981; Penn, 1982). In Oxfordshire, however, there is relatively little evidence of coastal progradation, perhaps because of the removal of the uppermost Forest Marble 'Rhythm' sediments by pre-Cornbrash erosion. However, at Shipton, sand-filled channels incised into the top of the Forest Marble (Allen & Kaye, 1973) are believed to have been formed during the end of Forest Marble regression. They may have been cut by streams draining the hinterland to the east, and were infilled by sand following their abandonment. The occurrence of worn and oyster-encrusted stegosaurian dinosaur remains in the basal Lower Cornbrash at Shipton (Galton & Powell, 1983) is further evidence of regression and probable emergence at the close of the Forest Marble 'Rhythm' in the Oxford area, as well as of erosion and reworking of the uppermost Forest Marble.

7.7.2 Regional variation and facies distribution

The Oxfordshire Forest Marble is dominated by thick units of lime sand which give way laterally to mudstones containing thinner interbedded units of oobiograinstone and packstone. These are the sediments of Lithofacies association A, which have been interpreted as the deposits of a belt of (?tidally-influenced) linear sand bars (see section 5.3.4). Undoubtedly the best exposure of this facies association occurs at Shipton-on-Cherwell, but there are also important extant exposures of the facies at East End, Long Hanborough, Kirtlington, Upper Greenhill, Wood Eaton and Temple Mills.

Between Burford and Witney, and further southwest, the Forest Marble 'Rhythm' becomes increasingly dominated by cross-bedded oobiograinstones, although interbeds of terrigenous mudstone are still present. It is possible that a more extensive oolite shoal was developed to the south of the Oxfordshire outcrop, trending southeastwards from the Cirencester area. This is envisaged as a more offshore setting than that in which the sand bars of Shipton were developed. Quartz sand which occurs locally in the Forest Marble between Burford and Witney (Richardson *et al.*, 1946) may have been deposited during the close of Forest Marble regression. T. Palmer (1974) suggested that this sand was probably sourced from Brabantia, transported westwards along channels similar to those formerly visible at Shipton.

Northeastwards from Shipton there is a change in the character of the Forest Marble sediments, with oolitic grainstones becoming less common in this direction. These facies changes mark a passage into an increasingly nearshore setting. At Stratton Audley and in the area around Buckingham and Milton Keynes, the Forest Marble 'Rhythm' comprises mainly micritic limestones (bio- and pel-packstones and wackestones with

only rare oolitic lithologies) interbedded with terrigenous mudstones. Care must be taken in this area if the deposits of the Forest Marble 'Rhythm' are to be correctly separated from those of older rhythms. As noted elsewhere in this thesis, T. Palmer (1974, 1979) incorrectly included the uppermost beds of the White Limestone in the Forest Marble at Stratton Audley and elsewhere. The uppermost bed of the Forest Marble 'Rhythm' in the region between Blackthorn Hill and Milton Keynes is a micritic, often porcellaneous limestone, a biopelackstone/wackestone assignable to Lithofacies 6. The top of this limestone is frequently bored or burrowed (Horton, Shepherd-Thorn & Thurrell, 1974). In a borehole at Great Linford (B20), rootlets are apparently developed in the upper part of the Forest Marble 'Rhythm', bearing witness to coastal progradation, at least in that area, at the end of the 'rhythm'. However, rootlets recorded at a lower horizon within the 'Blisworth Clay' by Horton et al. (op. cit.) are believed to be related to the close of Rhythm D regression.

Between Great Linford and Bedford, the Forest Marble 'Rhythm' is overstepped by the Upper Cornbrash. Similarly, east of the Oxfordshire outcrop, the overstep of the Forest Marble 'Rhythm' by the Cornbrash (and locally by the Kellaways Beds; e.g. Tattenhoe) is rapid. The Forest Marble 'Rhythm' is also overstepped by the Cornbrash between Quinton and Irchester/Rushden in Northamptonshire. In southwest Northamptonshire, the Forest Marble 'Rhythm' is dominated by terrigenous mudstones. At Croughton, ripple cross-laminated pelgrainstone and subordinate packstone are locally developed while oobiograinstone and packstone occur in the vicinity of Church Stowe and Grimscoate (Aveline & Trench, 1860; Thompson, 1891), and also at Quinton (Thompson, MS.). At Roade (Loc. 106), clays and fossiliferous, argillaceous limestones containing Praeexogyra,

Placunopsis, Corbulomima and other bivalves occur in the 'rhythm' (Thompson, 1924). The lack of exposures of the Forest Marble 'Rhythm' in this part of Northamptonshire is unfortunate, as sections given in the literature cannot always be interpreted with certainty. It is probable that only the upper part of the Forest Marble Formation of the Stowe-IX-Churches/Roade area, as recognised in this thesis, belongs within the Forest Marble 'Rhythm'; the lower part of the formation may be laterally equivalent to the Thrapston Clay Formation, which has been recognised further to the east. It would appear that the Forest Marble 'Rhythm' in this area was clearly deposited in a restricted marine, low energy, nearshore environment into which higher energy lime sands (mainly bioclastic) were occasionally swept. The environment was colonised by stress-tolerant bivalve faunas, essentially belonging to Biofacies 6 & 7. The terrigenous muds were probably derived from Brabantia, and perhaps also from the Mercian Archipelago. The fairly high freshwater run-off responsible for carrying the siliciclastic sediment into the 'East Midlands Embayment' at this time may have rendered the embayment brackish for long periods. Further south, reduced salinities are also suggested by many of the bivalve-dominated faunas of the Oxfordshire Forest Marble. Furthermore, terrigenous mudstones interbedded with oolitic grainstones at Kirtlington contain freshwater ostracods (Bate, 1965), probably transported by streams away from coastal lakes and marshes developed around Brabantia.

The occurrence of stenotopic 'Bradfordian' faunas within the Forest Marble 'Rhythm' along the southern margin of the 'Oxfordshire High', as well as further south (e.g. Harwell; B16), indicates that, at least for some of the time, normal marine conditions were maintained in the region south of Shipton. Facies and fauna changes within the Forest

Marble 'Rhythm' suggest that the northeastward passage from a normal marine into a predominantly brackish-marine environment was very rapid.

Facies distributions suggest that the marine transgression which initiated the deposition of Forest Marble 'Rhythm' sediments in Oxfordshire and Northamptonshire came from the Wessex Basin, and followed a path similar to that followed by earlier Middle Jurassic transgressions. The deposition of predominantly siliciclastic sediments developed in parts of northern Lincolnshire, at the same stratigraphic level as the Forest Marble 'Rhythm' further south, may have been initiated by a simultaneous transgression from the Anglo-Dutch Basin. However, the contemporaneity of these sediments is difficult to prove. The best documented occurrence of these ?Forest Marble 'Rhythm' sediments is at Nettleton (B83; Bradshaw & Penney, 1982) where they consist mainly of rootletted green, grey, olive-brown and khaki mudstones and claystones, often interlayered with subordinate white silt (included in the 'Blisworth Clay' by Bradshaw & Penney, op. cit.). Only the basal sediments of this rhythm (partly included in the 'Blisworth Limestone' by Bradshaw & Penney) contain marginal marine bivalves. The same rhythm at Worlaby (B86) appears to consist of fine sandstone and silty mudstone (mostly included in the 'Upper Sandy Beds' by G. Richardson, 1979), again with bivalves only present at the base of the rhythm. The sediments of this rhythm are probably also present at both Tetney Lock (B84) and Cleethorpes (B85) where, as at Nettleton and Worlaby, they are likely to be contained largely within the Thrapston Clay Formation of this thesis. The lack of suitable data from the outcrop means that the full extent of this rhythm in north Lincolnshire cannot be established.

The apparent absence of sediments which can be assigned to the Forest Marble 'Rhythm' (or the possibly correlatable north Lincolnshire rhythm) along the outcrop between Quinton (B27) and Spital (Loc. 206), or in the subcrop to the southeast, may indicate that transgressions from the Wessex and Anglo-Dutch Basins did not meet up. However, the absence of the 'rhythm' across a large part of the east Midlands is probably also due to pre-Cornbrash erosion.

7.8 Lower Cornbrash 'Rhythm'

7.8.1 Introduction

The Lower Cornbrash has been called a 'rhythm' for convenience only, since it is a depositional unit very different in character to the rhythmic units discussed earlier in this chapter. However, like the earlier rhythms, the Lower Cornbrash 'Rhythm' was initiated by a rise in sea level. The marine transgression produced by this sea level rise was very extensive and the Lower Cornbrash can be traced throughout much of England south of the River Humber. Furthermore, contemporary deposits of very similar character are widely distributed in France. The great extent of this marine transgression, which can be firmly dated as being of discus Subzone age, supports a eustatic origin for the initiating rise in sea level. Figure 7.14 illustrates the extent to which the Lower Cornbrash 'Rhythm' is developed in the study area. The 'rhythm' (which coincides exactly with the Lower Cornbrash Member) is well developed in Oxfordshire and west Northamptonshire. It is overstepped by the Upper Cornbrash in the Milton Keynes district, but is still sporadically developed at Bedford. Further north, between Rushden and Barnwell, the Lower Cornbrash is very variable in thickness, a reflection of differing

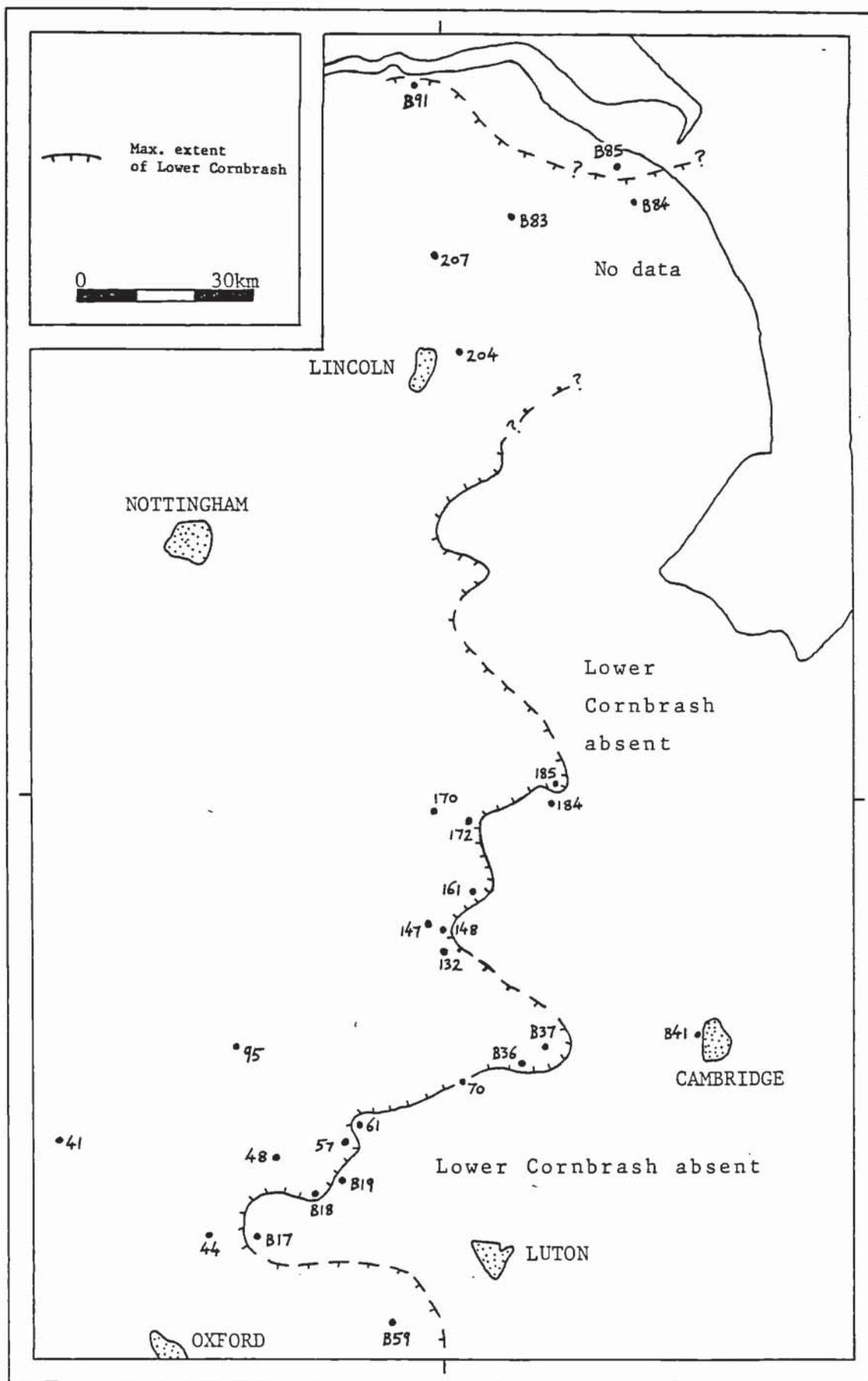


FIGURE 7.14 Geographical limits of the Lower Cornbrash.

amounts of pre-Upper Cornbrash erosion and reworking. In Lincolnshire, at outcrop, the Lower Cornbrash 'Rhythm' is only locally developed beneath the Upper Cornbrash. In the subcrop to the east and southeast of Bedford, Lower Cornbrash appears to be developed locally (e.g. Roxton, Wyboston) but in boreholes further north, the Cornbrash appears to comprise only Upper Cornbrash (cf. Penn et al., 1986). The Lower Cornbrash is, however, present at Nettleton (B83), Worlaby (B86) and Tetney Lock (B84).

Nowhere is the Lower Cornbrash 'Rhythm' seen to be closed by coastal progradation. At a few localities the 'rhythm' is capped by an encrusted hardground (e.g. Raunds, Loc. 132). At most places, the top of the Lower Cornbrash is defined by the erosive base of the Upper Cornbrash.

7.8.2 Regional variation and facies distribution

The Lower Cornbrash is a difficult depositional unit on which to undertake a facies analysis, largely because it is relatively condensed, but also because facies within the 'rhythm' do not change much, even over large areas. In the study area, the Lower Cornbrash is thin, reaching a maximum thickness of about 3-4m in Oxfordshire, and seldom exceeding 1-2m in the east Midlands. Rare ammonites (Clydoniceras) have been obtained from the Lower Cornbrash at outcrop at numerous localities between Sudbrooke Park (Loc. 204), near Lincoln, and Oxford (Douglas & Arkell, 1932), suggesting that throughout the study area, near-normal marine conditions were maintained during deposition of the Lower Cornbrash. However, the presence of ammonites in the Lower Cornbrash may also reflect a very slow sedimentation rate and consequent concentration of pelagic organisms.

Relatively few lithology types occur within the Lower Cornbrash 'Rhythm' of the study area: grainstones and grainstone/packstones are interbedded with bioturbated packstones and wackestones and, additionally, rare beds of terrigenous mudstone containing thin layers and laminae of lime sand also occur. In all lithologies, comminuted bioclastic debris is the most common grain type. In addition, pellets and subordinate intraclasts (particularly amorphous lumps) are usually also present. In the packstones and wackestones (which are typically softer-weathering and often 'rubbly' or 'marly'), the matrix consists mainly of lime mud, but also, in some instances, limited amounts of terrigenous mud. I have not found any ooids within the Lower Cornbrash of the study area, and this absence of ooids may characterise both the Lower and Upper Cornbrash in most (if not all) parts of England. Cornbrash limestones are more like the temperate water carbonates of Lees (1975) than are the limestones of the Forest Marble and White Limestone; the lack of ooids in the Cornbrash may, therefore, be related to global cooling in the Late Bathonian/Early Callovian (cf. Ager, 1975).

All Lower Cornbrash sediments studied can be interpreted as shallow, near-normal marine, subtidal deposits. Some areas of the sea floor were relatively protected and characterised by predominantly fine-grained sedimentation. Other parts of the sea floor were swept, at least periodically, by currents; in these areas, lime sands were mainly deposited. The different sediments may have been irregularly distributed to form a facies mosaic developed across an extensive carbonate platform.

The bio- and pelbiowackestones and packstones are the deposits of the relatively protected areas of sea floor. Lime sand, which was probably washed into these areas by intermittent currents, was subsequently admixed with lime mud by burrowing organisms, particularly

bivalves. The resultant muddy sand and sandy mud substrates were very stable and were colonised by the characteristic fauna of the Lower Cornbrash: Cererithyris, Obovothyris, Radulopecten, Meleagrinnella, Limatula, Pseudolimea, Homomya, Pholadomya, Ceratomya, trigoniids, Pygurus, Nucleolites and Acrosalenia.

