A SEDIMENTOLOGICAL AND PALAEOECOLOGICAL STUDY OF OXFORDIAN (UPPER JURASSIC) CORAL-DOMINATED REEFAL CARBONATES IN WESTERN EUROPE

(Volume 1: Text and Figures)

by

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A thesis submitted to the Faculty of Science
of The University of Birmingham for the degree of
DOCTOR OF PHILOSOPHY

School of Earth Sciences
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November 1995

Synopsis

The Late Jurassic was a time of intense reef development across much of western Europe, which lay on the northern margin of Tethys. There is a considerable diversity of coral reef types in terms of their architecture and geometry, palaeoecology and sedimentary regime. However, although many of these reefal units have been locally studied, there has hitherto been a lack of a coherent synthesis of Late Jurassic reef carbonates. The Oxfordian (Upper Jurassic) of England, France, Germany, Italy, Slovenia and Switzerland has been studied, and detailed comparative sedimentological and palaeoecological work has been carried out on twenty-four reef-bearing sections. This includes the description of a number of hitherto unstudied reef-bearing outcrops. The principal aims of this work are to: (1) identify and characterise different types of Late Jurassic coral reefs with regard to sedimentological and palaeoecological criteria; (2) identify the principal assemblages of macro-organisms, in particular the corals, and their facies occurrence within these reefs; (3) identify the major controls on Late Jurassic coral reef development; (4) develop a depositional model for Late Jurassic reef development relating these different reef types to each other within a spatial and temporal framework; and (5) assess the potential use of Late Jurassic corals as palaeoenvironmental indicators.

From this work eight distinct reef types and one associated facies have been recognised, which are described in detail. These reef types are clearly distinct from each other in terms of a number of sedimentological and palaeoecological criteria. The development of these different structural and compositional types is interpreted as being primarily a function of light intensity, hydrodynamic energy levels and sediment balance. A conceptual depositional model based on these parameters is presented. This preliminary model can be used in two ways: (1) as a predictive tool for Late Jurassic reefal carbonates; and (2) to highlight sedimentological and palaeoecoloical trends in Late Jurassic reef development.

The study has documented a decrease in coral generic richness with increasing palaeolatitute. It is assumed that this is correlated with temperature and a result of the "filtering-out" of stenotopic genera northwards. It has emerged that all high palaeolatitude coral faunas are of similar composition, regardless of facies, and are dominated by eurytopic forms. A growth rate study carried out on *Thamnasteria concinna* and *Isastraea explanata* revealed that they show marked variations in growth rate between reef types. However the study did not record a gradual decrease in coral growth rates with increasing palaeolatitude. It is argued that this is a consequence of the more equable Late Jurassic climate and the eurytopic nature of the two corals used in the study. Clear patterns with regard to coral growth forms and taxonomic composition are demostrated; these are described and their palaeoecological significance discussed. The study has also documented the importance of intra-reef microbialite in reef development and number of different types of microbialite have been identified.

FRONTISPIECE

ANUS, BURGUNDY, FRANCE.

Burgundy has some of the best, yet most understudied, outcrops of Late Jurassic coral reefs in western Europe. It also has some of the most comical place names! (Anus, the place, can be found on the D300 9 km NNW of the Saussois reef section.)

Dedication

This thesis is dedicated to my family.

I care for you more than words can say.

Acknowledgements

First and foremost I would like to thank Tony Hallam and Brian Rosen for their excellent supervision of this Ph.D. Their constant help, criticism and encouragement throughout the course of this work made the undertaking of this Ph.D. a most enjoyable and rewarding exercise. I am very grateful to Reinhart Gygi, Bernard Lathuilière, Markus Bertling, Dragica Turnšek, Massimo Sarti and Neville Hollingworth for introducing me to various field areas and for helpful field discussion.

I am also very grateful to the following for discussion on various aspects of this work: Nigel Cross, Jill Darrell, Rebbeca Day, Ian Fairchild, Jörn Geister, Ken Johnson, Reinhold Leinfelder, Noel Morris, Tim Palmer, Ewa Roniewicz, Arthur Satterley, Peter Skelton, Paul Taylor and Rachel Wood. In addition I would like to thank Reinhold Leinfelder, Tim Palmer, Finn Surlyk, Stephen Kershaw and Beris Cox for critically reviewing and improving the papers which form part of this thesis. I thank Paul Hands for his excellent preparation of thin sections and polished slabs. The financial and other help of Natural History Museum, and the funding of this work by NERC (studentship number: GT4/92/110/G) is gratefully acknowledged.

Finally to the all the postgraduates, research assistants and research fellows, in particular Suzanne Burns, Stephanie Kape, Mat Haywood, Debbie Walker, Jackie Kilawee and Gavin Thomson, for making my years in the Birmingham unforgettable: thanks.

CONTENTS

SECTION 1: INTRODUCTION AND BACKGROUND TO THE PROJECT

CHAPTER 1: Introduction, background and methods employed

SECTION 2: OBSERVATIONS

CHAPTER 2: Burgundy

2.5: Saussois

2.6: Roche aux Poulets

CHAPTER 3: Lorraine

3.2: Foug

3.3: Pagny-sur-Meuse

3.4: Lérouville

3.4.2. Reef 1: Lower reef complex

3.4.3. Reef 2: *Meandraraea* biofacies; upper reef complex

3.4.4. Reef 3: *Isastraea* biofacies; upper reef complex

3.5: St. Mihiel

3.6: Haudainville

3.7: Dompcervin

CHAPTER 4: Normandy and Ardennes

4.1: Ardennes

4.2: Normandy

CHAPTER 5: Swiss Jura

5.2: Liesburg

5.3: St. Ursanne

5.4: Courtételle

5.5: Péry-Reuchenette

CHAPTER 6: England and Italy

6.1: England

6.1.3. Haydon Wick, Wiltshire

6.1.4. Shellingford Cross-Road

6.1.5. Upware, Cambridgeshire

6.1.6. Yorkshire

6.2: Friuli, northern Italy: the "Al Faro" reefs,

SECTION 3: SYNTHESIS, DISCUSSION AND CONCLUSIONS

CHAPTER 7: Types of Late Jurassic coral reefs identified in the study

---

7.1: **Deep-water coral reefs: type I and II reefs**

7.2: **Shallow-water coral reefs**

7.2.1. **Type III reefs:**

7.2.2. **Type IV reefs**

7.2.3. Type V reefs

7.2.4: Type VI reefs

7.2.5. Type VII reefs

7.2.6: Type VIII reefs

7.2.7: Type IX facies

CHAPTER 8: Late Jurassic coral reef development: depositional model, trends and synthesis

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8.1: Depositional model

8.2. Sedimentological and palaeoecological synthesis

CHAPTER 9: summary and conclusions

REFERENCE MATERIAL

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

LIST OF PLATES

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

[Note: Plates are located in volume 2]

LIST OF TABLES

CHAPTER 1:
INTRODUCTION, PROJECT AIMS AND METHODS EMPLOYED

1.1: Background

Jurassic reef-bearing carbonates reached their maximum extent late in the period. This was primarily a result of the relatively high sea-level stand at that time which created vast areas of relatively shallow epicontinental sea (Hallam, 1975; Leinfelder, 1993). This, together with the more equitable Jurassic climate (Hallam, 1993), provided a suitable setting for extensive reef development over these areas. These reefs occur primarily in a Tethyan belt embracing Europe, North Africa and the Middle East, and are also known in the subsurface off the eastern North American margin, in the US Gulf Coast region and western Argentina.

In detail, this belt runs from Romania to Poland, southern Germany, Switzerland, France, eastern Spain, down to southern Portugal (Keupp, *et al.*, 1990) where the reefs join a belt of isolated reef occurrences situated in marginal basins on either side of the early North Atlantic (Eliuk, 1978; Jansa *et al.*, 1983, Ellis *et al.*, 1990; Leinfelder, 1989). The reef belt continues further down into Florida, where it can only be studied in the subsurface (Baria *et al.* 1982, Crevello and Harris, 1982). In the southern part of Tethys reef growth was more localised. Better known examples occur in Saudi Arabia (Okla, 1986; Mitchell *et al.*, 1988; El-Asa'd 1991), Israel (Piacard and Hirsch, 1987), Greece, (Decrouez, *et al.* 1983), Slovenia (Turnšek, *et al.* 1981), Italy (Sartorio, 1989), Northern Calcareous Alps (Fenninger, 1967; Steiger and Wurm, 1980), Tunisia (Gautret and Cuif, 1989) and Morocco (Adams, 1979; Auzende *et al.*, 1984; Hüssner, 1985). On a smaller scale reefal development occurs as far north as northern Germany (Bertling, 1993a and b) and southern England (Arkell, 1935; Ali, 1983; Hitchings, 1981). Other, less well known, high palaeolatitude Upper Jurassic reefal carbonates occur in the Neuquén Basin of Argentina and Chile (Legaretta, 1991; Morsch, 1989) and on the carbonate platforms of Ukraine (Leinfelder, 1993), and the Asian part of Tethys (Murata, 1962; Beauvais, 1986, 1989) (figure 1.1).

The Late Jurassic was a particularly intense time of reefal development across much of Europe, which lay on the northern margin of Tethys. The reefs that developed can be grouped into three broad compositional types: (1) coral-dominated reefs; (2) sponge-dominated reefs; and (3) microbial reefs (Leinfelder, 1993). Although the sponge- and microbial- reefs have received detailed sedimentological and palaeoecological treatment (Keupp *et al.* 1990; Leinfelder, 1993; Leinfelder *et al.*, 1993a), the coral-dominated reefs have been relatively under-studied. Early studies on these reefs were either mainly descriptive (Arkell, 1935; Menot and Rat, 1967), or purely taxonomic in nature (Roniewicz, 1966, 1976, 1982; Beauvais, 1964; Turnšek, 1975). More recently, palaeoecological and sedimentological work has been carried out on these some of these European coral reefs (Burgundy: Menot, 1991; Swiss Jura: Pumpin and Woltersdorf, 1964; Lorraine: Geister and Lathuilière, 1991.; England: Ali, 1978; Hitchings, 1981). However this work has been on a local scale, with little detailed attention being given to contemporaneous reefs in other areas. In particular, there has been no attempt to place the Sub-Boreal coral reefs of England, which in themselves have been relatively well studied (Ali, 1978, Hitchings, 1981), into the broader context of Late Jurassic coral reef development in general.

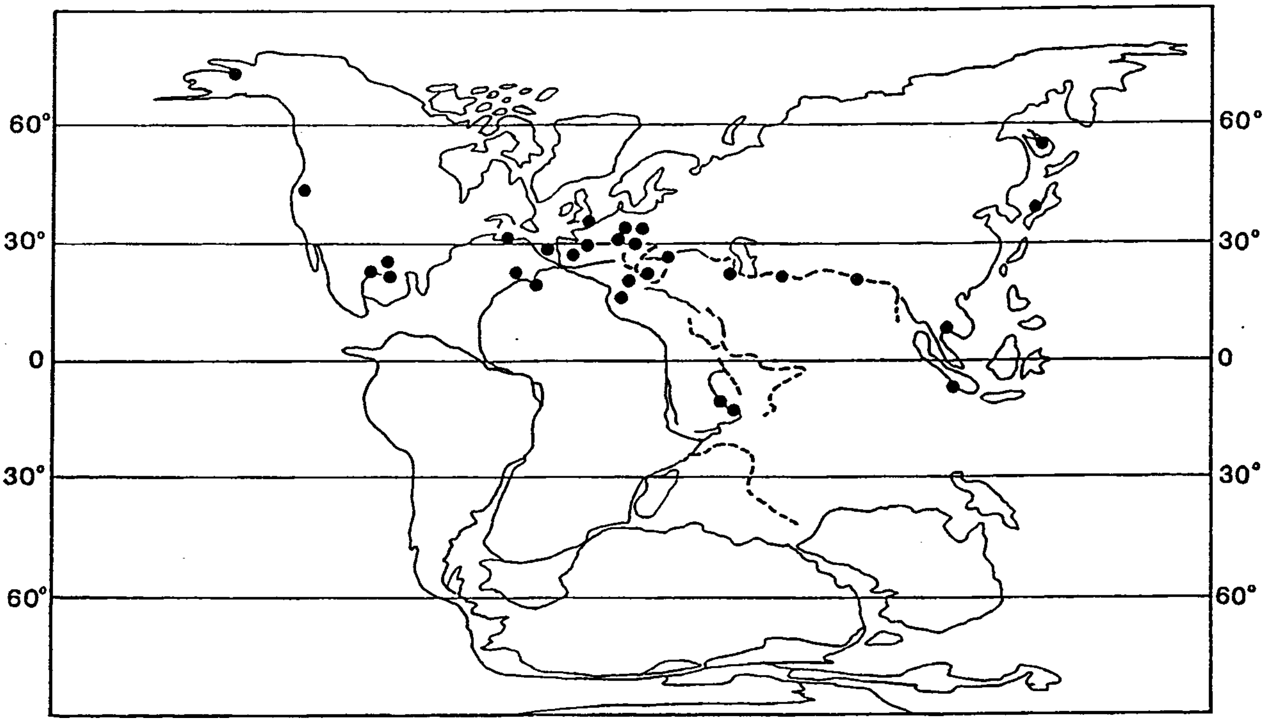


Figure 1.1: Global distribution of reef (all compositional types) during the Late Jurassic (modified and simplified from Flügel and Flügel-Kahuer, 1992; palaeogeographical reconstruction after Smith *et al.*, 1982).

There appears to be little understanding of what exactly the differences are between the reefs of the Sub-Boreal (England) and Tethyan (continental Europe) regions. Nor have there been many attempts to try to evaluate how important climate was, relative to other environmental factors, in causing these differences. Indeed the only real pan-European synthesis on Late Jurassic coral reef development has been by Beauvais (1964). However this work is again essentially taxonomic, lacking adequate sedimentological or palaeoenvironmental analysis; it is also now very out-dated. Brief reviews of the work carried out in individual areas are given in the relevant chapters in section two of this thesis.

In summary, it is clear from previous works that there is a considerable diversity in the types of these Upper Jurassic coral reefs with regard to their architecture and geometry, faunal composition, palaeoecology and sedimentary regime (Beauvais, 1975; Crevello and Harris, 1982; Leinfelder, 1993; Leinfelder *et al.*, 1994a). However, there have been very few attempts to identify these different types of coral reefs, characterise them, or to understand the factors controlling their development. In short, a coherent synthesis of Late Jurassic coral reef development in central western Europe has been lacking.

1.2: Project aims

The objective of this project was to study the Oxfordian coral-dominated reefal carbonates in central western Europe, aiming at a regional palaeoenvironmental synthesis along a broadly Tethyan-to-Boreal transect. The main aims of the study were to:

1. identify and characterise different types of Late Jurassic coral reefs with regard to sedimentological and palaeoecological criteria;
2. identify the principal assemblages of macro-organisms, in particular the corals, and their facies occurrence within these reefs;
3. identify the major controls on Late Jurassic coral reef development;
4. develop a depositional model for Late Jurassic reef development relating these different reef types to each other within a spatial and temporal framework; and
5. assess the potential use of Late Jurassic corals as palaeoenvironmental indicators on both syn- and autoecological levels.

The aim of this work was thus to identify broad patterns and styles of Late Jurassic reef-building rather than give a series of very detailed case studies. The study will concentrate on the corals which are the main framebuilders, although comments and observations on the associated fauna will also be made. A more thorough sedimentological and palaeoecological analysis is given to one important and common group of coral reefs (microsolenid biostromes) in order to understand more fully the fundamental controls on their framework construction and faunal composition.

1.3: Study area and stratigraphic framework

The Oxfordian (Upper Jurassic) strata of England, France, Germany, Italy, Slovenia and Switzerland have been studied, where comparative sedimentological and palaeoecological work has been carried out on 34 reef bearing sections (figure 1.2). This included the re-examination of previously studied reefal sections but more importantly the study of a number of previously undocumented and/or new sections. The latter include outcrops at Bêlleme (Normandy), Novion-Porcein (Ardennes), Haydon Wick (Wiltshire), Courtételle (Swiss Jura) and Polcenigo-Mezzomonte (Friuli, Italy). These sections were examined in greater detail and the reef facies were sampled more extensively. Previously studied sections have had to be re-examined in order to:

1. collect previously unrecorded data (such as coral skeletal biovolume, coral diversity data, degree of framework construction and intra-reef microfacies);
2. normalise for subjectivity of local workers allowing comparability between different sections; and
3. evaluate the effect of different outcrop quality and quantity on the data collected, especially on taxonomic lists.

Figure 1.2: Western European outcrops of Oxfordian coral reefs.

England
1: Yorkshire*
2: Cambridgeshire*
3: Wiltshire & Oxfordshire*

Paris Basin
4: Ardennes*
5: Lorraine*
6: Burgundy*
7: Berry
8: Normandy*

Switzerland
9: Swiss Jura*

Germany
10: Hannover*
11: West Pommerania

Slovenia
12: Western Slovenia*

Italy
13: Friuli*

Portugal
14: Central Portugal
15: Southern Portugal

* sections studied in the field for this thesis.

For details on the precise location of reef localities see the relevant chapters in section two of this thesis.

The only other area of significant Upper Jurassic coral reef development in central western Europe is in Portugal. This was not visited since it has recently been intensively studied by a number of German workers and the reef development is mainly of Kimmerigian age.

All the sections studied here have been confidently dated by local workers to be of Middle to Upper Oxfordian age. Detailed litho- and chronostratigraphies of each section are give in the relevant chapters in section two of this thesis. These reefal units can thus be regarded as effectively chronostratigraphic equivalents. This type of comparative work is important because it minimises the possibility that differences in reef character are related to evolutionary effects, and allows other factors like biogeographical and environmental constraints to be explored. This work is as close to a "snap-shot" of Oxfordian coral reef development in central western Europe as is currently possible.

1.4: Palaeogeography and palaeoclimate

Palaeogeographic and tectonic setting

All the sections studied were located on the northern Tethyan shelf (northern margin of the Neo-Tethys), with the exception of Slovenian and Italian sections which were on the southern margin. These Late Jurassic reefs developed on a relatively stable passive craton that was not structurally or tectonically complicated. The carbonate platforms therefore developed rather straightforward shallowing upward sequences. This is not the case in other areas such as the Portuguese reefs, where reef development is complicated, having been interrupted by salt diapirism and tectonic movements (Leinfelder, 1994), making the interpretation of the reefal facies more difficult.

Figure 1.3 summarises the palaegeographic configuration of the study area during the Late Jurassic. Between the southern European Tethys Ocean (Mediterranean Province) and the land-locked Boreal Sea (Boreal Province) was a series of islands defining a number of shallow marine basins (the Sub-Boreal Province) many of which received a considerable influx of siliciclastic sediments from these islands. Reef development occurred in the shallow water areas around these islands. This is the so-called "European Archipelago" of Fürsich and Sykes (1977). Towards the south, the Sub-Boreal Province was replaced by the Sub-Mediterranean Province which in turn graded into the Mediterranean Province (province names used are those of Fürsich and Sykes, 1977). The palaeogeographic configuration of the Sub-Mediterranean Province was considerably different. Reefal facies were deposited on a series of extensive ramps and distally steepened carbonate platforms south of the Ardennes and Ardenno-Rhenan Massifs (Anglo-Brabant landmass), or on completely isolated carbonate areas such as the Burgundy platform. Generally these carbonate platforms were free of siliciclastic influx, although in the Ardennes and Swiss platform sequences marly units do record rare pulses of siliciclastic influx. For more detailed palaeogeographies of this area see Wilson (1968), Bradshaw *et al.* (1992), Enay and Mangold (1980).

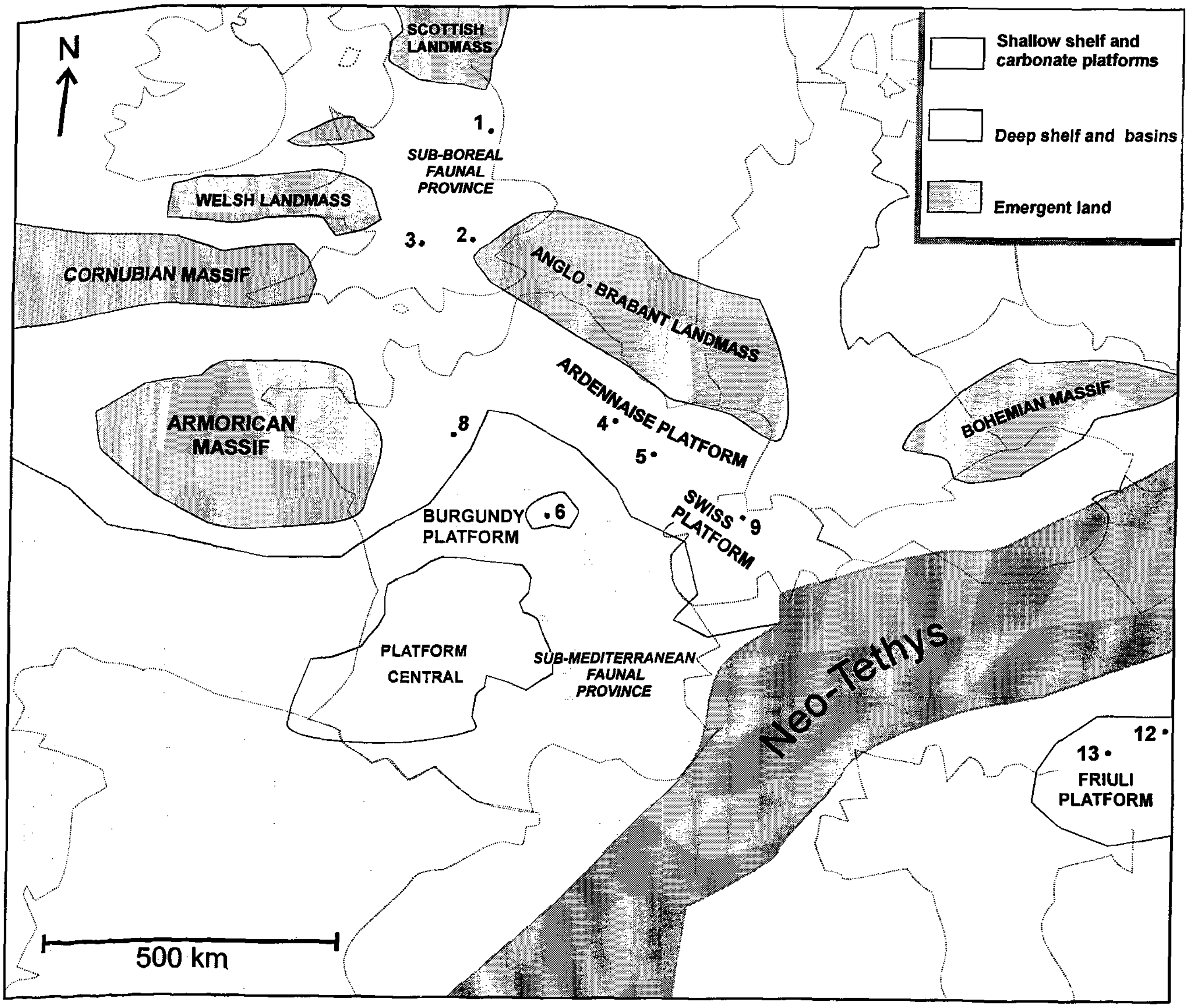


Figure 1.3: Simplified palaegeography of central western Europe during the Late Jurassic (modified from Wilson, 1968; Enay and Mangold, 1980; Brawshaw *et al.*, 1992). (Localities as in figure 1.2.)

Palaeoclimate

It has been well established that the Jurassic climate was more equitable than at present (Hallam 1975, 1984, 1993). The Jurassic climate had significantly lower equator-to-pole temperature gradients, an absence of permanent ice caps, and an atmosphere that was probably enriched with carbon dioxide with respect to the present. Therefore climatically controlled environmental gradients were not as steep as at present. Indeed, it appears that this equitability allowed a general spread of reef corals as far north as Scotland which lay at approximately 45°N, and strongly contrasts with the present day limits of reef growth which lie approximately 35° N and S of the equator (Rosen, 1981). Mid-latitudes experienced temperatures characteristic of the tropics today and the temperate belt extended into the polar regions. The Jurassic climate was dominated by monsoonal circulation (Parrish *et al.*, 1982) and rainfall in low and mid latitudes would have been strongly seasonal, with arid conditions prevailing at low latitudes (Hallam, 1993). The existence of low latitude seaways between the Tethys, Atlantic and Pacific oceans allowed active inter-latitudinal marine circulation among continental blocks, and this was a major cause of climate amelioration (Chamley, 1989)

The most important advances in Jurassic palaeoclimatology in recent years have been in the use of general circulation models (GCMs) to model the Jurassic climate. Most notable of these are the Kimmeridgian and Tithonian GCMs of Moore *et al.* (1992a and b) and Valdes and Sellwood (1992). There is generally good agreement between palaeoclimatic data derived from the geological record (i.e. from the distribution of organisms and sediments) and that from modelling experiments, provided substantially higher atmospheric carbon dioxide levels are assumed for the Jurassic. The Valdes and Sellwood (1992) palaeoclimatic model for the Kimmeridgian predicts the temperature difference between the Swiss Jura and Yorkshire (the latitudinal limits of this study) to be about 4°C with very little change throughout the year. The authors predict surface temperatures for December-January-February to range from 24°C (Swiss Jura) to 20°C (Yorkshire) with very similar June-July-August temperatures (assuming 1050 ppm CO_2) (Valdes and Sellwood (1992) figure 2). The Moore *et al.* (1992a; figure 6) GCM for the Kimmeridgian/Tithonian also predicts a similar range in surface temperatures (20-15°C for December-January-February temperature; 20-25°C for June-July-August temperatures (assuming 1120 ppm CO_2)).

1.5: Methods, techniques and material

1.5.1. Fieldwork

The project was fundamentally a field-based one with over 8 months of fieldwork having been undertaken. Sections were logged and reef and reef-related facies were locally mapped. Field photo-documentation of the reefs and associated facies was extensively carried out. Due to the large area covered by the study it was extremely important to devise a rapid and standardised method for the collecting of comparable field data. This was done by devising a "standard summary sheet" (figure 1.4). These standard summary sheets include information on a series of key sedimentological and palaeoecological criteria in coral reef development. These summary sheets thus provided the focus and framework for much of the data collected in the field.

REEF STRUCTURE AND FACIES

Reef feature	
General	
Unit name	
Stratigraphic age	
Dimensions and form	
Reef form	
Vertical extent	
Lateral extent	
Max. syn-depositional relief	
Internal architecture	
Facies and sedimentology	
Intra-reef sediment	
Inter-reef sediment	
Pre-reef unit	
Post-reef unit	
Sedimentary structures	
Early cementation?	
Depositional environment	
Position on platform	
Sedimentary regime	

PALAEOECOLOGY

Reef feature	
Coral fauna	
Number of genera	
Dominance patterns	
Dominant growth form	
General colony size	
Coral skeletal biovolume	
Associated fauna	
General development	
Main taxa	
Extent of bioerosion	
Algae	
Type	
Volume of algae	
Role in reef building	
Microbialite	
Type	
Volume	
Role in reef-building	
Miscellaneous	
Zonation; succession	

Figure 1.4: The "standard reef summary sheet". See Appendix 1 for definition of terms.

Summary sheets for all the reefs studied are presented in Appendix 1. The standardisation of the data collected also made it easy to make qualitative comparisons between different field areas. The standard summary sheets also form the basis for the characterisation of the different reef types that have been identified in this thesis. For explanations of the terms and definitions used in the summary sheets see Appendix 1.

Although the study has concentrated on the coral framebuilders, general qualitative observations on the associated fauna (as defined in Appendix 1) have also been made. These include observations on their general degree of development (i.e. the relative richness and abundance of the associated fauna) and which groups, if any, dominate. In particular special attention was made to the distribution of nerineid gastropods, diceratid bivalves and red algae with regard to the coral frameworks. These three groups of organisms are commonly cited in the literature as being common accessory organisms in Late Jurassic coral reefs. However it is not clear from the literature whether these are ubiquitous and generally present in Upper Jurassic coral reefs or whether they occur only in certain reef facies. Also the degree and type of bioerosion within these coral reefs, which is also poorly addressed in the literature, needed assessing.

1.5.2. Type of field data collected

The broad nature of the project was such that fully quantitative methods of collecting reef data as reviewed by Perrin *et al.* (1995) were deemed either too time consuming or unfeasible considering the nature of the outcrops. Therefore semi-quantative data collecting methods were generally employed. These methods were used to collect data on the amount of coral skeletal biovolume, the various importance of different growth forms and on patterns of taxonomic composition in the different coral assemblages. This, together with the use of the standard summary sheets, provided a "rapid survey technique" similar to that used in present day ecological studies. These data were collected by visually estimating the percentages of various reefal components. Where this was compared with more quantitative methods to test accuracy (such as working with quadrats or mapping coral colonies on photos) they were found to compare favourably. This approach was felt appropriate since it is the relative importance of the measured variables in different reef types that is the significant factor in this comparative study.

At selected outcrops quantitative methods for collecting coral data were employed. The sampling procedure used to collect quantitative coral diversity data was by means of a randomly placed 5 square metre quadrat (see Perrin *et al.*, 1995). These quadrats are place on the exposed cross-section of the reefs. Within each quadrat the frame-building genera were identified, then the proportion of each genus, as a percentage of the total coral skeletal biovolume, was estimated. This method was used on the microsolenid biostromes since they do not show any major vertical or lateral faunal variation, being compositionally homogeneous. Therefore measurements taken from the quadrat can be assumed to be representative of the biostrome as a whole. (In many other reef types this assumption cannot be made since even within the reef body faunal composition can rapidly change even within the same microenvironment. Thus quantitative analysis of these reefs, if at all possible, is far more difficult and more reef area needs to be sampled before ecologically meaningful results can be obtained.)

1.5.3. Facies analysis

Facies analysis was carried out on both the intra- and inter-reef sediment in the field, and subsequently in the laboratory through the use of a polarising microscope. This has enabled various types of intra-reef microfacies to be identified. The polarising microscope was used to investigate grain and matrix components, cements and microfabrics. Thin sections of the sediments were then classified according to Dunham (1962) and Folk (1962). This was achieved by using the comparison charts of Baccelle and Bosellini (1965), and those of Schäfer (1969). These charts contain frequency estimations of bioclasts, peloids, ooids, oncoids and lithoclasts. However, they only offer a semi-quantitative method of comparison, but experiments by various workers in the past (Dennison and Shea, 1966; Strasser, 1979) have shown that the results obtained using these charts compare favourably with those obtained by the more quantitative method of point-counting. Thin section constituents for this study have been divided up, with the use of these comparison charts, into percentage micrite, sparry cement and carbonate grains (M/S/C ratio). Patterns within Upper Jurassic intra-reef sediments are little known and poorly studied. Large slabs of reef limestone were cut and polished in order to examine the details of the reefal fabric.

Collection. Through the course of the project a large collection of Upper Jurassic reefal material has been collected (approximately 2.9 metric tonnes worth) and is housed in the Natural History Museum (Department of Palaeontology) and the University of Birmingham (School of Earth Sciences).

1.5.4. Diversity: definitions and its measurement

One of the most intriguing aspects of Oxfordian coral reefs is the apparent coral taxonomic diversity gradient that existed from low diversity reef communities at high palaeolatitudes to the extremely high diversity communities at lower palaeolatitude. For example, 13 coral species are documented to occur in the Oxfordian coral reefs of England (excluding the enigmatic Steeple Ashton coral fauna which is discussed in chapter 8), compared with 184 coral species in the Oxfordian reefs of the Swiss Jura (Arkell, 1935). These species numbers are likely to be much exaggerated because ecophenotypic variation of coral species has not been taken into account in the older literature. Moreover, most of the published data concerning the coral diversities of these reefal units are simply a measure of the total number of species that have been recorded in a particular area. Strictly speaking this measure is "species richness" not "species diversity" (as defined by community ecologists). Richness is obviously an inadequate measure of diversity since it provides only very limited ecological information and is affected by the amount of collecting and the sampling procedure, both of which can vary from area to area. The total number of species is of course important; however a second concept, that of faunal heterogeneity, is also very significant. Faunal heterogeneity (how evenly the different species, genera or growth forms are distributed in an assemblage) is of great importance since communities dominated by different taxa, or growth forms, are likely to reflect different environmental conditions. Species diversity (ecologically speaking) combines both concepts - that of heterogeneity and that of total abundance. In this study special attention has been given to dominance pattern as well as faunal richness. At selected localities diversity patterns were also studied by the use of diversity and evenness indexes such as the Shannon-Wiener and Simpson indices, which give quantitative, non-subjective grounds to draw comparisons in terms of diversity and dominance patterns. These indices are given by:

1. Shannon-Wiener (S-W)

$$H = -\sum_{i=1}^{s} (P_i)(\log_2 P_i)$$

Where H= Shannon-Wiener index of species diversity.

S=total number of species (species richness).

P_i=proportion of the total sample belonging to the i^{th} species.

2. Simpson (S)

$$D = 1 - \sum_{i=1}^{s} (P_i)^2$$

Where D= Simpson's index of species diversity.

S= total number of species (species richness).

P_i= proportion of individuals of spicies *i* in the community.

3. Evenness

$$E = \frac{H}{H_{\max}}$$

Where *E*= equitability (eveness); range 0-1.

H= observed species diversity.

H_{max}= maximum species diversity (=$\log_2$ S).

Data needed to use these indices is collected by the quadrat method outlined above.
However the application of such statistical techniques is limited by 2 factors:
1. the availability of good outcrop with well preserved corals; and
2. time constraints.

What must also be considered are the interpretational consequences of different sample sizes and sample populations, which are going to be a function of differences in outcrop quantity and quality. For example the outcrops studied in the Ardennes are excellent and very large, consequently there is a large sample population to sample from. Thus even rare components of the coral fauna are likely to have been recorded, resulting in a relatively high generic richness. Conversely, at many other localities (for example St. Miheil, Lorraine and some of the upper patch reefs in the Swiss Jura) the outcrop is small and/or of poor quality, hence the sample population is very low. Here the rare elements of the assemblage are less likely to be recorded, resulting in a lower richness being recorded. Therefore the size of the sample population needs to be taken into account when making direct richness comparisons. True diversity, which also provides information on dominance patterns, is less affected by the size of the sample population since less importance is attached to the rare elements of the assemblage.

1.6: Upper Jurassic coral taxonomy: systematics used and problems

Upper Jurassic coral taxonomy is presently in a deep state of confusion as a result of different workers using different criteria to define their taxa. Some researchers attach much significance to septal structure whereas others place more emphasis on septal ornamentation; still others see the occurrence of a wall as highly important (Turnšek, 1972). Clearly there is a desperate need of consistency between worker in the use, and priority, of these characters. A start has been made by the *International working group on Scleractinians*, which has published a standard descriptive list of coral features (Beauvais *et al.*, 1993). However this work is still in its infancy. Another problem is that the older literature emphasises good surface preservation as a basis of identifying general calicinal features, which can then be used to identify taxa. The more modern approach is to use thin sections and SEM to determine the microornamentation details and/or the microstructure of the calicinal elements. Many of the taxonomic names in common usage are based on the old surface-based morphological approach, and the internal details of their type specimens are in many cases not known.

The taxonomy that my research has been based on is essentially that of Roniewicz (1976, 1966). The reasons for such a choice are:

1. It is the most up to date monograph on Upper Jurassic corals with species-level identifications;
2. Roniewicz provides clear and detailed plates, including thin sections, that are essential for accurate coral identifications; and
3. She is consistent in the characters used which include both micro-ornamental and microstructural features, considered to be of fundamental importance in coral systematics.

However, the main problem with the publications of Roniewicz (1976,1966) is that although these are good monographs, the fauna of these areas is not especially rich and therefore does not cover all the material that was encountered in the present pan-European project. Therefore in addition to these works the taxonomic literature of Turnšek (1972), Beauvais (1964), Wells (1956), Lauxmann (1991), Bertling (1993b) and Geyer (1954, 1955) were consulted, though using the synonymies of Roniewicz as far as possible. The early monographic works of Koby (1880-1889), Michelin (1840-43) and Milne-Edwards and Haime (1851), are also particularly useful for identifying different growth forms and growth habits. In terms of a working taxonomy for this project the important factor is self-consistency in the use of synonymies. In the past comparisons, and therefore a synthesis, has been hindered by different workers using different classifications and synonymies in different areas.