The biograinstones, or more commonly grainstone/packstones, were deposited as lime sands and muddy lime sands affected by fairly continuous current activity. They constituted a less stable substrate than the sandy muds, and this was colonised by species typical of Biofacies 3, notably deep burrowing bivalves (Homomya, Pholadomya, Pleuromya), trigoniids, occasional brachiopods, Radulopecten vagans and Meleagrinnella echinata; the latter is often abundant in 'poorly-washed' lime sands. *The lime sands are sometimes poorly laminated but more commonly thoroughly bioturbated.* Thalassinoides is developed in both the biograinstones/packstones and in the wackestones/packstones. Clydoniceras, although not particularly common, has been found in all Lower Cornbrash lithologies.

The lack of any regional pattern of facies variation means that it has not been possible to reconstruct the Lower Cornbrash palaeogeography of central and eastern England. No true coastal facies have been recognised within the study area. This is perhaps because the extensive discus Subzone transgression completely inundated the Mercian Archipelago and large areas of Brabantia and the Pennine High, with the result that shorelines were far removed from the outcrop area. However, a possible transition into a more marginal depositional environment on passing northwards towards the Market Weighton Block is suggested by the absence of brachiopods, bryozoans, echinoids and ammonites from the Lower

Cornbrash in northern Lincolnshire and Humberside (e.g. Worlaby, Nettleton).

7.9 Upper Cornbrash

The basal Callovian Upper Cornbrash is the most extensive member of the Great Oolite Group. However, while in many respects lithologically similar to the Lower Cornbrash, it is more closely related to the overlying formations than it is to the rest of the group. It is not a self-contained depositional unit like the Lower Cornbrash but is, instead, the basal part of a depositional sequence which includes both the Kellaways Clay and Kellaways Sand, and maybe also the Lower Oxford Clay. The contact between the Upper Cornbrash and Kellaways Clay is often gradational. Certainly the Upper Cornbrash contains ammonite and brachiopod faunas very different to those of the Lower Cornbrash and earlier Bathonian formations. For this reason the Upper Cornbrash is not discussed in great detail in this thesis. Any worthwhile study of the Upper Cornbrash must also involve a study of the Kellaways Beds; this is beyond the scope of the present study.

Everywhere the Upper Cornbrash occurs it is characterised by a sharply defined, often erosive base. Pebbles of reworked, lithified Lower Cornbrash limestone and reworked Lower Cornbrash fossils are often incorporated into the basal sediments of the Upper Cornbrash, particularly at outcrop between Milton Keynes and Peterborough and in the subcrop to the east and southeast. The pebbles of limestone, which are typically bored and encrusted, can be collected in large numbers at Thrapston (Loc. 148). In some cases they may be reworked from a hardground which originally capped the Lower Cornbrash.

Like the Lower Cornbrash, the Upper Cornbrash is a condensed limestone. In addition to the basal pebble bed, intra-Upper Cornbrash pebble beds have been recorded locally, as at Newport Pagnell (Horton, Shephard-Thorn & Thurrell, 1974). Pellets and bioclasts are the main grain types present within the Upper Cornbrash; ooids have not yet been observed. Faunal associations are similar in character to those found within the Lower Cornbrash, although many of the species are different. The Upper Cornbrash probably contains a slightly higher diversity of stenotopic taxa, such as bryozoans and echinoids. It is probable that sediments of the Upper Cornbrash were deposited in a fully marine, offshore but relatively shallow environment.

An initial study of the distribution of the Upper Cornbrash and Kellaways Clay in southern and central England suggests that, in some areas, the basal Kellaways Clay may be laterally equivalent to the Upper Cornbrash developed elsewhere (i.e. locally the basal Kellaways Clay may be of macrocephalus Subzone age), the former perhaps representing a more offshore facies. However, if this hypothesis is to be confirmed, a great deal of further work must be done on lateral facies relationships and the palaeontology/biostratigraphy of the relevant beds.

7.10 Controls on rhythmic sedimentation

The Recent sediments of the West Mississippi Embayment, which were used as an analogue for Rutland Formation rhythms by Bradshaw (1978), have a rhythmic character produced entirely by delta-switching. Coastal progradation has occurred when the rate of longshore sediment supply has been high, as is the case when actively depositing deltas are in the vicinity. Shoreline retreat has followed each progradational phase, brought about against a background of continuous subsidence, when

a change in delta position has caused a sudden decrease in sediment supply. This pattern of sedimentation has resulted in a stacked sequence of coastal offlap rhythms being preserved in the shallow subsurface. However, the great extent of some Rutland Formation rhythms and the lack, or unsuitable geometry, of a sufficiently large and adjacent contemporary site of sediment input led Bradshaw (op. cit.) to conclude that the West Mississippi Embayment model was not the principal control on the generation of Rutland Formation rhythms. If we are confident that the simple siliciclastic rhythms within the Rutland Formation were not the product of delta-switching or some related process, we can be even more certain that the predominantly carbonate, shallowing-upwards rhythms of the upper Great Oolite Group were produced by a different process. These carbonate rhythms must have been generated by fluctuations in relative sea level, produced either by tectonically-induced subsidence or by eustatic rises in sea level, combined with subsequent facies-belt progradation.

Both T. Palmer (1979) and Sumbler (1984) have suggested that the rises in relative sea level responsible for initiating shallowing-upwards depositional cycles recognised within the Oxfordshire White Limestone were produced by subsidence. However, a eustatic origin for the sea level changes should not be ruled out. In effect, it is very difficult, working within the confines of a single region, to distinguish between the product of a tectonically-induced rise in relative sea level and the product of a genuine eustatic sea level rise. Indeed, eustatic sea level changes can only be recognised by comparing areas with different tectonic/subsidence histories, which, in the Bathonian, is very difficult to do because of the problems of correlation.

There is, however, well-documented evidence which suggests that eustatic change of sea level occurred in the Jurassic; this has been reviewed most notably by Hallam (1963, 1969b, 1975a, 1978, 1981b). From a graphical plot of the areas of continents covered by sea at various times throughout the Jurassic, Hallam (1969) inferred that a gradual marine transgression over the continents occurred between the Early Hettangian and the Late Oxfordian. This was interrupted by regression in the Early Bathonian and ended by a marked regression at the close of the Jurassic. The gradual transgression was attributed to a global, eustatically-controlled rise in sea level. Hallam (1978) later refined this work, adopting a stage-by-stage vertical sequence analysis of the shallow marine northwest European onshore succession, in order to establish whether the progressive eustatic rise in sea level which occurred through most of the Jurassic was gradual or episodic. Using this approach, Hallam (op. cit.) was able to recognise a number of widespread, synchronous cycles of deepening/transgression and shallowing/regression, independent of local tectonics and facies development, the more important of which can be traced globally; from this he was able to conclude that the progressive Hettangian to Oxfordian/Kimmeridgian transgression was clearly episodic.

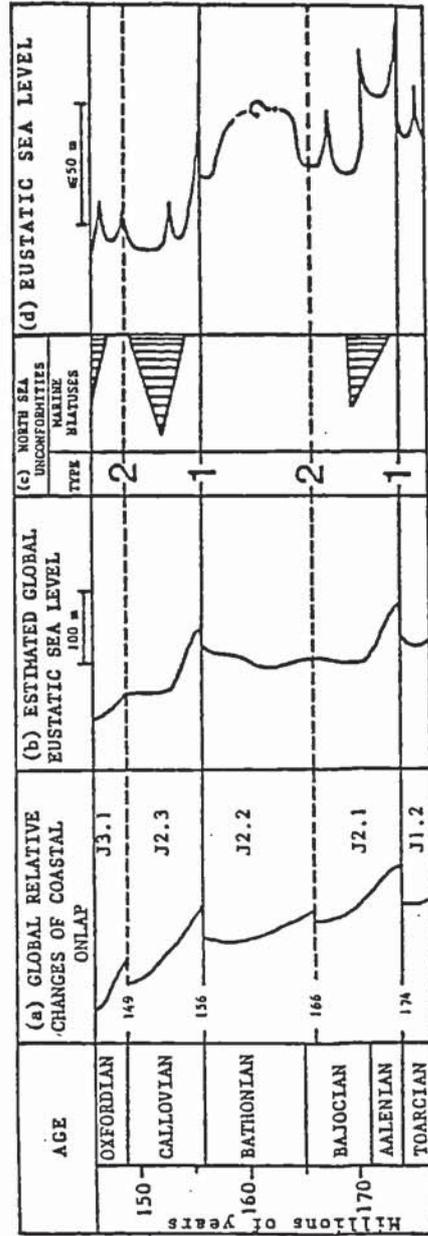
At about the same time, Peter Vail and his Exxon colleagues evoked a global eustatic control to explain unconformity-bounded sequences within the Jurassic which they recognised using seismic stratigraphy. Vail et al. (1977) identified four Middle Jurassic global unconformities, which define three cycles of relative change of coastal onlap; a similar pattern of cycles was subsequently recognised by Vail & Todd (1981) working in the Northern and Central North Sea. While Vail & Todd's work is undoubtedly open to some criticism (e.g. Miall, 1986), the

a) Vail & Todd's global coastal onlap curve.
 b) Vail & Todd's eustatic sea level curve, constructed on the basis of seismic sequence analysis by relating coastal onlap curves, stratal patterns and facies from the North Sea to the global coastal onlap curve and by superimposing the short-term changes so-determined on a

long term Jurassic sea level plot derived from geohistory curves corrected for compaction.
 c) Vail & Todd's North Sea unconformities. Type1 unconformities are distinguished from those of Type2 by the truncation of tilted strata and the possible presence, in the case of the basal Aalenian unconformity, of deep water lowstand deposits.

d) Hallam's eustatic sea level curve, determined by stage-by-stage vertical sequence analysis of the N.W. European onshore succession reviewed against global onshore data, combined with data from a study of the area covered by the sea in successive Jurassic stages.

FIGURE 7.15 Chart comparing the eustatic sea level curves of Vail & Todd (1981) and Hallam (1978)



four major Middle Jurassic unconformities they recognised have a widespread distribution in the British and northwest European area (Bradshaw & Cripps, in prep.) and can be accurately dated as early scissum Subzone (opalinum Zone, early Aalenian), early subfurcatum Zone (Late Bajocian), early discus Subzone (discus Zone, Late Bathonian) and late lamberti Subzone (lamberti Zone, Late Callovian). The Great Oolite Group is largely contained within the J2.2 cycle of Vail & Todd (op. cit.), bounded by the subfurcatum and discus Zone unconformities.

Both Hallam (1978, 1981b) and Vail & Todd (1981) have produced eustatic curves for the whole Jurassic which, on the whole, are quite similar; these are presented together in Figure 7.15.

That global fluctuations in sea level occurred during the Jurassic would appear to have been proved by both Hallam and Vail and his associates. Unlike the present-day, however, when global sea level is controlled largely by the size of the ice-caps developed at the poles, the Jurassic is believed to have been a time when the poles were ice-free. We can, therefore, be fairly sure that the principal control on global sea level at that time was the volume and geometry of the world ocean basin.

The hypothesis most commonly put forth to explain changes in the cubic capacity of the ocean basins during the Jurassic, and at other times, is that they were produced by uplift and subsidence of mid-oceanic ridges (Hallam, 1963; Valentine & Moores, 1970; Hays & Pitman, 1973). Acceleration of sea-floor spreading rates resulted in an increase in the volume of mid-ocean ridges and a consequent decrease in the volume of the ocean basin, thereby producing a eustatic rise in sea level. However, it is likely that large scale eustatic sea level changes in the Jurassic

were the result of more than one process, all of which were connected with the disintegration of Pangaea.

The volume of the world ocean basin can vary by changes in either its area or its depth relative to the world shelf break (Worsley et al., 1984). A decrease in volume and rise in sea level can be caused particularly by the production of new, hot, expanded ocean floor (i.e. at mid-ocean ridges) and by the attenuation of the continental crust as a consequence of rifting. Conversely, an increase in volume and lowering of sea level occurs as the world ocean floor ages, cools and subsides, or as accreting continents collide, thicken and decrease in area (Worsley et al., op. cit.). Worsley et al. stated that the fact that poorly conductive continental platforms, when static, become thermally elevated would also cause a lowering of sea level and increase the volume of the world ocean. However, while I accept that it would cause a lowering of sea level relative to the elevated continental platform, this process would only affect the volume of the world ocean when it causes flooding of a continental platform or emergence of a previously submerged platform. All three processes mentioned above can have a marked effect on the total area of continental platform inundated by the sea. It should be noted that increasing the area of continental platform covered by the sea must, at the same time, reduce the volume of water contained within the world ocean basin.

In the Permian, Pangaea was a static amalgamation of continents. It is likely that, as is the case with the static African craton today, Pangaea was thermally elevated, a direct consequence of the supercontinent's near stasis and the resultant heat build-up at its base (see Worsley et al., 1984 for discussion). As Pangaea began to fragment, a number of processes occurred, the net result of which, during the

Jurassic and Cretaceous, was an overall eustatic rise in sea level and a progressive transgression over most continental platforms. Initially, rifting would have increased the area of continents, reduced the volume of the global ocean basin and encouraged a rise in sea level. Subsequently, the development of new mid-ocean ridges and the production of new oceanic crust would have also decreased the volume of the ocean basin and encouraged the eustatic sea level rise. Finally, as continents began to move over the mantle, they encountered cool, subducted lithosphere beneath their leading edges and were able to dissipate 'subtectospheric' heat build-up through the ocean crust (Worsley et al., op. cit.). This reduced the elevation of these continents and encouraged marine transgression over them.

The combination of these processes produced the pattern of marine transgression and regression identified in the Jurassic by Hallam, Vail and others. While the transgressive-regressive events recognised within the Great Oolite Group of the study area are much smaller scale events than the eustatically-controlled cycles recognised by Hallam (1978), they must be seen against this background of eustatic sea level fluctuation. Furthermore, the Lower and Upper Cornbrash transgressive events have been identified as eustatically-controlled phenomena by both Vail & Todd (1981) and Hallam (op. cit.). The basal Callovian sea level rise is known to have facilitated a major migration of macrocephalitid ammonites and the eventual unification of the Boreal and Tethyan faunal provinces (Hallam, 1975a). It may be that these latest Bathonian and earliest Callovian rises were connected with the commencement of sea-floor spreading in the Central Atlantic (Scientific Party, Leg 76 D.S.D.P., 1981). It is possible that the basal hodsoni Zone relative rise in sea level, which initiated Rhythm C of this thesis, may also have been

eustatically controlled. This transgressive event was the most important one to affect the east Midlands in the Bathonian, prior to the Lower Cornbrash transgression. It appears to be widely traceable at outcrop in southern England, at least as far south as northern Dorset, and may be traceable further afield in northwest Europe. Whether other rhythms were of eustatic origin is, as I have already noted, very difficult to assess. Certainly Bradshaw (1978) believed that the Rutland Formation rhythms of the Lower and Middle Bathonian were generated by a series of episodic eustatic rises (intensely complicated by local tectonism and sedimentation patterns); however, he also accepted that they may have been produced by evoking a steady eustatic rise in sea level superimposed on an irregular pattern of subsidence. The problem of the origin of these rhythms will only be resolved by facies study of contemporary rocks elsewhere in northwest Europe, and in areas beyond. However, the lack of Bathonian ammonites in most parts of the world (Arkell, 1956), and the consequent problems of correlation, will no doubt hamper such work.

It should be noted, as a final point, that, whereas Hallam (1978) talked in terms of sea level changes of up to about a hundred metres being involved in generating the large scale cycles of the Jurassic, changes of relative sea level need have been no greater than 10-15 metres to have generated most of the rhythms identified in this thesis, and some of the rhythms may have been initiated by relative sea level rises of only a few metres.

7.11 Rhythms and time-correlation

If the rhythms recognised in this thesis were initiated by rapid eustatic sea level rises, they can safely be utilised, as Bradshaw (1978) used Rutland Formation rhythms, for time-correlation, particularly in

strata where conventional methods are inadequate. Even if the rhythms were the result of regional subsidence, they may still be used for this purpose, at least within the confines of a particular area, for, in geological terms, the transgression initiated by subsidence is still likely to have been a rapid event.

The main problem involved with using rhythmic events for time-correlation is that it is impossible to be sure that a given rhythm at one location is the same as the rhythm with which it has been correlated at another location. This problem can only be resolved by identifying the essential character of a given rhythm and by following it gradually across country, from one locality to the next. Even then, new data may show that mis-correlations have been made: correlation using rhythmic events should perhaps be regarded as a case of 'making the best of a bad job'!

However, the fact that, as noted in section 4.8, most of the limited biostratigraphic data available for use in correlating the upper Great Oolite Group strata of the study area does not conflict with correlations made on the basis of event stratigraphy is reassuring. Of course, the cynic might argue that this is not surprising since fossils have been used, in some instances, to recognise a particular rhythm, and to correlate that rhythm from section to section. This argument is only partially valid though, since, wherever possible, rhythms have been identified on the basis of their lithological character.

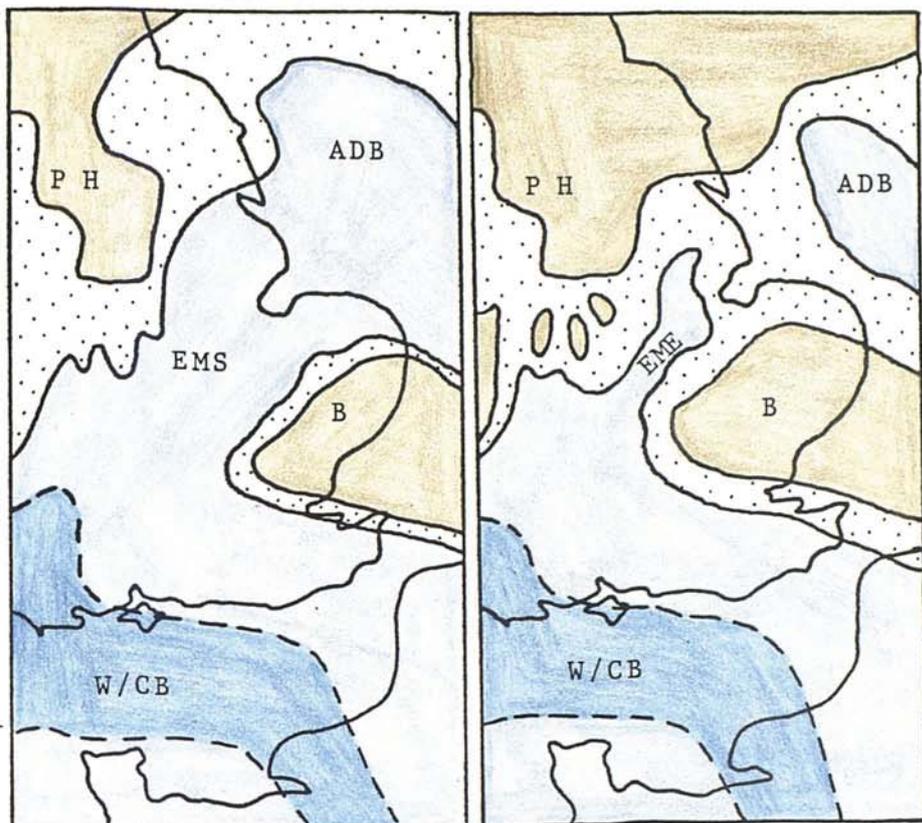
CHAPTER 8

PALAEOGEOGRAPHY AND DEPOSITIONAL HISTORY

8.1 Palaeogeography

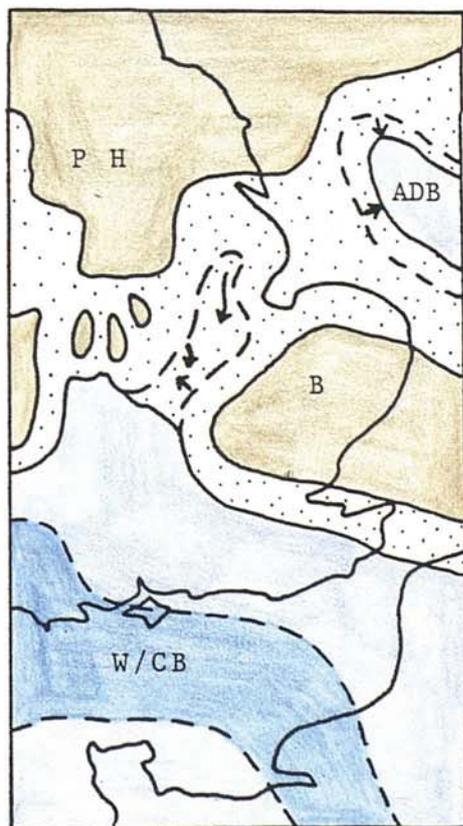
The main features of palaeogeography which affected the study area in the Middle Jurassic were reviewed in Chapter 2. However, during the Middle and Upper Bathonian the detailed palaeogeography of the Oxfordshire-east Midlands region was in a continual state of flux. The exact position of a given coastline varied throughout each of the transgressive-regressive events discussed in Chapter 7. Brabantia and other land areas contracted during the early stages of each *rhythmic* event, then gradually expanded as coastlines prograded during the regressive phase of each rhythm.

Seas were maintained throughout the Bathonian in the Wessex and Anglo-Dutch Basins. The study area essentially constituted a relatively flat platform, developed at about mean sea level throughout the period, which lay between these two 'marine reservoirs'. The platform probably sagged downwards slightly between the Mercian Archipelago/Pennine High and Brabantia, with the 'synclinal axis' of the platform lying to the west of today's Middle Jurassic outcrop and trending SW-NE. Transgressions into the study area appear to have followed the line of this 'downwarp', with the sea sometimes invading the study area from both the northeast and southwest. At times (Rhythm C, Lower Cornbrash 'Rhythm'), the transgressions from these two sources met, producing the 'East Midlands Seaway', a shallow water marine connection between the Wessex and Anglo-Dutch Basins developed around the northwestern margins of Brabantia. Less extensive transgressions (Rhythms A, B, D, E and



A

B



C

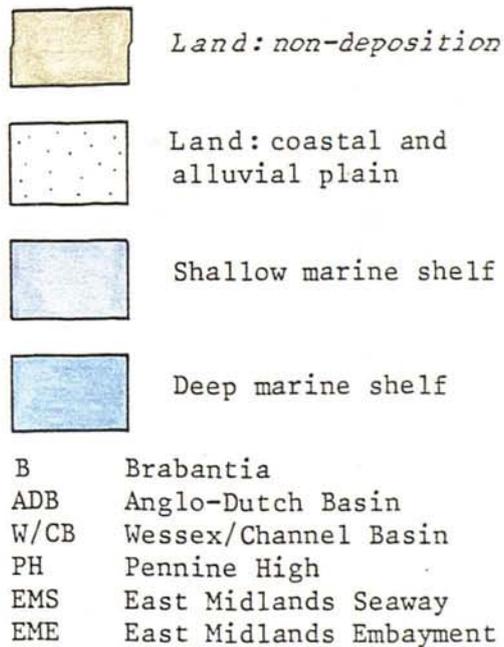


FIGURE 8.1 Generalised Bathonian palaeogeography of southern and central England: a) following a major transgression; b) following a minor transgression; c) during a major regression.

Forest Marble 'Rhythm'), coming principally from the Wessex Basin, gave rise to the large 'East Midlands Embayment', a shallow, often restricted-marine gulf closed at its northeastern end. The maximum extent of this embayment was different in different rhythms, with greater relative rises in sea level producing more extensive marine transgressions and therefore the largest embayments. Coastal progradation at the end of some rhythms (particularly Rhythms A and D) was so extensive that it appears to have rendered nearly the whole area of the 'East Midlands Embayment' emergent. During these major regressions, the Mercian Archipelago/Pennine High and Brabantia land areas were probably linked by a complex of islands and freshwater marshes, swamps and lakes. The closing and emergence of the 'East Midlands Embayment' gave rise to a SE-NW trending shoreline crossing the region now occupied by north and northeast Oxfordshire. The 'carbonate island' sediments of Palmer & Jenkyns (1975) are herein believed to be the deposits of supratidal carbonate marshes developed along this coastline at the close of both Rhythm D and E.

Figure 8.1 illustrates the generalised palaeogeography of the study area: a) when a major transgression had opened up the 'East Midlands Seaway'; b) when a lesser transgression had produced the 'East Midlands Embayment'; c) during an important regression, when coastal progradation had rendered much of the study area emergent.

8.1.1 Palaeogeography and distribution of facies in Rhythm C times

Figure 8.2 is based on a map produced by Bradshaw & Cripps (in prep.) and shows the distribution of land and major depositional environments in southern and central England and adjacent areas following the basal hodsoni zone ?eustatic rise in sea level. While the

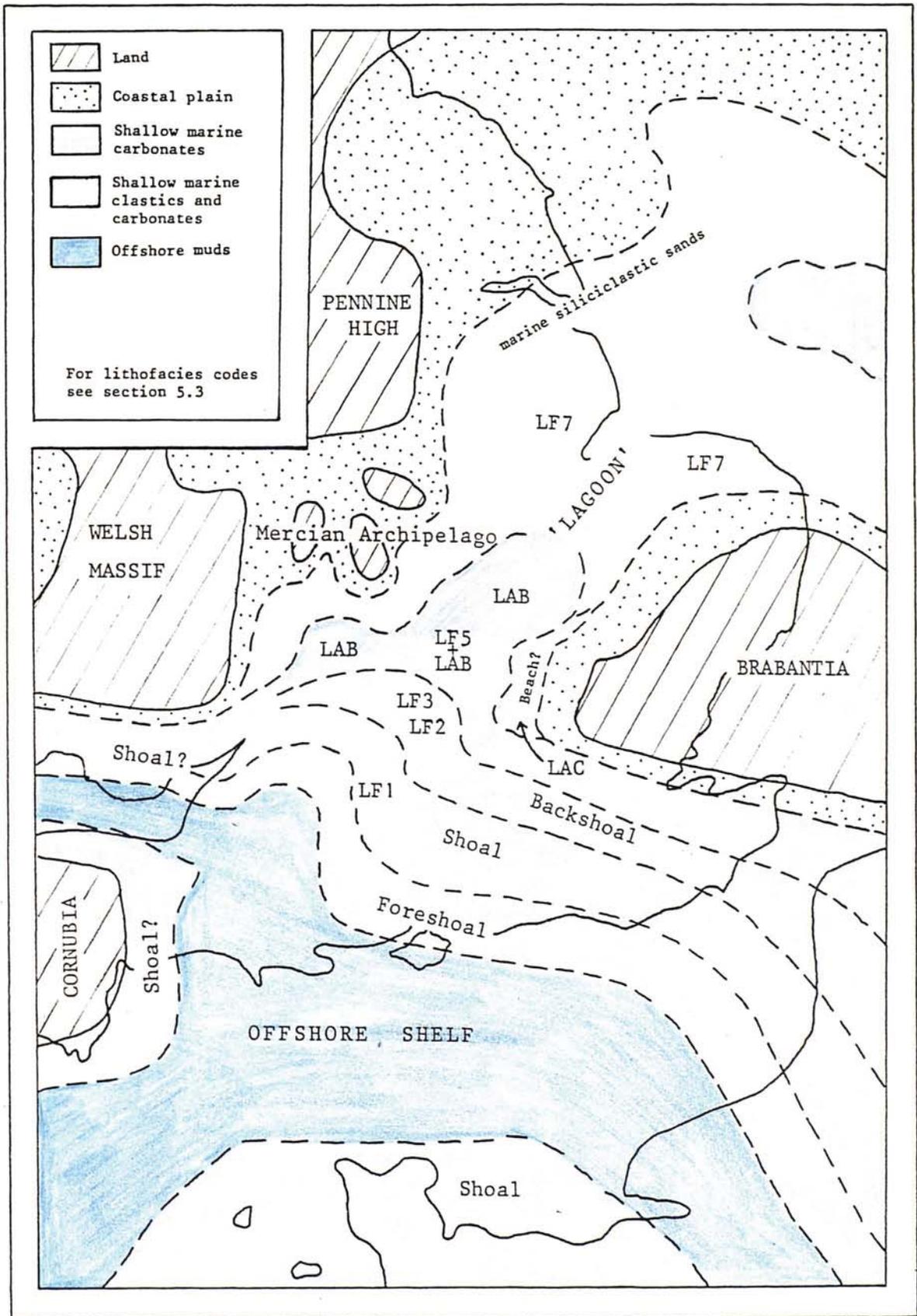


FIGURE 8.2 Palaeogeography of the English area in Rhythm C times (hodsoni Zone)

distribution of facies was different at other times in the Middle and Upper Bathonian, the general pattern of facies distribution was similar; this map is therefore used more as a general example, rather than as a specific example, of a Late Bathonian palaeogeographic map.

The Channel, Wessex and Bristol Channel Basins appear to have been areas of offshore shelf deposition throughout most of the Bathonian. The principal sediments which accumulated in these areas were open marine calcareous shales deposited below both normal and storm wave base: typical 'Fuller's Earth facies'. In the hodsoni Zone, the fine grained argillaceous carbonate sediments of the upper part of the Fuller's Earth Rock (Rugitela and Ornithella Beds) were deposited in this offshore setting in some areas of Avon, Wiltshire, Somerset and Dorset.

Further north at outcrop, 'Fuller's Earth facies' deposits of hodsoni Zone age (e.g. the Hawkesbury Clay of Cave, 1977) interdigitate with oolitic limestones (Tresham Rock, Athelstan Oolite), interpreted as the deposits of oolite shoals. Similar oolites occur at the same stratigraphic level in the subcrop across a broad band which runs NW-SE between Gloucestershire and the Kent/Sussex area, and on into northern France. It appears that oolite shoals were extensively developed at this time, landward of the offshore shelf. The main belt of well laminated or cross-stratified oograinsstones (cf. Lithofacies 1 of this thesis, developed within Rhythm C west and southwest of Shipton) comprises sediments deposited above normal wave base, in a region of sea floor regularly agitated by currents (storm and tidal). Foreshoal deposits, consisting predominantly of bioturbated, argillaceous oopackstones with ?storm-deposited grainstone interbeds, have been identified to the southwest of the main oograinsstone belt; these were probably deposited between normal and storm wave base.

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Sediments of Lithofacies 2, bioturbated oo- and intragrainstones, were deposited on the proximal side of the shoals, and not only during Rhythm C times. Such sediments occur in the lower part of Rhythm C throughout the southwest part of my study area; they interfinger both with sediments of the continually active shoal and also with quieter water sediments deposited further east and northeast. The distribution of protected subtidal facies across the 'East Midlands Seaway', which at this time connected the Anglo-Dutch and Wessex Basins, was discussed in Chapter 7. Coastal plain sediments accumulated around the fringes of Brabantia and probably also around the Pennine and Welsh landmasses; a coastal plain may also have been developed over the Charnwood-Nuneaton and Market Weighton Blocks at this time.

Figure 8.3 is a schematic block diagram which illustrates the depositional setting of the major facies types which accumulated across central and southern England in Rhythm C times.

8.2 Depositional history

The story of this thesis begins after regression had brought to a close the Cranford Rhythm. Extensive coastal progradation may have rendered most, if not all, of the east Midlands (including northern and eastern parts of Oxfordshire) emergent.

A relative rise in sea level initiated the Rhythm A marine transgression into the study area. The incursion of the sea apparently came only from the southwest and south, from the Wessex Basin; there is no indication that the sea transgressed from the northeast (from the Anglo-Dutch Basin) or entered the region through the gap between the Mercian Archipelago and Pennine High. The maximum northeastward and

eastward extent of the transgression was probably not much beyond the present limits of Rhythm A sediments (Figure 7.2).

Localised carbonate deposition was initiated at least as far northeast as Cranford, but for the most part only in the area west of today's outcrop. Predominantly terrigenous mud, with quartz and bioclastic sand interlayers, were deposited in more proximal areas; locally oyster reefs were developed, as at Nassington. Carbonates and mixed siliciclastic-carbonate sediments accumulated more extensively in the Oxfordshire area, at least as far northeast as Ardley. In the area between Ardley and Shipton, pelletal packstones and wackestones (often argillaceous) were deposited and were colonised by corals, bivalves and gastropods. Further southwest and south, pelletal and oolitic grainstones and packstones accumulated in a slightly more offshore setting.

Regression and coastal progradation at the close of Rhythm A caused widespread emergence throughout the east Midlands. The uppermost sediments of the rhythm were colonised by horsetails and other plants, or were locally removed by erosion. Coastal progradation spread at least as far southwest as Slape Hill and Shipton.

Rhythm B was initiated by a second relative rise in sea level. A marine transgression, spreading from the southwest, reached Lincoln and Spital in the northeast, and Bedford, Upwood and Peterborough in the east. A marine incursion coming through the gap between the Pennine High and Charnwood-Nuneaton Blocks (along the line of the Carboniferous Widmerpool Gulf) has been detected. Carbonate deposition became widely established during Rhythm B across much of the 'East Midlands Embayment', except in proximal areas where argillaceous carbonates passed laterally into predominantly siliciclastic sediments.