Ecophenotypy and diagenetic alteration must be borne in mind when examining corals as they may exert a considerable influence on their form and appearance, and may thus lead to incorrect identifications. The problem of ecophenotypy is especially pronounced in the older literature where almost all variations in growth form were erroneously assigned different species names, which consequently resulted in artificially long species lists. For example, the abundant Oxfordian coral *Thamnasteria concinna* (Goldfuss, 1826), is commonly a massive to domal form, but it may also occur as lamellar, encrusting, mammillose and even sub-ramose to ramose forms. These are likely to be simple vegetative responses to different environmental conditions rather than different species. Therefore I do not consider species such as *T. mammosa* (Milne-Edwards & Haime, 1851) as valid, especially in the light of the fact that one may identify a complete gradation between different forms. Moreover, it is now commonly believed that *Thamnasteria dendroidea* (Lamouroux) is simply a branching morphotype of *Thamnasteria concinna*, (Geister and Lathuilière 1991; B. Lathuilière pers. comm, 1993). *T. concinna* is a good example of a coral that exhibits a strong ecophenotypic plasticity. However, this pattern is likely to be complicated by the high degree of homeomorphy between some species, and one must be careful not to exaggerate the extent that corals can "mould" themselves into different growth forms as a result of different environmental conditions. More recent work, particularly on Recent corals, has begun to seriously question the significance of ecophenotypy and whether different growth forms in certain cases do in fact represent different species. For example, the formerly single "species" of *Montastrea annularis* was believed to occur in three different growth forms. More recently this has been split up into 3 different species on the basis of DNA studies (see Veron, 1995). The use of molecular and genetic techniques in modern coral studies is beginning to illustrate the danger in relying too heavily on morphology and calical structure for coral systematics (see Veron, 1995 for review).

The taxonomic work on the coral fauna in this thesis has generally been at generic level. The justification for this is:

1. the very poor state of Jurassic coral taxonomy at species level. At generic level the taxonomy, although still poor, is much more likely to represent true groupings. In most areas generic level identification of the framebuilders is possible;
2. poor preservation of many of the corals in this project has masked the calicinal detail needed for species level identifications; and
3. at generic level it is often possible to make identifications of the corals in the field (at least at a "field name" level), thus allowing possible faunal analysis to be carried out in the field.

Methods of determining coral taxa: At most localities it was possible to assign "field names" at generic level to the coral fauna in the field. This was aided by using a series of silicon carbide filing papers to grind down the top surface of the coral, preferably at the sediment coral interface. This provided flat surfaces from which identifications could be made. In the laboratory more accurate identification of the coral fauna was carried out by means of thin sections and polished slabs. Coral thin sections were left un-stained so that negative prints could be taken directly from the slides (i.e. omitting the photo negative stage). These negative prints, which can be produced in a matter of minutes, aided identifications greatly. "Field names" may subsequently change after more detailed re-examination in the laboratory. Where dissolution of the aragonitic skeletons has not been replaced by calcite, latex peels of the external moulds were made. Best results were achieved where these external moulds occurred in fine micritic sediments. Latex peels were extensively used in Ardennes where the external moulds occur in microbialite which produced some remarkably detailed peels (see plates in chapter 4).

1.7: Previous classifications and models of Upper Jurassic coral reef development

There have been surprisingly few attempts to classify different types of Late Jurassic coral reefs, and still fewer attempts to try to understand the relationship of these different reef types to each other. Previous classifications and models are briefly reviewed below.

- Beauvais (1975) in "Upper Jurassic Hermatypic corals"

This early attempt was a simple three-fold classification of Late Jurassic coral reefs. She distinguishes three groups of reefs:

(1) Coral "patches" or "bioherms". Corals form an essential part of the rock and are generally in life position. The form of the reefs is lenticular and they range in thickness from 10cm to 30m. These reefal units can be divided into two sub-types:

a) reefs dominated by globular or flat coral colonies, occurring in muddy sediment; and

b) reefs rich in dendroid colonies occurring in oolitic sediments.

Associated organisms include *Diceras*, *Nerinea*, *Ostrea* and echinoids. Quoted examples are the "Argovian" and "Sequanian" bioherms of the east Paris Basin and the Swiss Jura, and the Kimmeridgian of the Southern French Jura.

(2) Coral Biostromes. These are less diverse in species and in genera than the coral bioherms. The corals, which are lamellar or spherical in form, are assembled in thin beds which are intercalated with marly or detrital sediments. The reefs do not possess significant relief. Quoted examples of these coral beds are Fringeli and Liesburg in the Swiss Jura, and Arc-sur-Cicon in the French Jura.

(3) Coral rubble beds. These are coral units formed by the physical destruction of reefs. Quoted examples are Valfin in the French Jura and Shellingford Cross Roads quarry in Oxfordshire, England.

- Roniewicz (1975) in "Upper Jurassic Coralliferous Limestones from the Holy Cross Mountains (Poland)".

Although this is only a local work it can also be applied outside Poland. In this work the reef types are defined primarily by the dominant coral growth form and to a lesser extent their taxonomic composition. It is assumed that water energy is the main factor controlling the development of these reefs. Three main types of coral reef are distinguished:

(1) very shallow water, high energy reefs, with massive colonies;
(2) very shallow water, lower energy reefs, with branching colonies; and
(3) calmer water reefs, with sheet form colonies

The problems with the classifications of both Beauvais (1975) and Roniewicz (1975) is that they are rather over-simplified, lack rigorous characterisation of different reef types and the palaeoenviromental constraints on the development of these reefs are too general.

- Crevello and Harris (1982) In "Depositional Models for Jurassic reefal build-ups" (figure 1.5 and 1.6).

This is a more comprehensive and detailed classification of all Jurassic build-ups including sponge, thrombolite and mixed composition reefs (figure 1.5). The classification emphasises the major reef-frame-building assemblages which, if combined with studies of the associated facies, provide a basis for interpretation of depositional setting and palaeoenvironment (figure 1.6). The model also begins to outline in a broad way the relationship between coral, sponge, thrombolite and mixed composition reefs. The main problem with this classification is that the coral reefs are not treated in detail and hence the model and classification, with regard to coral reefs, is again over-simplified and too broad. Moreover, much of the work is based on data collected from the literature and borehole data rather than comparative outcrop study.

- Leinfelder (1993) in "Upper Jurassic reef types and controlling factors: a preliminary report" (figure 1.7 and 1.8).

Despite being a "preliminary report" this is the most thorough and comprehensive synthesis of late Jurassic build-ups presenting a fairly detailed classification and paleoenvironmental model for all types Late Jurassic reef (i.e. microbial dominated reefs, sponge reefs and coral reefs) (figure 1.7 and 1.8). Like the Crevello and Harris (1984) model it also addresses the relationship of these broad reef types to each other and suggests possible transitions and gradations between these different reef types.

Criticisms:

1. The classification does not distinguish different coral reef types in any detail, and provides little characterisation of these reefs. The classification and model presented later in this thesis (chapter 8) seeks to complement the Leinfelder (1993) model by increasing the resolution of the coral end-member of this classification.

2. Poor choice of axes for depositional model. The model considers *water depth, increasing sedimentation rate* and *increasing frequency of nutrient/oxygen fluctuation* as being the three main controlling factors in the development of these reefs.

Water depth *per se* is not a major determinant of reef development and composition. However, light and energy levels (both of which mainly correlate with depth) are, and strongly influence the type and

Depositional setting	**Dominant reef builders**	**Accessory organisms**	**Classification**
<u>Deep, quiet water</u> 1. fore-reef slope 2. deep water lagoon 3. deep water areas of a ramp setting 4. basin floor	Siliceous sponges (hexactinellids and lithistids) and stromatolites	Brachiopods, echinoderms, ophiuroids, belemnites, ammonites, foraminifera, ostracods, serpulids, bryozoa, bivalves, calcareous sponges, *Tubiphyties*, gastropods and corals	1. Sponge-algal build-ups 2. Sponge build-ups 3. Algal build-ups
<u>Wave-agitated platforms</u> 1. lagoon behind reef belt 2. shallow water areas of ramp settings	Corals, siliceous sponges (hexactinellids and lithistids), calcareous sponges, stromatolites and calcareous algae	Bivalves, chaetetids foraminifera, bryozoa ophiuroids, belemnites, gastropods, brachiopods, skeletal algae, echinoderms, stromatoporoids, stromatolites and corals	1. Coral-dominated patch reefs 2. Coral-stromatoporoid patch reefs 3. Sponge-coral-algal build-ups 4. Stromatolitic build-ups 5. Bioclastic piles
<u>Platform margin</u> 1. Open ocean facing	Corals, stromatoporoids and calcareous sponges	Bivalves, chaetetids foraminifera, bryozoa ophiuroids, belemnites, gastropods, *Tubiphyties* sp., brachiopods, skeletal algae, echinoderms and crinoids	1. Stromatoporoid build-ups 2. Coral build-ups 3. Calcisponge build-ups

Figure 1.5: Classification, depositional setting and reef-building fauna of Jurassic build-ups (after Crevello and Harris, 1984).

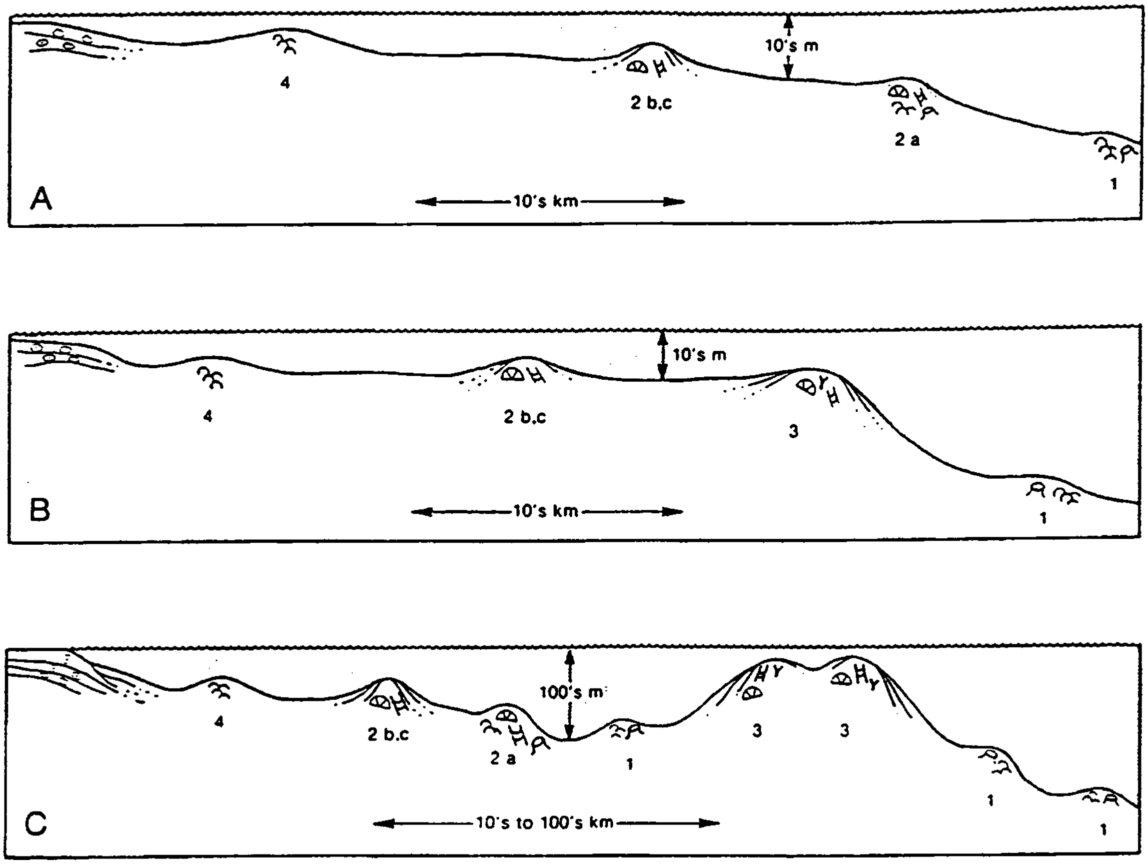


Figure 1.6: Depositional model for Jurassic build-ups (after Crevello and Harris, 1984). Idealised cross sections through the location of Jurassic reefal carbonates across a gently sloping platform (A); a steepened platform margin (B), and a steepened, or rimmed, platform margin facing an open ocean with an intra-shelf basin or deep-water lagoon (C). The distribution of the major framebuilders is assumed to be related to the physical energy (wave related) and local environmental stresses (temperature, salinity, nutrients, or turbidity).

Type 1: sponge and sponge-algal mounds.

Type 2a: sponge-coral-algal build-ups.

Type 2a and c: coral-dominated patch reefs and bioclastic piles.

Type 3: stromatoporoid-coral platform margin build-ups and back-reef coral-stromatoporoid patch reefs.

Type 4: stromatolite build-ups.

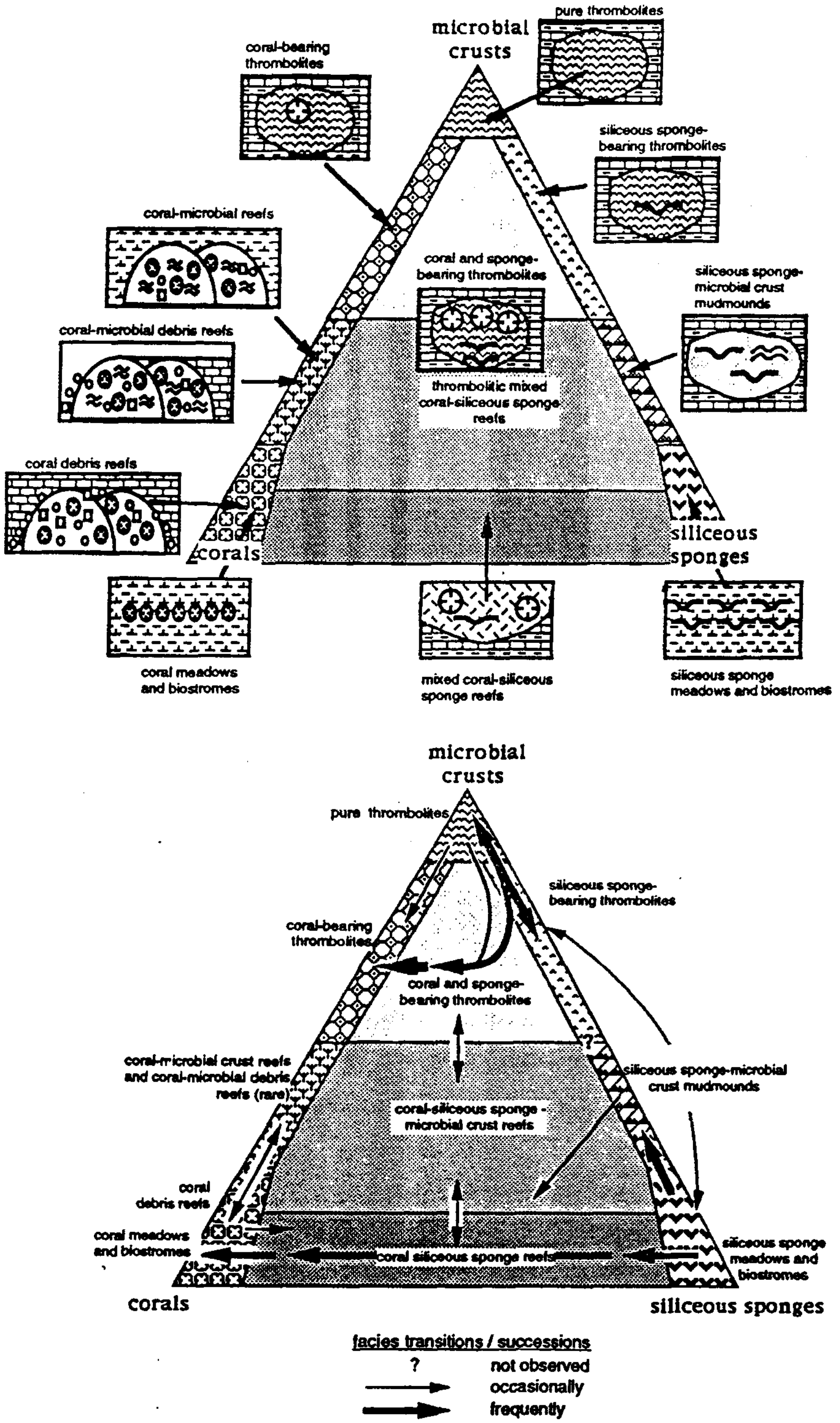


Figure 1.7: Upper Jurassic reef types (after Leinfelder, 1993). Top: Different reef types plotted on a compositional triangular diagram with the end members being coral facies, siliceous sponge facies and microbial facies. Bottom: Successions and facies transitions of Upper Jurassic reef types.

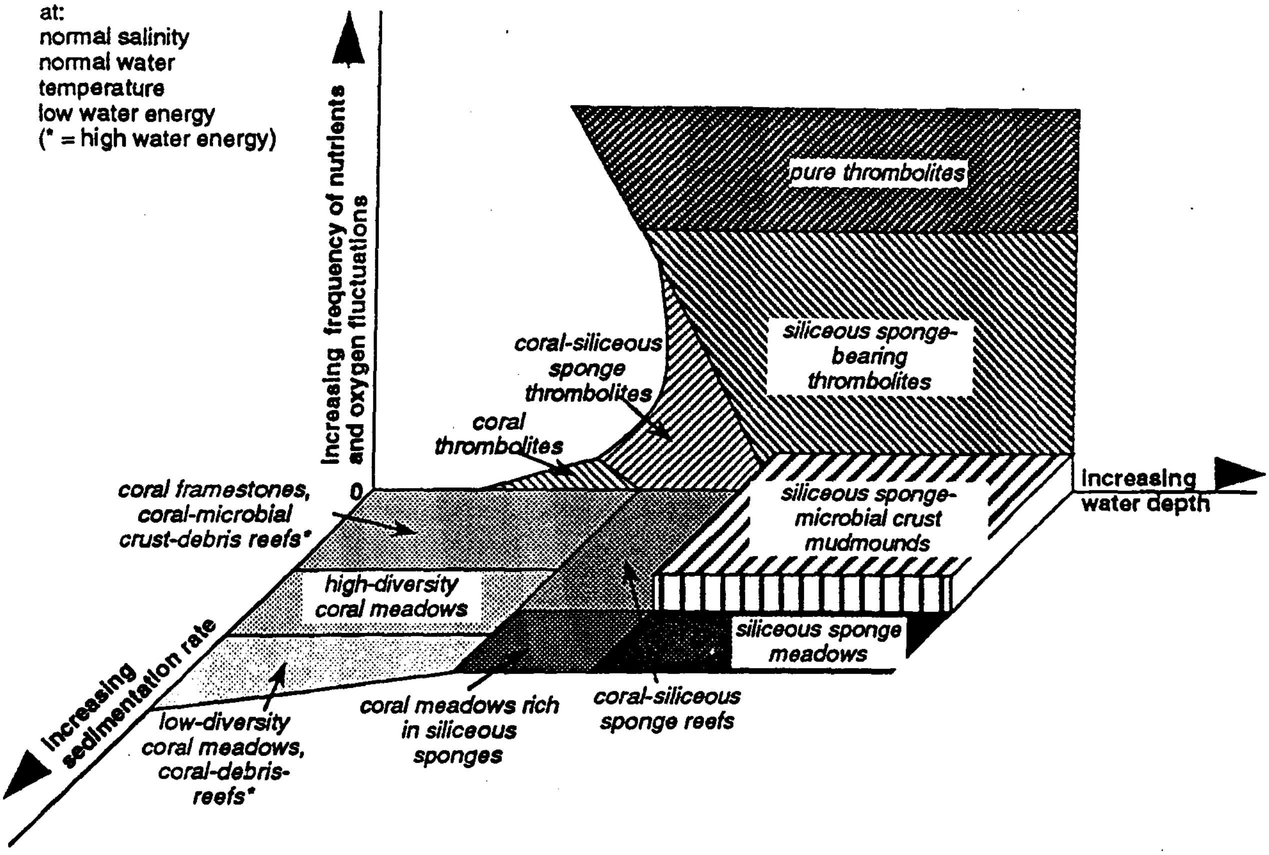


Figure 1.8: Depositional model for Jurassic build-ups (after Leinfelder, 1993). This model assumes that differences in background sedimentation rate, bathymetry and oxygen levels are the dominant factors determining the occurrence and character of Upper Jurassic reefs. Microbial crusts only occur when sedimentation is very low or ceases. Reefal metazoans are assumed to be increasingly excluded by fluctuating oxygen/nutrient levels, leading to microbial facies.

composition of reef development. But light and energy levels vary independently of each other with depth and therefore need to be treated separately. For example, in a shallow clear water, reef environment energy levels can be:

a) very high if in an exposed platform edge situation; but also

b) very low if in a protected, back reef, environment.

Thus, these two shallow water reefs are likely to have different biological and physical attributes, but on Leinfelder model would plot at the same point since they occur at the same water depth (although this is qualified on the model with the use of an asterisk). It is paramount if one is to construct a depositional model for reef development that one uses, and distinguishes between, the fundamental parameters of light and energy levels. It would have been better in my opinion if the *water depth* axis on Leinfelder's model had been replaced with light intensity, since it is this that controls the change from coral to sponge faunas on this axis (see chapter 7, section 7.1 and chapter 8, section 8.1).

The second axis of *increasing sedimentation rate* is over-simplistic since the controlling factor on reef development is not simply the sedimentation rate but rather the balance between sediment supply and sediment removal to and from the reef (see chapter 8, section 8.1).

Finally the third axis of *increasing frequency of nutrient/oxygen fluctuation* is problematic since identifying nutrient levels in the fossil record is, to say the least, contentious and speculative. It is difficult to establish even static nutrient conditions let alone to assess the frequency of nutrient fluctuation and flux. Hence, this is not a particularly practical parameter to use in a general classification.

These problems arise since the model attempts to squeeze all three different reef types into the same depositional model. This is probably unrealistic since it is likely that the controlling factors in coral reef development are different from those of sponge reefs and thrombolite reefs.

1.8. Terminology

Rigorous definitions of what are, and are not, “reefs” are impractical and unworkable. In this thesis “reefs” are defined in a very broad, structural and compositional sense to encompass all facies with significant component of potential framebuliders, whether or not the reef had syn-depositional relief or was potentially wave resistant. Where it is very clear that the reefal unit was sheet-like with very little syn-depositional relief the term “biostrome” is used, which in this thesis is understood to be a type of reef. Unless otherwise stated, “reef” refers to “coral reef” and is synonymous with “build-up”. For a detailed discussion on reef definitions and terminology see Longman (1981) and Rosen (1991). Likewise “framework” is also used here in a very broad sense to include all types of reefal fabrics which had in situ and potentially framebuilding elements, even if the framebuilders were not densely packed or intergrowing; it is used purely as a descriptive term to describe the growth fabric of the reef. This is a deviation from the idealised concept of framework (see Rosen, 1991 for definition) but serves for the purposes of this thesis. (For a discussion on framework terminology and concepts see chapter 8, section 8.2.2) The terminology of the microbial carbonates in this thesis is that of Riding (1991). Unless stated otherwise “microbialite” refers to the “cryptic microbial carbonates” of Riding (1991).

CHAPTER 2: BURGUNDY

2.1: Introduction

During the Oxfordian a steep-walled carbonate platform lay in what is now the region of Burgundy (Enay and Mangold, 1980). The platform was completely isolated and consequently a very pure sequence of carbonates developed. In the basinal areas adjacent to the platform deep-water sponge- and ammonite-bearing marls were deposited contemporaneously with the coral reef facies. The facies mapping carried out by Mégnien *et al.* (1970) suggests a facies distribution which would broadly correspond to barrier type reef with a ENE-WSW orientation (figure 2.1).

The platform carbonates crop out in northern Burgundy as a series of exposures that stretch from the Cure valley in the north-east to the Loire valley in the south-west (figure 2.1). The transect studied for this chapter is located in the department of the Yonne where the exposures are located in the Yonne valley between the town of Clamency and the village of Mailly-la-Ville (figure 2.2; plate 2.1-fig 1). The reason for choosing this transect is because it is well exposed and represents a complete section through the reef complex from the fore-reef and reef-front through to back-reef areas. The transect corresponds to the northern margin of the Burgundy carbonate platform.

<u>Chrono- and lithostratigraphic framework</u>. The stratigraphy of the area can be simplified into four units: Pre-reefal limestones (Calcaires à Chailles noduleuses et à glauconie); a lower reefal complex (Complexe récifal inférieur); an upper reef complex (Complex récifal supérieur); and post-reefal limestones (Calcaires de Cravant) (figure 2.3). The upper part of the "upper reef complex" consists of non-reefal lagoonal and beach facies, and is referred to as the "Terminal unit". The reefal units are dated as Middle to Upper Oxfordian age (Transversarium to Bimammatum Zones). More accurate dating is not possible due to lack of ammonites within the reef facies. However ammonites in the lateral equivalents of the reef facies suggest that the lower reef complex is of Transversarium Zone age and the upper reef complex is of Bimammatum Zone age (Menot, 1980).

<u>Previous work</u>. Given the quality and quantity of the outcrop in this region the Oxfordian coral reefs have received surprisingly little detailed inspection. The works of Mégnien *et al.* (1970); Menot & Rat (1967), and Menot (1991, 1980, 1974) are essentially sedimentological in nature. In these works the reefs are examined from a sedimentological and stratigraphic view point with an emphasis on different facies types and their spatial and temporal distribution. They establish a series of reef sub-environments across the platform from reef-front to back-reef (figures 2.4, 2.1, 2.2; plate 2.1-fig 1). These works thus provide the spatial and stratigraphic framework for the present study. Detailed reefal palaeoecology, especially of the coral fauna, has largely been ignored, although Mégnien *et al.* (1970) and Menot (1991) have carried out some palaeoecological work. Indeed, to my knowledge there is still no systematic work of the coral fauna. This chapter provides the first comprehensive account of the

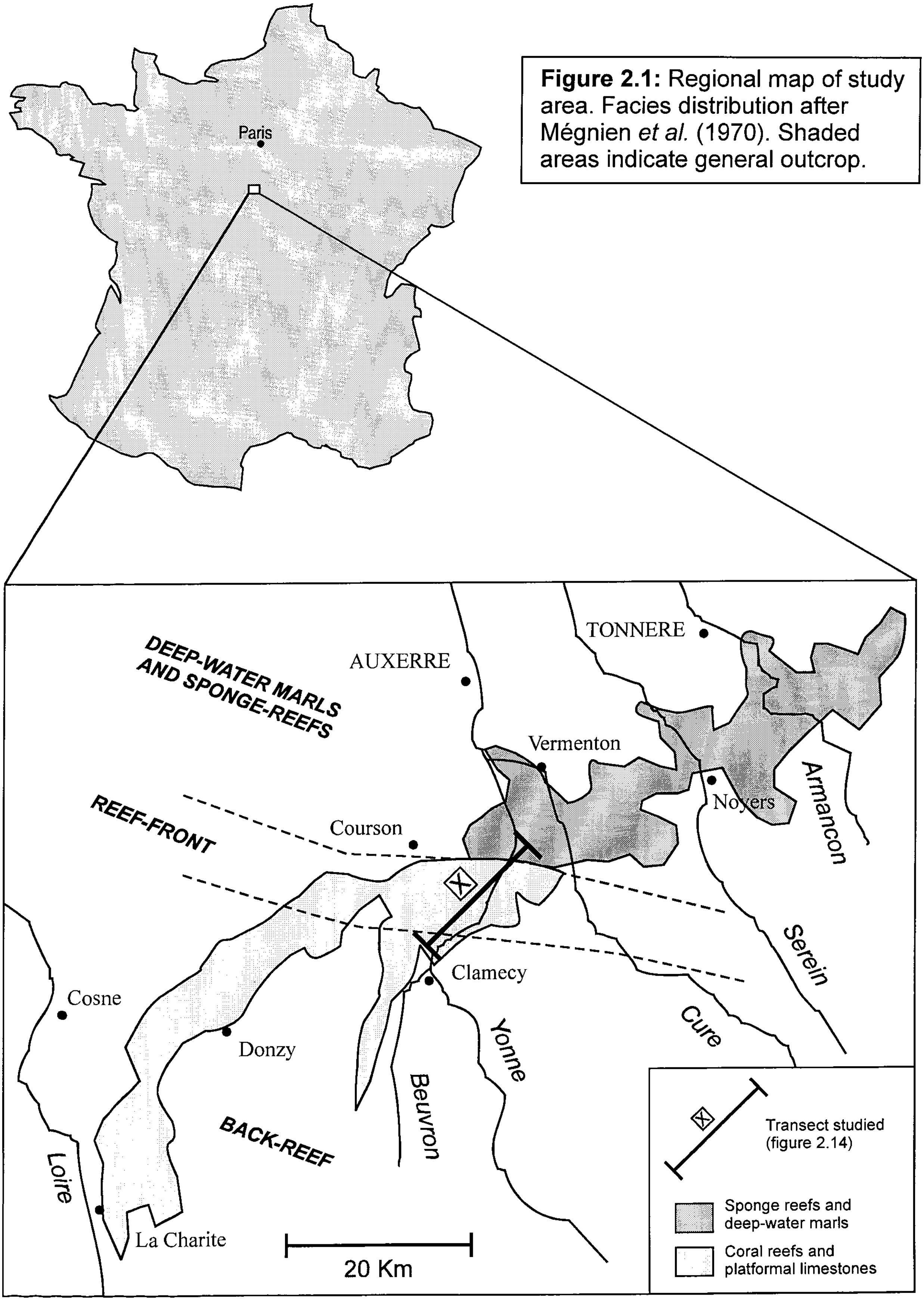


Figure 2.1: Regional map of study area. Facies distribution after Mégnien *et al.* (1970). Shaded areas indicate general outcrop.

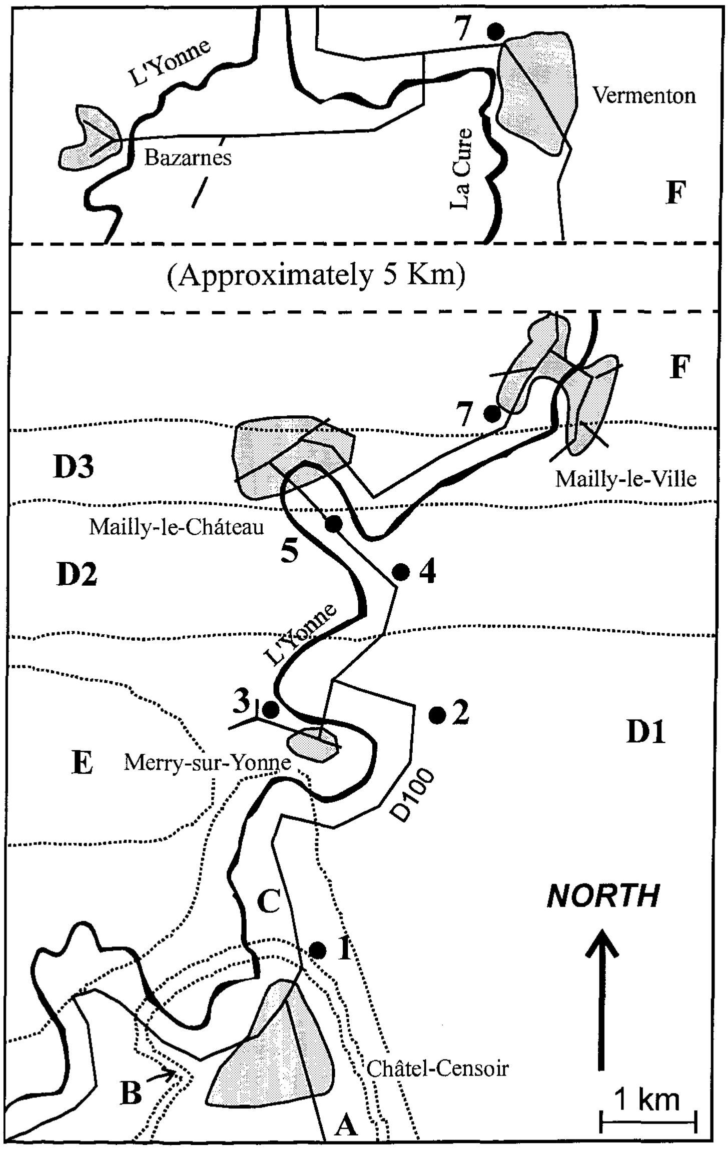


Figure 2.2: Detailed locality map of sections studied and the distribution of the main reef faicies. (Modified after Menot, 1980)

Units:

A: Callovian substrate

B: Oxfordian pre-reefal micritic limestones (Transitional units)

C: Lower reefal unit

D: Upper reefal unit: D1: Back-reef units
D2: Reef-front
D3: Fore-reef facies

E: Terminal unit (inter- and supra-tidal facies)

F: Off- and post-reef marls and sponge reefs

Sections:

1: Châtel-Censoir (2.2)
2: Rocher du Saussois (2.5)
3: Roche aux Poulets (2.6)
4: Bois du Parc (2.4)
5: Quatre Pieux (2.3)
6: South of Mailly-la-Ville (not examined)
7: Vermenton (not examined)

(Numbers in brackets refers to chapter section)

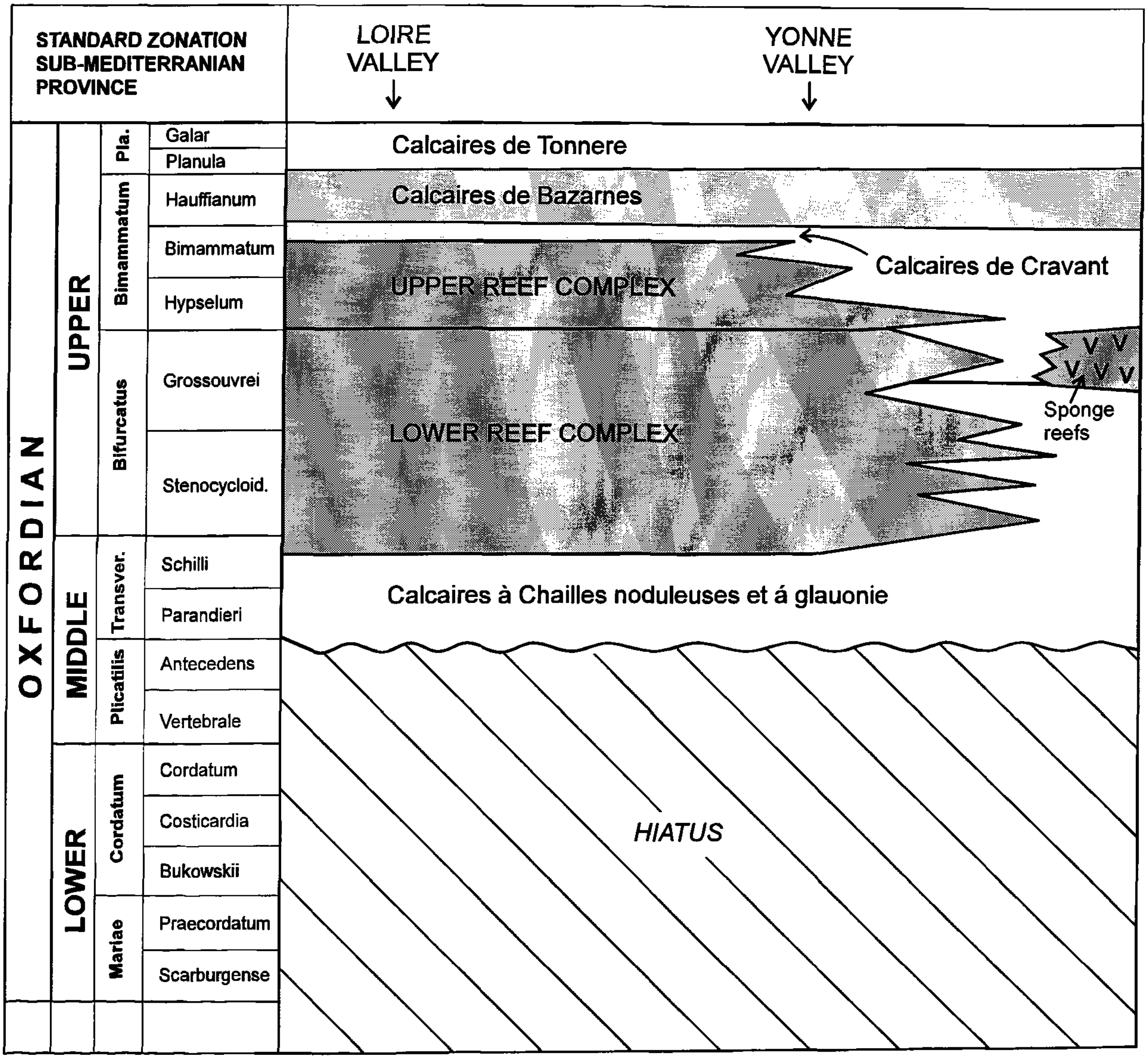


Figure 2.3: Simplified chrono- and lithostratigraphy of the Burgundy region. (After Enay and Mangold, 1980).