Argillaceous and silty pelbiowackestones and packstones accumulated across large areas of the 'East Midlands Embayment' during Rhythm B times. These sediments were densely colonised by 'fields' of Kallirhynchia sharpi. Locally, oyster-rhynchonellid low-relief 'reefs' developed; elsewhere, small coral shoals developed. Coral shoals were much more widely established at this time further southwest in the Oxfordshire area. In both the southwest part of my study area and in the the Peterborough-Stamford district and areas to the north, relatively winnowed sediments (intra-, pel-, oo- and biograinstones/packstones) were deposited. These were colonised by the mollusc-dominated faunas of Biofacies 3. In Lincolnshire, sediments of Lithofacies association B type were deposited and colonised by Biofacies 4 faunas.

Coastal progradation during the Rhythm B regression probably rendered much of the 'East Midlands Embayment' area emergent. In the Oxfordshire area, evidence for this emergence comes from Croughton, Ardley and Wood Eaton. Some areas of the 'East Midlands Embayment' (e.g. Peterborough, and perhaps areas to the northwest) probably remained covered by a shallow sea during the Rhythm B regression and cementation of the sea floor appears to have occurred locally at this time. Similarly, the southwestern part of my study area probably remained submerged. Erosion is believed to have removed the coastal plain sediments deposited during the latter stages of Rhythm B across much of Northamptonshire prior to the next transgression.

The basal hodsoni Zone transgression is believed to have been initiated by a eustatic rise in sea level. Transgressions coming from both the southwest and northeast met to form the 'East Midlands Seaway', a marine connection between the Wessex and Anglo-Dutch Basins. However,

no marine incursion appears to have come along the line of the Widmerpool Gulf at this time.

Carbonate sand bars of Lithofacies association B became established over much of the floor of the seaway between Oxfordshire and northern Northamptonshire. The fauna which colonised stable substrates associated with the sand bars were relatively diverse, reflecting the less environmentally-stressful nature of much of the 'East Midlands Seaway' compared with the 'East Midlands Embayment' of earlier rhythms, including those of the Rutland Formation. Northwards and eastwards, the sand bar complexes gave way to less carbonate-rich, more-restricted environments where oyster banks were commonly developed.

To the southwest, in Oxfordshire, bioturbated clean and muddy lime sands (Lithofacies 2 and 3) accumulated in the lee of extensive ooid shoals developed largely outside my study area.

Very shallow subtidal or intertidal, storm-deposited pelletal laminites and predominantly bioclastic lime sands (Lithofacies association C) were deposited along the western margin of Brabantia, particularly in the Bedford-Milton Keynes district. In the late stages of Rhythm C, this depositional environment prograded westwards. However, there is generally little evidence for coastal progradation at the close of Rhythm C; instead, the close of the rhythm was apparently characterised by a widespread break in sedimentation, with hardgrounds forming in Oxfordshire and areas further southwest.

Both Rhythm D and Rhythm E were initiated by relatively small marine transgressions, coming only from the southwest. The Rhythm D transgression spread carbonate deposition at least as far northeast as Irchester; the Rhythm E transgression appears not to have penetrated the east Midlands much beyond Croughton. Both were closed by extensive

coastal progradation. At the end of both rhythms, supratidal carbonate marshes, trending NW-SE, were developed in the Oxfordshire area. The whole of the region to the northeast of these carbonate marshes was emergent at the time they were in existence.

Following the Rhythm E regression, much of the east Midlands and Oxfordshire area was affected by erosion. The orbis Zone may have been a time of non-deposition throughout the study area.

Further marine transgression initiated deposition of the Forest Marble 'Rhythm'. The main transgression came from the southwest and reached as far as Northampton/Milton Keynes. A possibly contemporary transgression from the Anglo-Dutch Basin appears to have penetrated north Lincolnshire.

Elongate lime-sand bars developed in the Oxford area, but unlike the comparable sand bars of Rhythm C, terrigenous mud accumulated in inter-bar areas. This suggests that at this time there was a greater input of siliciclastic sediment derived from Brabantia and the Mercian Archipelago, perhaps reflecting a higher rainfall. In the northeast part of the 'East Midlands Embayment', oyster banks developed and predominantly terrigenous mud accumulated. The faunas of this area were relatively restricted, low-diversity and mollusc-dominated. Further to the southwest, the environment was less stressful and along the southern edge of the 'Oxfordshire High', diverse, normal marine, 'Bradfordian' faunas are found in the Forest Marble 'Rhythm'.

As with Rhythm C, there is relatively little evidence of coastal progradation at the close of the Forest Marble 'Rhythm'. This may be partly because the uppermost Forest Marble sediments have been removed by erosion over a large region, prior to the eustatic rise in sea level which initiated deposition of the Lower Cornbrash. Most of the study

area was drowned by the Lower Cornbrash transgression, and condensed, normal marine, shallow water carbonate sedimentation was widespread, not only in the study area but also throughout southern England and northern France. The Lower Cornbrash 'Rhythm' was apparently not terminated by coastal progradation, only by a major break in sedimentation.

A further eustatic sea level rise in the macrocephalus Zone spread condensed, normal marine, shallow water sedimentation even further onto Brabantia and other land areas in northwest Europe. The Upper Cornbrash is essentially the basal deposit of a transgressive sequence which includes the overlying Kellaways Beds and Lower Oxford Clay; this has not been studied in detail during the course of this study.

CHAPTER 9

CONCLUSIONS

This thesis is the result of a mainly field-based study of the sedimentology and palaeontology of the upper Great Oolite Group of Oxfordshire, Northamptonshire, Lincolnshire and adjacent counties. Further data have been obtained from the subcrop to the east of the Middle Jurassic outcrop. The sediments studied probably accumulated in a period of between 3.3 Ma and 7.3 Ma.

In Chapter 2, the structural, climatic and palaeogeographic setting of the study area was surveyed. In the Middle Jurassic, the east Midlands was a relatively tectonically-stable area situated between the London-Brabant Massif to the southeast and the Pennine High to the northeast. The Islip-Riseley Line has been identified as the northwestern margin of the London-Brabant Massif. The most positive part of the U.K. sector of the London-Brabant Massif underlies East Anglia and is delineated by the Cretaceous overstep onto the pre-Permian basement. Subsidence rates in the Bathonian were significantly greater in the Wessex Basin than in the east Midlands area; throughout the period, the Wessex Basin remained a more offshore setting.

Much of the London-Brabant Massif was emergent throughout the Bathonian. To distinguish the structural block from the landmass, the margins of which fluctuated in response to tectonic movements, eustatic sea level changes and coastal progradation, the name Brabantia was introduced for the latter. Brabantia exerted a considerable influence on sedimentation patterns in the study area during the Middle and Upper Bathonian. The Pennine High and Mid-North Sea High are also envisaged as

having been landmasses in the Bathonian. The Charnwood-Nuneaton fault-bounded structural blocks of the Midlands are thought to have been tectonically-positive features in the Jurassic and may also have been developed periodically as land areas: possibly islands surrounded either by the sea or by brackish and freshwater swamps. This area has herein been termed the Mercian Archipelago. The sediments studied were deposited in an area, repeatedly invaded by the sea, which lay between the Pennine High/Mercian Archipelago and Brabantia.

The Bathonian climate which affected the study area is envisaged as having been warm and equable: predominantly humid but periodically arid, at least locally. Some degree of seasonality is indicated. Both central and eastern England were affected by storms which exerted a significant control on sedimentation.

The lithostratigraphy of the upper Great Oolite Group of the study area has had a very complex historical development which is reviewed in detail in Chapter 3. The lithostratigraphic terminology employed in north Gloucestershire and Oxfordshire has differed from that used in the east Midlands because past workers have tended to work only in one area. The differences are often artificial and an attempt has therefore been made to marry the two systems of nomenclature. The validity of existing lithostratigraphic units is examined and, where appropriate, these have been redefined. The area of usage of the Ardley and Bladon Members of the White Limestone Formation and both the White Limestone and Forest Marble Formations has been extended northeastwards into the east Midlands. A number of formal and informal lithostratigraphic units have been abandoned, particularly the Blisworth or Great Oolite Clay and the Blisworth or Great Oolite Limestone. Three new formal lithostratigraphic units have been introduced in this thesis,

and a widely used name (the Kallirhynchia sharpi Beds) has been formalised. The Thrapston Clay Formation has replaced the Blisworth Clay throughout much of the east Midlands. While developed at the same stratigraphic level as the Forest Marble, the sediments of the Thrapston Clay are believed to be older, age-equivalent to the upper part of the White Limestone of Oxfordshire. The Irchester and Longthorpe Members are introduced as new subdivisions of the White Limestone, the former being applied in the area between Milton Keynes and Oundle, the latter between Oundle and Stamford. Both new members occupy the same stratigraphic interval as the Ardley and Bladon Members.

Ammonites have been widely used in the Jurassic as correlative tools. However, the paucity of ammonites in the Bathonian has hampered attempts to erect a Bathonian ammonite zonal scheme. The virtual absence of ammonites in the upper Great Oolite Group of the study area means that ammonites are of only limited importance for correlation within this area. The usefulness of other taxa for biostratigraphic correlation is therefore analysed in Chapter 4. Gastropods, particularly species of Aphanoptyxis, are found to be of considerable correlative value within the White Limestone of the study area. A number of species of brachiopod (e.g. Digonella digonoides, Kallirhynchia sharpi) also appear to have an important local correlative role. On the other hand, the correlative value of ostracods and foraminifers, at least within the confines of the study area, is questionable.

In this thesis, time-correlation has been achieved using a combination of event stratigraphy and ammonite, gastropod and brachiopod biostratigraphy. Shallowing upwards sedimentary rhythms which have been traced through part or all of the study area are regarded as having been initiated by rapid relative rises in sea level; therefore, the base of

each rhythm is taken as an approximate time-line. Biostratigraphic data are generally compatible with this hypothesis, but are not always available.

The sediments of the upper Great Oolite Group of the study area are mixed siliciclastic-carbonate, shallow marine to coastal plain deposits. These were deposited on a near-horizontal platform in parts of the east Midlands but as this shelved away southwestwards towards the Wessex Basin it developed into a homoclinal ramp. Gross facies distributions on this ramp are similar to those predicted by Irwin's (1965) model for carbonate sedimentation in an epeiric sea. Ooid shoal complexes were extensively developed on the 'Cotswold-Weald Shelf' between Gloucestershire and Sussex. The majority of facies studied were deposited in environments landward of these shoals (cf. Zone Z of Irwin). There is a lack of deposits unequivocally formed in an intertidal setting in the upper Great Oolite Group of the study area. Storm, rather than tidal currents may have been the most important control on sedimentation in the east Midlands.

Nine lithofacies and five lithofacies associations have been recognised within the study and were discussed in Chapter 5. The lithological characteristics of each facies were described in detail and comparisons were made with modern siliciclastic and carbonate sediments to shed light on depositional environments. At the time of deposition, adjacent lithofacies are believed to have graded laterally into each other. Thus lithologies transitional between two or more lithofacies have frequently been identified during this study. The vertical distribution of lithofacies in extant sections is illustrated in Enclosures A-1 to A-16.

Faunas characteristic of 'normal' marine through restricted, marginal marine to freshwater environments have been encountered in the upper Great Oolite Group of the study area. Most common are faunas interpreted as having been slightly less than 'normal' marine in character. These are usually dominated by molluscs (bivalves, gastropods) but also contain hardy representatives of stenotopic benthic taxa such as brachiopods, bryozoans, corals and echinoderms; some species of these latter groups may be extremely abundant at certain horizons.

The principal controls on faunal distribution are believed to have been a combination of environmental stress (particularly salinity and salinity fluctuations) and substrate stability. As different elements of the Great Oolite biota had different life requirements, observations have been recorded on the probable life habits of both the major groups of fossils and on particular species encountered during this study.

Within the Great Oolite Group, species are commonly found in recurring associations. The primary control on the composition of such associations (called biofacies in this thesis) was invariably substrate type. However, the exact composition of any example of a particular faunal association was also controlled by other factors such as salinity, turbidity, turbulence and intra-specific competition.

Nine biofacies have been recognised in this thesis. The biofacies which typically contain the most diverse faunal associations occur in lithologies interpreted as having been stable muddy sand and sandy mud substrates: Biofacies 3, 4 and 5. Less diverse, mollusc-dominated faunas are associated with shifting lime sands (Biofacies 1, 2) and 'soupy', pelletal lime muds (Biofacies 6). Specialised faunas (Biofacies 8) are associated with firm and hard substrates (e.g.

hardgrounds). An increase in environmental stress could reduce the diversity of any biofacies. Biofacies 6 and 7, in particular, are characterised by stress-tolerant species.

The Great Oolite Group of central and eastern England was deposited as a series of stacked sedimentary rhythms. Although initiated by marine transgression, each rhythm is dominated by its regressive, shallowing-upwards component. The simplest rhythms, the product of relatively minor transgressions, are wholly siliciclastic in character in the east Midlands but contain carbonates further to the southwest. More complex rhythms, initiated by greater relative rises in sea level, contain a carbonate component in the east Midlands as well as further southwest. The rhythms of the lower Great Oolite Group have been studied in detail by Bradshaw (1978). Therefore, only rhythms younger than the Cranford Rhythm of Bradshaw form the subject of this thesis.

Seven depositional units have been recognised within the upper Great Oolite Group of the study area, beneath the Upper Cornbrash. In ascending order, these are: Rhythm A, Rhythm B, Rhythm C, Rhythm D, Rhythm E, the Forest Marble 'Rhythm' and the Lower Cornbrash 'Rhythm'. The maximum regional extent of, and facies distributions within each rhythm are discussed in Chapter 7.

Both Rhythm C and the Lower Cornbrash 'Rhythm' are believed to have been initiated by eustatic sea level rises. The cause of the relative rises in sea level which initiated the other rhythms is uncertain: either a eustatic or tectonic origin is possible. Transgressions from both the Wessex Basin and the Anglo-Dutch Basin are believed to have linked up around the northwestern edge of Brabantia during Rhythm C and the Lower Cornbrash 'Rhythm', thereby forming the 'East Midlands Seaway', a shallow water connection between these two

areas of deeper water. In the Forest Marble 'Rhythm', transgressions from both the Anglo-Dutch and Wessex Basins have been recognised, but they are thought not to have met up. At other times, marine transgressions coming only from the southwest gave rise to the 'East Midlands Embayment', a gulf closed at its northeastern end; however, during Rhythm B, the sea may have also entered the 'East Midlands Embayment' at its northern end, along the line of the Carboniferous Widmerpool Gulf.

Further work is still required to confirm some of the hypotheses presented in this thesis. Furthermore, our understanding of rhythmic sedimentation, Bathonian depositional environments and palaeogeography, and Middle Jurassic palaeoecology would be greatly enhanced if this work were followed up by additional research. In particular, the following areas of enquiry would add significantly to the results presented herein:

(i) This facies analysis has concentrated on the area between Stamford and Oxford. Important facies changes which occur to the north and northeast of Stamford would be better understood if all extant exposures in, and borehole cores from this northern area were studied in detail. Data from the southern North Sea could be integrated in such a study so as to better elucidate facies relationships between the Midlands Platform and the Anglo-Dutch Basin.

(ii) Similarly, a better understanding of regional palaeogeography and facies changes towards the Wessex Basin would be gained by a facies analysis of the upper Great Oolite Group both at outcrop in Gloucestershire and in cored boreholes to the south of the Oxfordshire outcrop.

(iii) Important data on Bathonian rhythmic sedimentation could be gained from a facies study of the Great Oolite Group of Kent, the

Boulonnais and the Ardennes. This should be undertaken firstly to identify rhythmic units within the succession and secondly to see whether such rhythmic units can be correlated with those of the study area. A literature review suggests that the successions in these areas, particularly in Kent and the Boulonnais, are very similar to that of the east Midlands.

(iv) Correlation of rhythmic units within the study area may be refined by a detailed micropalaeontological study. Past attempts at correlation using micropalaeontology have failed because they have been based on lithostratigraphic, not event stratigraphic units.

(v) Further work should be carried out on the faunas of the upper Great Oolite Group. A taxonomic revision of both brachiopods and bivalves is needed. The study of biofacies/lithofacies relationships and biofacies composition in different areas and at different stratigraphic horizons, where substrate remains constant, will improve our knowledge of the life habits and stress tolerances of individual species or groups of species within particular Bathonian faunal associations.

In this thesis I have attempted to present the results of an extended period of research on the English Bathonian, and in particular, on the sedimentology, stratigraphy and palaeontology of the upper Great Oolite of central and eastern England. However, I regard this thesis only as an interim report, for there is still much to learn about the Great Oolite Group.

PLATE 1

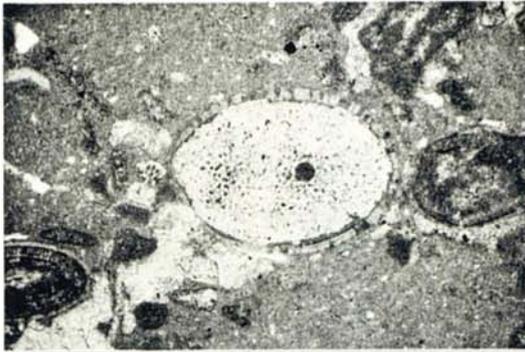
Photomicrographs: grain types

- A. Oopackstone/wackestone; Forest Marble/White Limestone contact, Stratton Audley (Loc. 44)
- B. Biooograinstone; Forest Marble, Shipton (Loc. 16)
- C. Oograinstone; Forest Marble, Shipton (Loc. 16)
- D. Oograinstone; Forest Marble, Shipton (Loc. 16)
- E. Biointragrainstone; Forest Marble, Blackthorn Hill (Loc. 42)
- F. Intragrainstone; White Limestone, Kirtlington (Loc. 26)
- G. Intrapackstone/grainstone; White Limestone, Deanshanger (Loc. 97)
- H. Intragrainstone/packstone; White Limestone, Croughton (Loc. 81)

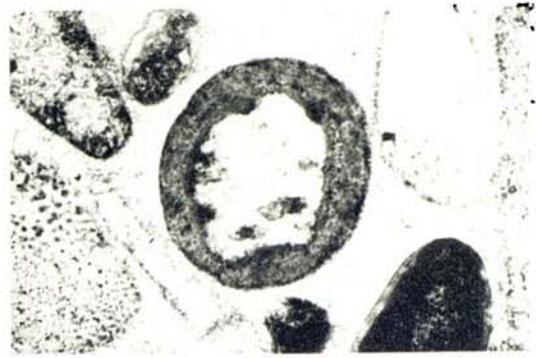
Scale (A-D): 1mm = 20 μ m (E-H): 1mm = 50 μ m

'True ooids' (Plate 1B-1D) have not been distinguished in this account from 'superficial ooids' (Plate 1A). The difference in the thickness and shape of an ooid cortex generally only reflects variations in the size and shape of the nucleus. Ooids with a large nucleus are typically of 'superficial' type.

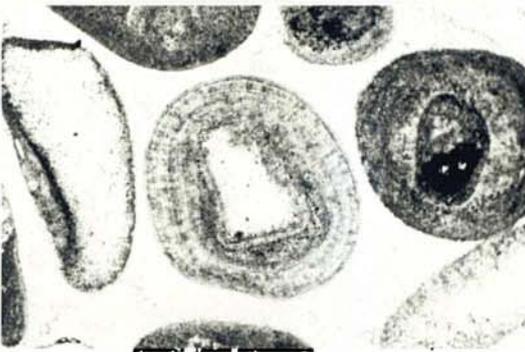
Well developed ooids are found in the upper Great Oolite Group of the study area particularly in the Forest Marble, but they also occur in *some facies* within the Ardley, Bladon, Irchester and Longthorpe Members. In the White Limestone, however, ooids and other grains have often been so intensely micritised that they can now be identified only as peloids/amorphous lumps (Plate 1E, 1F) or coated grains (Plate 1H). These are classified as intraclasts in the terminology used in this thesis. Intraclasts of botryoidal or eroded lump type also occur, in both the Forest Marble and the White Limestone. The example seen in Plate 1G is from the White Limestone at Croughton.



A



B



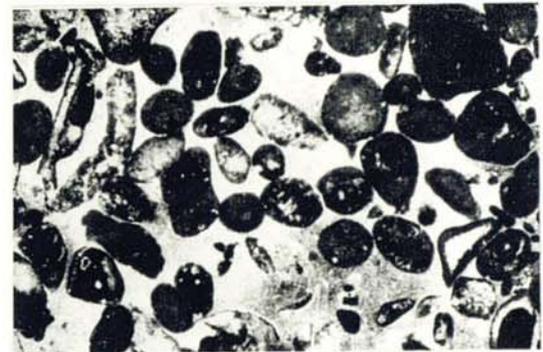
C



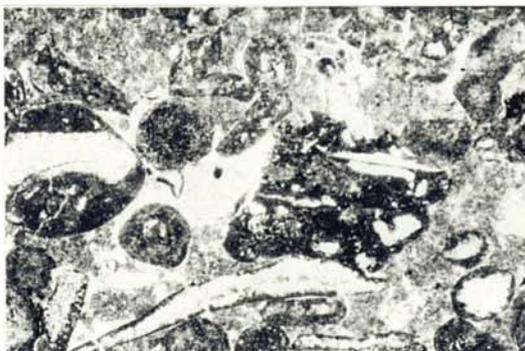
D



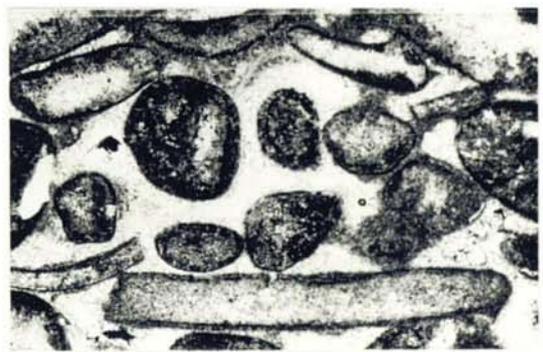
E



F



G



H

PLATE 1

PLATE 2

Photomicrographs: grain types and fabrics

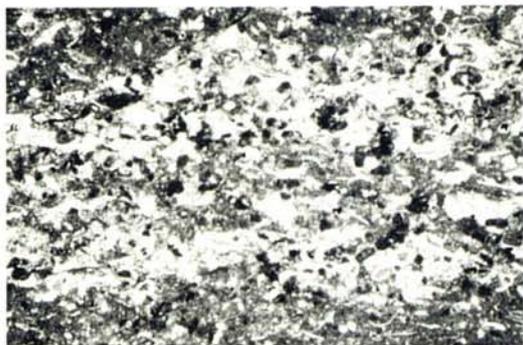
- A. Pelbiograinstone and pelpackstone/wackestone laminae; Lithofacies association C, Rhythm C, Blisworth East (Loc. 107)
- B. Pelbiograinstone/packstone; Lower Cornbrash, Broomhill (Loc. 41)
- C. Pelbiopackstone/wackestone; Forest Marble, Stratton Audley (Loc. 44)
- D. Quartz-sandy pelbiopackstone; Shipton Member, Wood Eaton (Loc. 24)
- E. Pellets protected from compaction; top of the Ardley Member, Croughton (Loc. 81)
- F. Sarcinella socialis, a colonial serpulid; Longthorpe Member, Spire Wood (Loc. 175)
- G. Shrinkage cracks; uppermost bed of the White Limestone, Croughton (Loc. 81)
- H. Birdseyes; uppermost bed of the White Limestone, Croughton (Loc. 81)

Scale (A; C-H): 1mm = 50 μ m (B): 1mm = 20 μ m

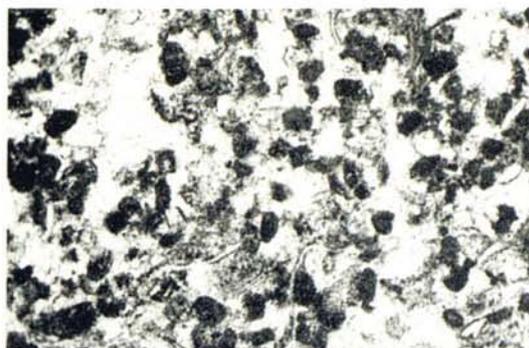
Pelletal/bioclastic limestones (Plates 2A-2E) are common in the White Limestone and Lower Cornbrash; they also occur in the Forest Marble at Croughton and Stratton Audley, and in areas to the east and northeast. They are developed particularly in Lithofacies 4 and 5 and in Lithofacies association C. In the latter (Plate 2A) grainstone/packstone layers are frequently interlaminated with pelpackstone/wackestone laminae. Wackestone layers may be compacted locally into grumuleuse micrite, particularly where the proportion of rigid skeletal debris present is low. Pellets are commonly protected from compaction by large skeletal grains, such as the gastropod shell seen in Plate 2E. Within both the K. sharpi Beds and the Shipton Member, pelletal lithologies commonly contain abundant quartz sand and silt (Plate 2D).

Plate 2F is a photomicrograph of part of a Sarcinella socialis colony. This gregarious serpulid is common in oyster-rich sediments developed within the Longthorpe Member.

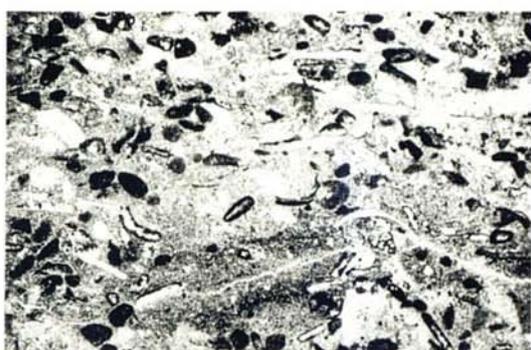
Fenestrae are characteristic of Lithofacies 6 sediments developed in the upper part of the White Limestone in northeast Oxfordshire (Rhythms D and E). Both branching shrinkage cracks (Plate 2G) and birdseyes (Plate 2H) occur in the facies. The latter commonly occur in distinct laminae, often with their longest axis aligned parallel to the bedding.



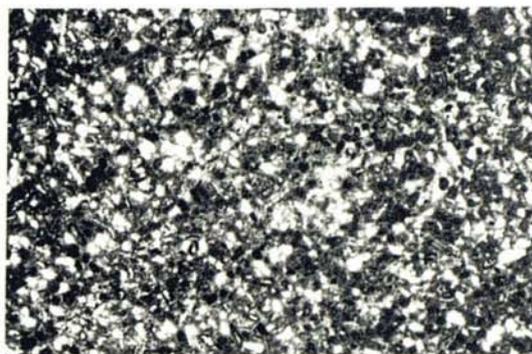
A



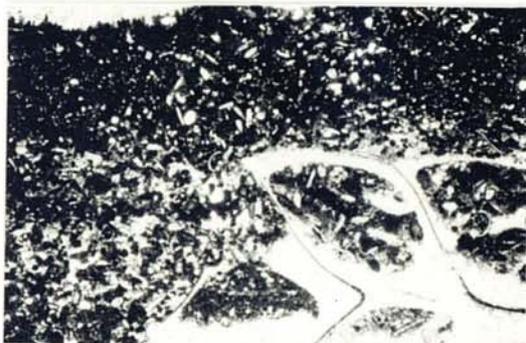
B



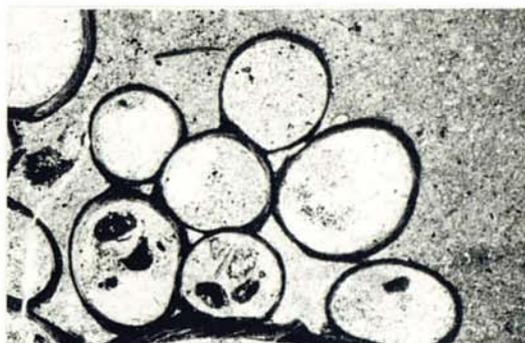
C



D



E



F



G



H

PLATE 2

PLATE 3

Field photographs: base of the Ardley and Irchester Members

- A. Foss Cross Quarry (Loc. 1) B. Slape Hill (Loc. 15)
C. Slape Hill (Loc. 15) D. Whitehill Quarry, Gibraltar (Loc. 17)
E. Wood Eaton (Loc. 24) F. Irchester North Pit (Loc. 123)

From Cirencester to Northampton the base of the Ardley Member is well-defined. The lowermost limestones of the Ardley Member are usually well-cemented, resistant grainstones and packstones which stand out above the softer limestones of the underlying Shipton Member (cf. T. Palmer, 1979). This lithostratigraphic junction, which roughly corresponds with the morrisoni and hodsoni Zone boundary (and which is marked by a dashed line in Plates 3A-3E) is seen particularly well in the photographs from Slape Hill (3B, 3C) and Wood Eaton (3E).

Plate 3F shows that, to the east and northeast of Northampton, the base of the Irchester Member (dashed line in the top right of the frame) is similarly distinctive and overhangs the underlying, less resistant Kallirhynchia sharpi Beds. In the Irchester area, the latter comprise *interbedded units of interlayered bioclastic sand and terrigenous mud and nodular units of biopelwackestone/packstone*, typical of Lithofacies association D.

The base of both the Ardley and the Irchester Members either approximately or exactly coincides with the base of Rhythm C. *Throughout much of the study area, the basal c.0.10-0.25m of Rhythm C consists of interlayered sands and mud (often containing abundant plant debris and fish teeth) which are developed beneath the lowermost limestone bed of the Ardley/Irchester Member (e.g. Plate 3C, 3D).* In Oxfordshire, these sediments are included within the Shipton Member on lithostratigraphic grounds. In the east Midlands, they have usually been included within the Irchester Member rather than the K. sharpi Beds.

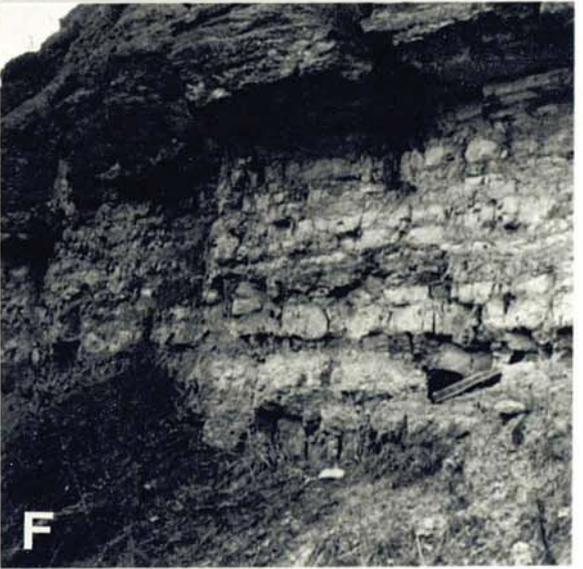
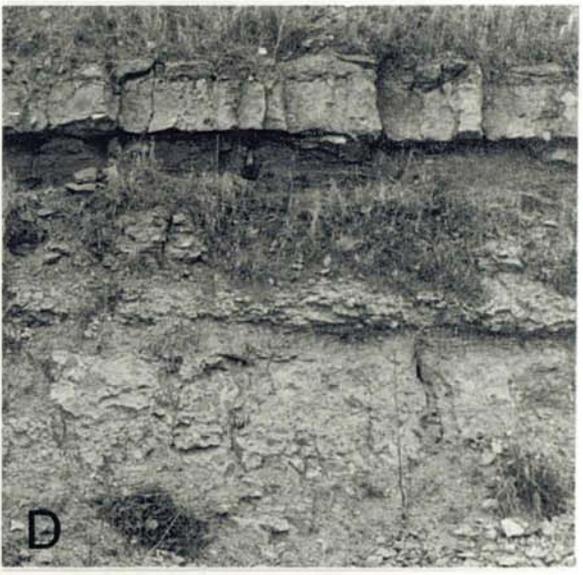
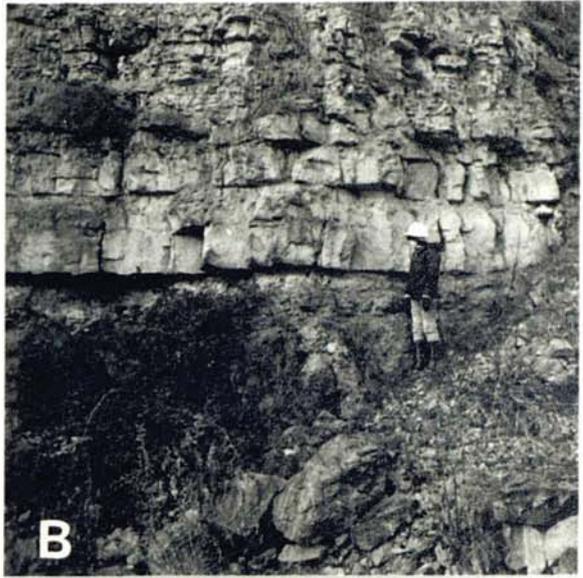
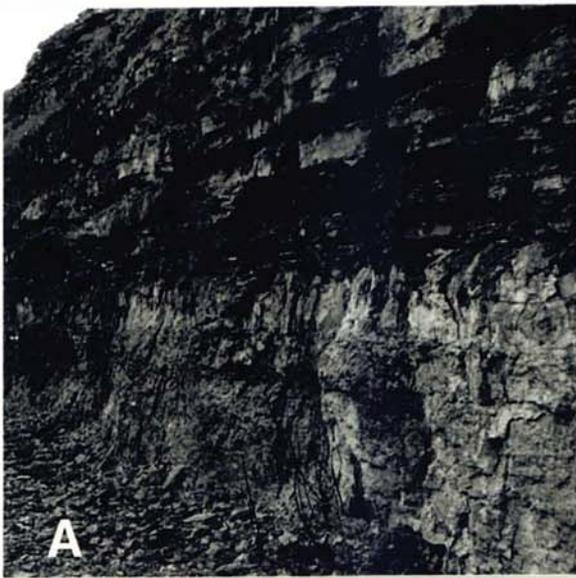