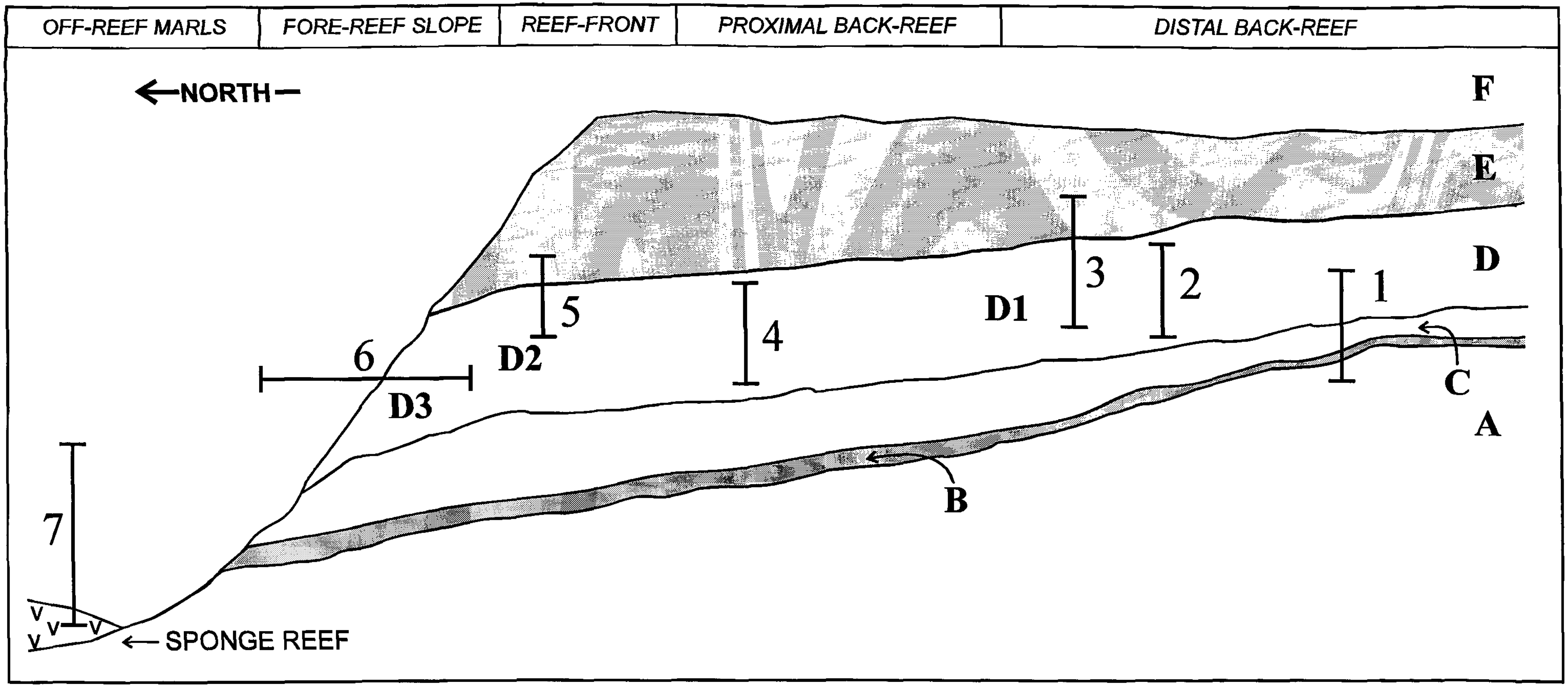


Figure 2.4: Schematic section through the Burgundy reef complex. Highly simplified and not to scale. (Modified from Menot, 1991).

__Units:__ A: Callovian substrate
B: Oxfordian pre-reefal micritic limestones (transitional facies)
C: Lower reefal unit
D: Upper reefal unit: D1: Back-reef units
D2: Reef-front
D3: Fore-reef facies
E: Terminal unit (inter- and supra-tidal facies)
F: Off- and post-reef marls and sponge reefs

__Sections:__ 1: Châtel-Censoir (2.20)
2: Rocher du Saussois (2.50)
3: Roche aux Poulets (2.60)
4: Bois du Parc (2.40)
5: Quatre Pieux (2.30)
6: South of Mailly-la-Ville (not examined)
7: Vermenton (not examined)

coral fauna of the area. The early works of Cotteau (1852-1857) are detailed monographs on the mollusc and brachiopod fauna and provide a useful reference for lower level systematic work.

In this chapter the reef analysis is carried out according to the reef zones identified by the aforementioned workers (figures 2.2 and 2.4):

Reef Zone	Locality	Chapter section
Coral reef installation	Châtel-Censoir	2.2
Reef-front	Quatre Pieux	2.3
Proximal back-reef	Bois du Parc	2.4
Distal back-reef coral banks (lower section)	Rochers du Saussois	2.5
Distal back-reef coral banks (upper section)	Roche aux Poulets	2.6

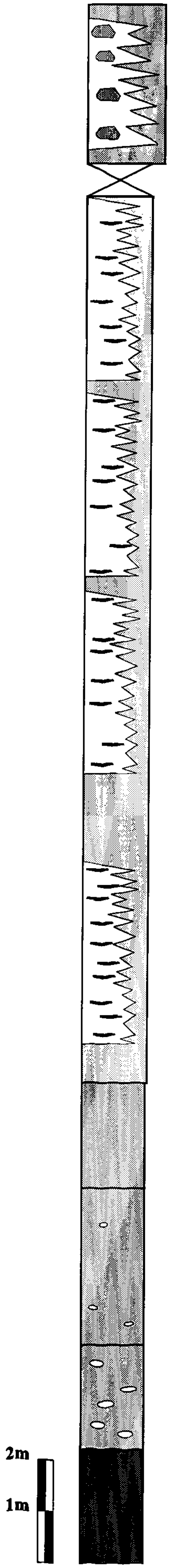
2.2: CHÂTEL-CENSOIR

2.2.1. Introduction and facies sequence

At the level crossing 1 km north of Châtel-Censoir is a railway cutting that exposes a 27 m composite section at the base of the reefal complex. The shallowing upward section exposes a complete sequence from deep-water pre-reefal limestones through to reef installation and subsequent reef growth (figure 2.5, plate 2.1-fig 2). The section therefore allows the study of relatively deep-water pioneering and early sucessional stages in late Jurassic coral reef development. This first reefal unit corresponds to the lower reef complex (figure 2.3).

Facies sequence (modified from Menot, 1991) from base up:

- The sequence begins with a 130-140 cm thick fine grained glauconitic rich limestone (glauconitic pelbiomicrosparite to pelbiomicrite). The macrofauna includes bivalves, terebratulids, *Millericrinus* fragments, sponges, serpulid tubes and rare *Pleurotomaria* gastropods. The ammonite fauna (*Perisphinctes* cf. *plicatilis, Cardioceras laevigatum, Cardioceras vertebrale* and *Pachyceras* sp.) suggests a Middle Oxfordian (Plicatilis Zone) age.
- This is overlain by 4 m of a nodular calcareous mudstone (pelmicrites to pelmicrosparites) rich in ammonites and *Pholadomya.* The cephalopod fauna (*Paracoenoceras giganteum, Perisphinctes pumilus, Dichotomosphinctes antecedens, D. Elisabethae, Ochetoceras canaliculatum, Subdiscosphinctes* sp. and *Ochetoceras* sp.) suggests a Middle Oxfordian (Tranversarium Zone) age. Bivalves (*Pholadomya ampla, Plagiostoma* sp. *Trigonia* sp.*)*, brachiopods (*Zeilleria censoriensis, Galluennithyris maltonensis*) and sponge spicules are abundant.



Upper reef complex

Various types of reefal development, generally as high diversity patch reefs.
Wide range of lithofacies from fine micrites to coarse grained bioclastic packstones.
Wide range of growth forms, in particular branching ramose forms becoming common.
Associated fauna generally poorly developed.

Lower reef complex

Microsolenid biostrome

Bioclastic packstone to wackestone. Micritic mudstone in areas.
Total coral skeletal biovolume 40 - 70%.

Percentage of coral skeletal biovolume					
Genus		Family		Growth-form	
Microsolena	42	Microsolenidae:	75	platy - sub-massive:	94
Dimorpharaea	27	Other:	25	phaceloid:	3
Thamnasteria	8			branching ramose:	2
Comoseris	5			solitary:	1
Isastraea	7				
Fungiastraea	3				
Thecosmilia *Montlivalitia*	3				
Dendraraea	2				
Clausastraea	1				
Stylosmilia *Cladophyllia*	1				
Dermoseris	<1				
Actinaraea	<1				

GENERIC RICHNESS:		14
EVENNESS:		0.65
DIVERSITY INDEX	[SHANNON-WIENER]:	2.48
	[SIMPSON]:	0.73

Rich and diverse associated fauna: bivalves, echinoids, crinoids brachiopods, crustaceans and serpulids. Stromatolitic crusts.

Transitional micritic limestones

Nodules and sponges virtually disappear, increased abundance of microsolenids, coral plates better developed and thicker (2-3mm - 1cm). Chlamytids still present, brachiopods become rare.

Nodules less abundant and more irregular in form, nucleus often a lithistid sponge
Ammonites very rare. *Pholadomya* virtually disappears.
Chlamytids well represented.
Cidaris spines and sponge spicules very common.
Development of a rich brachiopod fauna towards the top of the unit.

Compact nodular limestone. Ammonites and *Pholadomya* rare.
Microsolenids present from base up, however rare and very poorly developed (<1mm)
Lithistid sponges appear 30 cm from base.

Pre-reefal micritic limestones

Nodular calcareous mudstone with thin horizons of argillaceous limestone.
Ammonites and *Pholadomya* common.
These unit rest unconformably on Callovian limestones.

Figure 2.5: Schematic field log of the Châtel-Censoir section. (See text for details).

The next unit, a series of micritic limestones with brachiopods, sponges and rare microsolenid corals, signifies the initiation of the coral reef. Although the lithofacies is similar to previous units there are significant changes in the faunal composition. These beds are a transitional facies between non-reefal and reefal limestone.

- In the first 2 m the ammonites and *Pholadomya* become less abundant whilst plate-like lithistid sponges and extremely thin (less than 1 mm and sinuous in longitudinal section) microsolenid corals appear.
- The next 3 m see a continued decrease in the abundance of ammonites and large *Pholadomya* virtually disappear. Conversely pectinid bivalves (*Aequipecten* cf. *inaequivalvis, Chlamys subarticulatus, Terquemia ostreiformis*) and cidaroid echinoids become more abundant and better represented. Towards the top of this unit a rich and abundant brachiopod fauna develops (*Zeilleria censoriensis and Galluennithyris maltonensis* are common).
- Within the last 2.5 m of the unit both the sponges and siliceous nodules disappear and the brachiopods become less abundant, although the pectinid bivalves show no significant changes. However the most noticeable change is in the microsolenid corals which become more abundant and better developed, with coral plates reaching 1 cm in thickness.
- Overlying these beds is the reef proper which is described and discussed below.

2.2.2. Reef structure and facies

Reef structure and framework development

The reefal unit is 15 to 20 m thick and has a lateral extent of at least 350 m giving the reef a distinctly sheet-like form. The reef has well developed planar bedding surfaces on a metre scale. The bedded nature of the reef and its sheet-like geometry justifies the term *biostrome* to describe this reef (plate 2.2-fig 1). The framework is constructed almost exclusively by platy corals and the coral skeletal biovolume ranges from 30% (near the base of the biostrome) to 50-60% (in the main body of the biostrome) (plate 2.2-fig 2). Laterally the degree of framework development is extremely uniform.

Facies and sedimentology

The intra-reef sediments are fine grained, creamy coloured bioclastic wackestones and packstones. At a microfacies scale the M/S/C ratio is: 80-60/0/40-20 (biomicrites) (plate 2.3). Carbonate grains are almost totally bioclasts with only rare intraclasts and show no preferred orientation. These are fine grained (0.1 mm), very angular and poorly sorted. The bioclasts are not highly micritized and only the occasional larger bioclasts (4 mm) possesses spongiostromate coatings which are 0.3 mm thick. The most abundant bioclasts are of corals (50%), echinoids (25%) and bivalves (20%), although fragments of serpulids, sponge spicules and forams are also present. The matrix is completely micritic and composed of very fine detrital material and peloids. It lacks peloidal laminations or rinds, although on the large planar fragments relatively thick (4 mm) laminated spongiostromate crusts can develop.

2.2.3. Palaeoecology

Associated fauna

The associated fauna is rather poorly developed. The most obvious macrofaunal elements are bivalves (*Plagiostoma*, *Chlamys* and *Nanogyra*) and cidaroid echinoids. Also present, though far from abundant, are serpulids, thecidean brachiopods, bryozoans, forams and crustaceans (*Pithonoton* (*Pithonoton*) sp). These groups often encrust the undersides of the coral plates. Bioerosional activity is high: *Lithophaga* borings are abundant and *Entobia* traces are also present.

Coral fauna

The coral fauna is almost exclusively composed of platy corals. The dimensions of these coral plates increase from approximately 2 mm thick and 10 cm across at the base of the biostrome, to 2-4 cm thick and 20 cm across in the main body of the biostrome (plate 2.2-fig 3). The latter sized plates construct the vast majority of the biostrome framework. Taxonomically the fauna is dominated by microsolenids especially of the genera *Microsolena* and *Dimorpharaea*. Generic richness is relatively low, and generic dominance patterns are high. The coral fauna recorded at this locality is as follows:

Phaceloid branching		**Massive-Lamellar**		**Family composition:**	
(3%)		**(94%)**		**Microsolenidae**	**75**
Thecosmilia	2	*Microsolena*	42	**Other**	**25**
Dermoseris	<1	*Dimorpharaea*	27		
Stylosmilia	<1	*Thamnasteria*	8	**Generic richness:**	**14**
Cladophyllia	<1	*Isastraea*	7		
		Comoseris	5	**Eveness index:**	**0.65**
Branching ramose		*Fungiastraea*	3		
(2%)		*Clauasterea*	1	**Diversity indexes:**	
Dendraraea	2	*Actinarea*	<1	Shannon-wiener:	2.48
				Simpson:	0.73
Solitary					
(1%)					
Montlivaltia	1				

[Figures refer to the proportion of the total coral fauna each genera, family or growth form represents and is expressed as a percentage of the total coral skeletal biovolume. This applies to all subsequent coral lists where this data is available.]

2.2.4. Depositional environment

The location of the biostrome low in the shallowing upwards sequence, just above sponge- and ammonite-bearing micritic limestones, suggests a relatively deep-water environment. This inference is corroborated by the lack of evidence for wave, current or storm reworking, suggesting a position well below normal wave-base. Hence a calm, low energy regime is envisaged. The microfacies, dominated by detrital bioclastic material of immature nature and lacking laminated peloidal fabrics, suggests a relatively high detrital sedimentation rate.

2.3: QUATRE PIEUX

2.3.1. Introduction and facies sequence

The Quatre Pieux abandoned quarry reveals a 30 m high section of three facies developed during a shallowing upward, aggradational, sequence (figure 2.6; plate 2.4-fig 1).

From base up the sequence is as follows:

- 15 metres of well developed reef framework (see below for description and discussion).
- 15 metres of *Diceras*-rich micritic and wackestones (plate 2.4-fig 2). Coral material is rare, fragmented and evidently derived; in situ corals are absent. The diceratid valves are usually disarticulated and locally concentrated in lensoid beds a few meters across. The facies exhibits a well developed, often laminated (on a mm scale) bird's eye textures. The microfacies shows a marked degree of variability and grades from pelmicrites through to pelspirites and pelbiosparites. Many of the valves have peloidal crusts. Calcified cyanobacteria include *Bacinella*, *Thaumatoporella* and *Arabicodium*. Forams are common (textulariids, valvulinids, verneuillids, miliodes, lituolids and triloculines) (Menot, 1991). The sediments are locally well bioturbated. The facies characteristics suggest an upper infra-tidal to inter-tidal position for these beds and a somewhat quiet water environment, perhaps just behind the reef front. These beds represent the lower part of the terminal facies.
- 5 metres of pebbly beach gravel (plate 2.4-fig 3). Gravely oolitic grainstones containing well rounded spherical to oval intraclasts of oolitic grainstone and coral fragments, which can be up to 10cm in diameter. Bioclastic material is abundant and composed mainly of coral, echinoids, bivalves and red algae. A characteristic feature of the biopelsparitic microfacies is the presence of thick (50µm) fringes of early isopachous fibrous cements (Menot, 1991). Dispersed bird's eye textures are present. These gravelly conglomerates were deposited in an intertidal regime and represent the upper part of the terminal facies.

(For more details of this depositional sequence see section 2.7.)

2.3.2. Reef structure and facies

Reef structure and framework development

The reefal unit is a minimum of 15 m thick and at least 200 m across (in outcrop) with a relatively uniform and continuous framework construction. The form and geometry of the reef cannot be established from the outcrop. The framework is constructed by massive and branching phaceloid colonies and is bound together by microbialite. Coral skeletal biovolume is high and can reach 60-85%. The reefal unit is massive, with no discernible internal architecture. All framebuilders are in situ with no evidence of rolling.

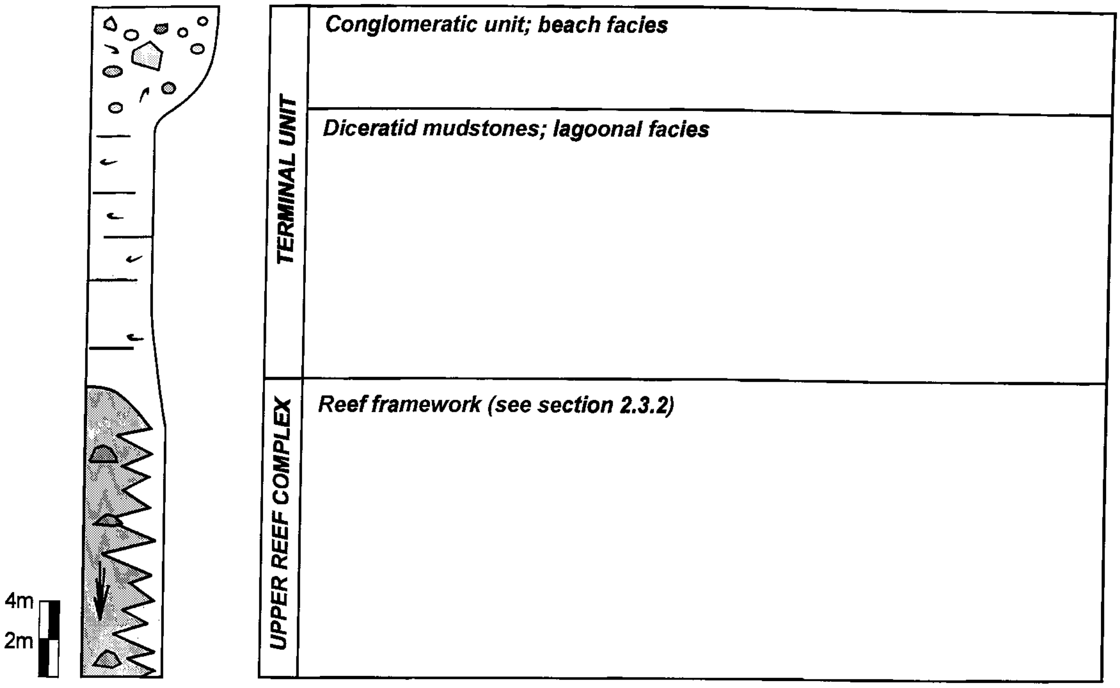


Figure 2.6: Schematic field log of the Quatre Pieux section. (see section 2.3.1 for details).

<u>Facies and sedimentology</u>

The intra-reef sediment is a hard, dense creamy micrite (plate 2.5-figs 1-3). There are a variety of textural types present from coarse grained packstone and grainstone to small patches of wackestone. There are rapid transitions from patches composed of micritic mudstones to patches of pure bioclastics grainstones. The transition between textural types can be both gradational and continuous or sharp and erosive (plate 2.5-figs 2-3). Between coral colonies micro-spur and groove structures are present.

At a microfacies scale (plates 2.6-2.7) the proportions of micrite to sparite to carbonate grains is approximately 50 (down to 0) /10-20 (up to 45-50) / 40%, but marked variations are present. The matrix is peloidal and exhibits both dense peloidal rinds and well developed laminations, commonly graded, with individual laminae about 0.3 - 0.5 mm thick. These lamellae are both planar and domal in form and are defined by variations in the size and packing density of the peloids, the amount of bioclastic material within the laminae and the amount of sparite present within the lamellae (plate 2.7-figs 1-2). These laminated peloidal fabrics are identical with those described from a variety of reefal settings both ancient (Sun and Wright, 1989 and references therein; Fürsich *et al.*, 1994) and Recent (Macintyre, 1985 and references therein) and conform to the "fine-grained, well laminated agglutinated stromatolites" of Riding (1991). Peloidal rinds can grade into laminated crusts. In the Quatre Pieux reef these peloidal rinds and laminations are an important and characteristic feature of the intra-reef sediment. Peloids dominate over fine detrital material which constitute less than 30% of the matrix. The peloids show a considerable range in size reaching a maximum of 0.3 mm across. They are poorly sorted, angular to sub-rounded, with little distortion by compaction. There is a complete gradation in size and form of peloids. Small-scale internal discontinuity surfaces over which subsequent peloidal structures can develop are clearly visible. Large peloids (intraclasts) floating in sparite are common and there is equivocal evidence of syn-sedimentary fragmentation of sparite cement. These features suggest syn-sedimentary cementation.

The bioclastic material is coarse grained (1 cm-1 mm, down to 0.5 mm), angular and very poorly sorted. The bioclasts exhibit no micritization which is another important and characteristic feature of the microfacies. Crust formation on the bioclasts is poorly developed. Bioclastic composition is essentially of coral material (80%), but serpulid, foram, chaetetid, bryozoan, echinoid and bivalve material, though rare, is also present. Forams can be locally very common. Coarse (0.4 mm) angular peloidal intraclasts are abundant. Local patches of intrasparite (intraclastic grainstone) occur, where over 70% of the carbonate grains are intraclasts floating in sparite (peloidal matrix less than 1%) (plate 2.7-fig 3). The lithoclasts are angular to subrounded, moderately sorted and coarse grained (0.5-1 mm). This intrasparitic microfacies is common in the more open areas of the reef framework. No clear preferred orientation or compaction features have been observed. In the upper part of the reef framework local bird's eye textures can be observed.

A slightly different microfacies occurs within and around the branches of the phaceloid colonies. Here local baffling resulted in a markedly lower energy microenvironment increasing the local sedimentation rate and consequently producing a distinctly muddier microfacies. Here the microfacies has a higher proportion of fine detrital material within the matrix with a corresponding decrease in the sparitic component. Laminated peloidal crusts, so abundant in the general intra-reef sediment, are completely absent, however crust development on the in situ coral branches is common.

2.3.3. Palaeoecology

Associated fauna

Field observations indicate that the associated fauna is extremely poorly developed. The main evidence of the associated fauna comes from thin section work. Serpulids, chaetetids, bryozoans, echinoids, gastropods, calcified cyanobacterial crusts and bivalve material can be recognised. Forams are relatively abundant and include boring and encrusting forms. Boring organisms include boring forams such as *Bullopora* (plate 2.8-fig 1-2), small boring sponges and annelids. *Berenicid*-type bryozoans are found encrusting in-situ phaceloid branches (plate 2.8-fig 3). Boring bivalves such as *Lithophaga* and *Gastrochaenea* are conspicuously uncommon. The over-riding feature of the associated fauna is that it is very species-poor and abundances are exceedingly low.

Coral fauna (plates 2.8 - 2.10)

The coral fauna is dominated by massive forms although branching phaceloid forms are also abundant. Branching ramose forms are notably absent. The phaceloid branching and solitary forms includes *Calamophylliopsis*, *Mitrodendron*, *Dermosmilia*, *Donacosmilia*, *Thecosmilia*, *Montlivaltia*, *Epistreptophyllium* and *Pleurophyllia*. Out of 50 randomly chosen branching phaceloid coral fragments: *Calamophylliopsis* (10%), *Mitrodendron* (8%), *Dermosmilia* (5%), *Donacosmilia* (3%), *Thecosmilia* (3%), other phaceloids (6%). (In brackets is the percentage of each genus as a proportion of the total coral skeletal biovolume as suggested by the sample). These branching phaceloid colonies form thickets generally greater than 0.4 m in height and occasionally reach 1.6 m high. The branch thickness of these colonies is around 1-2 cm. All the phaceloid colonies generally have high branch density per colony with the development of tight parallel branched coral thickets. However, *Mitrodendron* (which is especially characteristic of this assemblage) has a much more variable branch thickness ranging from 0.8 to 3 cm, and the branch density per colony is slightly lower than other phaceloids in the assemblage (plate 2.9-figs 1-2; plate 2.10-fig 1).

The massive forms include *Stylina, Cyathophora, Pseudocoenia, Solenocoenia, Heliocoenia, Meandrophyllia* and *Isastraea*. Out of 50 randomly chosen massive coral fragments: *Meandrophyllia* (28%), *Pseudocoenia* (15%); *Microsolena* (10%); other and unidentified specimens (12%). (In brackets is the percentage each genera as a proportion of the total coral skeletal biovolume as suggested by the sample). These massive framebuilders occur as large 30 by 30 cm coral heads. Encrusting corals although volumetrically insignificant can be abundant in the exposed parts of the reef and include forms of *Microsolena* and *Stylina*. These coral crusts are 3-4 mm, rarely up to 1 cm, thick, and up to 10 cm across (plate 2.10-fig 2).

With 21 genera identified, the reef has a high richness. An interesting and characteristic feature of the coral assemblage is the relative abundance of amphiastrids (such as *Mitrodendron, Donacosmilia* and *Pleurophyllia*) which make-up over 11% of total coral skeletal biovolume. Although amphiastrids cannot be said to dominate the assemblage their occurrence is notable since this group of corals is usually absent or extremely rare in other contemporaneous coral reef faunas (such as Lorraine, Swiss Jura and England). *Meandrophyllia* is the most common genus in the assemblage with at least 3 species identified (*M. amendei, M. enwardsi and M.* sp.). Dominance patterns are moderate with no one genus clearly dominating the fauna. This fauna appears to be very similar to the external reef zone of the Slovenian reef complex (Turnšek *et al.*, 1981); the significance of this is discussed later.

Quatre Pieux coral fauna:

Phaceloid branching (35%)	**Massive (65%)**	**Lamellar/encrusting (Insignificant)**
Calamophylliopsis	*Meandrophyllia*	*Stylina*
Mitrodendron	*Pseudocoenia*	*Microsolena*
Dermosmilia	*Microsolena*	
Donacosmilia	*Isastraea*	**Solitary**
Thecosmilia	*Comoseris*	**(Insignificant)**
Stylosmilia	*Heliocoenia*	*Epistreptophyllum*
Pleurophyllia	*Synastraea*	*Montlivaltia*
	Stylina	
	Solenocoenia	
	Cyathophora	
	Pachygyra	
	(large tabular sp.)	

2.3.4. Depositional environment

The position of the reef in the shallowing-upward sequence and its association with beach and other inter-tidal deposits indicates a particularly shallow-water depth for reef formation. The presence of local bird's eye textures in the upper parts of the reef suggest that the reef itself may have undergone episodic emergence. Therefore it is likely to have developed in relatively shallow water, probably around the upper sub-tidal zone. This together with the exposed, reef front, position of the reef would suggest that energy levels would have been relatively high. The abiotic effects of this high energy on the reef were to: 1) actively pump water through the framework increasing cementation rates and hence producing rapid, early cementation and the development of sparite-dominated textures. This process was of utmost importance since it increased the rigidity of the reef structure; 2) produce reef debris and bioclastic material; and 3) prevent the deposition of lime mud hence producing clean intra-reef sediments. Bioclastic sedimentation rates within the reef do not appear to have been high as indicated by the relatively small proportion of bioclastic material present in the intra-reef sediment. Moreover the immature nature of the bioclasts (angular, lack of well developed spongiostromate coatings and lack of micritization) suggests that the bioclastic material that was produced was rapidly incorporated into the reef framework. This low intra-reef sedimentation rate allowed the development of laminated peloidal textures. The presence of a well developed fore-reef slope facies just to the north of this reef, south of Mailly-la-Ville (Mégnien *et al.*, 1970; Menot, 1991, 1980) indicates that there were effective transport mechanisms removing debris and bioclastic material away from this reef complex. The platform edge thus conforms to a "by-pass" type margin (Schlager and Ginsburg, 1981). Large amounts of microbially mediated peloidal cements rapidly precipitated around the reef framework. This gave the reef structural rigidity in this high energy environment. In short, a well lit, high energy reef front environment where the sediments produced were rapidly incorporated into the reef framework or effectively transported away.

2.4: BOIS DU PARC

2.4.1. Introduction

This is a disused quarry which is now a national natural park. The quarry is about 100 m by 50 m by 40 m (plate 2.11-fig 1). Only the reef facies is exposed and the top and bottom of the reef unit are not visible.

2.4.2. Reef structure and facies

Reef structure and framework development

From the dimensions of the quarry, framework development appears to be very extensive. The geometry and form of the reef are unattainable from outcrop. The reef fabric is massive with no visible internal architecture (plate 2.11-fig 1). The framework is constructed mainly by in-situ branching ramose and branching phaceloid forms, though massive colonies also contribute. The total coral skeletal biovolume is variable but generally high (30-65%).

Facies and sedimentology

Intra-reef sediments range from coarse grained grainstones through to wackestones and mudstones with very rapid variations between the two which can be both gradational and erosive. In outcrop the intra-reef sediment is characteristically hard, dense and creamy coloured, suggesting a high microbial content of the facies. Geopetal fills in the dense micrite are common and are a result of: (1) boring bivalves boring directly into micrite; and (2) early dissolution of coral branches within the micrite (plate 2.11-figs 2-3). Both processes imply extremely early cementation of micrite and relatively low sedimentation rates. Storm shell beds are present.

Two microfacies can be recognised: (1) microbial biopelmicrites and biopelsparites; and (2) detrital pelmicrites. The microbial biopelmicrites and biopelsparites dominate the intra-reef sediments (plates 2.12-2.13) with the detrital pelmicrites only occurring as local patches. The biopelmicrite-biopelsparite is characterised by coarse angular and unsorted bioclastic material (50-60%) set in a pelmicritic matrix (30-50%) with varying amounts of sparite (10-20%). The bioclastic material is essentially monomictic, being almost totally composed of coral fragments (>95%), with bivalve fragments being the only other significant constituent (5%). However echinoids, bryozoans, serpulids, calcified cyanobacterial crusts and foram fragments are also present. A very characteristic feature of the bioclasts is that they lack micrite envelopes. Spongiostromate coatings are present on bioclasts; however they are generally poorly developed and thin (<0.2 mm thick). The bioclastic material is highly unsorted with fragments ranging in size from greater than 2 cm to less than 0.2 mm, and predominately of angular shape. The immature nature of the bioclasts (angular, unsorted, poorly developed crusts and lack of micritization) suggest that the bioclasts have undergone little reworking and were rapidly incorporated into the reef framework. No grain orientation is evident.

The pelmicritic matrix shows well developed laminated fabrics on a sub-mm scale with only small patches of homogeneous matrix (plate 2.12). These laminated fabrics can be up to 3 cm thick and are identical to those described from the Quatre Pieux reef. The development of these fabrics was often terminated by sudden influxes of bioclastic material. Several generations of crust formation can be distinguished. The matrix is clearly peloidal, often with free peloids "floating" in cements. There is no evidence of compaction with peloids retaining their original spherical shape, providing further evidence for the very early cementation of the intra-reef sediment. The peloids are spherical and well sorted (150-200 µm to 500-600 µm, average 200-350 µm), especially in small pockets and borings. The large peloids (1 mm) represent intraclastic material. Calcified cyanobacterial crusts can be common in the microfabric (plate 2.13). Small patches of bioclastic wackestone to mudstones (detrital pelmicrites) occur in the more sheltered areas of the framework such as the area in and around large branching thickets. Bioclasts, although less abundant (10%), can be highly micritized. The micritic matrix is more homogeneous suggesting greater compaction and laminated crusts are no longer present. The matrix is composed mainly of fine detrital material and microbial micrite is generally less evident. Forams are very common. At the top of the section local isopachous cements are present (Menot, 1991).

2.4.3. Palaeoecology

Associated fauna

The associated fauna is very poorly developed, with few species and low abundances. However forams, algae (plate 2.11-fig 4) and calcified cyanobacterial crusts can be relatively abundant. The calcified cyanobacteria have been identified as *Bacinella*, *Thaumatoporella*, *Lithocodium* and *Cayeuxia* (group: Hedstroemia; see Riding, 1991; plate 2.13). Also present, though rare, are echinoids, chaetitids, terebratulids, rhynchonellids, gastropods, pectinids, sponge spicules, serpulids and bryozoans. Bioeroders such as *Gastrochaenea* and *Lithophaga* show moderate activity often boring directly into the microbialite. Forams include textularinids, valvulinids, verneuillids, conicospirillinids, placopsilinids, miliolids, *Haplophragmium* and rare lenticulinids (Menot, 1991).

Coral assemblage (plates 2.14-2.17).

21 genera have been identified. 4 genera occur both as massive and branching ramose forms (*Meandrophyllia, Microsolena, Pseudocoenia* and *Thamnasteria*). The coral assemblage is dominated by branching phaceloid and ramose forms which make-up 60% of the coral skeletal biovolume. The branching phaceloid forms are generally smaller than the branching ramose forms, with colonies rarely exceeding 1.3 m in height and branch thickness is generally low (around 1 cm). The common genera are *Dermoseris* (very abundant; plate 2.14), *Calamophylliopsis* (abundant; plate 2.15), and *Stylosmilia* (present). *Thecosmilia*, *Dermosmilia* and *Cheilosmilia* also occur but are very rare and often only as fragments. The epithecal banding of *Dermoseris* indicates a growth rate of 7-9 mm/yr. The common

branching ramose forms are *Pseudocoenia* (*Pseudocoenia limbata*), *Latiastraea* and *Meandrophyllia*. These branching ramose colonies form dense thickets 0.4-1 m high and 1 m across but can reach 2-3 m high and 4 m across. The colonies have thick (2-3 cm in diameter), straight and parallel branches (plate 2.16).

Massive forms include tabular forms (10 by 30 cm), platy forms (2-3 by 20 cm), small dome-shaped forms (10 by 10 cm), and occasional very large forms (70 by 30-40 cm) (plate 2.17-fig 3). Of the massive forms *Meandrophyllia*, *Isastraea*, *Stylina*, *Cyathophora*, *Pseudocoenia* are common. Many of these have undulating, knobbly, top surfaces. Indeed there is a complete gradation from massive forms with undulating surfaces to forms with protruding knobs, to sub-ramose forms and finally to branched ramose forms (plate 2.17-figs 1-2). Many of the small massive forms with knobbly surface may represent the initial stages of ecomorphogenesis whilst the fully branching ramose forms are the end product of this process. However, at present this can only be speculated. The bases of these branching ramose colonies are platy-massive and between branches are occasional bridging plates.

Branching ramose	**Branching phaceloid**	**Massive**
(40%)	(20%)	(40%)
Latiastraea (a)	*Dermoseris* (a)	*Cyathophora* (a)
Meandrophyllia (a)	*Calamophylliopsis*	*Isastraea* (a)
Pseudocoenia (a)	*Stylosmilia*	*Meandrophyllia* (a)
Microsolena	*Cladophyllia*	*Pseudocoenia* (a)
Thamnasteria	*Donacosmilia*	*Stylina* (a)
Dendraraea	*Rhabdophyllia*	*Comoseris*
	Thecosmilia	*Meandaraea*
Solitary		*Microphyllia*
(insignificant)		*Microsolena*
Cheilosmilia		*Thamnasteria*
Haplarea		

[a: abundant]

2.4.4. Depositional environment

Energy levels of the Bois du Parc reef were likely to have been lower than those of Quatre Pieux as a consequence of its more landward, back-reef, position. The presence of virtually intact colonies of fragile forms such as *Cladophyllia* and *Calamophylliopsis* (indeed all branching forms) provide evidence a calmer water environment. Nevertheless water depth remained very shallow as indicated by isopachous cements at the top of the outcrop, suggesting an infratidal-intertidal regime (Menot, 1991). Sedimentation rates were low and large amounts of bioclastic material were not produced. Bioclastic material that is present is likely to have been of either storm or bioerosional origin. Large volumes of microbial micrite rapidly developed within the reef framework and underwent extremely early cementation. In summary there can be inferred a well lit, calm back-reef setting where sedimentation rates were low, but where rapid lithification prevented extensive grain working and micrite envelope development.

2.5: SAUSSOIS

2.5.1. Introduction

This section comprises a series of large cliffs outcropping on the northern bank of the Yonne (plate 2.18-fig 1). Although there is an extensive area of exposure the outcrop is highly weathered, making field observations extremely difficult.

2.5.2. Reef structure and facies

Reef structure and framework development

The reef development here is extensive, with the reef attaining a thickness of at least 50 m and a lateral of extent of at least 400 m. The form of the reef cannot be established from outcrop. Framework construction, although very poor, is mainly by massive colonies, with branching forms being of secondary importance. Taking the whole reefal unit into account the coral skeletal biovolume is very low (less than 20%). The reefal unit exhibits a well developed internal structure as revealed by differential weathering of limestone (plate 2.18-figs 2-3). This internal architecture is in the form of planar bands 3-8 m thick of alternating degrees of framework construction. The resistant bands have formed where framework construction is better developed, resulting from higher coral skeletal biovolumes. The less competent bands generally have lower coral skeletal biovolumes and may simply represent bioclastic piles with little in-situ framework. The boundaries between the two bands are extremely gradational giving the outcrop a rather "corrugated" structure. The top of the section is capped by a 7 m thick band where there is a significant increase in massive domal forms.