PLATE 3

PLATE 4

Field photographs: miscellaneous

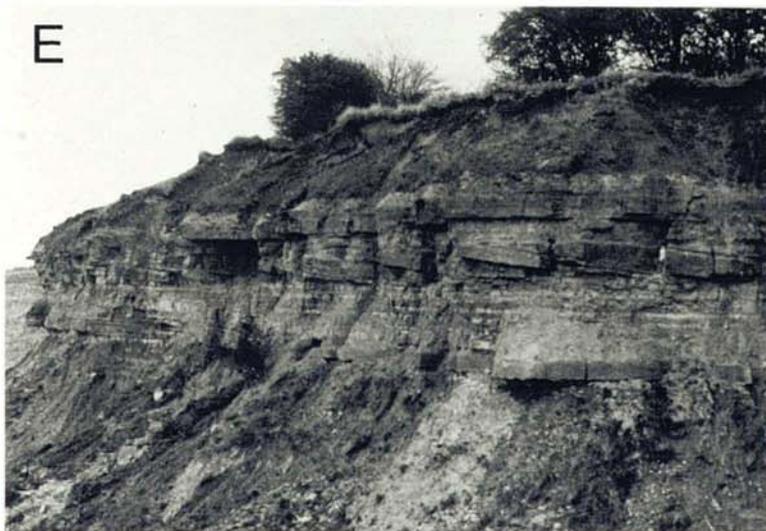
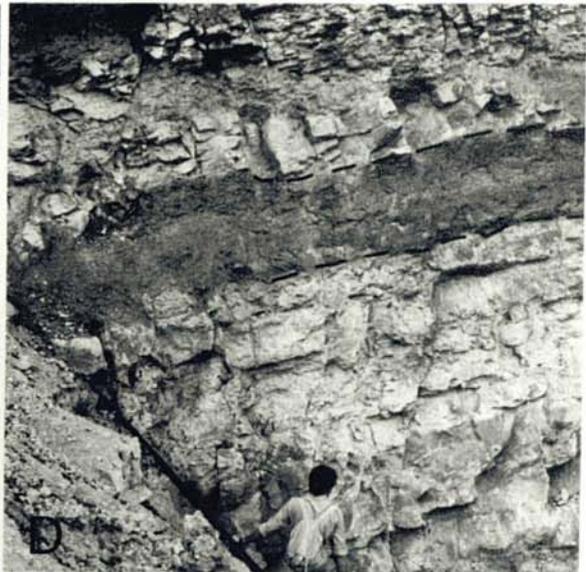
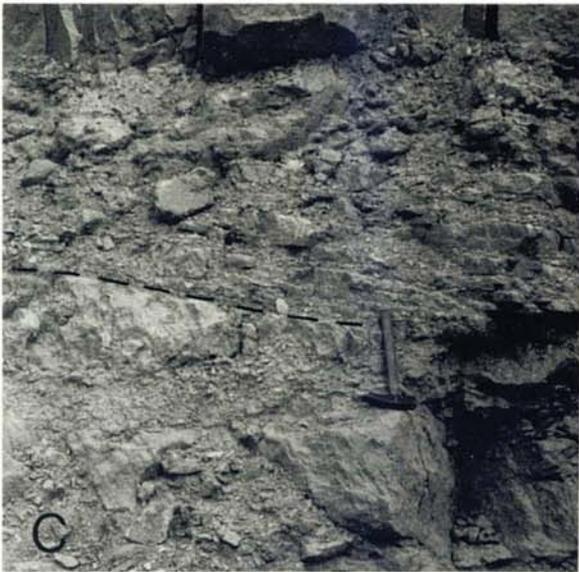
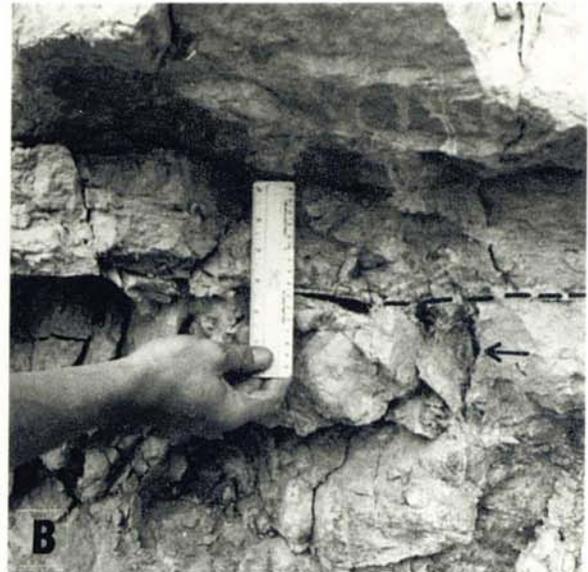
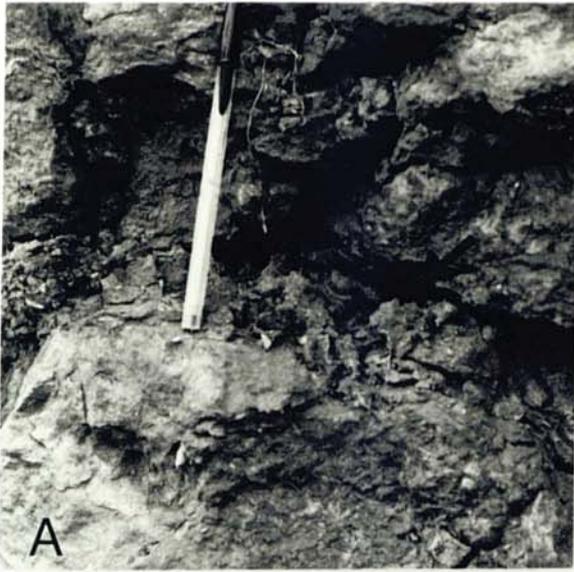
- A. Base of Rhythm C, Wellingborough No. 5 Pit (Loc. 124)
- B. Base of Rhythm C, Wood Eaton (Loc. 24)
- C. Erosive base of Lithofacies association C sediments, Croughton (Loc. 81)
- D. Oyster lumachelle in the upper part of the White Limestone, Wood Eaton (Loc. 24)
- E. The upper Great Oolite Group succession, Irchester Old Lodge Pit (Loc. 122)

Throughout the study area, the base of Rhythm C is a sharp, surface, erosive on both a local and a regional scale. At Wellingborough (Plate 4A; arrowed), the base of the rhythm coincides with the base of the Irchester Member. The interlayered sand and mud at the base of Rhythm C is better cemented than the similar sediments developed at the top of Rhythm B, and does not contain Kallirhynchia sharpi. At Wood Eaton (Plate 4B), the base of the rhythm (dashed) lies approximately 0.10m below the base of the Ardley Member. Rare rootlets (arrowed) occur at the top of Rhythm B and are truncated at the base of the overlying rhythm.

At Croughton (Plate 4C), laminated sediments of Lithofacies association C are developed at the top of the Ardley Member. These sediments are sharply separated from the underlying 'A. ardleyensis Bed' (=Lithofacies 5), with the latter being completely cut out locally by low-angle erosion surfaces (dashed).

Oyster lumachelles are commonly developed in the upper White Limestone in the northern part of the study area, but are rare in the formation in Oxfordshire. However, at Wood Eaton, an oyster lumachelle is well developed towards the top of the formation (upper half of Plate 4D). It comprises a mass of broken oyster shells in an argillaceous matrix; the shell debris was derived from a nearby oyster reef.

The Irchester quarries are the finest White Limestone exposures in Northamptonshire. At Irchester Old Lodge, the type section of the Irchester Member, sediments of Lithofacies association B are well developed in that member. In Plate 4E, cross bedded oolite grainstones dominate the upper part of the member, whereas the lower part consists predominantly of argillaceous sediments deposited in an inter-bar trough. However, the sediments of Lithofacies association B exhibit considerable lateral variability in the Irchester quarries. The base of the Irchester Member is sharply overhanging, while the underlying K. sharpi Beds are poorly exposed. The Thrapston Clay is also largely overgrown.



Thrapston Clay Formation	
Irchester Member	White Limestone Formation

PLATE 4

PLATE 5

Field photographs: miscellaneous

- A. Thalassinoides in the uppermost bed of the White Limestone, Stratton Audley (Loc. 44)
- B. Diplocraterion in Lithofacies association C sediments, Weston Underwood (Loc. 62)
- C. The upper White Limestone section, Croughton (Loc. 81)

Thalassinoides burrows are encountered in a variety of lithologies within the White Limestone. Open burrow systems were particularly excavated by crustaceans in lime sands stabilised by either lime mud or by interstitial cementation. The burrow illustrated in Plate 5A is developed in the uppermost bed of the White Limestone (a biopelwackestone/packstone) at Stratton Audley. The sediment probably became a firmground, as a result of early, partial lithification, during the Rhythm E regression. The burrow is filled by Forest Marble 'Rhythm' sediments, including abundant lignite and vertebrate material. The crustacean microcoprolite Favreina also occurs in the burrow.

Diplocraterion (Plate 5B) is encountered in the upper Great Oolite Group only in Lithofacies association C sediments within Rhythm C. It is particularly common in the Bedford-Milton Keynes district.

Plate 5C illustrates the upper part of the section at Croughton. The top of the Ardley Member/Rhythm C is a sharp, planar surface which caps a Lithofacies association C laminite. No hardground is developed here, although hardgrounds are common at this level in Oxfordshire. The basal bed of the Bladon Member (and of Rhythm D) is a rubbly weathering coral bed. Above this is a better-cemented bed containing Aphanoptyxis bladonensis, which is, in turn, overlain by a dark, rootletted terrigenous mudstone developed at the top of Rhythm D. The limestone component of Rhythm E is a single fining upwards unit, of Lithofacies 5 and 6 sediments, which is extensively rootletted in the upper part. Terrigenous muds (Lithofacies association E) which are developed in the upper part of Rhythm E at Croughton (in the lower part of the Forest Marble Formation) are not visible in Plate 5C.

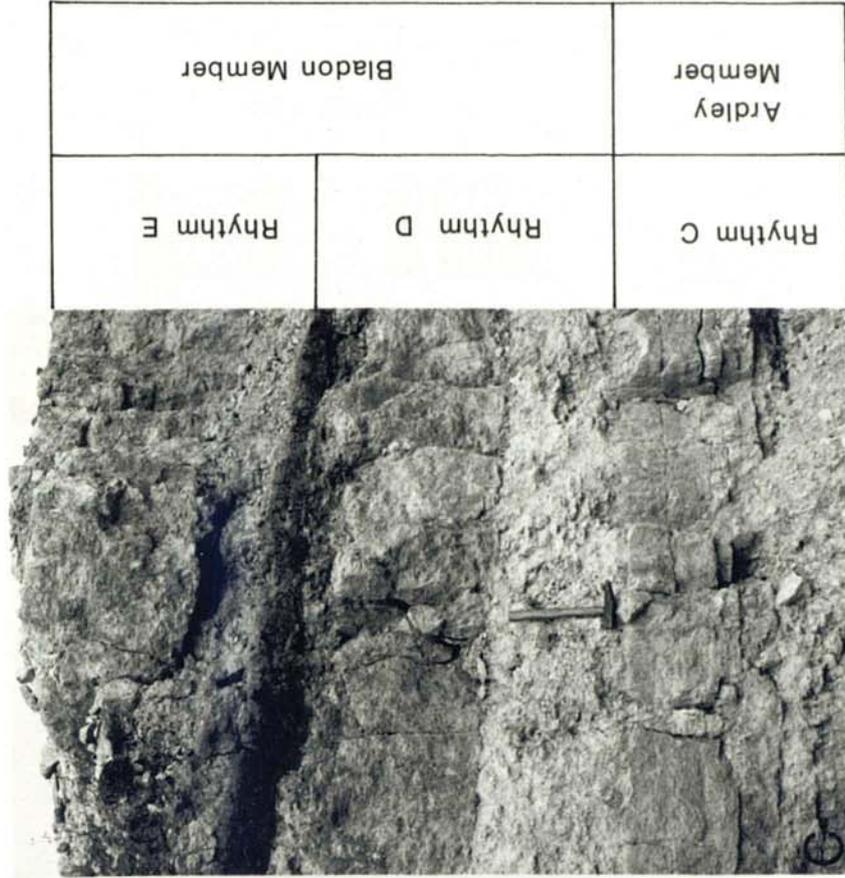


PLATE 5

PLATE 6

Miscellaneous photographs

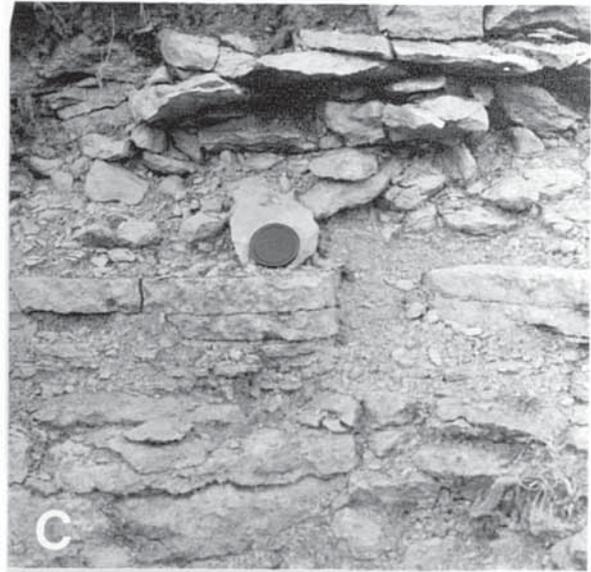
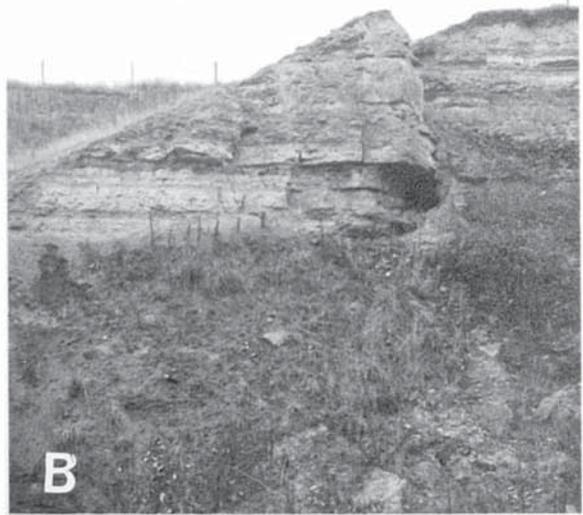
- A. Polished block, lower part of the Ardley Member, Croughton (Loc. 81)
- B. White Limestone, Cranford South Pit (Loc. 139)
- C. Top of the Ardley Member, Great Rollright (Loc. 33)
- D. Great Oolite Group section, Stratton Audley (Loc. 44)

Sandy mud and muddy sand substrates result either from the partial winnowing of mud away from sand sediments or by the admixing of discrete mud and sand laminae by bioturbation. This second process is illustrated in Plate 6A, where lime sand and lime mud initially deposited in individual layers has been partially admixed, giving rise to both packstones and wackestones.

The base of the Irchester Member stands out above the underlying K. sharpi Beds at Cranford (two-thirds of the way up Plate 6B), as in areas to the south. However, north of Cranford, beds in the lower lithostratigraphic unit become increasingly resistant, whereas the reverse is true of the Irchester Member, which passes northwards into the thinner and less resistant Longthorpe Member.

At Great Rollright (Plate 6C), a thin laminite horizon (*Lithofacies association C*) is developed at the top of the Ardley Member. The lens cap in Plate 6C rests on the oyster-encrusted, planar hardground which caps the laminite horizon.

Stratton Audley (Plate 6D) formerly exposed a fine White Limestone section. Unfortunately, the quarry is now flooded, and only the uppermost part of the White Limestone, and the overlying Forest Marble and Cornbrash are still visible. The uppermost limestone bed of the White Limestone (which contains A. bladenensis) and the underlying clays were wrongly included in the Forest Marble by T. Palmer (1974, 1979). The Forest Marble is only 2.07m thick at Stratton Audley.



Forest Marble Formation	White Limestone Formation
-------------------------------	---------------------------------

PLATE 6

PLATE 7

Field photographs: Forest Marble and Thrapston Clay

- A. Site cleared by the Nature Conservancy Council at Thrapston (Loc. 148)
- B. White Limestone and Forest Marble contact, Shipton (Loc. 16)
- C. Forest Marble, Wood Eaton (Loc. 24)
- D. Forest Marble, Wood Eaton (Loc. 24)

The type section of the Thrapston Clay Formation, where the formation is 3.52m thick and comprises variegated, unfossiliferous terrigenous mudstones, is seen in the top left of Plate 7A; the overlying Cornbrash is also visible. The underlying White Limestone (Irchester Member only) is seen in the foreground.

In Oxfordshire, the Forest Marble is dominated by sediments of Lithofacies association A. The contact between the Forest Marble and the underlying White Limestone is seen in Plate 7B (dashed). The base of the Forest Marble 'Rhythm' is erosive and, in this part of the Shipton Quarry, has cut down through Rhythm E and much of Rhythm D.

The sediments of Lithofacies association A comprise units of cross bedded oobiograinstone (e.g. Plate 7C) and units of terrigenous mudstone. Often these very different lithologies are thinly interbedded, as in Plate 7B. In Plate 7D, a unit of cross bedded limestone (highlighted by dashed lines) wedges out in the left of the picture, to be replaced by terrigenous mudstone. The lime sands of this facies association are mostly the deposits of linear, low-relief sand bars. The terrigenous muds are believed to have been deposited primarily in troughs between adjacent bars.

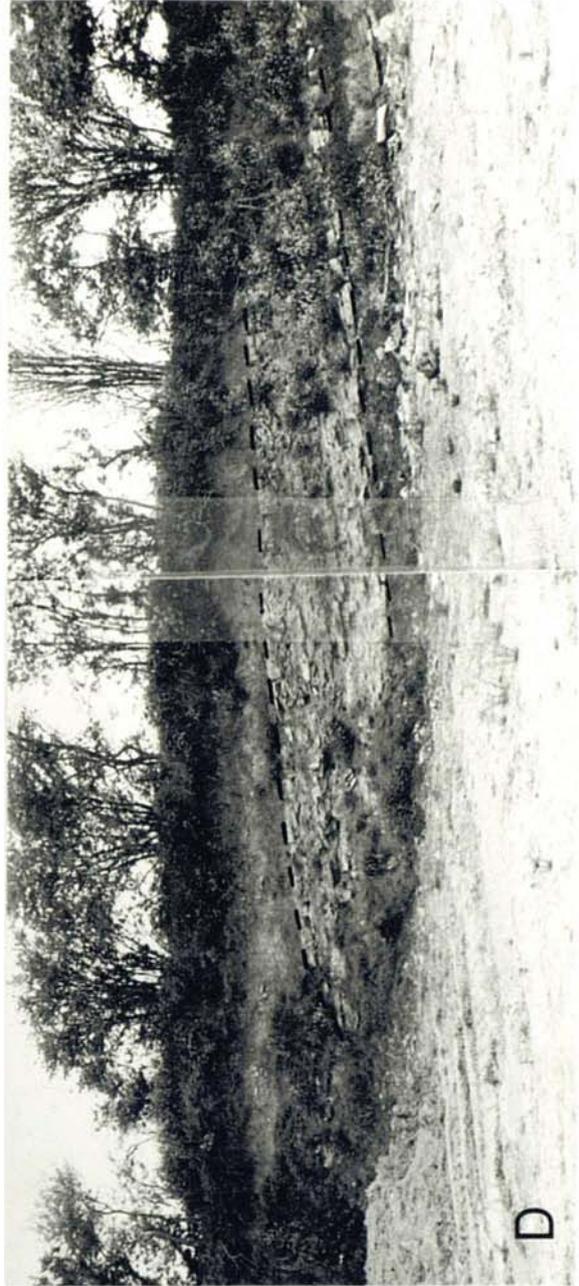
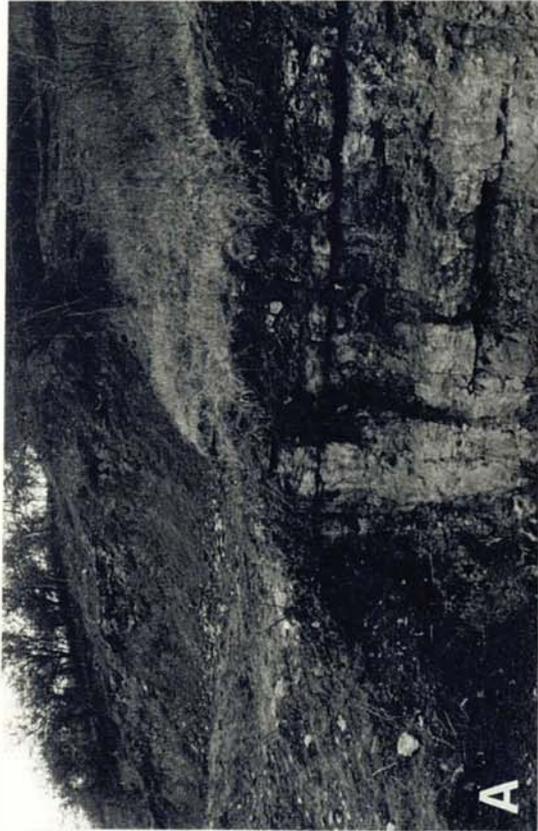
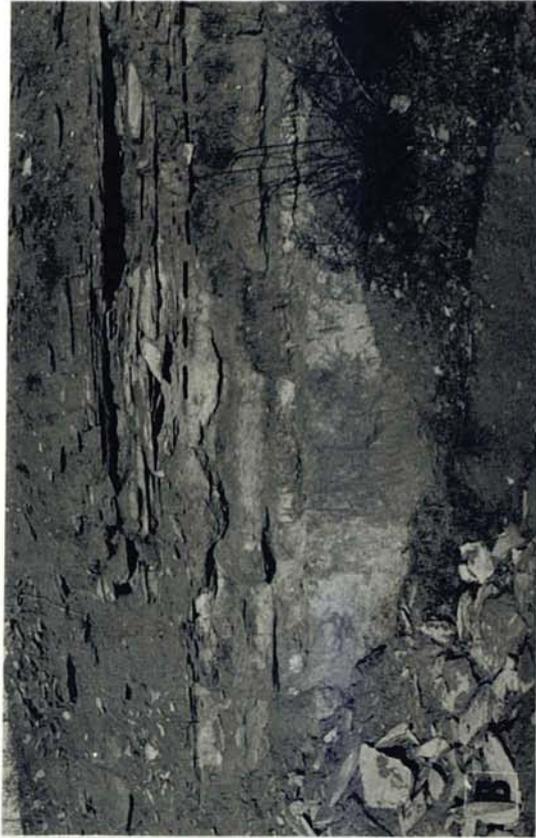


PLATE 7

PLATE 8

Field photographs: Lithofacies associations B and C

- A. Lithofacies association B sediments, Kirtlington (Loc. 26)
- B. Lithofacies association B sediments, Whitehill Quarry, Gibraltar (Loc. 17)
- C. Lithofacies association C sediments, Blisworth East (Loc. 107)
- D. Lithofacies association C sediments, Cosgrove (Loc. 100)

Lithofacies association B sediments vary from bioturbated wackestones and packstones or interlayered wackestones and grainstones to cross bedded grainstones; they are believed to be the deposits of a complex of low-relief, elongate sand bars similar to those of the Forest Marble. A relict large-scale cross bed developed at Kirtlington is seen in Plate 8A. Here, the sediments between the surviving foresets have been extensively bioturbated and are dominated by intrabiopackstones. They were initially deposited as laminated grainstones with subordinate micrite drapes, but the lime sand and lime mud were subsequently admixed by burrowing organisms. At Whitehill Quarry, Gibraltar (Plate 8B), cross bedded grainstones within Lithofacies association B are better developed. In this case, the sediments have not been affected by bioturbation and are still dominated by grainstones.

Lithofacies association C sediments (Plate 8C and upper half of 8D) are developed particularly in the upper part of Rhythm C in the area between Blisworth, Milton Keynes and Bedford. They comprise intrabiograinstones and packstones and laminated biopelpackstones and wackestones which were deposited by storm currents in a very shallow subtidal or possibly intertidal environment. Locally, these sediments exhibit probable hummocky cross stratification (Plate 8D?).



PLATE 8

PLATE 9

Field photographs: Lithofacies association C

- A.-C. Ardley Member/Rhythm C, Pury End (Loc. 96)
- D. Irchester Member/Rhythm C, Blisworth East (Loc. 107)
- E. Ardley Member/Rhythm C, Kirtlington (Loc. 26)

Lithofacies association C sediments were probably deposited by storm currents in a very shallow subtidal or beach setting. Where best developed, they consist of couplets similar to those described by Kreisa (1981). A typical couplet comprises a lower unit of massive intrabiograstone/packstone (unit 1) and an upper unit of finer-grained, finely laminated biopelackstone/wackestone (unit 2). Two such couplets can be seen in Plate 9D: the pen (0.15m long) rests on the top of one couplet, while the laminated unit 2 of the second couplet can be seen near the top of the pen. The base of each couplet is sharp, and sometimes loaded. Concentrations of Aphanoptyxis ?ardleyensis occur at the base of one example of unit 2 in the Ardley Member at Pury End (Plate 9C).

Commonly, either unit 1 or unit 2 is developed in isolation, rather than as part of a couplet. Plate 9E shows a probable occurrence of ?hummocky cross stratified unit 1 at the top of the Ardley Member/Rhythm C at Kirtlington. Isolated occurrences of finely laminated unit 2 sediments are illustrated in Plates 9A and 9B. In both cases, scour structures typical of hummocky cross stratification are present (cf. Mount, 1982, fig. 7, 8).

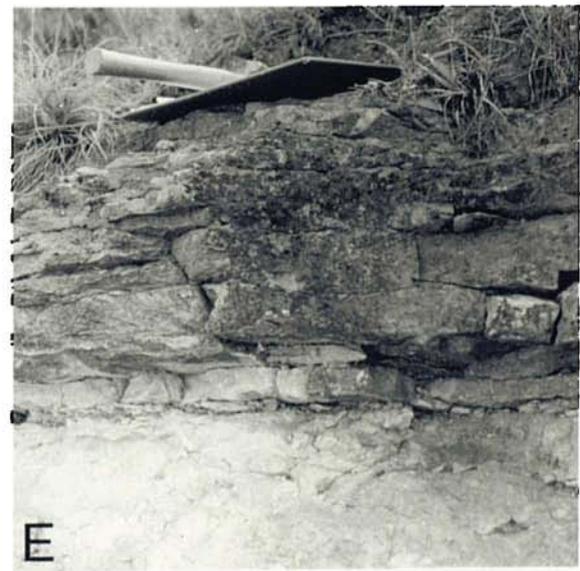
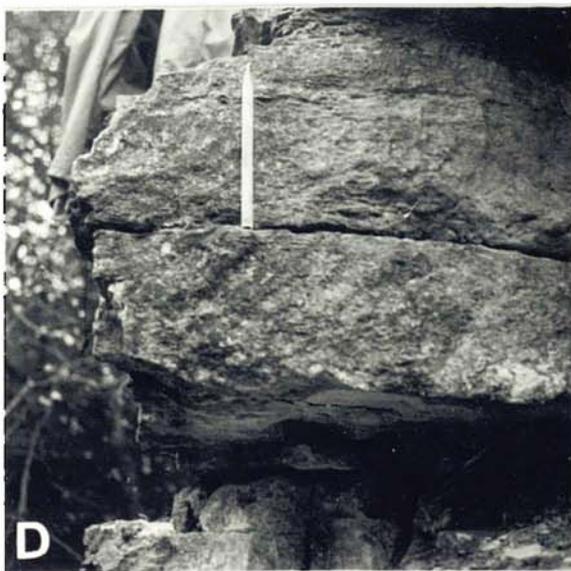
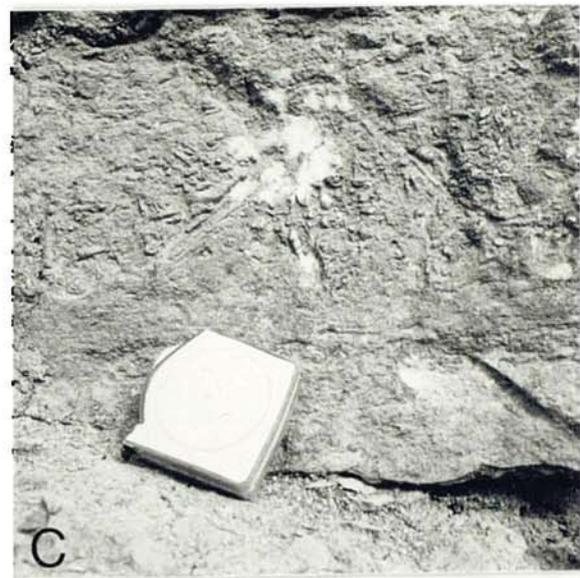
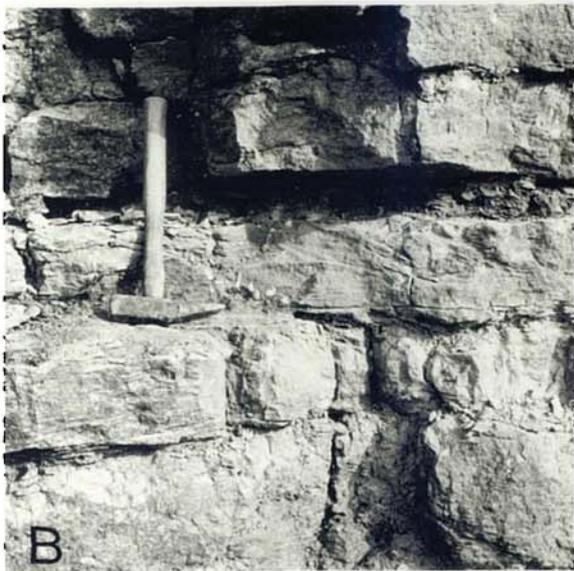


PLATE 9

PLATE 10

Polished slabs: Lithofacies association C

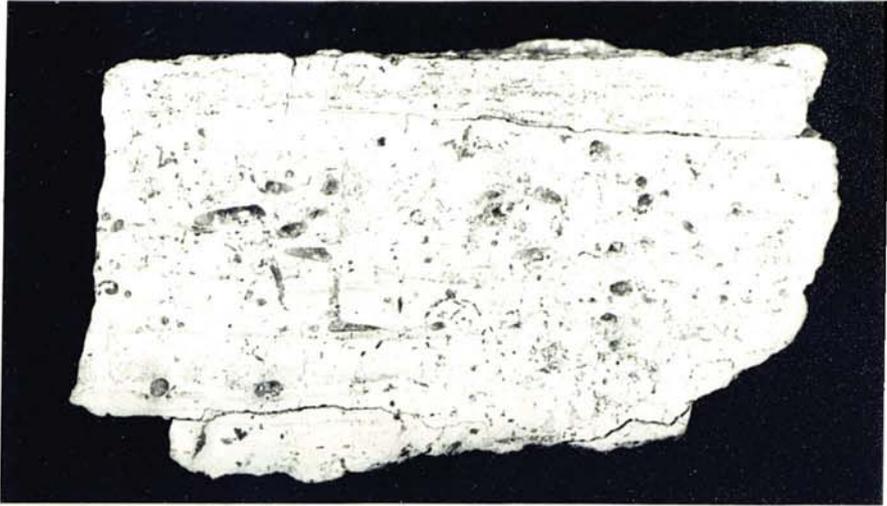
- A. Uppermost bed of the Ardley Member/Rhythm C, Croughton (Loc. 81)
- B. Upper part of Rhythm C, Hartwell (Loc. 101)
- C. Uppermost bed of the Ardley Member/Rhythm C, Great Rollright (Loc. 33)
- D. Uppermost bed of the Ardley Member/Rhythm C, Croughton (Loc. 81)

Unit 2 of Lithofacies association C comprises finely laminated pelletal and bioclastic limestones. These are illustrated in Plates 10A-10D. Usually, the darker laminae are grainstone/packstone layers, whereas the pale laminae comprise pelwackestone/mudstone. However, it is thought that even the mudstone laminae were deposited as muddy, pelletal sand, but that the pellets were subsequently compacted to produce grumuleuse micrite layers. Occasional coarser than normal oolitic and bioclastic laminae also occur. These laminated sediments were mechanically deposited, probably by storm currents. They may be beach deposits.