Facies and sedimentology

At outcrop the intra-reef sediment appears as a coarse grained chalky bioclastic packstone, occasionally wackestone. Storm channels with large well rounded coral colonies are present. At a microfacies scale carbonate grains make up 30 to 50% of the section with the matrix being composed of sparite and micrite in approximately equal proportions. Texturally the microfacies varies between packed biomicrite through to poorly washed biosparites and biosparites (plate 2.19). The carbonate grains include both bioclastic (20%) and lithoclastic material (30%). The bioclastic material is *not* dominated by coral fragments, but is present in approximate equal proportions to other bioclastic material such as bivalves (20%), echinoderms (20%) and other organisms (forams, gastropods, brachiopods, calcified cyanobacteria etc. (20%)). The general grain-size is coarse (1-3 mm, average: 1.5 mm) with sub - well rounded grains predominating. Grain sphericity is generally low with many of the grains, such as the coated bivalve fragments, being barrel shaped and showing a preferred orientation parallel to the depositional surface. Spongiostromate coatings around the carbonate grains are common but not particularly well developed (crusts on grains rarely exceed 0.5 mm in thickness).

Micritization of carbonate grains is common. Peloidal packstone and wackestone intraclasts are very abundant. The carbonate grains are generally texturally mature.

The matrix is composed of micrite (30%) and sparite (20%), though generally separated into areas where the matrix is mostly micrite or sparite. The micritic matrix where protected is clearly peloidal, otherwise generally homogeneous with a slightly microclotted texture. Peloidal rinds, lamellae and intergranular crusts seem to be absent. Micrite/sparite ratios tend to be lower within the top band.

2.5.3. Palaeoecology

Associated fauna

The associated fauna is poor to moderately well developed. Terebratulid brachiopods such as *Galliennithyris* and *Juralina*, are particularly common. *Trichites* and *Nerinea* are common in local zones. Also present are bivalves (especially abundant are forms with a foliaceous microstructure and pectinids) and echinoids. The associated fauna tends to be better developed in the bioclastic rich zones, i.e. areas with poor framework development; this is especially so for the trichitid bivalves and nerineid gastropods. The bioeroders are represented by *Lithophaga* although they are not abundant.

Coral assemblage

Due to poor outcrop quality detailed analysis of the coral assemblage was not possible. 20 genera have been identified. The most common growths are massive domal forms 30 by 20 cm, (occasionally up to 60 cm across) though small heads 10cm across and 1- 3 cm thick plates are also abundant. Branching forms can reach 1-1.5 m high. One colony of the branching ramose *Dendraraea* is seen to initially have grown vertically to a hight of 1.1 m, with the branches subsequently gradually spread out horizontally; eventually the branches grew parallel to bedding for over 3 m. At the top of the section there is a significant increase in the proportion of domal stylinids (*Pseudocoenia* and *Stylina*). The coral fauna is as follows:

Branching ramose (?15%)
Pseudocoenia limbata
Thamnasteria dendroidea
Dendraraea

Branching phaceloid ?25%)
Stylosmilia
Thecosmilia
Aplosmilia
Calamophlliopsis
Dermoseris

Massive (?60%)
Meandaraea
Stylina
Dimorpharaea
Comoseris
Microsolena
Thamnasteria
Clausatraea
Pseudocoenia
Diplocoenia
Meandrophyllia
Ovalastraea
Isastraea
Actinaraea

Solitary
(insignificant)
Montlivaltia

2.5.4. Depositional environment

The evidence of frequent storm beds and the lack of evidence for current or wave reworking suggests that these reefal units were deposited somewhere between storm- and normal wave-base. The top of the section with its slightly higher energy facies (coarser grains, cleaner sediments, lower micrite/sparite ratios) suggests proximity to normal wave-base. The large volumes of bioclastic material and low coral skeletal biovolumes suggests high sediment production. However the mature nature of the allochems suggest that they were not rapidly incorporated into the reef framework but were subject to micritization and spongiostromate crust development, hence not constantly agitated by water movement. This, together with the lack of sediment export mechanisms, produced large bioclastic piles which occasionally led to local burial of reef framework. There is also the possibility that sediment has been imported into the depositional environment from the reef front and proximal back-reef areas.

2.6: ROCHE AUX POULETS

2.6.1. Introduction

To the west of Merry-sur-Yonne, a small dry valley cuts deeply into the back-reef formation of the upper reef complex revealing a number of cliffs 45 m high. However, although outcrop is extensive, it is of poor quality and highly weathered, making study difficult. The lower part of the reefal units exposed correspond to the upper part of the Saussois exposures (Menot, 1991). The sequence shallows upwards from reefal units at its base to lagoonal and beach facies at the top of the sequence (Terminal units). Hence the outcrop can be regarded as the upper part of a composite section through a distal back-reef aggradational succession (figure 2.7) (also see section 2.7).

The sequence begins with a 2 m thick debris bed deposited in two channels. The debris in the lower channel is rich in diceratids, nerineids and brachiopods. The sediment is a gravelly oncoidal packstone and grainstone. The bioclastic material consists of bivalves, gastropods, echinoids and brachiopods and possesses well developed spongiostromate coatings; coral debris is rare. The second channel is dominantly coral debris and molluscan material is less evident. These channel units represent material deposited from a shallow water (above normal wave base) environment. Above these channel deposits is the main body of the reef (24 m thick) which is discussed below. This is overlain by a thick (20 m) succession of sub- to inter-tidal lagoonal deposits. These are fine grained pelbiosparites with well developed laminated bird's eye structures. Diceratids are locally abundant. The section is capped by a 2 m beach facies with well rounded and polished pebbles of corals, and bioclasts of *Diceras* and *Nerinea*. These lagoonal and beach deposits form the Terminal unit of the reef sequence.

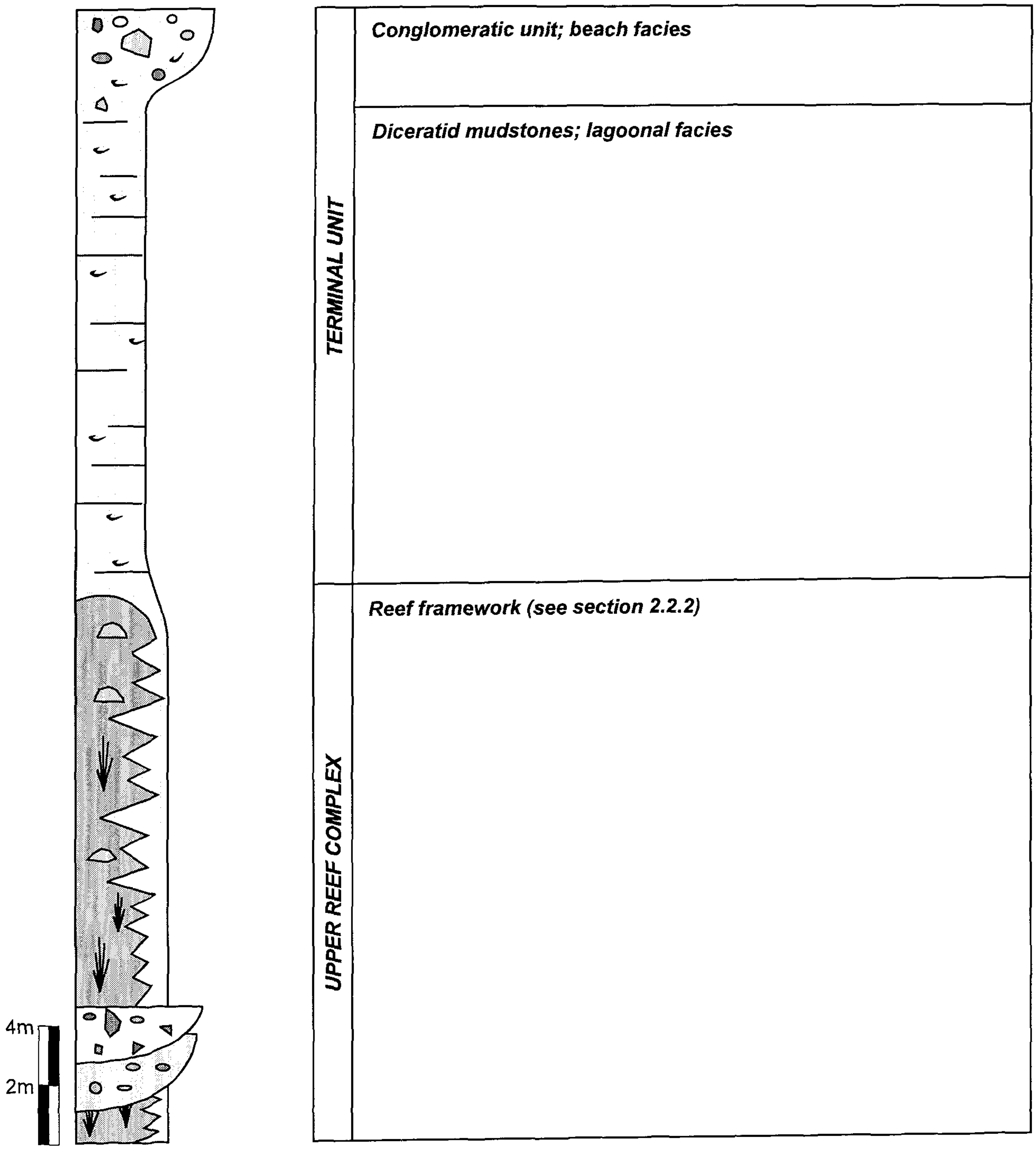


Figure 2.7: Schematic field log of the Roche aux Poulets section. (See section 2.2.1 for details).

2.6.2. Reef structure and facies

Reef structure and framework development

The reefal facies is organised in series of coral banks and bioherms with a total thickness of approximately 24 m. The form of individual build-ups varied from small domal forms (18 m across, 4-6 m thick) to more tabular forms (over a hundred metres across and 18m thick). The total lateral extent of the reefal facies is at least 160 m. Individual build-ups are separated by framework-poor bioclastic piles. The reefal facies lacks internal organisation, though in some areas a "corrugated" structure, identical to that present at Saussois, can be seen (plate 2.20-fig 1). Framework construction is poorly developed with very low coral skeletal biovolume, generally less than 30%. The main framebuilders are massive corals. There is no evidence of framework binding by algae or microbialite. Clear erosive surfaces truncating branching phaceloid thickets are present near the base of the outcrop (plate 2.20-fig 2).

Facies and sedimentology

The intra-reef sediments are essentially bioclastic wackestones and packstones. At microfacies scale the sediments are biomicrites with M/S/C: 50-60/5/35-45. The carbonate grains include both bioclastic material (90%) and intraclastic material (10%). The bioclastic material is not dominated by coral fragments which constitute approximately 50%, but echinoid (30%) and bivalve (10%) material is relatively common; the remaining 10% consists mainly of brachiopods, serpulids, algae and chaetetids. Sponge spicules are numerically abundant. The grain size is generally fine (0.5-0.1 mm) though larger (3-4 mm) fragments are also present. The carbonate grains appear to be immature being poorly sorted, angular, lacking well developed spongiostromate crusts and are not highly micritized. Large articulated bivalve and brachiopod valves are present. The matrix is composed of fine bioclastics, intraclastics and peloidal micrite. Peloidal rinds and lamellae are absent.

2.6.3. Palaeoecology

Associated fauna

Although the associated fauna is generally poorly developed there is a wide variety of taxa present. In particular brachiopods are quite common and are represented by terebratulids (*Juralina bauhini*, *J. rauraca* and *J. cotteaui*). Red algae such as *Solenopora jurassica* are present. Spherical chaetitids heads up to 10-15 cm diameter are notably relatively abundant. Also present, though not abundant, are cidaroid echinoids, serpulids, trichitid bivalves, other unidentifiable bivalve material and foraminifera (textularids, miliolids, and lituolids). Diceratids and nerineids are practically absent, except where they have been brought into the reef complex within debris beds. Bioerosional activity is not conspicuous.

Coral assemblage

The community structure of the coral fauna is difficult to assess due to the poor quality of the outcrop. However massive colonies seem to predominate in the main body of the reef and include hemispheroids about 30 cm in diameter, thick plates 10-15 cm thick, and small heads about 10 cm in diameter. Branching phaceloids are only common at the base of the section and form dense thickets up to 1.7 m high and 3 m across. Taxonomically this reefal unit seems quite rich with *Microsolena*, *Stylina*, *Isastraea* and *Pseudocoenia* being particularly abundant. The coral fauna is as follows:

Phaceloid branching	**Solitary**	**Massive**	
Calamophylliopsis	*Montlivalitia*	*Thamnasteria*	*Stephanastraea*
Stylosmilia		*Microsolena* (c)	*Dimorphastarea*
Thecosmilia (c)	**Branching ramose**	*Stylina* (c)	*Meandraraea*
Aplosmilia	*Pseudocoenia*	*Isastraea* (c)	*Meandrophyllia*
Enallhelia		*Comoseris*	*Ovalastraea*
Dermoseris		*Pseudocoenia* (c)	Unidentified sp.
		Pseudocoeniopsis	Unidentified sp.
[c: common]			Unidentified sp.

2.6.4. Depositional environment

The position of the reef in the shallowing upward sequence and its association with inter-tidal pelmicrite deposits indicates a particularly shallow-water depth for reef formation. The reef is likely to have developed in shallow water probably around the upper sub-tidal zone. Energy levels are likely to have been relatively low due to the landward, back-reef, position of these reefs which is reflected by the fine grained biomicritic microfacies of the intra-reef sediments.

2.7: Evolution of the Burgundy carbonate platform

The necessity to re-evaluate the evolution of the Burgundy carbonate platform stems from the problematic sections at Quatre Pieux and Rochers aux Poulets. These sections show a conformable sequence from reefal limestone through to lagoonal fenestrate pelmicrites (diceratid mudstones) and finally beach conglomerates (see figures 2.6 and 2.7). This sequence has previously been interpreted as an aggradational sequence from a upper sub-tidal zone (reef facies) to sea level (beach facies) (Menot, 1991).

The first problem arises since the Quatre Pieux reef has been interpreted as a platform edge, shallow water, high energy reef (Mégnien *et al.*, 1970; Menot & Rat, 1967; Menot, 1991, 1980, 1974; also see section 2.3). Thus if the reef simply aggrades it should be overlain *directly* by high energy beach facies, which is not the case. Moreover the fenestrate pelmicrites and the beach facies are likely to have been deposited in similar water depths within the upper sub-tidal to inter-tidal zone, though in different energy regimes. Thus aggradation from inter-tidal zone fenestrate pelmicrites would not in itself produce a beach facies.

The second problem with Menot's (1991, 1980, 1974) interpretation is that he suggests that the facies sequence of the two sections are time equivalents and assumes that all the beach and lagoonal facies across the platform were deposited contemporaneously (see Menot, 1980, figure 2). This is unreasonable because: a) the two sections are approximately 2 km apart and the beach facies is unlikely to have been so extensive; and b) the lagoonal units in the two sections have a significantly different thickness (see figures 2.6 and 2.7) and hence must represent different lengths of time. (This assumes similar sedimentation rates at the two sections for which there is no evidence to the contrary.)

The following re-interpretation of the platform sequence presents a more satisfactory scenario that solves the two problems outlined above.

Re-interpretation of sequence (figure 2.8):

S-L 1: The platform sequence was deposited above the Middle Oxfordian regional unconformity (sequence boundary) within a trangressive system tract. Initially rapid sea-level rise resulted in the deposition of deep water ammonite- and sponge-bearing mudstones above the drowned Callovian substrate (Calcaires à Chailles noduleuses et à glauconie; pre-reefal mudstones) (also see figures 2.13 and 2.14). As these aggraded the first coral-bearing reefal unit developed over the expanse of the platform. This is the lower reefal complex represented by the microsolenid biostrome of the Châtel-Censoir section.

S-L 2: As the platform aggraded into shallower water platform interior packstones were deposited (somewhere between storm wave base and normal wave base) and the upper reef complex began to develop. This is represented by the reef at Saussois and the similar reefal unit above the microsolenid biostrome at the Châtel-Censoir section. At this stage there is no evidence for platform interior restriction and an open platform is envisaged. The contemporaneous platform edge sequence is not seen but since there is no evidence of platform interior restriction a well developed outer reef complex is unlikely to have been present at this time.

S-L 3: As aggradation continued the platform edge sequence aggraded to shallower water and developed a high energy outer reef unit (the Quatre Pieux reef). Contemporaneously in the platform interior the lower energy reefs of Bois du Park (proximal back-reef) and Rochers aux Poulets (distal back-reef) developed.

S-L 4: Platform interior energy levels began to decrease as the outer reef complex developed further towards sea level. This is reflected in the slightly lower energy microfacies of the Rochers aux Poulets when compared with that of the Saussois reef. At the very edge of the platform the reef began to aggrade to sea level and back-reef energies dropped off significantly. Inter-tidal pelmicrites begin to develop in back-reef environments and were deposited on the interior part of the Quatre Pieux reef and in the platform interior. This is documented by the deposition of pelmicrites above the Quatre Pieux and Rochers aux Poulets reefs (lower Terminal unit).

S-L 5: The outer reef rapidly aggraded to sea level and developed a local high energy beach facies (upper Terminal unit), whilst in platform interior settings the pelmicrites continued to be deposited.

S-L 6: The platform edge reef and its associated beach deposits began to back-step into the platform interior (as a consequence of their deposition during a transgressive systems tract) and began to onlap the pelmicrites. This occurred first in a platform edge setting (Quatre Pieux sequence) and progressively later towards the platform interior. This resulted in a thicker lagoonal pelmicrite sequence in more platform interior settings (such as at Rochers aux Poulets). The two vertical lines indicated on this diagram are the Quatre Pieux section (1) and the Rochers aux Poulets section (2).

The beach facies are therefore *diachronous*, and not time equivalents, across the platform. This platformward diachronous deposition of beach deposits allowed deposition of this facies across the platform without requiring an unreasonably extensive beach environment at any one particular time. Hence the beach facies at Quatre Pieux and Rochers aux Poulets, although being lithological equivalents, were not deposited contemporaneously.

Figure 2.8: (Figure on the next page). Conceptual model illustrating the stages in the evolution of the Burgundy carbonate platform. S-L (sea-level) numbers on the figures refer to the text above. The diagram is not to scale.

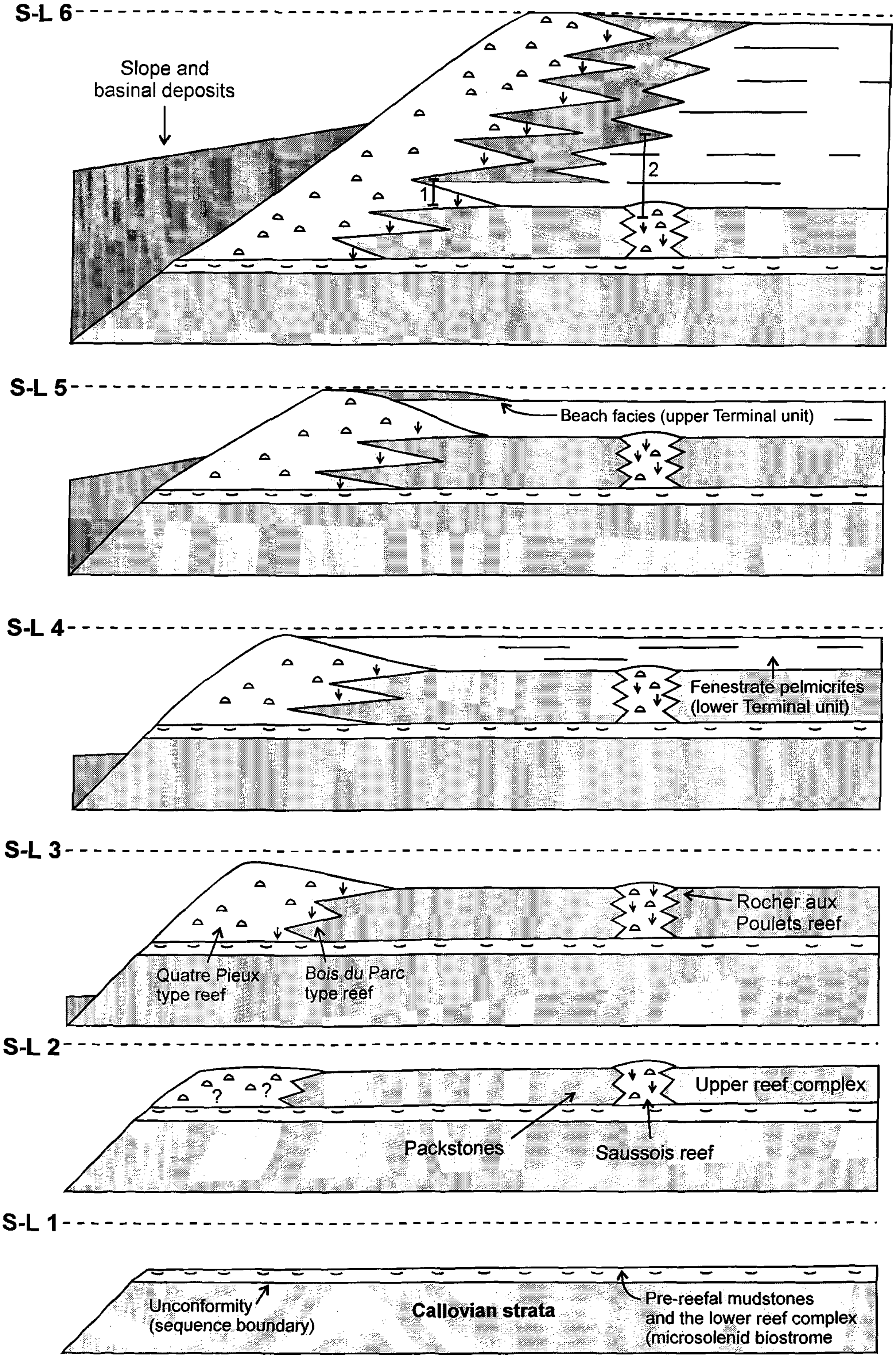


Figure 2.8: See previous page for figure caption.

CHAPTER 3: LORRAINE

3.1: Introduction

The reefs of the Lorraine region represent build-ups which developed in various sub-environments of an extensive carbonate ramp. The reefal outcrops are located in the Department of Landers, south of Verdun (figure 3.1). Previous work on the area has been mainly stratigraphic and sedimentological (Humbert, 1971; Hilly and Haguenauer, 1979; Menot, 1980; Enay and Boullier, 1981). Palaeoecological and taxonomic studies on the coral fauna include the works of Beauvais (1964), Michelin (1840-1843) and Geister and Lathuilière (1991). Poirot (1987) and Vadet (1987) have carried taxonomic studies on the associated fauna of these reefs.

Chrono- and lithostratigraphic framework (after Enay and Mangold, 1980) (figures 3.2 and 3.3): The Jurassic stratigraphy of the north-eastern Paris Basin commences with a thick sequence of ammonite-bearing clays Liassic deposited during trangressive phase. This is overlain by Aalenian iron oolites, deposited in a shallow marine environment. During the Middle Jurassic a widespread carbonate platform developed. This platform, mainly of Bajocian age, was subsequently drowned under a thick sequence of clay deposits. The carbonate platform was re-established during Middle Oxfordian times, where a general shallowing upward trend persisted throughout much of the Middle and Upper Jurassic. The final emergence of the platform came towards the end of the Portlandian.

The Oxfordian in this area begins with the "Argiles de la Woëvre", a clay formation the upper part of which belongs to the Lower Oxfordian *Mariae* Zone. This grades into the "Terrain à Chailles" a series of marl-limestone intercalations. This formation terminates with a hardground formed by a pavement of large oyster valves, or with an iron oolite. The Terrain à Chailles is overlain by the "Formation récifale de Lorraine" which is formed by two successive reefal units.

1. The lower reef complex ("zone construite inférieure" of Humbert (1971); "complex récifale inférieure" of Hilly and Haguenauer (1979); and "Episode récifale inférieure" of Menot (1980)). This is characterised by a dense interlocking framework of platy microsolenid coral and a rich and abundant associated fauna. Its thickness ranges from 5-35 m. At its top it is separated from the upper reef complex by an oncoidal limestone south of Commercy, and a crinoidal limestone ("Pierre d'Euville-Lérouville") to the north.
2. The upper reef complex ("zone construite supérieure" of Humbert (1971); "complex récifale supérieure" of Hilly and Haguenauer (1979); and "Episode récifale supérieure" of Menot (1980)). This contains a suite of different reef types that developed in a number of different reef sub-environments. Its thickness is ranges from 10-20 m. The reefs of this unit are overlain by 40-80 m of pure well bedded micritic mudstones ("Calcaire de Creue").

According to Enay and Boullier (1981), based on a on a study of ammonites and brachiopods, the age of the "Formation récifale de Lorraine" is Middle Oxfordian (top of the *Plicatilis* zone to the base of the *Bifurcatus* Zone).

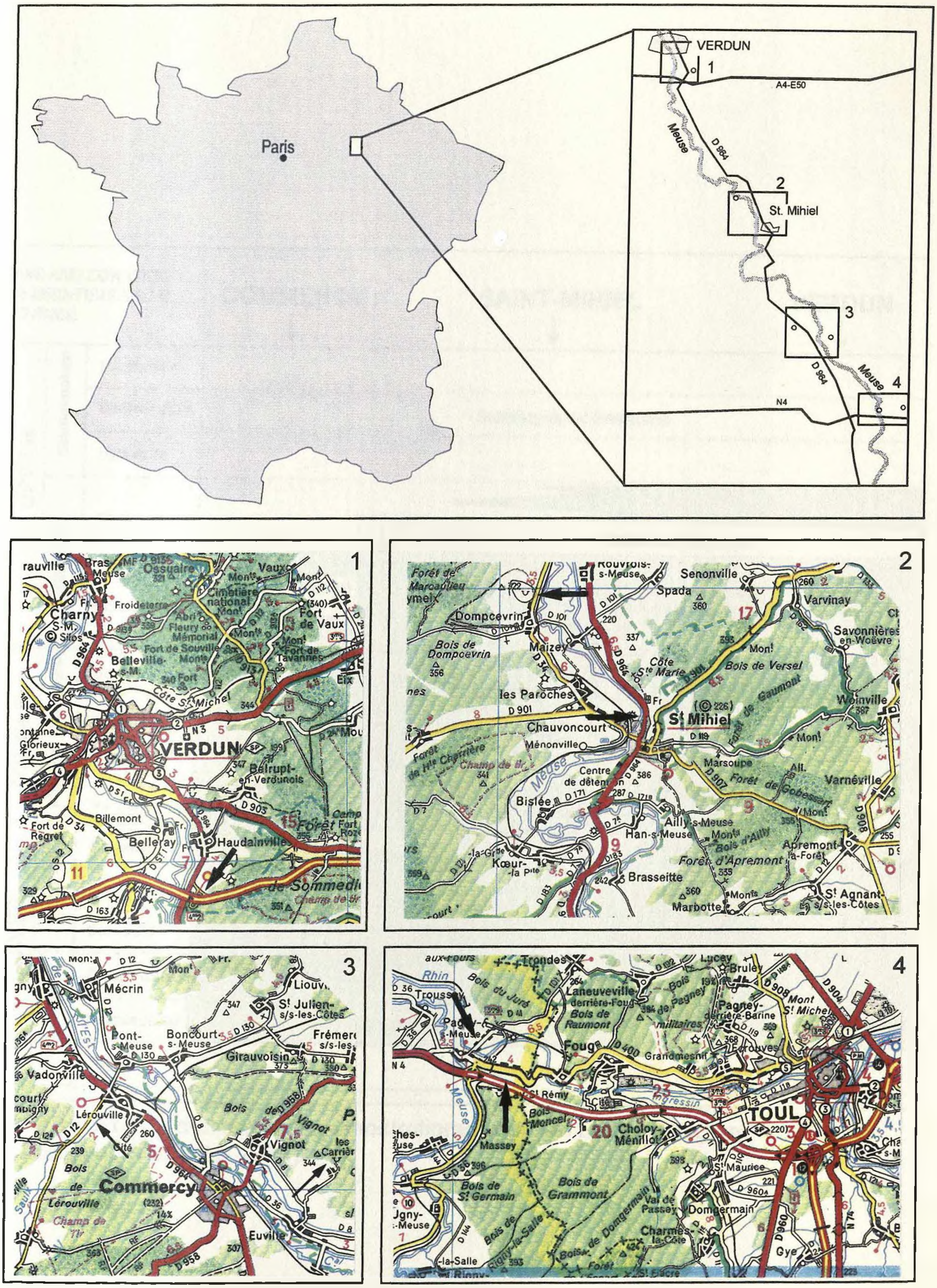


Figure 3.1: Location map of the sections studied in Lorraine. Scale for the detailed road maps is 1:200 000.

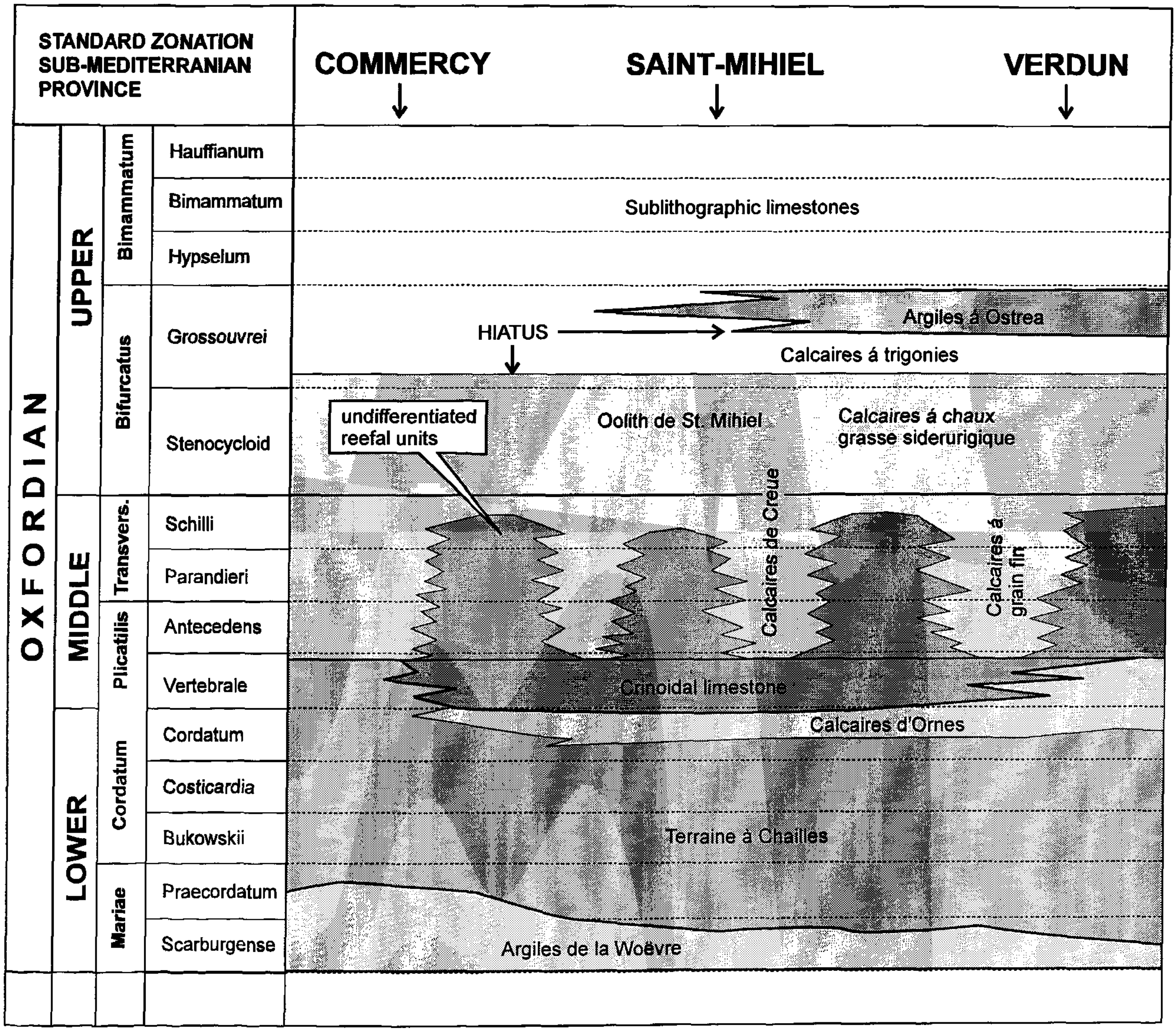


Figure 3.2: Simplified chrono- and lithostratigraphy of the Lorraine region. (After Enay and Mangold, 1980).

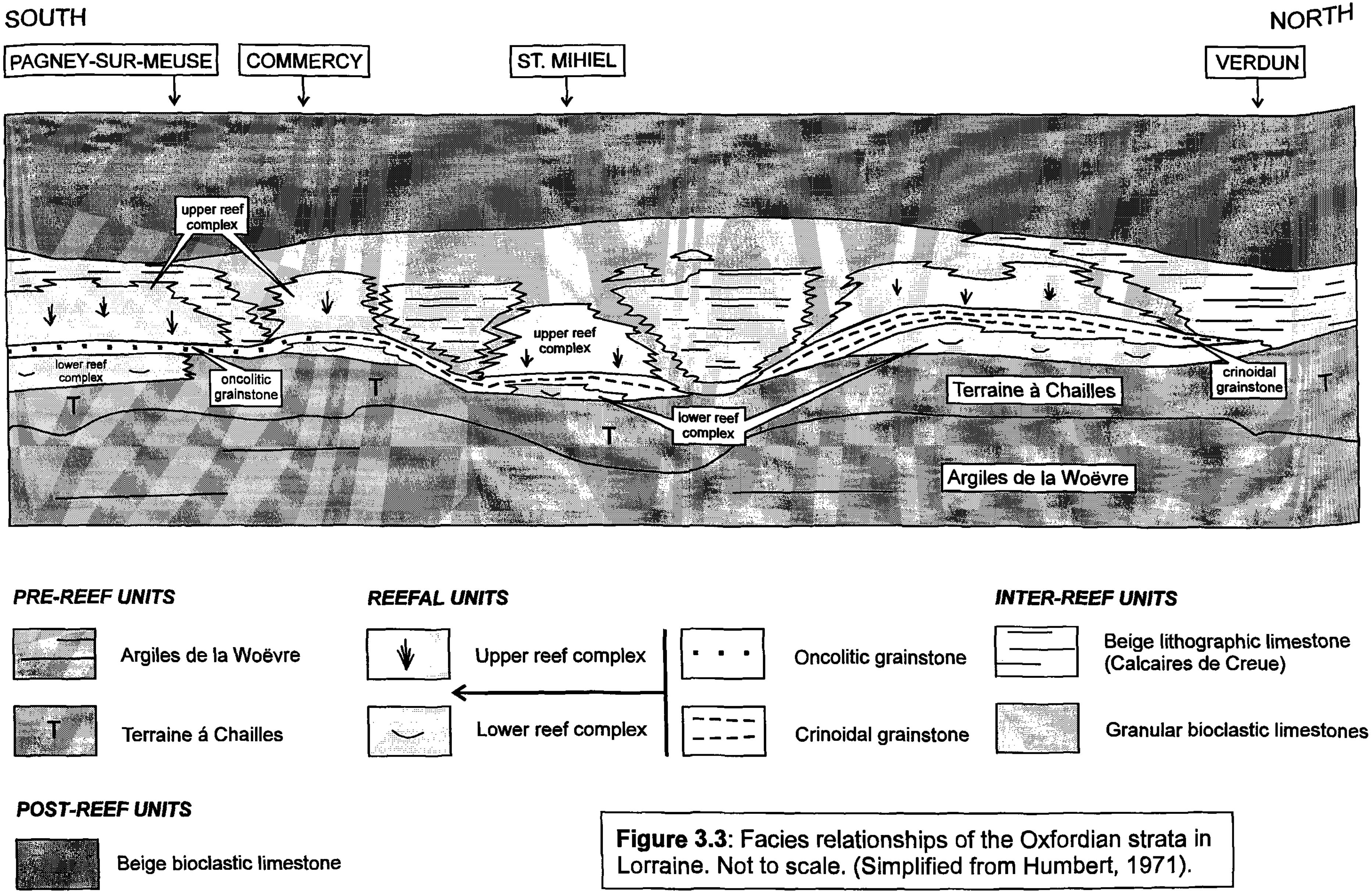


Figure 3.3: Facies relationships of the Oxfordian strata in Lorraine. Not to scale. (Simplified from Humbert, 1971).

3.2: FOUG

3.2.1. Introduction and facies sequence

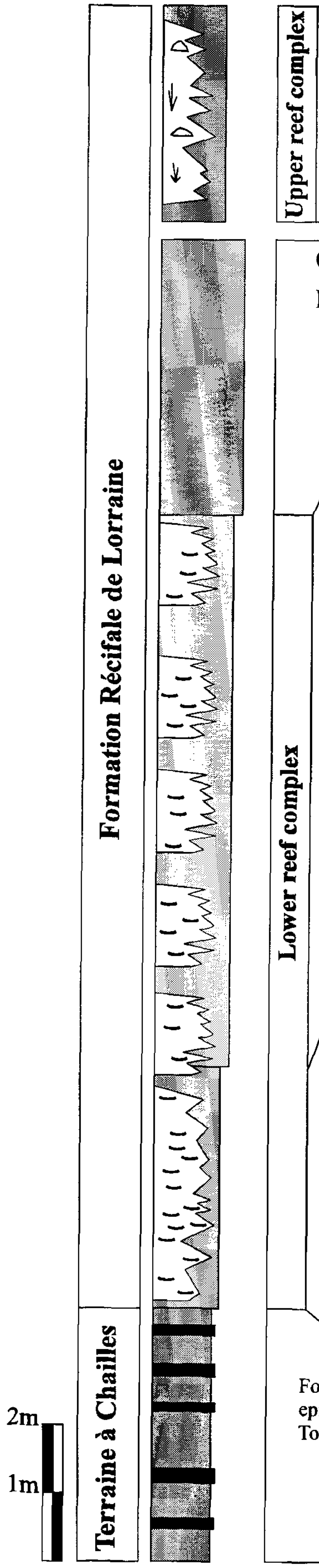
Between the villages of Foug and Pagny-sur-Meuse, the Toul to St. Dizier highway cuts through two low lying hills exposing several hundred meters of the lower reef complex (plate 3.1). The sequence exposed developed during a shallowing-upward succession beginning with deep-water muddy marls (the Terrain à Chailles) and terminates with a shallow-water oncolitic facies (figure 3.4; plate 3.1). The section therefore allows the study of relatively deep-water pioneering and early sucssional stages of Late Jurassic coral reef development, in a similar fashion to the outcrop at Châtel-Censoir in Burgundy. The reef complex established itself on relatively deep-water ammonite-bearing muddy sediments (the Terrain à Chailles) (plate 3.2-fig 1). Two reefal units can be distinguished:

1) a marly biostrome referred to as the "coral marl"; and
2) a more bioclastic rich biostrome referred to as the "coral limestone".

The names of these two reefal units are those used by Geister and Lathuilière (1991). The distinction of the two reefal units is based on both sedimentologcal and palaeoecological grounds.

Facies sequence, from base up (figure 3.4; plate 3.1):

- Terrain à Chailles. The uppermost 8 m of a fossil-rich marl complex with intercalated muddy limestone beds is exposed at the base of the outcrop. The top of the sequence is marked by a well developed hardground formed by a thin and continuous band of 2 to 4 superimposed valves of the oyster *Deltoideum delta* (plate 3.2-fig 1). These valves provided an ideal habitat for a strongly polarised associated fauna (plate 3.3-figs 1-2). The top surfaces are commonly bored by clionid sponges and lithophagan bivalves. The undersides have a diverse assemblage of cryptobionts such as serpulids, thecidean brachiopods, bryozoans, sclerosponges and calcareous sponges. The development of this hardground probably reflects a sudden and significant decrease in sedimentation rates. This drop in sedimentation rates also allowed the subsequent coral reef to develop.
- Coral marl. This was the first reefal unit to develop in the shallowing-upward sequence. Coral growth commenced some 15 to 20 cm above the oyster band. The thickness of this first biostromal unit at this locality is approximately 3.5 m. The coral fauna is dominated by foliaceous and platy pioneering colonies of the microsolenid *Dimorpharaea*.
- Coral limestone. Conformably above the coral marls is a second 8 m thick biostromal unit - the coral limestone. This is distinguished from the coral marl by the marked and sharp decrease in terrigenous material. Although the sedimentological contact is sharp in some areas the framework of the coral marl continues across the boundary into the coral limestone. The base of the coral limestone can be clearly picked out by the overhangs produced by differential weathering of the less resistant coral marls below (plate 3.4-figs 3-4). This decrease in terrigenous material is also responsible in a shift in the composition of the coral fauna. A microsolenid still dominated but in this



Upper reef complex

Wide range of reef types from low diversity coral thickets to high diversity coral patches. Lithofacies range from fine micritic mudstones to bioclastic grainstones. Associated fauna generally poorly developed.

Upper reef complex not exposed at this locality.

Oncolitic Limestone

Poorly sorted packstone to grainstone.

Lower reef complex

Coral limestone: Foug 1

Microsolenid biostrome unit 1.

Poorly sorted bioclastic wackestones and packstones. Occasional thin siliciclastic bands. Total coral skeletal biovolume: 40-50%.

Percentage of coral skeletal biovolume

Genus		Family		Growth-form	
Dimorpharaea	17	Microsolenidea	73	platy - sub-massive	89
Isastraea	4	Other	27	phaceloid	3
Microsolena	52			branching ramose	7
Styliosmilia	1			solitary	1
Comoseris	4				
Meandaraea	1				
Fungiastraea	3				
Actinaraea	5				
Montlivaltia	1				
Thecosmilia	2				
Pseudocoenia	<1				
Dendraraea	7				
Thamnasteria	3				

GENERIC RICHNESS: 13
EVENESS: 0.65
DIVERSITY INDEX [SHANNON-WIENER]: 2.40
[SIMPSON]: 0.69

Coral Marl: Foug 2 - Microsolenid biostrome unit 2

Dimorpharaea	53	Microsolenidea:	67	platy - sub-massive:	91
Isastraea	10	Other:	33	phaceloid:	5
Microsolena	8			branching ramose:	2
Styliosmilia	3			solitary:	2
Comoseris	6				
Fungiastraea	6				
Actinaraea	3				
Montlivaltia	2				
Thamnasteria	5				
Dendraraea	2				
Thecosmilia	2				

GENERIC RICHNESS: 11
EVENESS: 0.71
DIVERSITY INDEX [SHANNON-WIENER]: 2.45
[SIMPSON]: 0.69

Marly wackestone with high siliciclastic component; total coral skeletal biovolume 50 - 80 %.

Fossil rich marls with intercalated muddy limestone bands. A rich and abundant epifaunal bivalve assemblage. Coral virtually absent, occasional *Montlivaltia* present. Top of unit marked by a strong secondary hardground formed by oyster valves.

Figure 3.4: Schematic log of the Foug section.

case it is the genus *Microsolena*. The unit is terminated by a hardground (Geister and Lathuilière, 1991) although this was not accessible.

- Oncolitic limestone. The section is terminated by a 6 m thick unit of clean oncolitic grainstones. The oncoids are fine-grained (up to 2 mm in diameter) and formed by calcified cyanobacteria and nubecularian foraminifera encrusting skeletal fragments. The oncolite has a rich fauna and there is a pavement of large oriented bivalves suggesting significant current action.

3.2.2. Reef structure and facies

Reef structure and framework development

Coral marl. The thickness of this first biostromal unit is approximately 3.5 m and has a lateral extent of at least 250 m. The framework is constructed almost entirely by platy microsolenid colonies, especially *Dimorpharaea*. Coral skeletal biovolumes are exceedingly high, around 60% and locally reaching 80% (plates 3.2-figs 2-3). The coral colonies form a dense interlocking framework within a muddy marly matrix. Framework construction is extremely uniform and continuous. The reefal unit is vaguely bedded on a decimetre scale and has a sheet like, biostromal appearance.

Coral limestone. The coral limestone is distinct from the coral marl in that there is a marked decrease in terrigenous material. The framework construction is again by platy microsolenid corals (though different genera) and is slightly less well developed, with coral skeletal biovolumes around 50% (plate 3.4-fig 3). Framework development is no longer continuous but develops as small build-ups laterally separated by framework-poor, bioclastic zones. These build-ups range in size from small, 1-3 m high, 5 m across mounds to more extensive domal build-ups 6 m high and 4 m across (plate 3.4-figs 1-2; top left of plate 3.1). There is a very gradual transition from reef framework to coral-free inter-reef sediments (plate 3.4-fig 2). The inter-reef sediments are coarse grained, poorly sorted bioclastic wacke- to packstones. They show clear bedding surfaces suggesting that the submarine relief of these reefs was never likely to exceed about 1.5 m.

The main differences between the coral marl and the coral limestone, with regard to reef framework development and facies, are:

- reduced siliciclastics in the coral limestone;
- lower coral skeletal biovolume in the coral limestone; and
- the coral limestone has less continuous framework development.

Facies and sedimentology

Coral marl. In the field the intra-reef sediment has a very muddy, dark grey/brown appearance with a very significant clay component (plate 3.2-fig 2). They are bioclastic packstones with M/S/C ratios of approximately 30/0/70 (biomicrites) (plate 3.5-figs 1-2). The carbonate grains are very angular, poorly sorted with grain sizes ranging from <0.1 - 1 mm (average 0.5 mm). They are essentially all bioclasts with lithoclasts being very rare (<5%). The bioclasts are mainly coral fragments (>80%) with the other main constituents being fragments of echinoids and bivalves. Also present are fragments of serpulids and sponge spicules. There is very little micritization and spongiostromate crusts are generally absent, and only developed on large coral fragments. However spongiostromate crusts can be well developed on the coral plates. No grain orientation is seen. The matrix is homogeneous, lacks laminated fabrics and made up of very fine detrital material and poorly defined peloids. Well defined, uncompacted, precipitated peloidal material is present within the calicular spaces of some of the larger coral fragments. Small (0.05 mm) pyrite fragments are present within the matrix.

Coral limestone. At outcrop the coral limestone is sedimentologically very distinct from the underlying coral marl. It is a white (a result of the marked decrease in siliciclastics), hard and resistant bioclastic packstone. However the microfacies is virtually identical to that of the coral marl, except for the absence of siliciclastics. There is no evidence of storm or wave reworking in either unit.

3.2.3. Palaeoecology

Associated fauna

Coral marl. The associated fauna is generally very well developed, in particular there is a very rich echinoid and bivalve fauna. Bivalves include *Nanogyra, Chlamys, Camptonectes, Ctenostreon, Plagiostoma* and *Pterocardia.* The echinoids include *Glypticus*, *Paracidaris*, *Hemicidaris*, *Rhabdocidaris*, *Pseudodiadema* and *Stomechimus* (Poirot, 1987; Vadet, 1987). Other groups present include crinoids (*Apinocrinus*), sclerosponges, siliceous and calcareous sponges, terebratulids and crustaceans. There is also a well developed cryptic fauna, essentially of serpulids, thecidean brachiopods and rare bryozoans. The boring intensity is high and mainly attributed to boring bivalves, although *Entobia* borings are also present (plate 3.6-figs 1-3).

Coral limestone. The community structure of the coral limestone is much the same as that of the coral marl, however the elements are markedly less abundant. The only obvious difference is the appearance of the bivalve *Trichites* within the inter-reef sediment. *Skolithos* burrows are also present in the inter-reef sediments.

Coral fauna

Coral marl. The framework of the biostrome is constructed almost entirely of platy colonies which constitute 91% of the total coral skeletal biovolume. These are generally 20-30 cm across 1-3 cm thick, though occasionally can be up to 5-10 cm thick (plate 3.2-figs 2-3). Although the general dimensions of the coral colonies are a few cm thick and tens of cm across there are rare colonies that are magnitudes much greater in dimensions. These colonies are over 1.5 m across and 50 cm thick and have a rather pediform growth-form. These extraordinarily large colonies are believed to be a response to local soft substrate and a lack of firm attachment areas. The larvae that are fortunate enough to attach themselves to a rare firm substrate, such as a shell fragment, can grow without competition for space to an abnormally large size. Other growth forms are rare and do not significantly contribute to the framework. Taxonomically the units are generically rather poor, with only 11 genera having been identified. They are dominated by the microsolenidae family of corals (67%) especially the genus *Dimorpharaea* (53%). The only branching ramose form in the assemblage is *Dendraraea* (plate 3.5-fig 3)

Coral limestone. The style of framework construction is identical to the coral marl although the coral skeletal biovolume is lower, with substantial zones of pure bioclastic material (plate 3.4-fig 1-2). The individual coral colonies tend to be slightly larger (2-5 cm by 50 cm). Pediform colonies over 1m across and 0.4 m thick, especially of *Microsolena*, occur as horizons near the base of the coral limestone and often form the first phases of colonisation within the coral limestone. The most significant and marked change between the coral marl and the coral limestone is in the coral community structure. Microsolenids still dominate the fauna (73%), but in the coral limestone it is the genus *Microsolena* that is dominant (52%); (*Dimorpharaea* only 17%).

In summary the main differences in the coral fauna between the two biofacies are:

- higher coral skeletal biovolume in the coral marl;
- the framebuilders are slightly thicker in the coral limestone; and
- the shift in community structure from *Dimorpharaea* dominating the coral marl to *Microsolena* dominating the coral limestone.

The coral assemblages for the two coral-bearing units are as follows:

CORAL MARL.

Phaceloid branching		**Massive-Lamella**		**Family composition**	
(5%)		**(91%)**		**Microsolenidae**	**67**
Stylosmilia	3	*Dimorpharaea*	53	**Other**	**33**
Thecosmilia	2	*Isastraea*	10		
		Microsolena	8		
Branching ramose		*Fungiastraea*	6	**Generic richness:**	**11**
(2%)		*Comoseris*	6		
Dendraraea	2	*Thamnasteria*	5	**Eveness index:**	**0.71**
		Actinaraea	3		
Solitary				**Diversity indexes:**	
(2%)				Shannon-Wiener:	2.45
Montlivaltia	2			Simpson:	0.69

CORAL LIMESTONE.

Phaceloid branching		**Massive-Lamella**		**Family composition**	
(3%)		**(89%)**		**Microsolenidae**	**73**
Stylosmilia	1	*Microsolena*	52	**Other**	**27**
Thecosmilia	2	*Dimorpharaea*	17		
		Actinaraea	5	**Generic richness:**	**13**
Branching ramose		*Isastraea*	4		
(7%)		*Comoseris*	4	**Eveness index:**	**0.65**
Dendraraea	7	*Thamnasteria*	3		
		Fungiastraea	3	**Diversity indexes:**	
Solitary		*Meandraraea*	1	Shannon-wiener:	2.40
(1%)		*Pseudocoenia*	<1	Simpson:	0.69
Montlivaltia	1				

3.2.4. Depositional environment

The change from Terrain à Chailles to reefal limestones to oncolitic limestone signifies a shallowing from a relatively deep water environment. There is no evidence of current wave or storm activity in the reefal units suggesting they developed well below normal wave base. The pavements of large oriented bivalves in the oncolitic limestone at the top of the section suggesting significant current action, and hence probably developed above normal wave base.

The sedimentation rates also varied throughout the development of this succession; the development of a hardground at the top of the Terrain à Chailles probably reflects a sudden and significant decrease in sedimentation rates. This drop in sedimentation rate also contributed to allowing the subsequent development of the coral marl. The cessation of muddy siliciclastic influx at the top of the coral marl marks the beginning of the coral limestone which developed in a relatively siliciclastic free sedimentary regime.

3.3: PAGNY-SUR-MEUSE

3.3.1. Introduction

The "Carrière du Revoi" Quarry south east of Pagny exposes a fresh, unweathered 50 m high section through the upper reef complex.

3.3.2. Reef structure and facies

Reef structure and framework development. The framework is constructed almost exclusively of phaceloid branching colonies grouped into thickets approximately 5-11 m high and 5 m across.

Occasionally these thickets coalesce forming a discontinuous framework up to 20 m across (plate 3.7-figs 2-3). Taking the whole unit into account coral skeletal biovolume is very low (<20%) and framework development is generally very discontinuous. However within individual thickets coral skeletal biovolume is very high (over 60%). There is no evidence of any substantial syn-depositional relief. The reefal unit has no clear internal architecture although there is very vague 1-2 m thick planar surfaces within the reef (plate 3.7-fig 1). Also present are storm-deposited shell horizons and lenses up to 50 cm thick and a few metres across.

Facies and sedimentology

At outcrop the intra-reef sediments appear as very fine-grained white chalky wackestone-mudstones (plate 3.7-fig 1). Microfacies analysis reveals a micrite-dominated fabric with M/S/C ratios of 70/5/15 (plate 3.8-fig 1). The microfacies is best described as pelmicritic to pelbiomicritic. The carbonate grains are fine (average less than 0.3 mm), very angular and moderately well sorted. This material is almost totally bioclastic and include fragments of serpulids, forams, oyster-type bivalves, ?bryozoans and echinoids. There is little grain micritization and spongiostromate crusts are not developed. The matrix is composed mainly of very fine detrital material and peloids. The fabric of the matrix is rather loose with frequent open spaces (?fenestrae), which are often infilled with fine peloids. The peloids are mainly lithoclasts and fragments of micritized grains rather than precipitated peloids (lithoclasts + fragments of micritized grains + faecal pellets / precipitated peloids: 60/40). Precipitated peloids are generally restricted to infilling cavities and burrows (plate 3.8-fig 1). The fabric is not homogeneous but has a rather blotchy, discontinuous appearance which is believed to be a result of the relatively high levels of bioturbation. The diameter of the burrows is approximately 0.5 mm, although well defined burrows rare. No clear laminated peloidal fabrics are seen, though some vague peloidal rinds are present. Spongiostromate peloidal crusts are well developed on branching phaceloid corals and can be up to 0.5 mm thick.

3.3.3. Palaeoecology

Associated fauna. This includes red algae up to 30 cm across (plate 3.9-fig 1), rhynchonellid brachiopods, nubeculinid forams, echinoid spines, serpulids, sponge spicules, ?bryozoans, bivalves and problematic encrusters (plate 3.8-fig 2). Boring is common but by small organisms and therefore does not make much of an impact and is not immediately apparent. These include small (0.5-1 mm) boring, boring forams (0.1 mm thick, 0.5 mm long; plate 3.8-figs 2-3) and *Entobia* borings. Boring intensity is low to moderate.

Coral fauna. The fauna is dominated by branching phaceloid forms which constitute over 80% of the total coral biovolume. Of these *Aplosmilia* (approximately 75% of the branching phaceloid coral skeletal biovolume) and *Stylosmilia* (20%) are by far the most abundant, although *Calamophylliopsis, Pleurosmilia* (plate 3.10-fig 2), *Thecosmilia* and *Dermosmilia* (plate 3.10-fig 1) are also present. The *Aplosmilia* colonies occur as very tightly branched colonies of parallel branches growing to a height of

3-4 m (plate 3.7-fig 3). The thinly branched *Stylosmilia* form smaller colonies, rarely greater than 1 m in height (plate 3.9-fig 1). The only other major contributors to the framework are the massive forms which constitute about 15% of the total coral biovolume. The most abundant genera are *Stylina* and *Pseudocoenia* which occasionally grows to a massive size (one *Stylina* colony was measured to be 1.7 m high and 1 m across (columnar growth form); plate 3.9-figs 2-3). The growth rate of these colonies was measured to be approximately 11 mm/yr. Also documented (Geister and Lathuilière, 1991) are coralliths with diameters between 5 and 15 cm across. One that was slabbed revealed a nucleus of *Comoseris* and a cortex of *Thamnasteria*. Generic richness is between 11 and 13 which is comparatively low when compared to contemporaneous reefs in the region. Dominance patterns are high and true diversity is quite low; one genus (*Aplosmilia*) constitutes nearly all the coral skeletal biovolume.

Branching phaceloid (80%)	**Branching ramose (5%)**	**Massive (15%)**
Aplosmilia	*Pseudocoenia (limbata)*	*Pseudocoenia*
Stylosmilia		*Isastraea*
Pleurosmilia		*Thamnasteria*
Thecosmilia		*Stylina*
Calamophylliopsis		*Meandraraea*
Dermosmilia		
?Cladophyllia		
?Dermoseris		

3.3.4. Depositional environment

The muddy nature of the intra- and inter-reef sediment suggests a quiet water environment that was occasionally subject to storm deposition. The pre-reefal limestones are not well exposed but appear to be bioclastic packstones-wackestones; there is no association of the reefs with relatively deep water facies (as there was with the reefs of Foug). The presence of storm deposits and ?fenestrae suggest a comparatively shallow water environment. From known growth rates of the branching corals (approximately 1.3 cm per year) it has been calculated that 10 m of the muddy sediment was deposited in less than 100 years (Geister and Lathuilière, 1991) suggesting a very rapid sedimentation rate and hence turbid environment. They suggest that this mud is imported into the reef thickets from a source elsewhere on the platform. These reefs have also been compared with the present day reefs of Gulf of Guacanayabo of Cuba (Zlatarski, 1980) where reefs of very similar sedimentological and ecological character to these *Aplosmilia* reefs thrive in a turbid environment.

3.4: LÉROUVILLE

3.4.1. Introduction

The "Carrière de la Mézengère", an abandoned quarry just south of Lérouville, reveals a 24m section through both the lower and upper reef complexes. The section reveals 3 successive reefal units intercalated by crinoidal and bioclastic limestones (plate 3.11-fig 1; figure 3.5).

3.4.2. Reef 1: lower reef complex

According to Debrand-Passard *et al.* (1980) and Humbert (1971) the first reefal unit in this section, by virtue of being stratigraphically below the crinoidal limestone, belongs to the lower reef complex. However the detailed section of Humbert (1971) (figure 3.3) reveals that this reefal unit occupies a stratigraphic position between the Foug biostrome (the type section for the lower reef complex), and the crinoidal limestone. Indeed, the first reefal unit at Lérouville is clearly distinct from the type reef of the lower reef complex at Foug with regard to both facies and framework development. To avoid confusion, this stratigraphically and compositionally distinct reefal unit is referred to as the "intermediate reefal unit" in this work.

3.4.2.1. Reef structure and facies

Reef structure and framework development

Quarrying of the crinoidal limestone has exhumed a large area of the primary palaeosurface of the intermediate reefal unit (plate 3.11-fig 1). Palaeorelief of the reef was approximately 20 m. The flanks of the reef are steep, dipping 30° at its top down to 6-10° near its foot (plate 3.11-fig 2). The visible lateral extent of the reef is 180 m; its thickness cannot be established since there in no cross-sectional outcrop (see caption for plate 3.12-fig 3). Coral cover (not to be confused with coral skeletal biovolume) is about 50% at the top of the reef dropping to less than 20% near its base, where the lower slope is covered by bioclastic sediments. At Euville (Côtillons quarry) there is an almost identical section to that encountered here with a similarly exhumed intermediate reefal unit (plate 3.12-fig 1). Here further evidence for the steep primary topography of the reef is provided by small scale slumps and tongues of bioclastic sediment on the reef slopes (plate 3.12-fig 2). The framework is constructed mainly by platy corals (plate 3.12-fig 3) although the branching ramose *Dendraraea* is abundant at the top of the unit.

Facies and sedimentology

The intra-reef sediments are coarse-grained bioclastic packstones with M/S/C ratios of approximately 40-50/0/50-60 (biomicrites). The carbonate grains are all bioclasts with anabsence of lithoclastic material. Coarse (0.5 mm), angular bioclasts predominate though the sediment is very poorly sorted with cm sized material also present. There is no grain micritization or spongiostromate crust development. Compositionally the bioclasts are mainly of corals (60%), echinoids (20%) and bivalves (20%). Other bioclasts include serpulids, forams, sponge spicules, bryozoan and gastropods. The matrix is generally homogeneous and composed of tightly packed peloids. Peloidal laminations and rinds are absent, though in areas vague peloidal laminations are present. Near the top of the reef crest

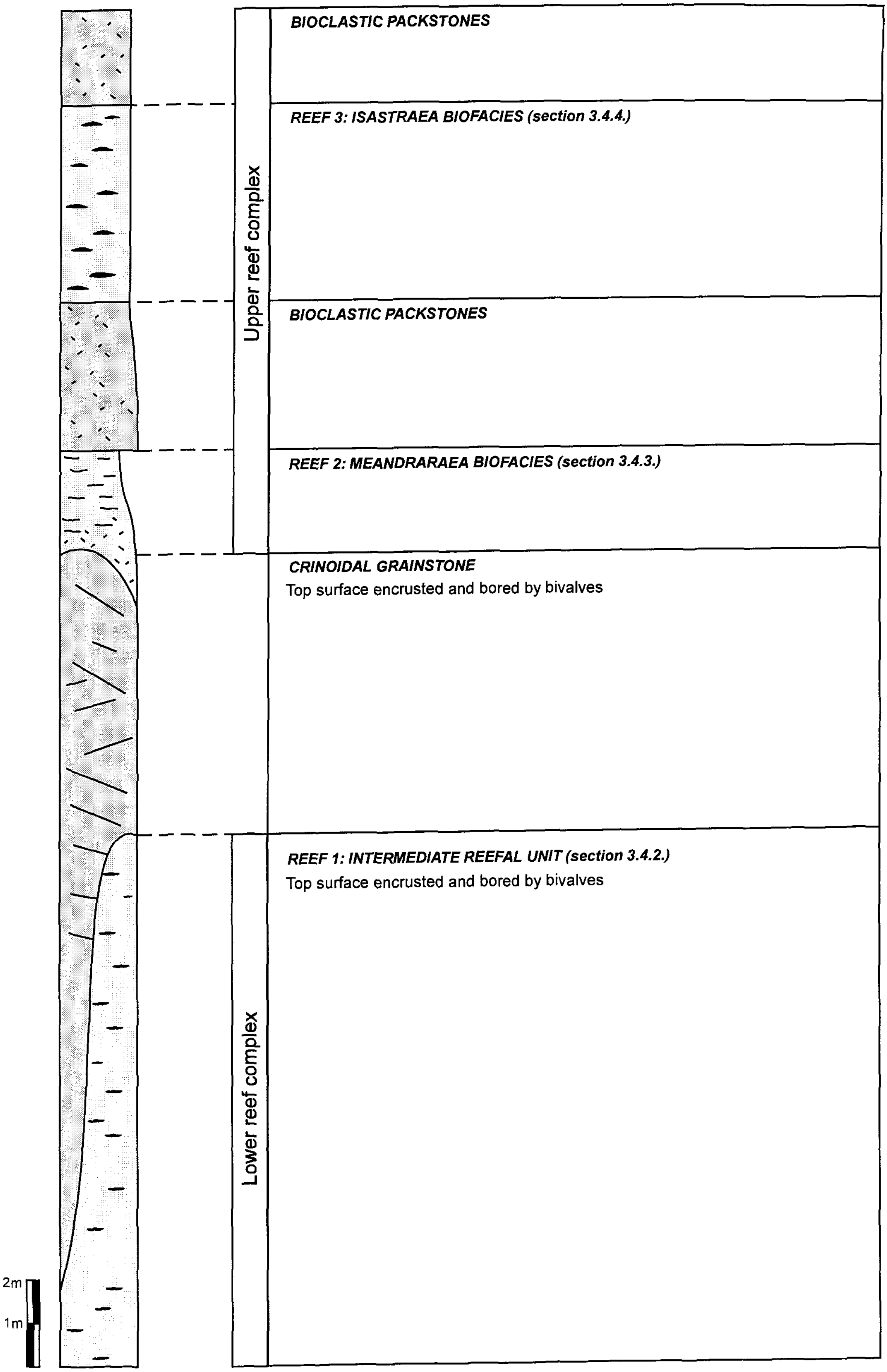


Figure 3.5: Schematic log of the Lérouville section.

the microfacies is more sparitic (locally up to 15%), and intraclasts are more common; peloidal fabrics are slightly better developed. Grain character and composition is much the same as the rest of the intra-reef microfacies.

3.4.2.2. Palaeoecology

Associated fauna. Poor outcrop surface makes data collection difficult. Associated fauna is generally moderately well developed. *Paracidaris* spines and encrusting bivalves are common. The fauna identified as bioclasts within the intra-reef sediment includes echinoids, bivalves, serpulids, forams, sponge spicules, bryozoan and gastropods. Bioerosional activity is moderate and solely by boring bivalves. Bioerosion is especially evident on the top surface of the reef and on local hardgrounds (plate 3.11-fig 2).

Coral assemblage. Again, poor outcrop surface makes data collection difficult. Platy corals dominate the fauna. The plates are 1-2 cm thick and 20 cm across, although they can be up to 5 cm thick, especially towards the top of the reef. The branching ramose *Dendraraea* is common at the top of the reef and forms colonies 1-2 m high. Compositionally the fauna appears similar to that of the coral limestone at Foug although the relative abundances of the various genera in this fauna cannot be established. *Isastraea, Actinaraea, Microsolena, Meandraraea* and *Dendraraea* are common.

Branching ramose
Dendraraea

Branching phaceloid
Calamophylliopsis
Stylosmilia

Massive
Clausastraea
Isastraea
Actinaraea
Microsolena
Meandraraea
Thamnasteria
Comoseris

Solitary
Montlivaltia

3.4.3. Reef 2: *Meandraraea* biofacies; upper reef complex

3.4.3.1. Reef structure and facies

Reef structure and framework development

This second reefal unit, which forms part of the upper reef complex, is only 2 m thick, though it extends laterally for at least 350 m. The contact with the crinoidal limestone below is gradational, with the crinoidal limestone grading into bioclastic limestone over 2.4 m, although locally hardgrounds are present. The top boundary with the bioclastic packstone is sharp (plate 3.13-fig 1). The framework is constructed primarily by very thin platy and lamellar corals and forms a tightly interlocking framework (plate 3.13-figs 2-3). Coral skeletal biovolume is 30%, locally 50%. No planar bedding is apparent, however the thin platy nature of the corals develops a slightly wavy fabric (plate 3.13-fig 1). The reefal unit is biostromal.

Facies and sedimentology

In hand specimen the intra-reef sediment is a fine chalky bioclastic wackestone. At a microfacies scale M/S/C ratios are around 80-90/<5/10-20 and best described as biopelmicrites. The carbonate grains are almost totally composed of bioclasts. They are fine grained (average: 0.1 mm; 90% of the grains are less than 0.5 mm) angular and poorly sorted. The bioclasts are mainly of coral (90%), though echinoid and bivalve material is also common. Other organisms include serpulid tubes, ?sponge spicules, encrusting bivalves and ?bryozoans. Large (0.6 mm) peloidal intraclasts are present. The bioclasts lack spongiostromate coatings and are not micritized. Spongiostromate crusts are even lacking on the branching phaceloid corals. The matrix is mainly of precipitated peloids (70%), the rest is made up of fine detrital material. The peloids are tightly packed, making individual peloids difficult to identify. Graded peloidal fabrics are present, especially under the coral plates. Local rudstone beds tens of cm thick are present, suggesting storm events.

3.4.3.2. Palaeoecology

Associated fauna. *Cidaris* spines, *Chlamys*, *Plagiostoma* and large (3-4 cm) terebratulid brachiopods are common. Organisms underencrusting the coral plates include serpulid, bivalves and ?bryozoans.

Coral assemblage. The coral assemblage is dominated by thin lamellar forms which constitute over 90% of the total coral skeletal biovolume. These coral plates are 1 cm thick, and 25 cm across (plate 3.13-figs 2-3), though there are zones where they are slightly thicker (2-3 cm). Towards the top of the biostrome some coral plates reach a thickness of over 10 cm. The only other conspicuous coral is the branching phaceloid *Calamophylliopsis*. Domed and branching ramose forms are completely absent. Taxonomically the fauna is not particularly rich, with only 10 genera having been identified. *Meandraraea* overwhelmingly dominates the coral fauna (constituting more than 60% of the total coral biovolume).

Branching ramose (insignificant)
Dendraraea

Branching phaceloid (10%)
Calamophylliopsis (c)
Stylosmilia

Massive-platy (90%)
Meandraraea (c)
Thamnasteria
Fungiastraea
Isastraea
Dermoseris
plocoid sp.

Solitary (insignificant)
Montlivaltia

3.4.4. Reef 3: *Isastraea* biofacies; upper reef complex

3.4.4.1. Reef structure and facies

Reef structure and framework development

This is the last of the three reefal units; it is at least 300 m across and 3-4 m thick (plate 3.14-fig 1). The framework is constructed almost exclusively by large thick platy and tabular corals, which forms a dense and interlocking framework (plate 3.14-fig 2) with the total coral skeletal biovolume reaching 50-60%. The reefal unit shows no sign of having developed any topographic relief and can be referred to as a biostrome. There is no clear internal structure to the biostrome although the platy nature of the coral framebuilders gives the impression of vague internal bedding (plate 3.14-fig 1).

Facies and sedimentology

The intra-reef sediments are bioclastic packstones with M/S/C ratios of approximately 60-70/0/30-40 (biomicrites). The carbonate grains are composed solely of bioclasts of which corals (90%), bivalves and echinoids predominate. Other bioclasts include fragments of serpulids and thecidean brachiopods, which are common. The bioclasts are coarse-grained (0.5-2 mm), angular and poorly sorted. They lack spongiostromate crusts and are not micritized. The matrix is homogenous, with no obvious peloidal fabrics and is primarily composed of fine compacted peloidal material. The inter-reef sediments are indistinctly bedded bioclastic limestone (?grainstones) composed mainly of strongly micritized echinoid and bivalve material (Geister and Lathuilière, 1991).

3.4.4.2. Palaeoecology

Associated fauna. Bivalves: *Lopha* and *Chlamys* (plate 3.15-fig 3) are common with *Entolium* and *Ctenostreon* present though rare. Echinoderms: *Paracidaris florigemma* (common); crinoid ossicles. Bioerosion: moderate; boring bivalves (plate 3.15-fig 1).

Coral assemblage. The coral fauna is dominated by thick platy corals, almost totally of the genus *Isastraea* (plate 3.14-fig 2). The coral plates are generally between 8 cm and 20 cm thick, and between 50 and 100 cm across, although plates 140 cm across are not rare (plate 3.14-fig 3). Other growth forms are insignificant and do not contribute significantly to framework construction. Taxonomically the fauna has a low generic richness with eight genera being identified. Dominance patterns are high, with the fauna being completely dominated by *Isastraea,* which probably constitutes over 80% of the total coral skeletal biovolume. The other massive forms, especially *Thamnasteria* (plate 3.14-fig 4), *Meandraraea* and *Fungiastraea*, make up the rest of the coral skeletal biovolume. One fragment of a branching ramose *Thamnasteria* was found.

Massive (100%): *Isastraea, Fungiastraea, Thamnasteria, Actinaraea, Meandraraea, Microsolena*
Branching phaceloid (% insignificant): *Calamophylliopsis*

3.4.5. Depositional environment of the reefal units

It is difficult to establish the depositional environment of reef 1 since facies associations with the reef are not well exposed. However the development of ripple surfaces (plate 3.11-fig 3) and onlapping by crinoidal sandwaves at the top of reef 1 suggests that it grew well above normal wave base before being drowned by crinoidal grainstones. Hence the depositional environment probably changed from quiet to moderate energy (below normal wave base) early in the development of the reef, to high energy (above normal wave base) at the top of the reef before it was drowned by crinoidal grainstones. Bioclastic material was transported down the reef slopes as sediment slumps and tongues. The development of well developed hardgrounds on the top surface of the crinoidal sandwaves suggests that by this time they had stabilised and sedimentation rates had dropped significantly, thus allowing reefs to subsequently develop.

Reefs 2 and 3 are likely to have developed in very shallow water since they are located on top of the antecedent topography created by a relatively thick unit of crinoidal sandwaves. These reefal units are thickest in the topographic lows of the crinoidal sandwaves (Lathuilière, pers. comm., 1993; pers. obs., 1993), and hence it is envisaged that reef development was preferentially within the protected areas below the crests of the sandwaves, allowing packstone sediments to develop in and around the reefs. Moreover, in the nearby Côtillons quarry at Euville, where a virtually identical sequence occurs, the lateral equivalents of the upper reef complex reefs are quiet water lagoonal micrites (Calcaires de Creue), providing further evidence for a shallow, quiet water interpretation for the these reefs (plate 3.11-fig 1). Bioclastic sedimentation rates within reef 2 appear to have been low. However the inter-reef grainstones of reef 3 suggest that the energy levels associated with this reef may have relatively high, perhaps developing in a more exposed location. This also resulted in a high bioclastic sedimentation rate.

3.5: ST. MIHIEL

3.5.1. Introduction

On the eastern bank of the Meuse, on the northern outskirts of the town of St. Mihiel, are 7 riverside bluffs known as the "Sept Roches" which provide a large exposure of reefal facies to study. This outcrop is the type area for most of the Oxfordian corals described by Michelin (1840-1843). Beauvais (1964) also collected intensively from this locality. However, the quality of outcrop is now extremely poor, being highly weathered and often covered by lichen and vegetation. Bluff 7 has a crypt excavated within it which is occupied by a statue of St. Mihiel (plate 3.16-fig 1). The inside of the crypt provides an excellent three dimensional view of the reef framework and degree of framebuilding. The outcrop exposes only the reefal facies which corresponds to the upper reef complex.