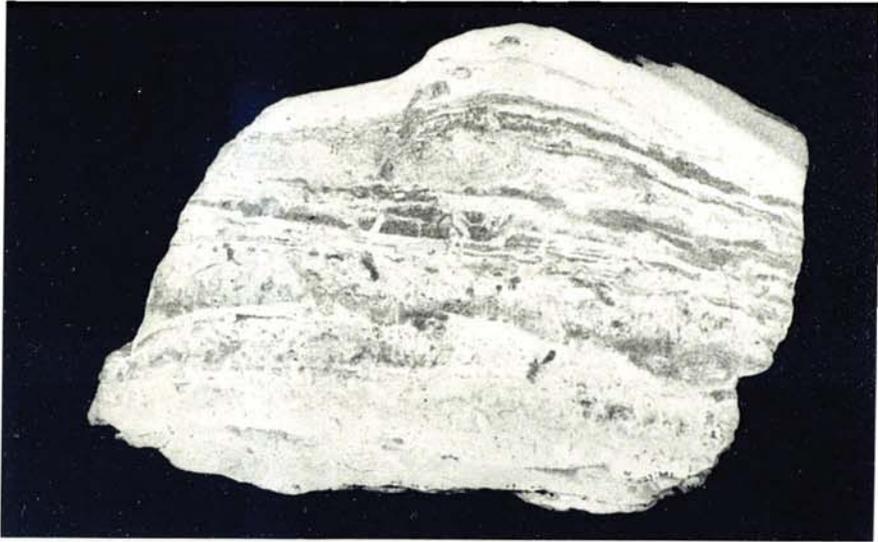
Laminations are commonly disrupted by bioturbation, but in this facies association, are seldom totally obliterated. Many of the vertical burrows found in unit 2 sediments were probably produced by vermiform organisms. However, some laminae may be disturbed by bivalve escape structures.

Locally (e.g. Plate 10D), concentrations of transported nerineid gastropods (in this case, A. ardleyensis) occur in the laminated sediments of unit 2. These gastropods were probably washed shoreward from areas where bioturbated pelletal muds of Lithofacies 5 were being deposited.

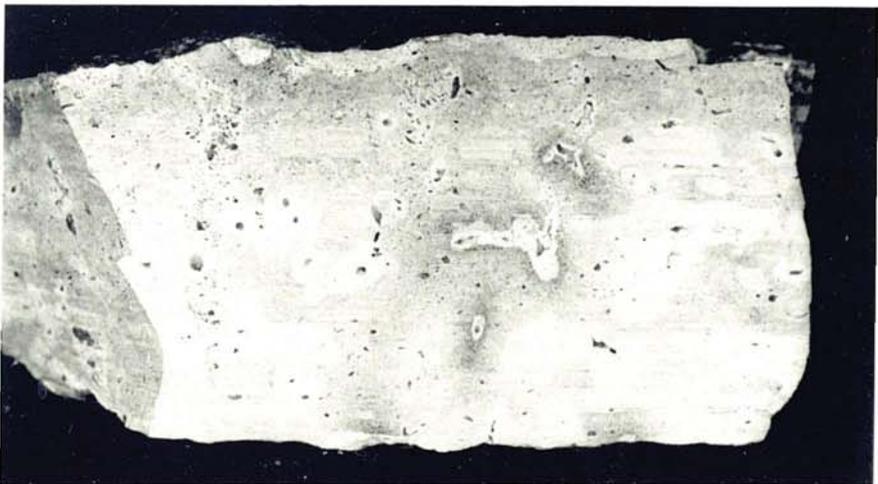
A



B



C



D

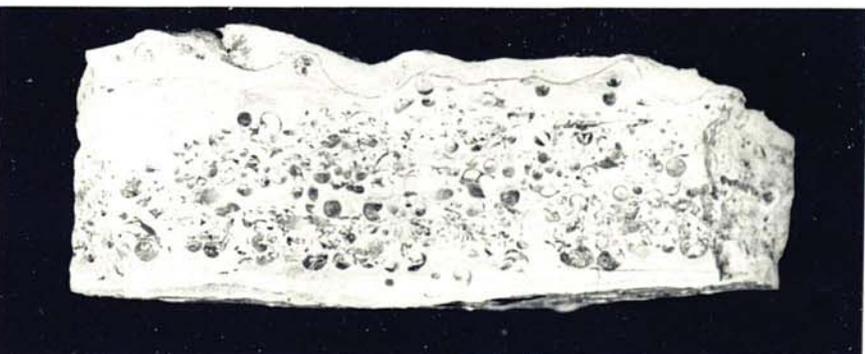


PLATE 10

PLATE 11

Field photographs: Lithofacies 7, Wellingborough

- A. Lower White Limestone succession, Wellingborough (Loc. 124)
B. Oyster-rhynchonellid bank, K. sharpi Beds, Wellingborough (Loc. 124)

As elsewhere in the area, at Wellingborough No. 5 Pit the base of the Irchester Member overhangs the less-massively bedded and more argillaceous sediments of the Kallirhynchia sharpi Beds (Plate 11A). Within the K. sharpi Beds here, an in situ oyster-rhynchonellid bank is developed (highlighted by dashed lines in Plate 11A). This bank or 'reef' is shown in more detail in Plate 11B (pen = 0.15m). Faunally, it is dominated by Praeexogyra hebridica and Kallirhynchia sharpi, with Modiolus (M.) imbricatus present in subordinate numbers. All three species are represented by individuals ranging from juvenile to gerontic. The fauna is contained in a matrix which comprises argillaceous, silty, biopelackstone/wackestone.

Lithofacies 7 (oyster 'reefs' and associated sediments), in addition to occurring in the K. sharpi Beds, is well developed locally in the Forest Marble, in the Irchester Member and in the Thrapston Clay; it is the dominant facies within the Longthorpe Member and within the upper part of the White Limestone north of Stamford.

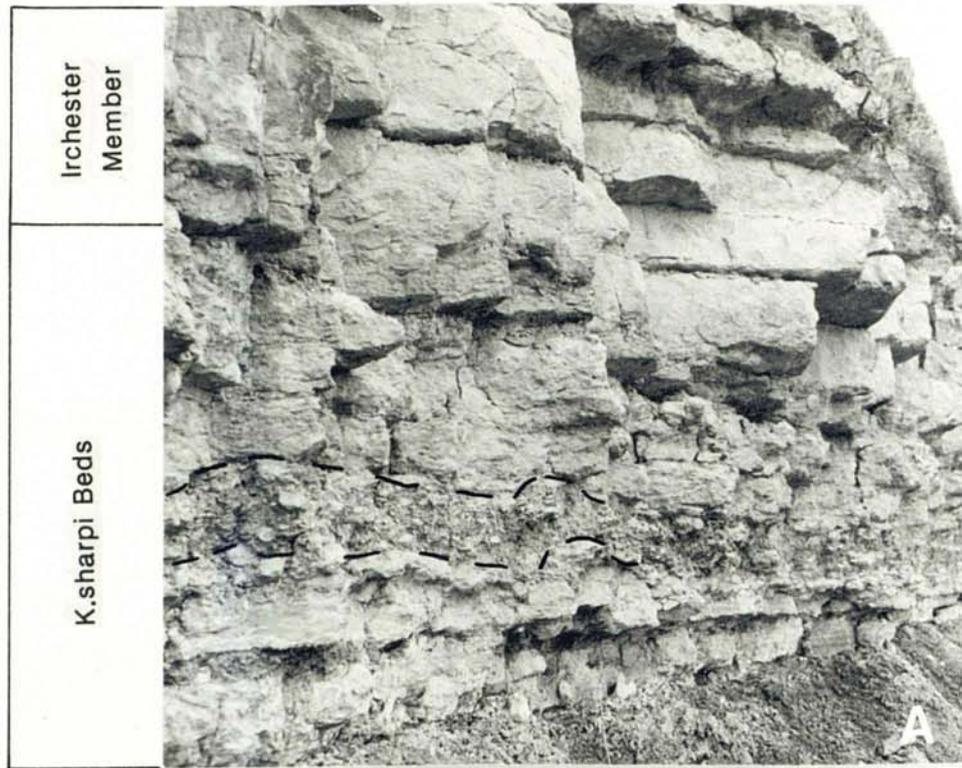


PLATE 11

PLATE 12

Miscellaneous photographs: Lithofacies 6

- A. Uppermost bed of the White Limestone, Croughton (Loc. 81); polished slab
- B. Uppermost bed of the White Limestone, Croughton (Loc. 81)
- C. Uppermost bed of the White Limestone, Weston Underwood (Loc. 62)

Lithofacies 6 comprises lime mudstones and subordinate pelbiowackestones, interpreted as having been deposited on an algally-colonised, supratidal carbonate marsh. Typically, as in Plate 12A, the sediments of this lithofacies exhibit irregular cryptalgal laminations. Deposition of this lithofacies occurred periodically, when lime mud was washed onto the marsh by onshore-directed, wind-driven currents. This happened when the marsh was flooded, perhaps during tropical storms. After each storm event, the marsh flat was re-colonised by algae. However, these have not been preserved and only the lamination indicates their involvement. Such sediments are found in both Rhythm D and Rhythm E in the study area.

Commonly, the supratidal marsh was heavily colonised by plants, particularly by sphenopsids. Equisetites roots are seen within a Lithofacies 6 lime mudstone in Plate 12B. In Plate 12C, however, a horsetail root is seen within a Lithofacies association C sediment, deposited at the close of Rhythm C. In areas around Milton Keynes and Bedford, no marine sediments have been identified within Rhythm D, which there consists only of regressive, terrestrial sediments. In this region, the first Rhythm D 'event' recognised is the plant colonisation of still soft Rhythm C carbonates. Subsequently, the terrigenous mudstones of the Thrapston Clay (Lithofacies association E) were deposited.

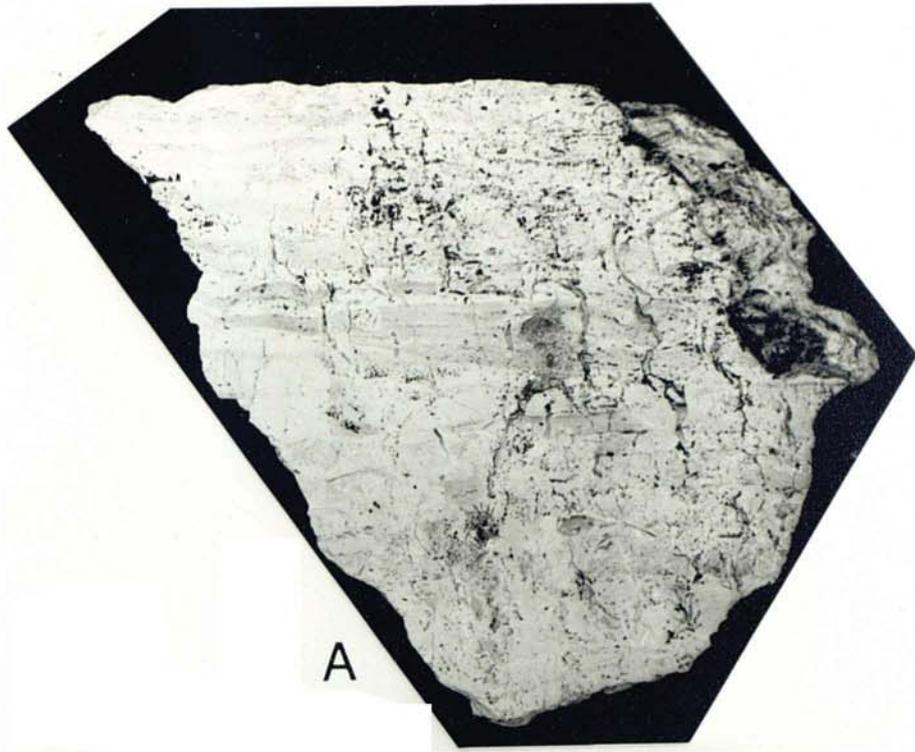


PLATE 12

PLATE 13

Field photographs: miscellaneous

- A. Forest Marble, Shipton (Loc. 16)
- B. An end-of-Rhythm E channel cut in the uppermost bed of the White Limestone at Stratton Audley (Loc. 44)
- C. An end-of-Rhythm D channel at Croughton (Loc. 81)

Plate 13A illustrates a face of the quarry at Shipton where the Forest Marble is dominated by the terrigenous mudstone component of Lithofacies association A. Elsewhere in the quarry, the Forest Marble is dominated by limestones (particularly oobio- and biooograinsstones), the deposits of large, elongate sand bars. In Plate 13A, the limestones present within the Forest Marble are thin wedges of lime sand which extend out from main masses of limestone into areas once occupied by inter-bar troughs. They may represent storm-generated spillovers. For the most part, terrigenous muds were deposited in the hollows between bars. The laterally-persistent limestone at the top of face is the Lower Cornbrash.

During the closing stages of many rhythms, particularly Rhythms C, D and E, channels were locally cut through the uppermost sediments of the rhythm by streams draining areas of emergent marshland. These channels were subsequently abandoned and passively-infilled by terrigenous mud of Lithofacies association E. Such channels have been encountered mainly in Oxfordshire, where the streams probably drained emergent areas to the east. The edge of one such channel, developed at the top of Rhythm E at Stratton Audley, is seen in Plate 13B (the hammer rests on the base of the channel). The channel just visible in Plate 13C was seen at the top of Rhythm D at Croughton. It was 0.65-0.70m deep and had an apparent width of 15m. There was a basal lag of crushed logs, and the channel was infilled by rootletted mudstone. At a number of localities, the bones of the large sauropod Cetiosaurus have been obtained from such channels.

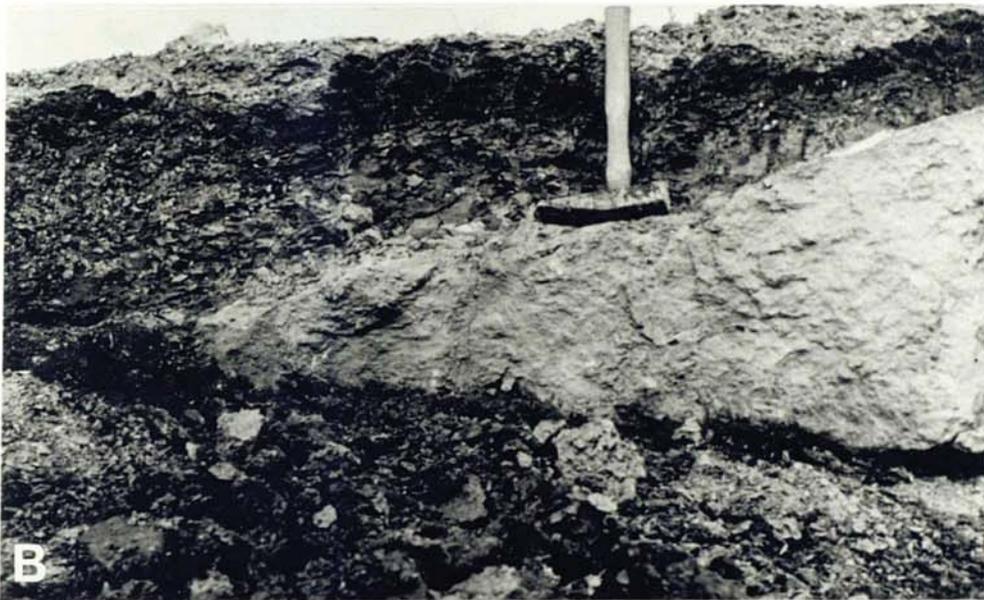


PLATE 13

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