3.5.2. Reef structure and facies

Reef structure and framework development. The reefal unit is at least 30 m high (visible) and 200 m across. Taking the whole reefal unit into account framework construction is extremely low, generally less than 20% with substantial zones which are essentially bioclastic piles completely void of framework construction. However some zones have very high coral skeletal biovolume, over 60%. The reefal unit has a well developed internal structure in the form of planar to sub-planar bands of differing degrees of framework construction (plate 3.16-figs 1-2). The hard (concave) bands represent zones with higher in situ coral skeletal biovolume and the soft (convex) bands possess less in situ coral skeletal biovolume. These bands are 2-11 m thick and their contacts are highly gradational. This internal organisation is thus identical to the "corrugated structure" observed at the Saussois reef, Burgundy. The framework construction is a result of coral growth with no evidence of microbial binding. The framebuilders are dominated by branching ramose (plate 3.16-fig 4), domal and tabular colonies. Reef development was often interrupted by storm events, resulting in the truncation of coral thickets (plate 3.16-fig 3). The top of the sequence is capped with a 4 m thick band with slightly different bio- and lithofacies characteristics.

Facies and sedimentology. The intra-reef sediments are coarse chalky, bioclastic packstones (plate 3.17-fig 1). Bioclastic material constitutes 50-60%; the rest is matrix, which is mainly very fine detrital material (biomicrites). Intergranular sparite is sparse and generally less than 5%. The bioclastic material is subangular to sub-rounded, moderately sorted and coarse-grained (average grain-size: 2-3 mm; range <0.1 to 40 mm). The bioclasts are not highly micritized (though micritization is present; plate 3.17-fig 2) and spongiostromate crust formation is not highly developed, even around coral branches. The bioclastic material is composed of corals 60%, bivalves (especially of oyster-type material) and echinoids 40%, though also present are calcified cyanobacterial crusts, gastropods, bryozoans, serpulids and forams. No grain orientation has been observed. The matrix is composed mainly of very fine detrital material and peloidal material (less than 15%) and lacks peloidal laminations or rinds. The intra-reef sediments of the bands with low in situ coral skeletal biovolumes, are similar to the above microfacies though slightly muddier (M/S/C ratios are 70/0/30). The grains are angular to subangular. The top band exhibits a slightly different microfacies: grains are slightly larger (average 3 mm), better sorted, sub-rounded to rounded, with a moderate preferred orientation. Intraclasts are relative common.

3.5.3. Palaeoecology

Associated fauna. The associated fauna is very poorly developed, with low richness and low abundances. The groups that are present, albeit rare, are serpulids, *Cidaris* spines, *Chlamys*, gastropods, forams, terebratulid and thecidean brachiopods and *Trichites*. Bioerosional activity is low-moderate and produced by *Lithophaga* and *Gastrochaena*. The bioerosion is exclusively on massive corals.

Coral assemblage. Branching ramose and massive forms dominate the fauna and are the main framebuiders; branching phaceloid although common are of secondary importance. *Thamnasteria dendroidea* is the main branching ramose coral and forms large very dense thickets up to 5 m across and 2 m high, with individual colonies being 70 cm high and 50 cm across (plate 3.16-fig 4). The branches of *Thamnasteria dendroidea* are thick (generally greater than 2 cm) and tightly packed. *Pseudocoenia limbata* is the only other branching ramose coral though its occurrence is rare. *Aplosmilia* is the main branching phaceloid and occurs as isolated colonies up to 40 cm high, occasionally reaching 60 cm.

The massive corals can be divided into two subgroups:

1) those that have a more domal growth form and are about 40 cm across and 30 cm thick, and are mainly *Isastraea*, *Meandraraea*, *Stylina* (plate 3.17-fig 3) and *Pseudocoenia*. Occasionally some of these colonies have grown to over 60 cm across (one colony of *Stylina* was recorded to be 66 cm across and 32 cm thick); and

2) those that have a sub-domal, sub-platy or tabular growth form and range from 15 cm across and 2-4 cm thick, to 35 cm across and 10 cm thick. These are mainly *Thamnasteria, Isastraea, Microsolena, Meandraraea* and *Meandrophyllia*.

Locally these massive forms can have an exceedingly high packing density. The thickets of *T. dendroidea* and zones rich in massive and tabular corals tend to occur as distinct zones with areas of mixed massive and branching ramose colonies being rare. The reefal unit is capped with a 4 m thick band which is dominated by stylinids; branching corals are absent. Taxonomically the reefal unit is relatively rich with 17 genera having been identified. 7 genera are common, in particular *Thamnasteria dendroidea*, *Stylina*, *Isastraea*, *Meandraraea and Meandrophyllia*.

Branching phaceloid

Stylosmilia
Cladophyllia
Aplosmilia
Calamophylliopsis
Dermoseris

Branching ramose

Dendraraea
Thamnasteria dendroidea
Pseudocoenia limbata

Massive

Meandraraea
Stylina
Meandrophyllia
Microsolena
Microphyllia
Pseudocoenia
Thamnasteria
Pachygyra
Isastraea
Actinaraea

Beauvais (1964) documents 25 species belonging to the following 18 genera:

Adelocoenia
Cladophyllia
Aplosmilia
Astraaea
Aulophyllia
Brachyseris
Cryptocoenia
Dendraraea

Isastraea
Microphyllia
Stylosmilia
Stereocoenia
Meandrophyllia
Microsolena
Thamnasteria
Rhipidogyra

Solitary: *Montlivaltia*

3.5.4. Depositional environment

There are strong similarities in facies between this reef and the Saussois reef, Burgundy, and therefore a similar depositional environment is envisaged (see chapter 2, section 2.5). The abundance of bioclastic material and the low intensities of bioerosion suggest that the vast majority of this material is produced by physical erosion.

3.6: HAUDAINVILLE

3.6.1. Introduction

A recent cutting for the motorway interchange 4 km SSE of Haudainville provides a series of exposures through the crinoidal limestone and upper reef complex (figure 3.6; plate 3.18-fig 1). Reef growth began on the upper surface of the crinoidal limestone, probably equivalent to that of Lérouville and Euville. Reef initiation was preceded by successive deposition of prograding bioclastic limestones which were subsequently colonised by massive corals (effectively progradation of reef framework into crinoidal limestone) (figure 3.7; plate 3.18-fig 2). These beds were in turn colonised by large thickets of branching corals, especially the branching ramose *Thamnasteria dendroidea*. The build-ups are terminated by onlapping of bioclastic sediments (plate 3.18-fig 3; plate 3.19-fig 1).

3.6.2. Reef structure and facies

Reef structure and framework development

The visible lateral extent of the reefal unit is at least 300 m by 300 m and up to 10-15 m thick. Reef development is discontinuous, with large volumes of inter-reef sediment between individual build-ups. The form of individual build-ups is rather domal; up to 6 m high and 15 m across (plate 3.18-fig 3; plate 3.19-fig 1). The framework is constructed primarily by branching forms especially branching ramose colonies, with thin lamellar and massive form also being abundant. For individual build-ups coral skeletal biovolume is between 20-50%, however since reef development is very discontinuous coral skeletal biovolumes for the reefal unit as a whole is very low. Storm events were very common and produced laterally persistent, marked truncation surfaces across the framework. These truncation surfaces are followed by the mud horizons resulting from the settling out of fines. Growth bands in the branching ramose corals suggest that the storm events occurred every 10-100 years (Geister and Lathuilière, 1991).

Facies and sedimentology

The intra-reef sediments are chalky bioclastic packstones/wackestones with M/S/C of ratios approximately 30-50/5-10/45-65 (biomicrites) (plate 3.19-figs 2-3; plate 3.20-fig 1). The carbonate grains show a bimodal grain-size distribution with average grain sizes of 1-2 mm and 0.1-0.5 mm. The coarser grained material is moderately well rounded (though some angular material is present), and have a high sphericity. Compositionally the bioclasts are the dominant component (over 70%), though lithoclasts are common (10-20%). The bioclasts are mainly of echinoids, corals and bivalves (especially oyster type material). The finer bioclasts are very angular, poor to moderately sorted, and are again mainly of corals (40%), echinoids (20%) and bivalves (20%). Also relatively common are fragments of calcified cyanobacterial crusts and sponge spicules. Grain micritization is generally low, but some of

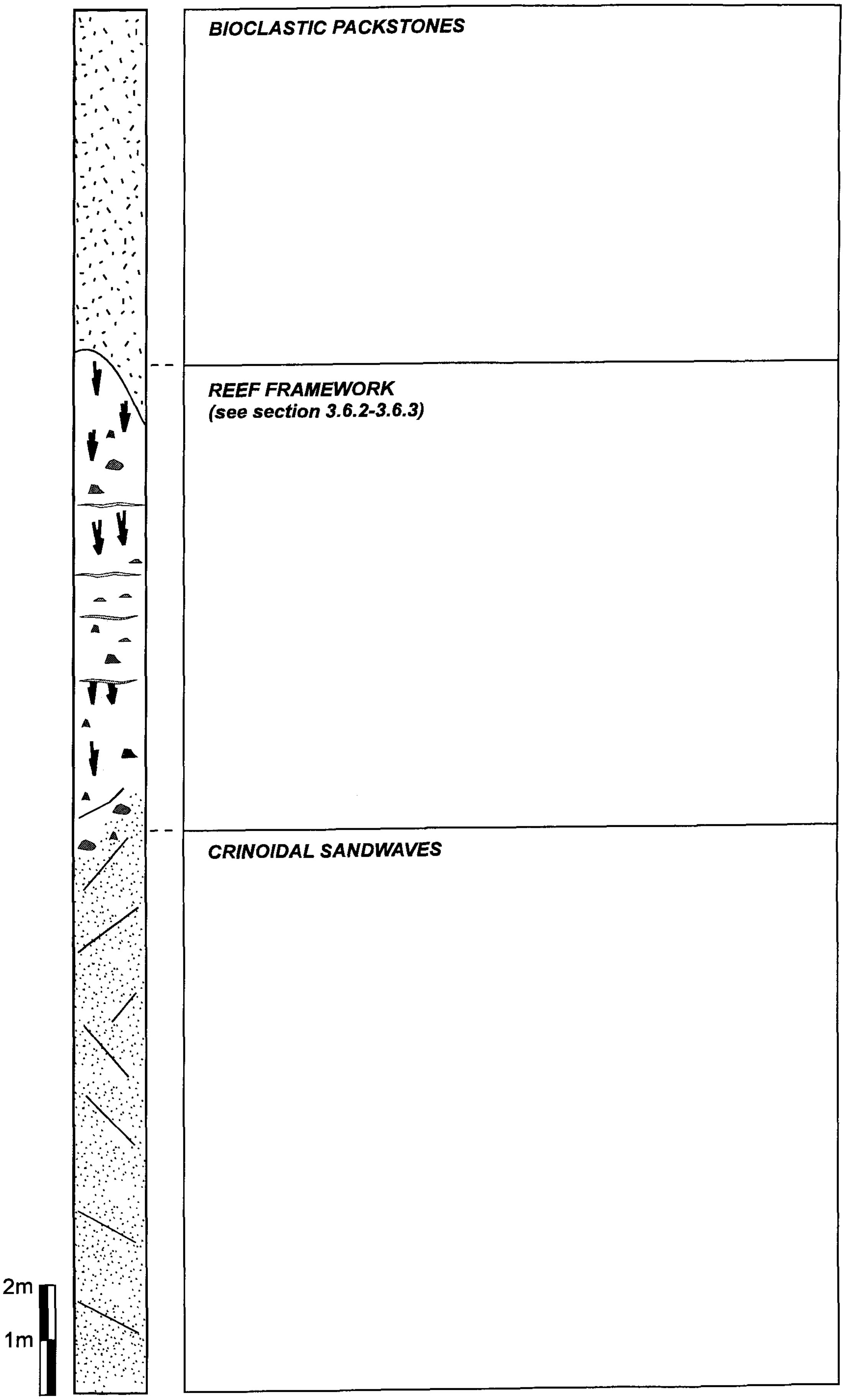


Figure 3.6: Schematic log of the Haudainville section.

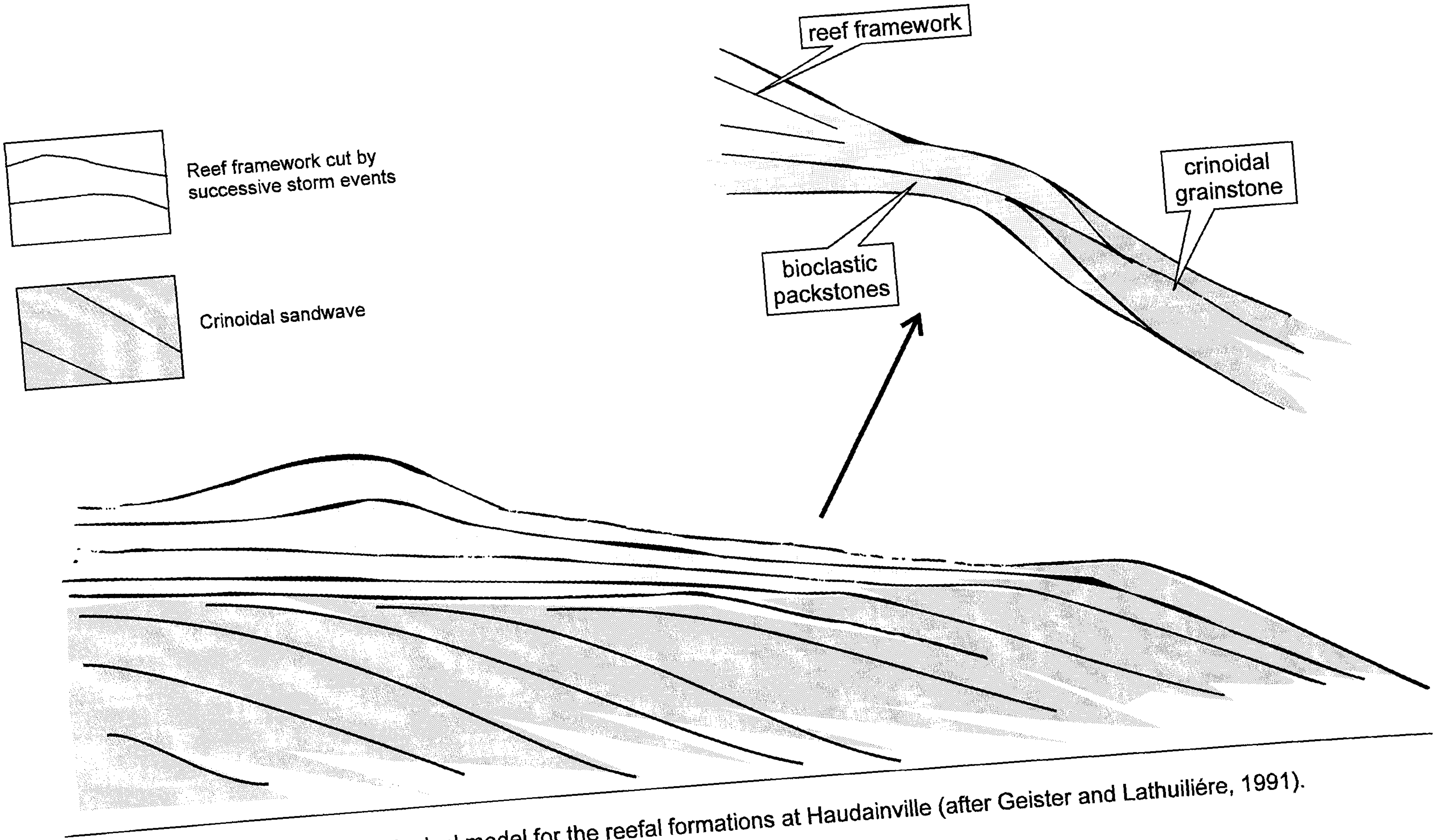


Figure 3.7: General sedimentological model for the reefal formations at Haudainville (after Geister and Lathuiliére, 1991).

the larger grains are well micritized. Spongiostromate coatings are not well developed, though again some of the larger grains have poorly developed (less than 0.3 mm thick) coatings. The lithoclasts are dark ?extraclastic pelmicrites. Grain orientation is absent. The matrix is composed of extremely fine grained detritus (70%) and peloids (30%). Peloidal laminations and rinds are lacking and the matrix is generally homogeneous, although some very vague peloidal rinds can be distinguished.

Locally there are areas of bioclastic packstone with M/S/C ratios of approximately 50/0/50 (biomicrite). These sediments are very similar to the Saussois-type microfacies (plate 3.19-fig 2). Here spongiostromate coatings are common though not thick (<0.4 mm) and grains can be well micritized. Lithoclasts are common (30%). The matrix is composed of detrital and peloidal material (both precipitated and detrital peloids). The matrix is homogenous and peloidal laminations or rinds are generally absent, although under coral plates laminated and rinded peloidal fabric are present.

3.6.3. Palaeoecology

Associated fauna. The fauna is moderately well developed with a number of groups being common including *Chlamys*, gastropods, echinoids and *Solenopora* (plate 3.20-fig 2). Terebratulid and rhynchonellid brachiopods are also present. Many of the platy corals are relatively well underencrusted by thecidean brachiopods, serpulids, forams, calcified cyanobacterial crusts, cementing bivalves, bryozoans and ?calcareous sponges. Boring intensity appears to be quite low and is mainly a result of bivalve activity. Burrowing is present in the inter-reef sediments.

Coral assemblage (plate 3.20 - plate 3.26)

The coral fauna is very rich particularly in terms of the coral growth forms which include:

- branching ramose forms: mainly in the form of large *Thamnasteria dendroidea* thickets (plates 3.21-3.22) and isolated *Dendraraea* colonies 1 m high, 3 m across;
- branching phaceloid forms: mainly *Aplosmilia* and *Calamophylliopsis* (plate 3.20-fig 3) developing as 1-2 m high colonies;
- massive domal forms: up to 1 m wide 0.8 m high;
- platy to tabular forms: 20-40 cm across and 5-15 cm thick; and
- lamellar and foliaceous forms: these form delicate sheet- and "rose-shaped" colonies (plates 3.23-3.26) and include forms of the genera *Fungiastraea*, *Meandraraea* and *Actinararea*.

Taxonomically the reefs are also rich, with 18 genera having been identified. The most abundant coral is *Thamnasteria dendroidea* which occur as large thickets (plates 3.21-3.22). Also common are *Dendraraea*, *Calamophylliopsis*, *Aplosmilia*, *Isastraea*, *Fungiastraea* and *Meandraraea*.

The coral fauna is as follows:

Branching ramose (40%): *Thamnasteria dendroidea, Dendraraea racemosa*

Branching phaceloid (20%): *Calamophylliopsis, Aplosmilia, Stylosmilia*

Massive (20%): *Isastraea, Fungiastraea, Actinaraea, Allocoenia, Comoseris, Isastraea, Actinaraea, Microsolena, Meandraraea, Thamnasteria, ?Clausastraea*

lamella/foliaceous (10%): *Fungiastraea, Meandraraea*

3.6.4. Depositional environment

Energy levels, as suggested by the microfacies and delicate foliaceous colonies, appear to be relatively low. Water depths are likely to have been quite shallow considering the reef's association with crinoidal sandwaves. Hence another rather quiet, protected, shallow water environment is envisaged. The reefs were prone to frequent storm events. The sedimentological model suggested by Geister and Lathuilière (1991) is shown in figure 3.7.

3.7: DOMPCERVIN

3.7.1. Introduction and facies sequence

A large disused quarry just north of Dompcervin exposes a 21 m composite section through the units overlying the "upper reef complex", in this region named the "Oolith de St. Mihiel". The outcrops do not reveal in situ reef framework; however there are a number of coral-rich channel deposits which have clearly been derived from a nearby reef (considering the volume and size of corals). The sequence reveals a number of horizons rich in red algae, nerineids and diceratids. No detailed analysis of the coral channels has hitherto been undertaken.

The whole section essentially represents a series of stacked, migrating channels and mobile sand shoals (figure 3.8). The section is dominated by various types of channel deposits and carbonate sand shoals which are locally well developed. The majority of the channels are infilled by fine grained pelsparites-oosparites. However a number of these channels contain considerable amounts of biogenic debris within a intrapelmicritic matrix. The channels can be split up into compositional types:

1) coral channels
2) Diceratid- and nerineid-rich channels
3) red algae rich channels
4) mixed composition channels

The channels vary in shape but are generally broad, 1-2 m deep and 10-20 m across (plate 3.27-fig 1). Sandwaves of peloidal sands with large (2-4 m high) avalanche forsets are also present. Within the fine grainstones small megaripple/ripple forsets approximately 30 cm high, and low angle planar laminations are occasionally present. The top of the sequence is capped with fine grained sublithographic limestones.

3.7.2. Coral-bearing facies: architecture and sedimentology

In the section studied (figure 3.9; plate 3.27-fig 1) in situ framework is not visible. However, considering the volume and size of corals in some of the channels, it is likely that in situ reef frameworks had developed close to these channel deposits. The coral-rich deposits occur within large broad channels up to 20 m across and 2.5 m deep (plate 3.27-figs 1). Coral material is extremely abundant and consists mainly of large massive rounded coral colonies (25 cm across) and dome-shaped colonies (up to 50 cm across) (plate 3.27-fig 2-4). Branching ramose are also present though less common. Total coral skeletal biovolume is very variable (5-50%), though none of the material is in situ.

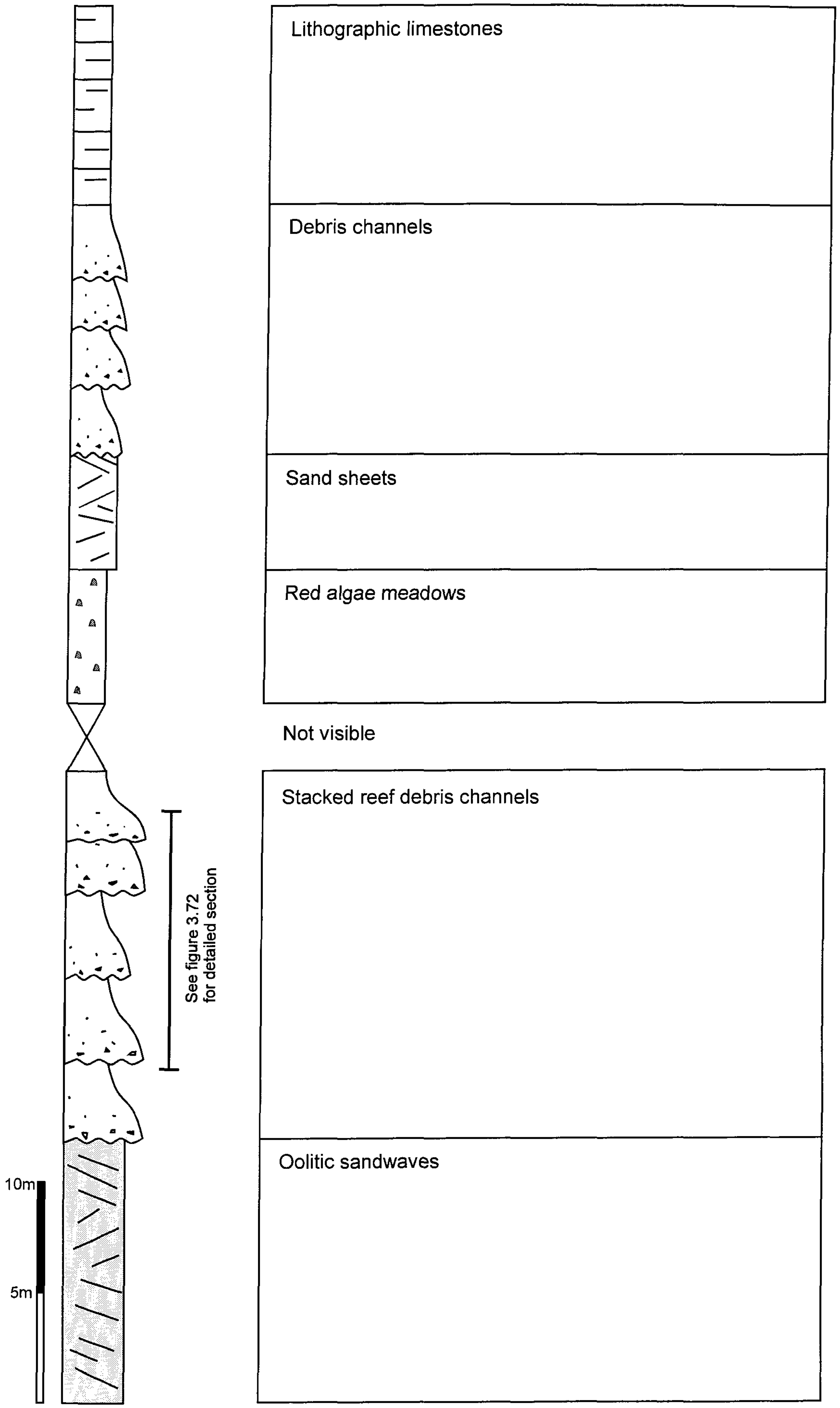
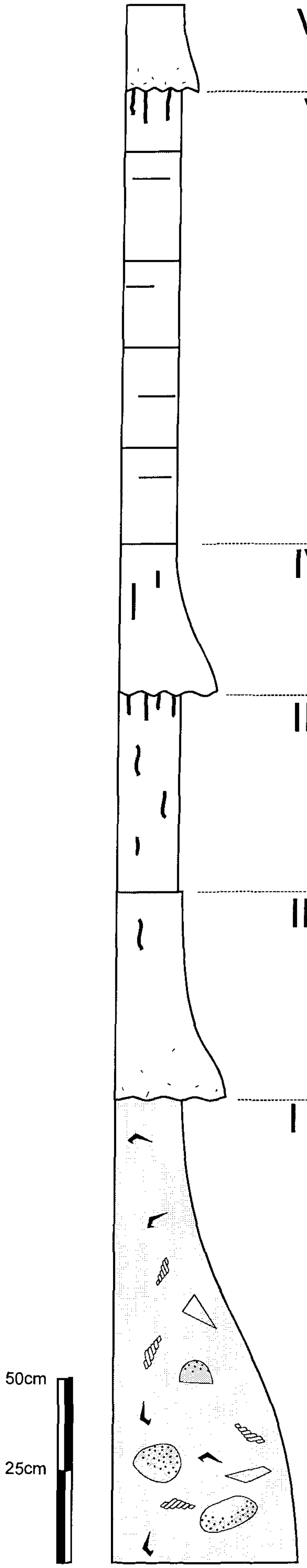


Figure 3.8: Schematic log of the Dompcervin sequence.



VI	Fine grained (0.1 mm) peloidal grainstones very locally packstones; (pelsparites). This unit repersents the margin of a large coral-bearing debris channel.
V	Very fine-grained (<0.1 mm) pelsparites. Burrows truncated by overlying channel.
IV	Fine-grained (0.1 mm) peloidal grainstones; pelsparites-pelmicrites. Pelmicritic extraclasts. Burrowed.
III	Fine-grained (0.1 mm) peloidal grainstones; pelmicrites. Heavily burrowed (*Skolithos* burrows 0.5-1cm in diameter). Shell bed near top of unit.
II	Coarse-grained (0.3-0.4 mm) oopelsparites-oosparites. Burrowed in areas.
I	Bioclastic/peloidal packstones (biopelmicrites). None of the biogenic material is in-situ. Large coral colonies (30 cm+) common. Large *diceratids and nerineids abundant. Also present are brachiopod and Trichites.* Some burrowing. This is the main body of a channel. Margins of the channel grade to fine pelsparites.

Figure 3.9: Schematic log of the Dompcervin section studied.

Facies and sedimentology

The reefal debris is concentrated in the central part of the channels. The intra-channel sediments in the main body of channel are chalky coarse-grained bioclastic-peloidal packstones. The microfacies reveal biopelmicrite-biointrapelmicrite textures with M/S/C ratios of 60-40/10/30-50 (plate 3.28-fig 1-3). The carbonate grains are very poorly sorted and range from less than 0.3 mm to boulder size, with 1 cm sized material being relatively common. There are also great variation in the degree of rounding. The carbonate grains include both bioclasts and peloidal fragments in roughly equal proportions. The detrital peloids include lithoclasts, fragmented micritized grains, amorphous oncoids, and micritized ooids. The bioclasts are taxonomically very rich and include abundant red algae, calcified cyanobacteria, forams, corals, oyster type bivalves, echinoids, brachiopods and serpulids. The most abundant bioclasts are of corals (50%), echinoids (20%), bivalves (20%) and algae/calcified cyanobacteria (10%). Grain micritization is high and spongiostromate crusts are common, ranging from 0.1-0.5 mm in thickness. Some of these crusts possess internal filaments and cavities and hence are best described as porostromate crusts. The matrix is dominated by fine detrital material, especially of peloids (micritized bioclasts), lithoclasts and very fine micritized ooids. The matrix is not laminated though vague rinds are present, though very rare; there is no grain orientation. There are local areas of sparite dominated textures with floating bioclasts (plate 3.28-fig 1). The intra-channel sediments change in nature from the centre to margins of the channel. The channels grade both vertically and laterally towards there margins into very fine grained (0.1 mm) well sorted pelsparites with very little if any large biogenic material (plate 3.29-fig 1).

3.7.3. Palaeoecology

Associated fauna.

The associated fauna is both rich and abundant, in particular there is a diverse molluscan fauna.

Bivalves: *Arca, Opis, Cardium, Astarte, Diceras, Liostrea, Ostrea, Lima, Mytilus, Trachites*

Gastropods: *Nerinea* (at least four different forms), *Bourguetia*

Other common organisms: forams, serpulids, echinoids, terebratulid brachiopods, red algae, calcified cyanobacteria (*Cayeuxia*) and *Lithocodium* (plate 3.29-figs 2-3).

Some beds (units III and V of figure 3.9) are highly burrowed, primarily by *Skolithos* trace fossils (plate 3.27-fig 5), which are characteristic of unstable sediments. *Trichites* can be common in these burrowed facies though the valves are generally thin (approximately 0.5 cm thick).

Red algae are common as small 5 cm high domes. Near the top of section there is a 2 m thick horizon where these domes occur in situ and are exceedingly common (can make up 20% of the facies in some areas). Corals are generally absent though small branching phaceloid forms, probably *Stylosmilia*, are quite common. These deposits are envisaged to represent red algae/*Stylosmilia* meadows.

Some corals are highly bored by boring bivalves such as *Lithophaga*, but although the boring intensity on individual coral colonies can be very high, the proportion of corals that are bored is not.

Coral fauna

Coral material is extremely abundant and consists mainly of large massive rounded corals (25-30 cm across), dome-shaped colonies (up to 50 cm across) and occasionally very large irregular colonies (an *Isastraea* was recorded to be 80 cm across). Over 80% of the material collected was of massive domal forms with the remaining material being composed mainly of branching ramose but also branching phaceloid forms. The branching ramose forms present are generally of the sub-branching type.

16 genera have been confidently identified. Plocoid stylinids and meandroid forms are common, in particular *Meandrophyllia* domes 10-30 cm across (plate 3.30-fig 5). However one must bear in mind that these are transported coral deposits and therefore taphonomic factors may have caused a change in faunal composition from the original source assemblage.

Also documented was an extraordinary "coral ball" (plate 30-figs 1-3). This large coral construction is essentially spherical and has a diameter of 58-60 cm. The whole surface of the coral ball is covered by one (perhaps more) colonies of ?*Diplocoenia* (plate 3.30-fig 4). However this is only a superficial coral cover or "skin" and internally the coral ball is infilled with loose chalky coarse-grained bioclastic packstone (biopelmicrite). The average thickness of the coral skin is 6-8 cm. It is believed that this coral ball developed as a result of episodic rolling of the colony.

Phaceloid branching		**Massive**	
Calamophylliopsis		*Meandrophyllia*	5
Stylosmilia		*Pseudocoenia*	3
		Isastraea	
Branching Ramose		*Heliocoenia*	
Pseudocoenia	2	*Stylina*	2
Meandrophyllia		*Pseudocoeniopsis*	
Thamnasteria	1	*Etallonia*	
Unidentified sp.		*Meandraraea*	2
Unidentified sp.		*Microphyllia*	
		?*Clausastraea*	
Solitary		?*Diplocoenia*	
Montlivaltia		Unidentified sp.	
		Unidentified sp.	

1: Very rare
5: Abundant

Beauvais (1964) documents 4 species:
Brachyseris curtata
Thamnasteria bourgeati
Stylina tuberfera
Allocoenia furcata

3.7.4. Depositional environment

The general depositional environment was one where sediment mobility, on various scales, was marked. Mobile sand shoal and channels dominated the environments and hence precluded coral reef development. The fineness of the oolite and peloidal sands suggests an environment where, although constant currents existed (winnowing out the muds), they were not extremely high energy. Abundant channels cut across the environment and brought in reefal debris from near-by in situ reefs. The composition of the reefal debris, rich in nerineids, diceratids and red algae, suggests that these channels were sourced from different reef types than those that are presently exposed (since the organisms are very rare or absent in the other reefs studied). In this respect the abundance in *Meandrophyllia*, which has not been documented to be abundant in these other reefs, is significant. The only in situ biogenic development was of red algae/*Stylosmilia* meadows which developed in calm water protected environments and are represented by units right at the top of the section, just below lithographic limestones.

CHAPTER 4: ARDENNES AND NORMANDY

4.1: ARDENNES

4.1.1. Introduction

The study localities are situated in northern France in the Ardennes region, north-eastern Champagne. The sections are located in three immediately adjacent quarries called l'Épine, approximately 12 km north north east of Rethel and 1300 m north east of the village of Novion-Porcien (figure 4.1).

Chrono- and lithostratigraphic framework. Bonte (1938) found several perisphinctid ammonites at l'Épine indicating a Middle Oxfordian age. This has been corroborated in this study by the finding of a *Perisphinctes* cf. *plicatilis.* According to Enay and Boullier (1981) the whole of the reefal formation that extends from Lorraine northwards is of Plicatilis Zone (Antecedens Sub-zone) age, through to the base of the Birfurcatus Zone. These Ardennes reefal units would appear to correspond to either the "upper reef complex" and/or the oolites overlying the upper reef complex of the Lorraine region (see section 3.7).

There is also evidence for the presence of another reefal unit below those that have been studied in outcrops. This evidence comes from:

(1) isolated blocks of a reefal fabric dominated by platy forms. This reefal fabric is very distinct from those that outcrop in the quarries; and

(2) a river deposit south of the study outcrops contains a rich association of corals clearly distinct from the reef faunas exposed. This fauna is rich in platy forms, especially of *Dimorpharaea, Microsolena, Comoseris*, *Isastraea* and *Thamnasteria.*

The composition and biofacies of this underlying unit is very similar to the microsolenid biostromes found in the lower reefal units of other areas (for example Burgundy, Lorraine and the Swiss Jura (chapters 2, 3 and 5; also see chapter 7, section 7.1 and Insalaco, 1996a). However the precise location of these lower reefs in the Ardennes region has yet to be located. This is the first documentation of a probable lower reefal unit in the Ardennes region. The stratigraphy therefore appears to be similar to that of the Upper Jurassic of Lorraine where these reefs occur within a shallowing-upwards sequence.

Previous work. The Late Jurassic reefs of the Ardennes region have received very little scientific attention. Munier-Chalmas (1894) first noted the occurrence of corals and gave very general descriptions. The reefs were first reliably dated by Bonte (1938), followed by Beauvais (1964) with similar results. More recently these findings were confirmed and regionally correlated by Enay and Boullier (1981). None of these works treat the reefs in any detail and there has been virtually no work on their structure, composition and palaeoecology. A detailed palaeoecological study, especially on the bioeroders and associated fauna, has been carried out by Bertling and Insalaco (in prep.).

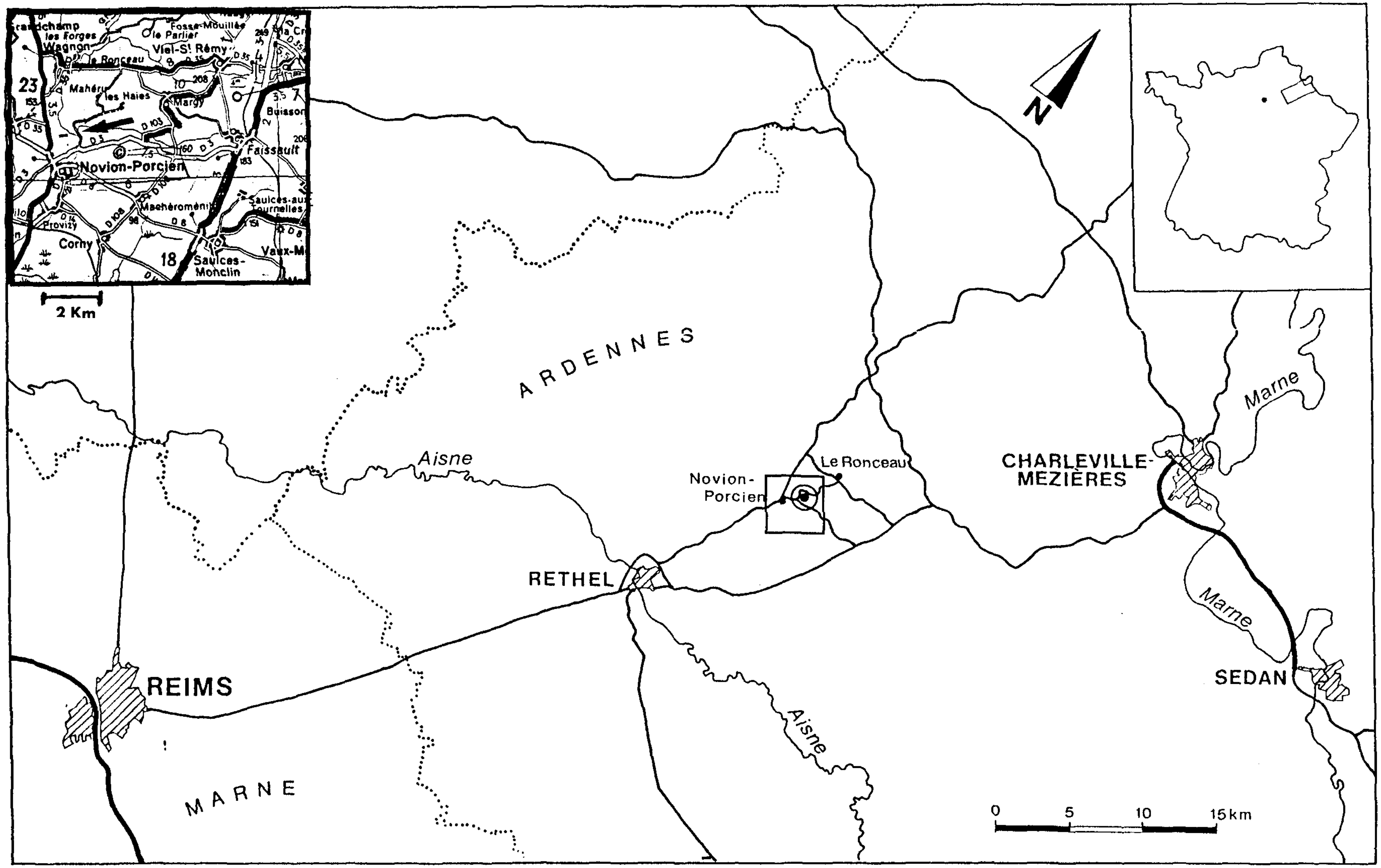


Figure 4.1: Location map of the study outcrops in the Ardennes. Scale for the detailed roadmap is 1:200 000

4.1.2. Facies sequence and analysis

Three main reef and reef related facies have been identified in outcrop: (1) mobile sand facies; (2) reef rubble facies; and (3) in situ reef framework. These three facies are interbedded with each other and can occur in any sequence (figure 4.2).

Reef rubble. This facies is the most widespread of the two coral facies and dominates the sequence in all three of the sections studied, especially quarry 3. The facies is well bedded on a metre scale and is packed with reef debris which is clearly not in situ, giving these units a distinctively rubbly, rudstone appearance (plate 4.2-fig 3; plate 4.3-figs 1-2). In places coral material can constitute up to 80% of the facies volume, and hence the facies can appear reefal (plate 4.3-figs 1-2). The style of bedding varies from planar parallel to non-parallel (plate 4.2-fig 2). The reef debris, although clearly not in situ, has not been transported far since (a) much of the material is composed of large-sized coral fragments and occasionally whole coral colonies; (b) the material shows very little evidence of abrasion, with even the most delicate of calicular structures remaining intact; and (c) most of the shell material is still articulated. Hence this material can be described as parautochthonous reef debris which has been deposited at, or very close to, the site of reef development ("autoparabiostrome" of Kershaw, 1994). Many of the coral branches and nerineid gastropods show a preferred orientation suggesting significant current action. The bases of these debris sheets are generally erosive and well developed erosive channels are common (plate 4.2-fig 2). The composition of this material is essentially reefal in origin and dominated by coral and mollusc debris. Although the material has not travelled far it clearly represents a mixed assemblage, mixing reef (dominantly coral) and off-reef (dominantly mollusc) faunas. The faunal assemblage can therefore be described as a specially averaged fauna. The reef debris is bound together by vast amounts of dense, hard, peloidal micrite (plate 4.3-fig 2).

On a microfacies scale the sediment is a bioclastic wackestone, locally packstone (biopelmicrites) with approximately 30-50% bioclastic material. The matrix is an inhomogeneous dense peloidal micrite, with a vague wavy lamination in areas. The peloidal material is polygenic in origin, comprising faecal pellets, highly micritized bioclasts, lithoclasts and peloids of presumed microbial origin. This admixture of peloids has subsequently been compacted and further bound by microbial peloidal material. The bioclastic material consists of angular, very poorly sorted grains ranging from less than 0.01 to 10 mm in size (average approximately 1 mm). It shows a considerable taxonomic richness, with corals, gastropods, bivalves, serpulids, red algae, echinoids, calcified cyanobacteria and forams being particularly abundant. Much of the bioclastic material shows a high degree of micritization and possess well developed spongiostromate coatings up to 3 mm thick. This would suggest that the bioclastic material was not rapidly buried but resident on the sediment surface for a considerable amount of time. Thus a low background sedimentation is envisaged in the source area.

Carbonate sand facies. This facies occurs as well developed carbonate sandwaves with large fining upward avalanche foresets and suggests effectively unidirectional flow (plate 4.2-fig 1). The structural

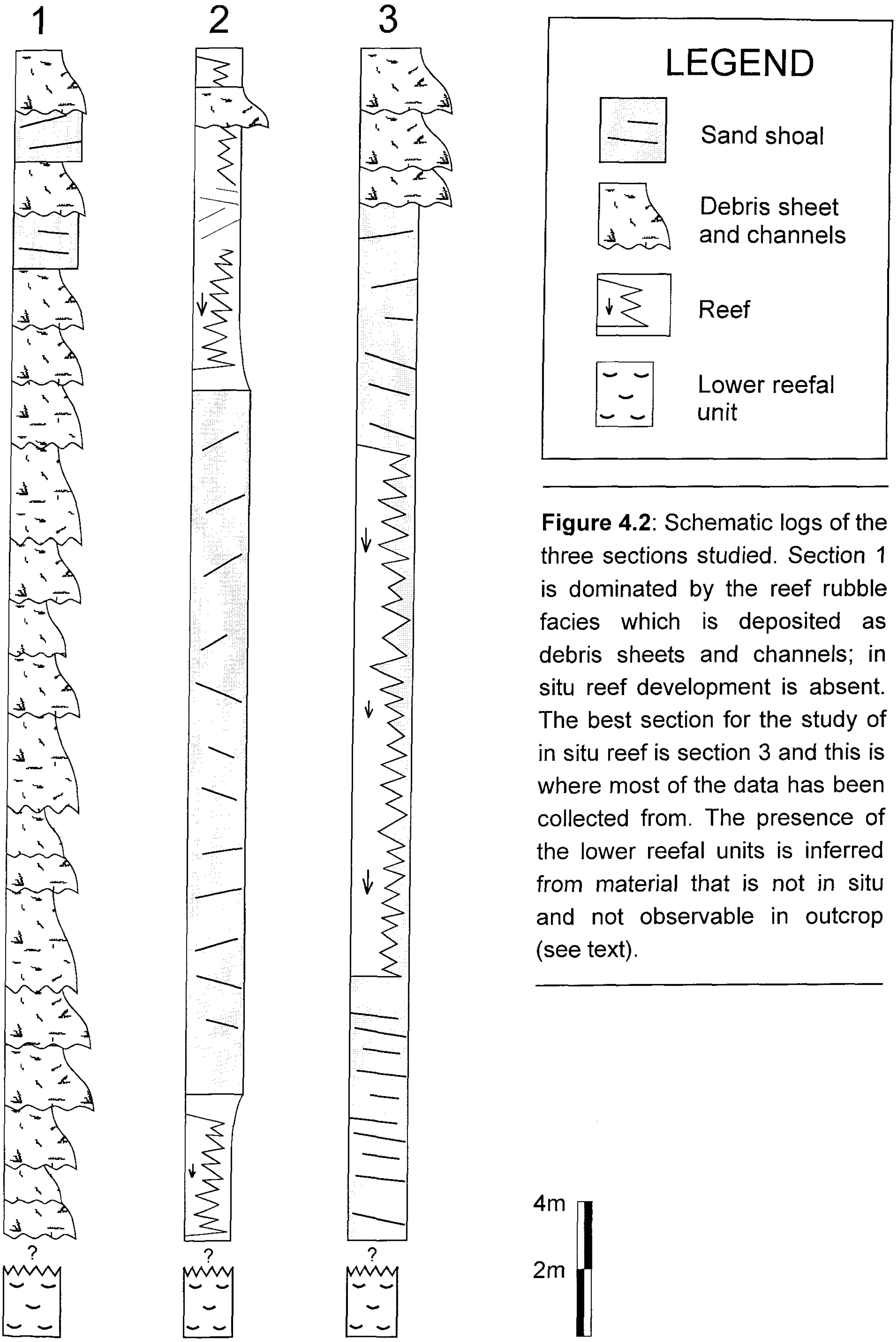


Figure 4.2: Schematic logs of the three sections studied. Section 1 is dominated by the reef rubble facies which is deposited as debris sheets and channels; in situ reef development is absent. The best section for the study of in situ reef is section 3 and this is where most of the data has been collected from. The presence of the lower reefal units is inferred from material that is not in situ and not observable in outcrop (see text).

style of the sandwaves, impoverished benthic fauna and lack of bioturbation indicate constantly shifting, unstable carbonate shoals. However the mature nature of the carbonate grains suggests that the grains had a high residence time on the sediment surface, allowing them to become well rounded, highly micritized and coated. This again suggests a contemporaneous more stable, lower energy source area with low background sedimentation rates.

The sands are well washed bioclastic grainstones (biosparites). Carbonate grains constitute 20-60% (average 50%) and are set in a sparitic cement, with micritic matrix generally less than 10%. The grains are moderately to well sorted, well rounded and generally coarse grained (finer bands: 0.2-0.5 mm up to 1 mm; coarser bands: 0.5-1.6 up to 3 mm). The carbonate grains include bioclastic material (15%), highly micritized and coated grains (50%) and intraclasts (15%). There is little evidence of compaction and cementation would appear to have been very early. Bioclastic material includes forams which are extremely common (numerically most abundant group), bivalves, gastropods and small rounded coral fragments.

In situ reef. In situ reef development occurs in small localised patches throughout the sections. The preserved reef patches tend to be domal in form, of small size (approximately 11 m high and 20 m across), lacking internal architecture (plate 4.1-fig 1) and dominated by thin branching ramose corals (plate 4.4-figs 1-2). Details of the facies, framework construction and palaeoecology of the in situ reef are given in subsequent sections. The fact that the sections are dominated by reef rubble facies suggests that in situ reef development was far more extensive than the present extent of reef framework indicates.

Inter-facies relationships and transitions

The field relationships between these three facies is shown in figure 4.3 and plate 4.1-fig 2. The relationship between in situ reef framework and clean carbonate sand changes throughout the growth of the reef. During the initiation and early stages of reef growth the lateral transition from the carbonate sand to in situ reef is gradational over approximately 3 to 4 m. From carbonate sandwave to in situ reef there are increases in the proportions of: oncoids; micrite relative to sparite; micrite relative to grains; peloidal intraclasts; coral bioclasts; and grain angularity.

During the later stages of reef development, reef growth accelerated and/or the rate of sandwave encroachment decreased, which resulted in the development of moderate reef relief (?5-8 m). This led to an onlapping relationship between carbonate sands and the reef in the latter stages of reef growth. The transition from carbonate sand to reef facies at the base of the reef follows the same patterns as the lateral transition, though it is far more rapid, occurring over 15 cm. This transition represents stabilisation of the sand facies. The reef is terminated by bioclastic material and reef rubble.

4.1.3. Reef-building, framework construction and cavity development

Reef growth commenced during phases of reduced sandwave mobility. During such periods the loose

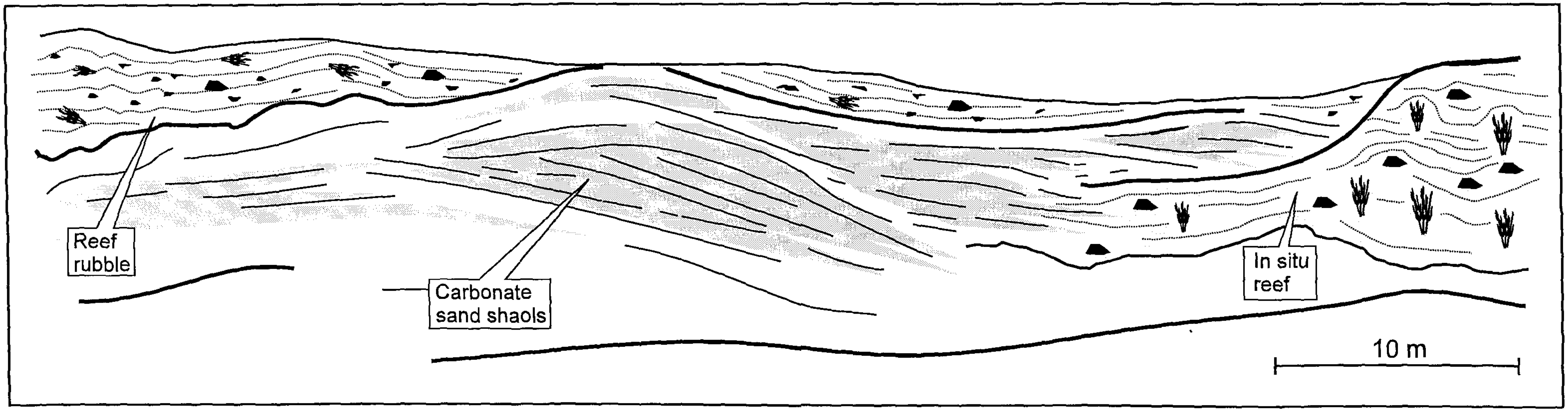


Figure 4.3: Feild sketch showing the relationships between the three main facies; l'Épine, quarry 3. Traced from photomontage.

carbonate sands were further stabilised by the swift development of microbial mats over the static sediments. The subsequent rapid cementation of the microbialite then provided a suitable substrate for coral colonisation. The reef construction is dominated by microbialite, which constitutes approximately 70% of the reef's total volume. Corals, although volumetrically of secondary importance to microbialite, representing only 10-15% of the total reef's volume, are nevertheless extremely important to the development of these reefs for three reasons: (1) they provided the "skeleton" over which the microbialite encrusted; (2) they provided the main component of vertical growth and hence defined the reef's form; and (3) they are primarily responsible for the formation of numerous reef cavities (see below). Framework construction and reef development was therefore a two step process. Firstly, the growth of branching ramose corals provided the primary loose framework which subsequently acted as a site for the precipitation of large volumes of peloidal material. Secondly, the early cementation of the microbialite bound the framework together and gave the reef structural rigidity. Intra-reef sediment is very scarce, constituting less than 10% of the reef, and is generally restricted to the cave cavities.

Throughout the development of the reef a number of small intra-reef cavities were created by the process of local, small scale "roofing over". These cavities, although small (generally less than 1 m across), are relatively frequent, accounting for approximately 10% of the total reef volume. Extending from the roofs of these cavities are well developed "pseudostalactites" and "pillows" of dense hard microbialite (plates 4.5-4.6). These are virtually identical in form to those described from Lower Kimmeridgian reefs at Le Chay, La Rochelle, France (Taylor and Palmer, 1994) and numerous Upper Jurassic reef localities in Portugal (Leinfelder *et al.*, 1993b).

The pseudostalactite is the more common of the two forms. The surface of the microbial pseudostalactite is made up of numerous accreted torpedo-shaped increments of microbialite ("microbial pendants") (plate 4.6-fig 3). Each microbial pendant is about 2-3 cm long and 1 cm in diameter. The shape of these increments is defined by the extremely early cementation of the micrite and gravitational forces pulling down on the free growing microbialite. Fine sediment must have adhered readily to the surface of the microbial mass (by cementation, surface tension or unknown microbacterial action) if the steep sides of the projecting knobs were to keep their shape. Bioclastic material constitutes 10 to 20% of the microbialite and is made up predominately of fine grained (less than 0.5 mm), angular, poorly sorted coral fragments. Large coral fragments up to 50 mm across are occasionally incorporated into the pseudostalactite.

A transverse section through these pseudostalactites reveals a megascopically clotted fabric, with clots of approximately 2-4 mm in diameter (plate 4.7-fig 1). Around the external region of the pseudostalactite, in between the microbialite, are numerous primary pores with similar dimensions and shapes to the clots (plate 4.2-fig 2). These voids can constitute up to 30% of the surface area in the outer regions of the pseudostalactite. They gradually decrease in number towards the centre of the pseudostalactite which is formed by dense microbialite and lacks voids (plate 4.7-fig 1). The darker clots in the core of the pseudostalactite represent the voids that have been infilled by silt-sized skeletal debris and peloids in a sparitic cement. Commonly these darker clots are only partly infilled with debris and peloids, with the remaining space being in-filled by sparite. This internal structure is therefore a consequence of the growth of the pseudostalactite, which developed a very porous structure. The voids in the centre of the pseudostalactite have had sufficient time to be infilled by later generations of microbialite, sparite and fine detrital material. The voids around the external part of the pseudostalactite, being much younger, have not had enough time to be infilled prior to the termination of pseudostalactite growth and therefore remain open.

The space created by these caves was infilled either passively by fine grained bioclastic sediment or actively by dense microbialite growing from the floors, walls and ceilings of these cavities (the main mechanism of cave fill). The sediment infill is composed of very fine grained, poorly cemented chalky sediment. Bioclastic material is rare, fine grained (grain size 0.1 - 0.5 mm), angular and often highly micritized. The matrix is a detrital fine lime mud with some local sparite cements. Forams are extremely abundant.

4.1.4. Depositional environment (figure 4.4)

The facies were deposited on a clean carbonate platform with no siliciclastic influx. The carbonate sands represent active, constantly shifting sub-tidal sand shoals. During periods of inactivity the sand shoals were further stabilised by microbial mats and colonised by reef organisms. Reef development occurred on these stabilised sediments and in quiet areas protected by shoals. The stable sediments and the rubble facies in between isolated reef frameworks contained a rich mollusc fauna. Tidal and storm blow-out channels were abundant and shifted across the depositional environment. Debris sheets rich in reefal material were deposited following storm erosion and surf disintegration of the reefs in the more exposed areas. Currents and wave action was generally strong, and sufficient to drive sandwave migration, develop tidal channels and prevent deposition of mud and silt. These facies developed in the upper sub-tidal zone and hence water depths were shallow, no more than few a metres. Conditions were fully marine, as indicated by the stenohaline nature of the fauna (see below).

4.1.5. Coral fauna

Facies distribution of coral fauna

The distinction of the two coral facies is based primarily on the presence or absence of in situ framework and the depositional style of the facies. However examination of the two facies reveals that their coral composition is different. The reef rubble facies is overwhelmingly dominated by branches of *Dendrohelia coalescens*, which constitutes up to 80% of the total coral skeletal biovolume (plate 4.3). Within the in situ reef frameworks dominance patterns are not so marked; *Dendrohelia coalescens*, although certainly present, is generally subordinate to *Thamnasteria dendroidea* and other branching forms (plate 4.4). This raises the question of whether the reef rubble facies represent debris from a reef type with a different coral assemblage to that of the in situ reef, or whether it reflects a taphonomic concentration of *Dendrohelia coalescens* derived from reefs of similar composition to those preserved in the sections?

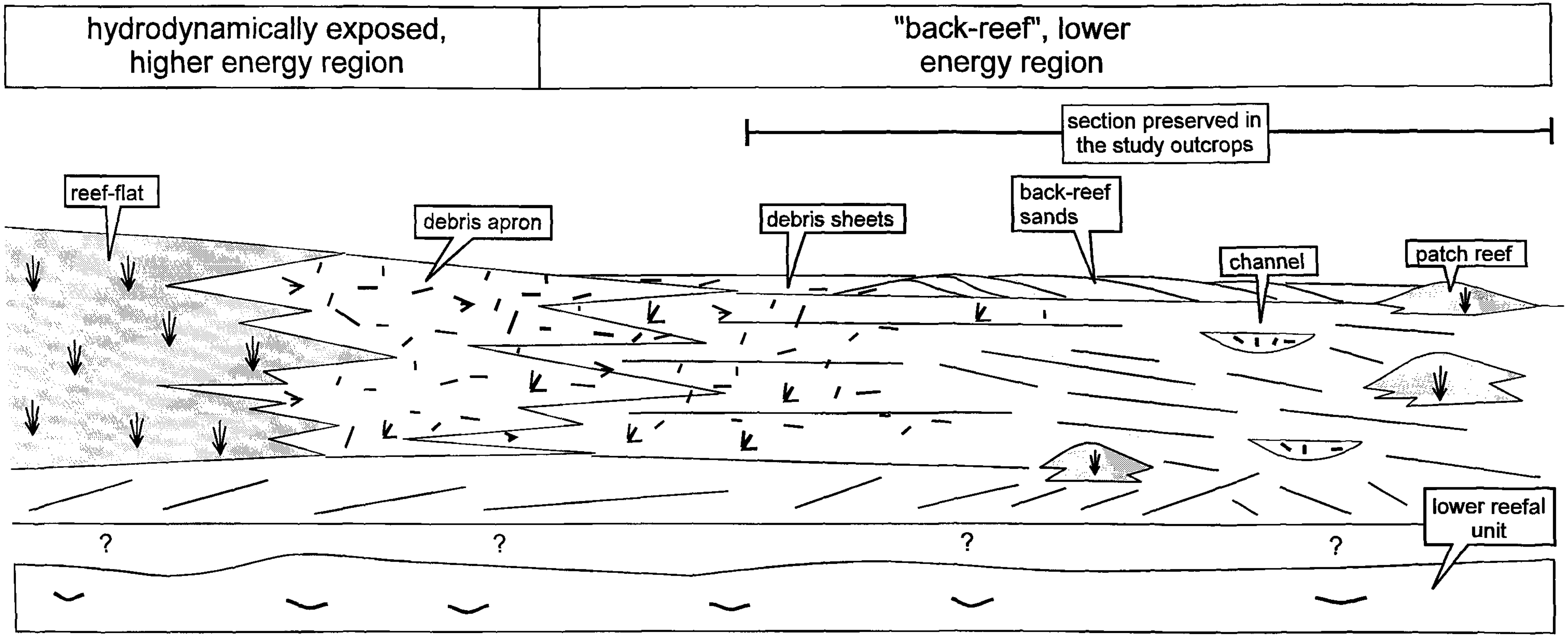


Figure 4.4: Schematic model for the development of the reefal units in the Ardennes. The higher energy reef-flat is inferred to be dominated by the branching ramose *Dendrohelia coalescens,* however this is not observed in outcrop. This reef-flat supplied vast amounts of *Dendrohelia* dominated reef debris to the "back-reef" areas and was deposited as reef rubble debris sheets. These gave way to an environment dominated by carbonate sands, channels and local patch reefs. The lower reefal unit appears to be dominated by platy microsolenids and is similar to other lower reefal units encountered in other regions (see text). The presence of this lower reefal unit in the Ardennes is inferred from isolated blocks of reef fabric and river deposits; it has not been located in outcrop.

Taphonomic concentration of *D. coalescens* in the reef rubble facies seems unlikely for two reasons:

1. taphonomic features of the mollusc and coral fauna in the reef rubble facies indicates that the material is not far travelled and has been deposited very near or even at the site of reef development. Therefore it is questionable whether there was enough transport time for such a concentration to occur; and
2. other branching corals, which should have been transported just as easily, are not present in significant numbers within the reef rubble facies.

Therefore it is likely that the *D. coalescens*-dominated rudstones represent autochthonous to proximal parautothchonous sheets of material derived from reefs compositionally different to those preserved in the sections studied. Thus two reefs types can be recognised: (1) *observed* reef patches not dominated by *D. coalescens*; and (2) *inferred* reefs dominated by *D. coalescens*.

Coral assemblage

Taking both reefal facies into account these reefs are taxonomocally very rich, with 26 genera having been identified. Compositionally, the coral fauna is typically “Tethyan”, containing many of the genera that are common in the Upper Jurassic reefs of Lorraine, Burgundy and the Swiss Jura.

The in situ patch reefs are dominated by loose colonies of branching ramose forms, which constitute over 70% of the coral skeletal biovolume and are the principal framebuilders. Four branching ramose forms have been identified: *Dendrohelia coalescens* (plate 4.9-figs 1-2), *Thamnasteria dendroidea* (two forms), *Allocoenia* sp. (plate 4.8-figs 3-4) and *Dendraraea racemosa*. *Thamnasteria dendroidea* dominates, though *Allocoenia* and *Dendrohelia* are also common.

Two forms of *Thamnasteria dendroidea* have been recognised:

1. form A, which is by far the more abundant of the two and is a very thinly branched form with branch thickness generally less than 0.8 mm (plate 4.8-figs 1-2). This form of *T. dendroidea* generally developed as very loose thickets with sinuous branches reaching a height of 1.5 m (plate 4.4).
2. form B has far thicker branches, generally greater than 15 mm and has a significantly higher branch packing density per colony. It developed colonies of similar dimensions to *form A*.

Although there may be some gradation between the two forms in terms of branch packing density, in the majority of cases *form A* developed as loose colonies and *form B* denser colonies. In terms of branch diameter there is a clear bimodal distribution of values around 0.6 mm (*form A*) and 15 mm (*form B*). These two forms have almost identical calicular structure (plate 4.8-fig 2), although the distance between adjacent calicular centres is significantly less in *form A* (1-1.5 mm in *form A*; 2-3 mm in *form B*). Whether these two forms represent different species or simply different growth forms remains unclear until more rigorous systematic analysis is undertaken.

Dendrohelia coalescens forms dense thickets of robustly branching colonies which can reach 1.7m in height and possess thick branches (generally greater than 2 cm thick). Branching phaceloid forms, although volumetrically much less dominant, still contribute to framework construction and are represented by some 7 genera; *Calamophylliopsis*, *Cladophyllia*, *Thecosmilia*, *Goniocora* and

Stylosmilia being the most abundant. These occur as loosely packed thickets occasionally reaching 60 cm in height.

The massive and solitary forms contributed very little to framework construction and are best interpreted as secondary framebuiders and dwellers. The massive forms are generally small dome-shaped forms rarely exceeding 5 cm in height and 7 cm across, whilst the solitary cylindroid forms are approximately 10 cm high and a few cm across. Although these constitute a small proportion of the coral skeletal biovolume as a consequence of their small size, they are numerically abundant and taxonomically rich. *Diplocoenia* (plate 4.9-fig 3-4), *Fungiastraea*, *Stylina*, *Latomeandra*, *Thamnasteria* (plate 4.9-fig 5) and *Microphyllia* are particularly abundant and characteristic of the fauna.

Within the caves very thin encrusting and foliaceous forms of *Thamnasteria* and ?*Isastraea* occur, in fact the only corals to do so. These foliaceous forms are extremely thin, less than 2 mm thick, and up to 12 cm across. In general they encrust the roofs and walls of the caves, though occasionally occur as foliaceous outgrowth directly off the walls of the caves. The plates are encrusted on both their upper and lower surfaces by thecidean brachiopods, serpulids, forams and microbialite; they can also be highly bored. The restricted coral fauna of these caves is probably a result of the extremely low light intensities within the cave. However the absence of zooxanthellate species that are particularly tolerant to low light levels, such as the microsolenids (see chapter 7, section 7.1; Insalaco, 1996a), may suggest that light levels were sufficiently low to exclude all zooxanthellate corals. If this is the case, these cave dwelling species of *Thamnasteria* and ?*Isastraea* may have been non-zooxanthellate.

In summary the sections provide evidence for the existence of two reef types (also see figure 4.4):

(1) *Dendrohelia coalescens*-dominated frameworks which developed in more exposed, higher energy, environments. *D. coalescens* developed as large dense thickets which could reach up to 2.3 m in height. Their dense thickets and thick branches presumably increased their mechanical strength, thus allowing them to colonise such wave-controlled environments. From these frameworks were produced vast amounts of reefal debris deposited as sheets and channels. These represent both storm erosion and surf disintegration of these frameworks.

(2) Small patch reefs developed in the more protected, lower energy environments. These reefs also had abundant branching ramose forms but *Dendrohelia coalescens* no longer dominated. In these reefs *Thamnasteria dendroidea* (form A) is the main framebuilder. Phaceloid forms such as *Calamophylliopsis*, *Thecosmilia*, *Goniocora* and *Stylosmilia*, and small dome-shaped forms of *Stylina*, *Fungiastraea* and *Diplocoenia,* are common. In these environments energy levels were comparatively lower and the environment was characterised by highly mobile carbonate sands and shifting channels. Here, the ability to cope with mobile sediments and episodic periods of rapid sedimentation was paramount.

Coral fauna from the in situ reefs:

PRINCIPAL FRAMEBUILDERS:

Branching ramose forms:

Dendrohelia coalescens
Thamnasteria dendroidea (form A)
Thamnasteria dendroidea (form B)
Allocoenia
Dendraraea

Branching phaceloid forms:

Goniocora
Latomeandra
Cladophyllia
Thecosmilia
Calamophylliopsis
Stylosmilia

SECONDARY FRAMEBUILDERS AND DWELLERS:

Massive forms:

Diplocoenia
Stylina
Fungiastraea
Microphyllia
Stephanastraea
Cyathophora
Isastraea
Meandrophyllia
Microsolena
Thamnasteria sp. 1
Thamnasteria sp. 2

Solitary forms:

Epistreptophyllum
Haplaraea

Encrusting forms:

Thamnasteria
Isastraea

Coral fauna from the reef rubble facies

In addition to the genera found in the in situ reefs four genera were found solely from the coral rubble facies: *Dermoseris, Montlivaltia, Mixastraea* and *Mesomorpha.*

Details of the growth form, habit and size of the coral fauna.

Coral	Growth form	Integration	Growth Habit, Size
Allocoenia	Branching ramose	Cerioid	Loosely packed thickets. Sinuous branches with a thickness of 1 cm. Colony height 60 cm
Calamophylliopsis	Branching phaceloid	Phaceloid	Loosely packed thickets; colony height 40 cm
Cladophyllia	Branching	Phaceloid	Densely packed thickets; colony height 50 cm
Cyathophora	Massive	Plocoid	Small dome shaped colonies. Colony width 10 cm; height 6 cm.
Dendraraea	Branching ramose	Thamnasteroid	Branch thickness, 1.5 cm. In situ colonies not seen.
Dendrohelia coalescens	Branching ramose	Plocoid	Large densely packed thickets. Branch thickness over 2 cm; colony height up to 2 m
Dermoseris	Branching phaceloid	Phaceloid	In situ colonies not seen
Diplocoenia	Massive to sub-branching ramose	Cerioid - sub-plocoid	Small dome shaped colonies, colony width 10 cm; height 6 cm. Some colonies show a sub-branching ramose form.
Epistreptophyllum	Solitary, Cylindroid	------------------	------------------
Fungiastraea	Massive	Thamnasteroid	Small dome shaped colonies. Colony width 10 cm; height 6 cm
Goniocora	Branching phaceloid	Phaceloid	Large loosely packed, thickets with steep angled lateral budding. Colonies up to 1.
Haplaraea	Solitary, Cylindroid	------------------	------------------
Isastraea	Massive,	Cerioid	Dome to plate-shaped colonies. 10 cm thick. ? Very thin foliaceous plates. Colony thickness 2 mm, width up to 12 cm
Latomeandra	Branching phaceloid	Phaceloid	Small colonies with few branches; height 15 cm
Meandrophyllia	Massive	Meandroid	Small dome shaped colonies. Colony width 10 cm; height 6 cm
Mesomorpha	Massive	Thamnasteroid	Small dome shaped colonies. Colony width 5 cm; height 3 cm
Microphyllia	Massive	Meandroid	Small dome shaped colonies. Colony width 8 cm; height 3 cm
Microsolena	Massive	Thamnasteroid	Small dome to platy colonies. Colony width 10 cm; height 4 cm
Mixastraea	Massive	Thamnasteroid	Small dome shaped colonies. Colony width 4 cm; height 3 cm
Montlivaltia	Solitary	------------------	------------------
Stephanastraea	Massive	Cerioid	Small dome shaped colonies, colony width 4 cm, height 3 cm
Stylina	Massive	Plocoid	Dome shaped colonies. Colony width up to 10 cm; height 10 cm
Stylosmilia	Phaceloid	Phaceloid	Loose thickets; colony high 80 cm
Thamnasteria	Massive	Thamnasteroid	Small dome shaped colonies. Colony width 5 cm, height 3 cm
	Encrusting	Thamnasteroid	Very thin foliaceous plates. Colony thickness 2 mm; width up to 12 cm.
Thamnasteria dendroidea	Branching ramose	Thamnasteroid	*Form A.* Mainly as very loose thickets with thin branches. Branch thickness generally <0.8 mm. Colony high over 1m
			Form B. Densely packed thickets with thick branches. Branch thickness generally over 15 mm. Colony high over 1m
Thecosmilia	Branching phaceloid	Phaceloid	Loose colonies; colony height 50 cm

(Data from both in situ reefs and reef rubble facies).

4.1.6. Associated fauna

The associated fauna is particularly well developed, with a comparatively diverse mollusc and echinoderm fauna (see list below). Also notable is the very high diversity of boring ichnotaxa. These include borings from a number of organisms including sponges (*Entobia*), phoronids (*Talpina*) and bivalves (*Gastrochaenolites*) which are all common, particularly *Entobia*. Forams are abundant and mainly small benthic agglutinates. The roof and walls of the reefal caves are encrusted by serpulids, thecedean brachiopods, encrusting forams, bryozoans and thin foliaceous corals; however this cryptic community is not well developed. The paucity of the cryptic community relative to similar habitats (e.g. Taylor and Palmer, 1994) is probably a result of the higher energy levels that the Ardennes reefs grew in (also see chapter 7, section 7.2). 15 cm large domes of red algae have been found in some of the rubble channels, though as yet not within the in situ reef.

List of associated fauna from the reef rubble facies (1) and reef facies (2). (From Bertling and Insalaco, in prep.).

		1	2
Gastropoda			
Pleurotomariacea	*Conotomaria* cf. *guirandai*		•
	Trochotoma (Discotoma) amata		•
	Trochotoma (Discotoma) mastoidea	•	•
Fissurellacea	*Rimulopsis* sp.		•
Patellacea	*Helcion (Helcion) valfinensis*	•	
Trochacea	*Angaria (Angaria) bistellata*		•
	Muricotrochus daedalus	•	
	Asperilla Stellata	•	•
	Chilodonata (Chilodonata) clathrata	•	•
Naritacea	*Neritopsis (Neritopsis) buchini*	•	
Subulitacea	*Bourguetia saemanni*	•	
Littorinacea	*Purpuroidea nodulata*	•	
	Purpuroidea moreana	•	
Cerithiacea	*Brachytrema (Petersia) buccinoidea*	•	•
	Xystrella? insculpta	•	
	Xystrella struckmanni	•	•
	Exellia cf. *gemmelaroi*	•	
	Rhabdocolpus humbertinum	•	
Strombacea	*Spinigera or Quadrinervus cf alta**	•	
Naticacea	*Globularia (Globularia) amata*	•	
	Tylostoma ponderosum	•	
Nerineacea	*Crytoplocus depressus*	•	•
	Cossmannea suprajurensis	•	
	"Nerinea" elongata	•	
	"Nerinea" subelegans	•	
	Ptygmatis ornata	•	
Bivalvia			
Aracacea	*Arca (Eonavicula) autissiodorensis*	•	
	Barbatia (Barbatia) clytia	•	•
	Barbatia (Barbatia) subtexata	•	•
	Grammatodon (Grammatodon) montanayensis		•
	Grammatodon (Grammatodon) elongatum	•	•
	Grammatodon (Grammatodon) corallivorus		•
Mytilacea	*Arcoperna? socialis*		•
	Lithophaga antica		•
	Modiolus (Modiolus) longaevus		•

List of associated fauna from the reef rubble facies (1) and reef facies (2); continued. (From Bertling and Insalaco, in prep.).

		1	2
Pteriacea	*Pteroperna polydon*	•	
	Hypotrema sp.		•
Limacea	*Antiquilima (ctenolima) aequilatera*	•	•
	Plagiostoma rathierana	•	•
	Plagiostoma tumida	•	
Ostreacea	*Liostrea sandalina*	•	•
Lucinacea	*Fimbraria dyonisea*	•	
	Lucinidae gen. indet.	•	
Crassatellacea	*Pressastarte substriata*	•	
	Astartopsis polita	•	
Tellinacea	*Quenstedtia?* n. sp.?	•	
Glossacea	*Ceratomyopsis cf. rupellensis*	•	
Gastrochaenacea	*Gastrochaena (Rocellaria) flora*	•	•
Pholadacea	*Jouanettia (Jouanettia) gelyana*		•
Megalodontacea	*Pterocardia buvignieri*	•	
Hippuritacea	*Diceras* cf.*arietina**	•	
Ammonoidea			
Perisphinctacea	*Perisphinctes* cf. *plicatilis*	•	
Articulata			
Terebratulaceae	*Juralina etalloni*	•	
Echinozoa			
Cidaroida	*Paracidaris* sp. (spines)	•	
Pedinoida	*Phymoperdina marchamensis*		•
Hemicidaroida	*Hemicidaris* sp. (spines)	•	•
	Hemicidaris crenularia		
	Gymnocidaris? sp. (spines)	•	
Phymosomatoida	*Phymechinus mirabilis*	•	
Polychaeta			
Serpulimorpha	*Spirorbis* sp.	•	
	Vermiliopsis sp.	•	
Crustacea			
Dromioidea	*Pithonoton (Pithonoton)* sp.	•	
Borings			
(by clionid sponges)	*Entobia cervicornis*		•
	Entobia n. isp.	•	
?	*Uniglobites* n. isp.	•	
?	*stellate boring* (juvenile sponge?)	•	
(by phoronids)	*Talpina bromleyi*	•	•
(by polychaetes)	*Cunctichnus probans*	•	
(by polychaetes)	*Spirichnus spiralis*	•	•
(by spionids)	*Meandropolydora sulcans*	•	•
(by eunicids)	*Caulostrepsis cretacea*	•	•
	Caulostrepsis n. isp.	•	•
(by eunicids?)	*Conchotrema canna*	•	•
(by acrothoracics)	*Rogerella pattei*		•
(by *Lithophaga*)	*Gastrochaenolites torpedo*	•	•
(by *Arcoperna*?)	*Gastrochaenolites lapidicus*		•
(by *Gastrochaena*)	*Gastrochaenolites dijugus*	•	•
(by *Jouanettia*)	*Gastrochaenolites orbicularis*		
(by sipunculids?)	*Trypanites*	•	
Other trace fossils			
(polychaete burrow)	*Arachnostega gastrochaenae*	•	•
(echinozoan bite)	*Gnathichnus* sp.	•	

(* Identification courtesy of Dr. Noel Morris of The Natural History Museum.) This material is housed at: (1) School of Earth Sciences, The University of Birmingham, England; (2) Department of Palaeontology, The Natural History Museum, London, England; (3) Geologisch-Paläontologisches Institut, Münster, Germany.

4.2: NORMANDY

4.2.1. Introduction

The section studied crops out in a recently reopened (1984) private Quarry (owned by Mr. Dagoneux). The quarry is located just to the south of the village of s/s Apainei, south of Bellême, in the Mortage region of Normandy (figure 4.5). The outcrop reveals a sequence of channelised oolitic and oncolitic limestones with small scale local reefal development (figure 4.6; plate 4.10-figs 1-3). The units studied form part of the "Couches a Diceras et polypiers" and "Oolithe de Mortagne et Bellême" and are of Middle Oxfordian age (Plicatilis to Cautisnigrae Zones) (Enay and Mangold, 1980). There has been no work carried out on the reefal unit of this quarry. Indeed the only work carried out on the reefs of this area has been by Dangeard (1951) and by Beauvais *et al.* (1974). Both these studies, which where carried out on now non-existent outcrops in Bellême, are essentially taxonomic, with little attention given to framework development and reef sedimentology.

4.2.2. Reef structure and facies

Reef structure and framework development

The individual reefal units are lensoid in shape with a visible lateral extent of approximately 30 m and a maximum vertical extent of 2.3 m. Similar reefal units have been documented 3 km to the north at Bellême (Beauvais, *et al.*, 1974) suggesting that these reefal patches have a wide distribution. Framework construction is primarily by loose branching ramose forms (plate 4.10-fig 4), although peloidal fabrics enveloping the coral framework suggests that microbial binding may have also occurred. Coral skeletal biovolume is approximately 30%. Locally, relatively large (up to 30 cm across) domed colonies of red algae seem to bind small patches of massive corals; however this is not widespread.

Facies and sedimentology (figure 4.6)

Four facies have been identified: (1) reefal facies (coral thickets); (2) oncolitic and oolitic grainstones, mainly deposited as channels and sheets; (3) coral rubble facies; and (3) diceratid channels and banks (plate 4.11). The first 7 m of the sequence consists of a series of channellized oolitic and oncolitic limestones. Within these units 0.3 to 1 m thick bedding is well developed. Also frequent are prominent surfaces spaced at approximately 2 m intervals which are believed to represent storm erosion surfaces. These are not accessible to confirm this.

Oncoidal and oolitic grainstones. These are very clean, well winnowed, moderate to poorly sorted, sparites and biosparite with very little matrix (less than 10%, peloidal where present; M/S/C: 0-5/10-15/10). The allochems are coated grains, bioclasts and peloidal lithoclasts. Skeletal material is predominantly of bivalves, gastropods and forams, though echinoderms and corals are also present.

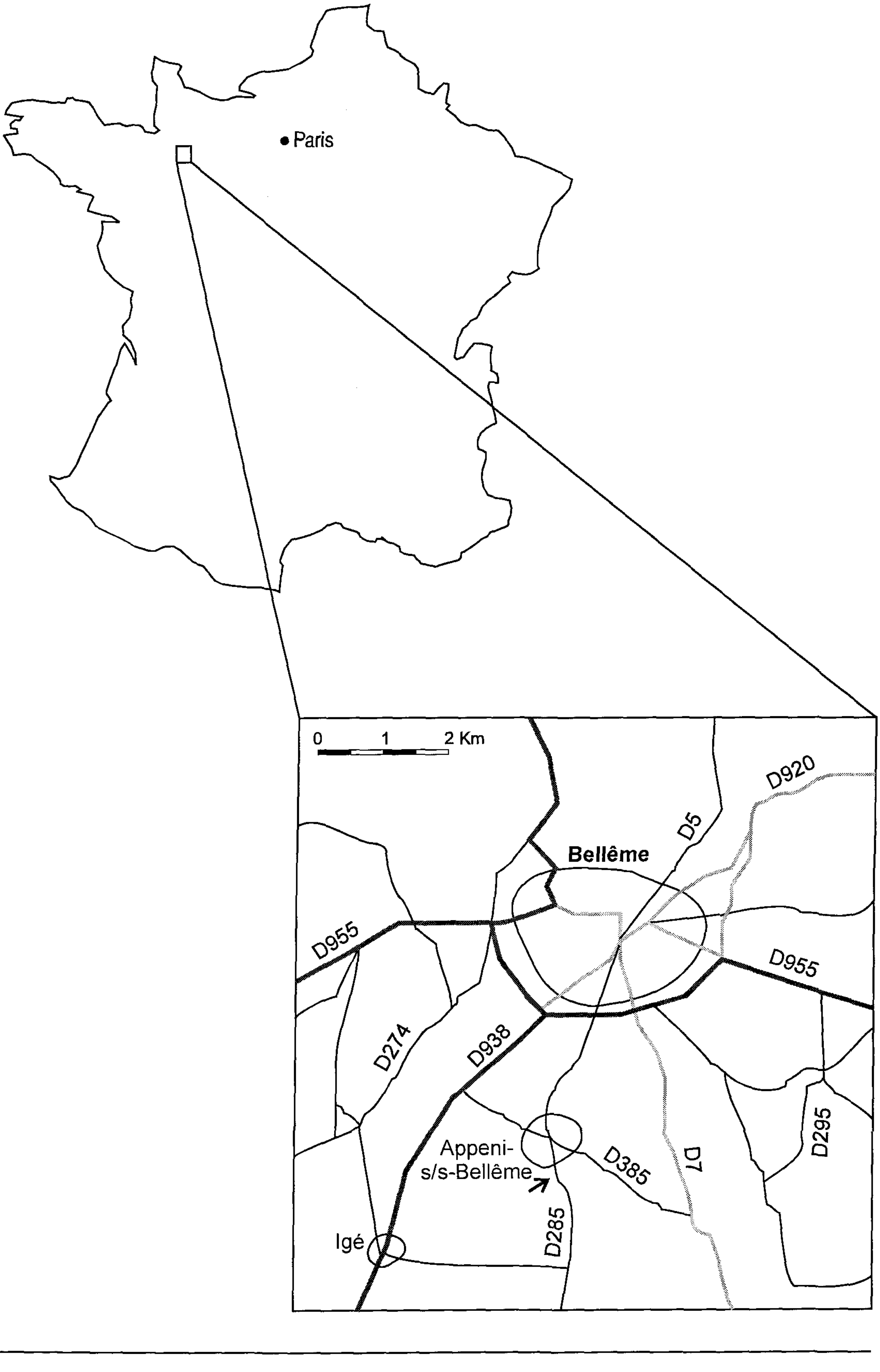
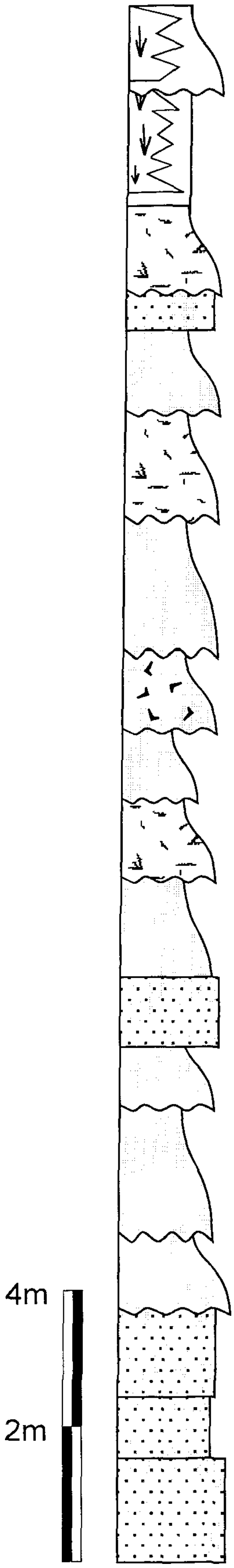


Figure 4.5: Location map of the section studied at Bellême, Normandy. Location of quarry section marked by arrow.



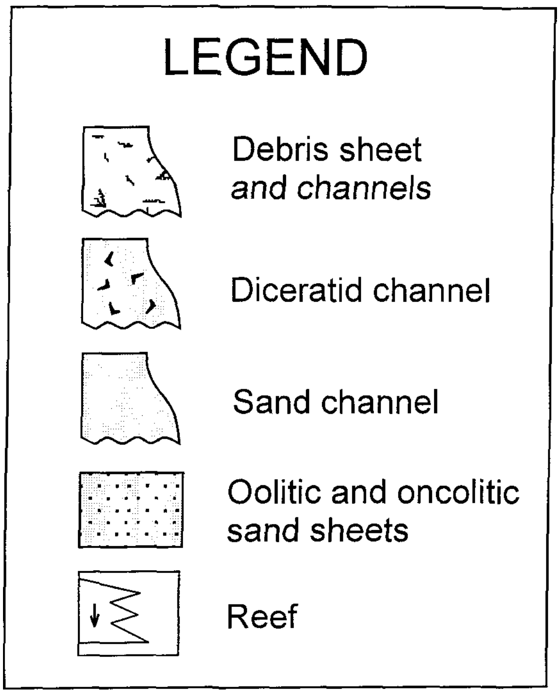


Figure 4.6: Schematic log of the Bellême section.

Almost all grains are either coated and/or have a well developed micrite envelope. Grain micritization is strong and abundant amongst bioclasts. Intraclasts of oncoidal grainstone, although small (general less than 10 mm) and not common, are present. Both poro- and spongiostromate oncoids occur, though the latter predominates (90% of the oncoids present are spongiostromate). Double and compound oncoids are common. Many of the nuclei from the oncoids have been dissolved away, suggesting that they were fragments of coral or diceratid. Elongate oncoids and shell fragments show a moderate preferred orientation parallel to bedding. These sediments have been deposited as shoals, or more frequently redeposited within storm channels and sand sheets.

Coral rubble. To the west of the quarry sheets of coral rubble dominate the sequence. Corals and nerineid gastropods are abundant though not in situ. The sediment is a poorly sorted gravelly oncolitic wacke- to packstone. M/S/C ratios are 10-30/0-10/70; onco-biopelmicrite. Intraclast are common and some large oncoids over 2 cm in diameter occur. Similar sediments occur in the diceratid channel deposits.

In situ reef. The intra-reef sediments are bioclastic mudstone to wackestone with small areas of grainstone; M/S/C ratios are approximately 40-60/0-10/30-50 (biomicrites). Oncoids are completely absent and the allochems are dominated by small (0.005 mm), angular and moderately well sorted bioclasts, mainly of coral. The matrix is almost totally composed of a dense peloidal micrite which lacks clear laminations though in areas vague peloidal rinds are present. Peloidal fabrics can be abundant around coral branches. Bioclasts and biomorphs possess spongiostromate crusts and coatings.

4.2.3. Palaeoecology

Associated fauna

The associated fauna is well developed in both the reef and oncoidal/oolitic facies. The bivalves appear to be the most abundant group within the reef. These include cemented forms such as *Liostrea* and byssate attached forms such as arcids and mytilids (*Arca, Barbatia, Modiolus* and *Opis*) which nestled themselves within the reef's framework. Free living and fissure dwelling forms such as *Chlamys* are also abundant. The diceratid *Eodiceras perversum* (pers. com. P. W. Skelton, 1995) is exceedingly common, occurring in rich concentrations in channel deposits and less frequently in in situ banks (plate 4.11); it was not found within the reefs. Boring bivalves (*Lithophaga* and *Gastrochaena*) are extremely common and their boring intensity is extremely high with some coral heads being completely destroyed (up to 16 borings per 5 cm^2 of coral surface; plate 4.12-figs 1-3). Traces of other boring organisms such as clionid sponges (*Entobia*) and *Talpina* are present though they appear to be less abundant. Gastropods are reasonably common in the sediments around the reefs and are represented by *Bourguetia, Nerinea, Turbo* and *Trochotomata* (also found within the reef). *Nerinea* is particularly common with at least 2 species being present (plate 4.12-fig 5). Red algae (*Solenopora*; plate 4.12-fig 4) and calcified cyanobacteria are abundant and the former can locally contribute to framework construction. Echinodermata are very poorly represented; crinoids are absent and regular echinoids are unusually scarce. Small terebratulid brachiopods can be found nestling within the reef framework. Foraminifera are relatively very abundant and include free living and encrusting forms including *Pseudocyclammina, Pseudocyclammina*, *Alveosepta*, *Conicospirilina*, *Camptocomphlodon* (Beauvais, *et al.*, 1974). Bryozoans, *Terebella* and *Serpula* are seen encrusting some of the coral branches though their occurrence is rare.

<u>Coral fauna</u>

Branching ramose growth forms dominate the coral fauna, representing approximately 70% of coral skeletal biovolume. These include:

1. the thinly branched form of *Thamnasteria* (*Thamnasteria dendroidea*; form A; branches up to 1 cm in diameter). This is the most dominant coral and forms the majority of the coral thickets. Its thin branches are straight to slightly sinuous in form and the colonies develop as rather loose thickets;
2. the thickly branched form of *Thamnasteria* (*T. dendroidea*; form B; branches 2 cm in diameter). This sub-ordinate to form A and only one in situ colony has been observed; and
3. the branching ramose stylinid (*Dendrohelia coalescens*) (plate 4.13-figs 1-2).

Also important are the large massive and domal forms which can be up to 40 cm in diameter and constitute approximately 20% of coral skeletal biovolume. These are almost exclusively massive plocoid forms such as *Stylina* and ?*Pseudocoenia* (plate 4.13-fig 3). Other growth forms (branching phaceloid, solitary and small domes) are of secondary importance in terms of colony size (generally less than 10 cm in diameter) and framework construction; together they represent approximately 10% of the total coral skeletal biovolume.

Fourteen genera have been identified. The coral fauna possess a high dominance pattern with *Thamnasteria dendroidea* (type A) dominating (constituting over ?50% of the total coral skeletal biovolume). The other major contributors to the coral skeletal biovolume are *Dendrohelia*, and the domal stylinids.

The Bellême coral fauna:

Large domal massive colonies (20%)

Stylina (3)
Isastraea (1)
Fungiastraea
?*Pseudocoenia*

Branching ramose colonies (70%)

Thamnasteria (type B) (1)
Thamnasteria (type A) (5)
Dendrohelia (4)

Other (10%):

Branching phaceloid

Aplosmilia (1)
Latomeandra (1)
Stylosmilia
Goniocora

Small domed colonies

Thamnasteria (2)
Solenocoenia (1)
Diplocoenia (2)
Stephanastraea (1)
Myriophyllia (1)

Solitary

Montlivaltia

[1: rare; 5: very abundant]
[no number: very rare, only one or two specimens found]

4.2.4. Depositional environment

The reefal thickets developed on a clean carbonate platform in the upper sub-tidal zone (a few metres in depth). Currents and wave action was generally sufficient to prevent deposition of mud and silt particles, and produce well winnowed inter-reef grainstones. These sediments were deposited as sand shoals and sheets in the more exposed, agitated areas of the platform and in quiet oncoidal flats behind inactive oolite\oncolite shoals. Coral patches and thickets developed in the more protected quieter waters around the shoals, where the sediments were more stable and where background sedimentation was lower. Episodic storms produced reef debris beds deposited in storm blow-out channels.

CHAPTER 5: SWISS JURA

5.1: Introduction

The Swiss Jura has long been considered the classic region of Late Jurassic coral reef development. This initially stemmed from the classic monographic works on the corals by Koby (1880-1889; 1894) and later from the studies of Arkell (1935, 1956) and Beauvais (1964, 1975). However, despite these works, there have been few modern palaeoecological and sedimentological studies on these coral reefs. One reason for this is that the present outcrop quality is generally very poor, with outcrops being badly overgrown and highly weathered. The exception to this is the detailed sedimentological and palaeoecological reseach of Pümpin & Woltersdorf (1965), but this concentrates only on one locality (St. Ursanne) and does not make detailed comparisons with other coral reefs in, or outside, this region. More recently the detailed stratigraphic studies of Gygi (1986, 1982, 1992) and Gygi & Persoz (1986) has established a precise chrono- and lithostratigraphic framework for the Swiss platform sequence and its basinal correlatives. These works also provide a good control on the platform palaeogeography and on the location of reef development relative to the platform geometry. The outcrops of Late Jurassic coral reefs are located in the north-west of the country in the canton of Jura where four sections were studied in detail (figure 5.1).

Palaeogeography and depositional sequence (mainly after Gygi & Persoz, 1986)

Oxfordian sedimentation in northern Switzerland occurred in a epicontinetal sea north of the Tethys ocean in water depths of approximately 80-100 m (Gygi, 1990). The Ardenno-Rhenan Massif to the north-west supplied the mainly siliciclastic mud that developed into a submarine bank until the Middle Oxfordian (the Terrain à Chailles Member). As the mud bank grew into shallow water an initial reefal unit developed over the expanse of the platform (the Liesberg Member; study locality: Liesberg). These units subsequently provided the antecedent topography for the development a Bahamian type platform which developed on the mud bank during the Middle Oxfordian, when the supply of siliciclastic sediments diminished (the St. Ursanne Formation).

The margin of this platform was formed by a series of oolite sand shoals; there is no evidence of reef development (carbonate sand facies of the St. Ursanne Formation). Mud bioherms developed just off the platform margin on the platform slope (the Pichoux Limestone). Behind the platform margin oolite sand shoals was a lagoon in which the first sediments to be deposited were slightly oncoidal oolites. Following a rapid increase in sea level a more open marine lagoon with good circulation was created. This lagoon was initially occupied with coral patch reefs (reefal facies of the St. Ursanne Formation; study localities: St. Ursanne and Courtételle) and later with fine fenestrate limestones when the lagoon became more restricted (the Vorbourg Member). Coevally with the platformal deposits, during times when sedimentation rates in the basin were low, siliceous sponge biostromes and bioherms developed over large areas (the Birmenstorf Member). These basinal facies are associated with ammonite-bearing units.

During the late Middle Oxfordian to Late Oxfordian the platform prograded 40 km basinward in 4 my, mainly a result of a second phase of strong siliciclastic influx. Coral reef development occurred close to the prograding platform margin in an environment strongly influenced by siliciclastic influx (Günsberg Member; study locality: Péry-Reuchenette). During the Late Oxfordian reef growth was generally scarce on the platform and only locally developed (Olton limestones).

Litho- and Chronostratigraphy

The stratigraphic framework for this chapter is that proposed by Gygi and Persoz (1986) and is summarised in figures 5.2, 5.3 and the table below. Reef localities marked with an asterix (*) indicate localities studied in detail for this chapter; in parenthesis are the chapter sections.

Reef locality	**Stage in platform development; location of the reef on platform**	**Stratigraphic unit**	**Age**
Liesberg* (section 5.2)	Early in platform evolution; platform wide	Liesberg Member	Middle Oxfordian: Transversarium Zone, Antecedens Sub-Zone.
St. Ursanne* (section 5.3)	Platform fully developed; platform interior	St. Ursanne Formation	Middle Oxfordian: Transversarium. Zone, Antecedens Sub-Zone - base of Bifurcatus Zone Schilli Sub-Zone
Courtételle* (section 5.4)			
Pichoux	Platform fully developed; basinward on the platform slope (below "shelf-break")	Pichoux Limestone	
Péry-Reuchenette* (section 5.5)	Platform fully developed; platform edge	Günsberg Member	Late Middle Oxfordian: Bifurcatus Zone, Schilli Sub-Zone - Bimammatum Zone, Hypselum Sub-Zone.
Olten	Platform fully developed; platform edge	Olten coral limestone	Upper Oxfordian: Bimammatum Zone, Hypselum Sub-Zone - Planula Zone - Galar Sub-Zone.

5.2: LIESBERG

5.2.1. Introduction and facies sequence

The Chestel quarry near Liesbergmüli at Liesberg provides an excellent, and relatively unweathered shallowing upwards section from deep water pre-reefal marls (Terraine à Chailles Member) through to shallow water coral patch reefs of the St. Ursanne Formation. The main focus of this part of the chapter is the reefal unit of the Liesberg Member, which was the first reefal unit to develop in the section and is located between the relatively deep-water Terraine à Chailles and the shallow-water facies of the St. Ursanne Formation (figure 5.4 plate 5.1- fig 1).

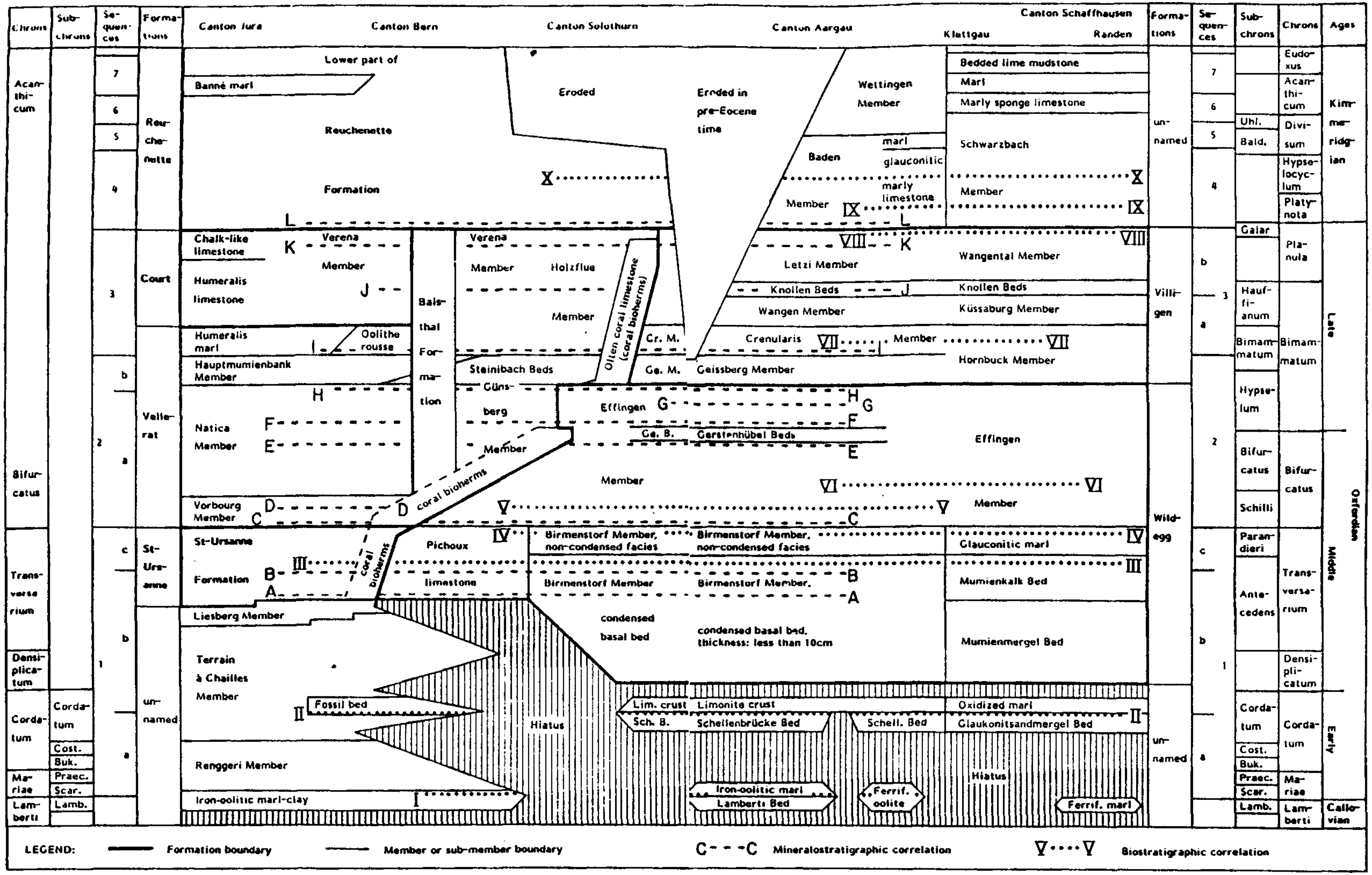


Figure 5.2: Chrono- and lithostratigraphic correlation chart for the Oxfordian and early Kimmeridgian of the Swiss Jura. The vertical extent of the lithostratigraphic and biostratigraphic units in this chart is unrelated to the time represented by the units. Bold lines are formation boundaries. (From Gygi and Persoz, 1986).

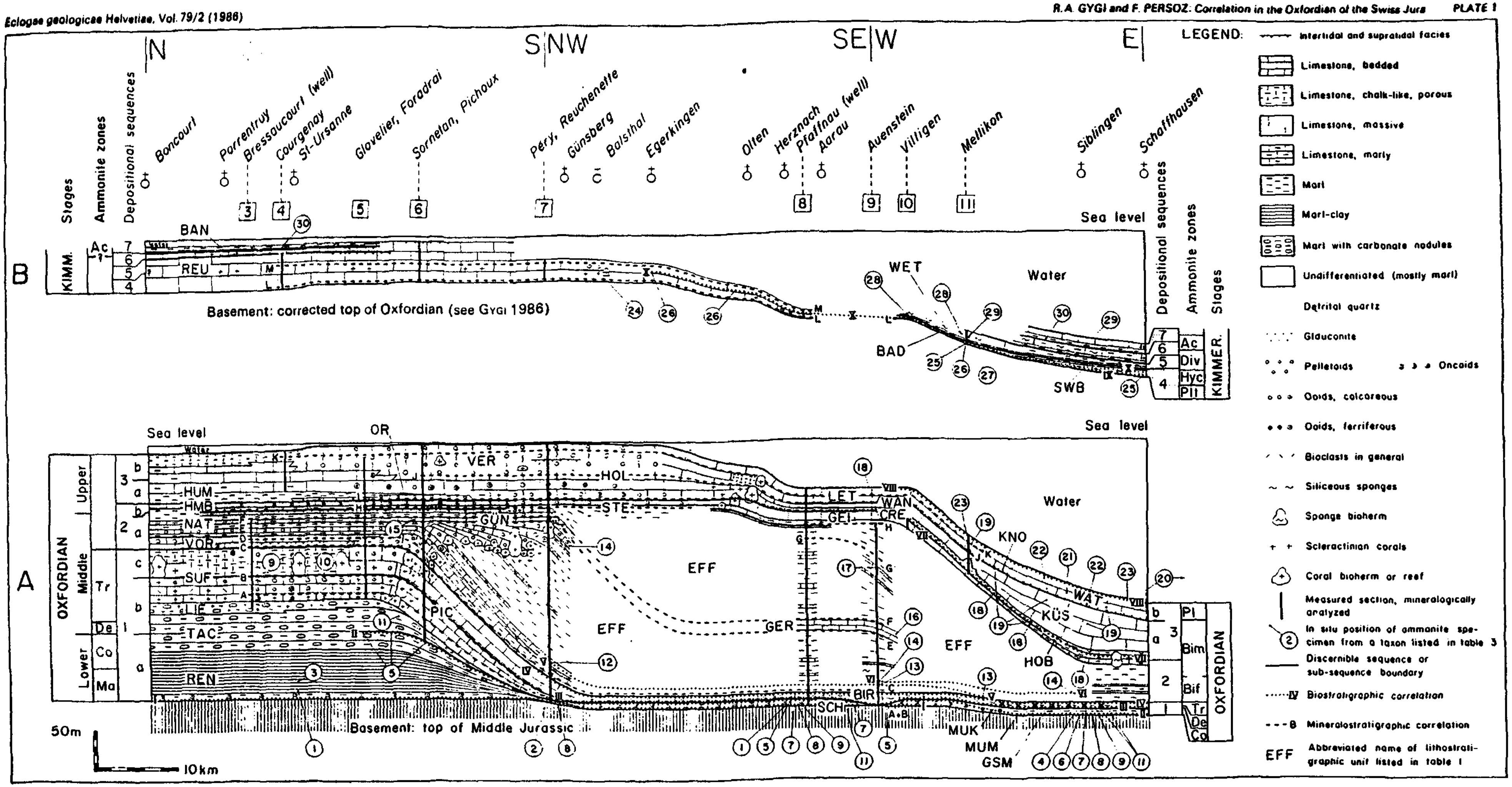
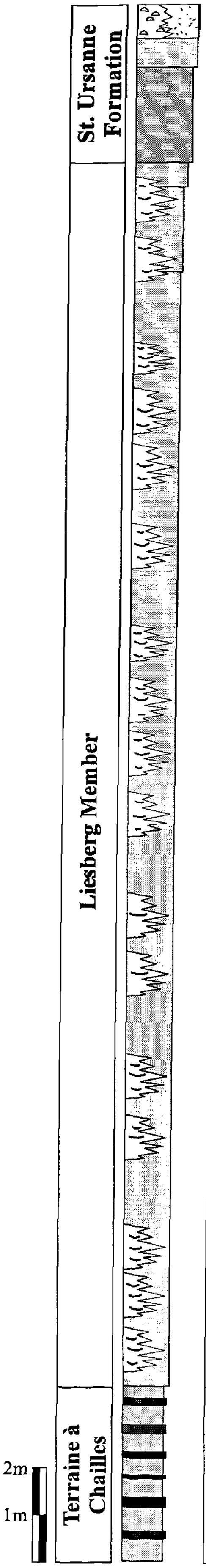


Figure 5.3: Geometry and time correlation of the Oxfordian and early Kimmeridgian of the Swiss Jura: palinspastic cross section 120 km perpendicular to depositional strike. The measured thickness are averaged. Thickness of the thin, iron-oollitic and glauconitic beds at the base of the Oxfordian had to be greatly exaggerated. (From Gygi and Persoz, 1986).



High diversity patch reefs.

Well sorted, clean oolitic grainstone

Bioclastic packstone with oncoids. Decrease in siliciclastic component. First appearance of massive colonies. First appearance of ***Stylina.***

Microsolenid biostrome

Marly limestone with a high siliciclastic component separated by thin muddy horizons.

Percentage of coral skeletal biovolume					
Genus		Family		Growth-form	
Dimorpharaea	**50**	**Microsolenidae:**	**56**	**platy - sub-massive:**	**80**
Microsolena	**3**	**Other:**	**44**	**phaceloid**	**9**
Thamnasteria	**4**			**branching ramose:**	**9**
Comoseris	**3**			**solitary:**	**2**
Isastraea	**16**				
Fungiastraea	**1**				
Thecosmilia	**8**				
Montlivaltia	**2**				
Dendraraea	**9**				
Calamophylliopsis	**<1**				
Stylosmilia	**1**				
Cladophyllia					
Goniocora					
Actinaraea	**2**				
Meandaraea	**<1**				

GENERIC RICHNESS: 15
EVENESS: 0.63
DIVERSITY INDEX: [SHANNON-WIENER]: 2.47
[SIMPSON]: 0.70

Total coral skeletal biovolume: 30 - 70%.
Extremely rich and diverse associated fauna of bivalves, sponges, echinoids, crinoids, brachiopods, serpulids, and bryozoans.

Grey marl with bands of ellipsoidal limestone concretions, and with occasional bands of continuous marly limestone.

Fossils mainly preserved in the nodules including ammonites, bivalves and serpulids. Corals virtually absent, *Montlivaltia* if present.

/\/\/\ True contact not visible because it is inaccessible and/or the *contact appears to have undergone tectonic movement*

Figure 5.4: Schematic log of the Liesberg section.

Facies sequence (figure 5.4); from base up:

Terraine à Chailles Member. This is a grey marl with bands of ellipsoidal limestone concretions and occasional continuous bands of marly limestone. The thickness of this unit is between 40 and 50 m. Ammonites are present though not abundant. Corals are virtually absent and if present are solitary montlivaltiids.

Liesberg Member. This is similar to the *Terraine à Chailles Member* in that it is a grey marl with limestone bands, however the limestone bands are more frequent and individual nodules are more irregular in shape. The most fundamental change between the two members is the sudden and massive appearance of coral which marks the boundary between the two units (plate 5.1-fig 2). The whole of the Liesberg Member can be regarded as a biostrome and is approximately 22 m thick.

St. Ursanne Formation. When the influx of siliciclastic argillaceous material ceased a series of packstones and grainstones of the St. Ursanne Formation were deposited. This started with the deposition of 2.24 m of bioclastic packstone with oncoids and was followed by 4.4 m of bioclastic oncolitic grainstone with some massive colonies (though not in growth position). This was followed by 6 m of oolitic grainstones which is overlain by the a reefal facies of the St. Ursanne formation. The contacts between these units are not visible.

5.2.2: The Liesberg Member

5.2.2.1. Reef structure and facies

Reef structure and framework development

The lateral extent of the biostrome at outcrop is over 170 m; however previous studies have shown that it has an extensive, platform-wide distribution (Gygi and Persoz, 1986). The unit is internally well bedded on a metre scale, and the reef has a distinctly sheet-like biostromal appearance (plate 5.1-fig 3). The framework is constructed almost exclusively of platy corals of various forms and is extremely well developed, with high coral skeletal biovolumes (40-70%, locally 20%) (plate 5.2-figs 1-3). Algae and microbialite play no role in reef building.

Facies and sedimentology

The intra-reef sediments are dark grey marly bioclastic wackestones (plate 5.1-fig 3; also see plates 5.2 and 5.5). At a microfacies scale they are best described as biomicrites (M/S/C: 70/0/30) and are generally similar to those documented in the coral marl facies at Foug, Lorraine (chapter 3, section 3.2). Also present in the more silty areas are small (less than 1 mm) fragments of quartz and pyrite. There is no evidence for current or wave reworking. The thickness of the Liesberg Member (approximately 22 m) and the very rapid time it was deposited in (a fraction of the Antecedens Subchron), suggests that the Liesberg Member experienced a relatively high average sedimentation rate (Gygi and Persoz, 1986).

5.2.2.2. Palaeoecology

Associated fauna

The associated fauna is extremely well developed, with a diverse assemblage of organisms. In particular there is an especially well developed cryptic and encrusting fauna which mainly encrusts the undersides of the coral plates. This includes calcareous sponges, demosponges, thecidean brachiopods, serpulids, *Berenicea*- and *Stomatopora*-type bryozoans, bivalves (oysters, pectinids, limids, boring bivalves) and forams (plates 5.2-5.3). Also very abundant are cidaroid echinoids spines and crinoid stems (*Millericrinus*) which are often still intact and occasionally in growth position, suggesting quiet water (plate 5.4-figs 2-3). Silicification of these organisms is common and is presumably a result of the redistribution during diagenesis of the silica derived from the siliceous sponges (plate 5.4-fig 1). Boring intensity is moderate and mainly by bivalves.

Coral fauna

The only branching ramose coral in the assemblage is *Dendraraea*, which in this biostrome has a rather peculiar growth habit. It occurs as loose colonies with thick branches (2-3 cm in diameter) and can be over 3 m across. After a short period of vertical growth the branches of these colonies spread out horizontally and presumable grew parallel to the depositional surface. Coupled with this lateral branch growth, the branches change their cross-sectional form from circular to oval, with the long axis parallel to bedding (figure 5.5). The coral fauna is dominated by platy forms although there is a considerable diversity in their detailed form and dimensions. These coral plates vary in form from very thin plates (1-1.5 cm thick and 35 cm across) to thicker tabular and sub-domal forms (15 cm thick and 30 cm across) (figure 5.6; plates 5.2 and 5.5). The majority of the framework is constructed by plates about 2-4 cm thick and 20-30 cm across. Thick tabular coral colonies become common at the top of the Liesberg Member, and just below the St. Ursanne Formation more massive domal colonies (30 cm across and 20 cm thick) appear. Taxonomically the fauna is dominated by microsolenids, especially *Dimorpharaea*. Generic richness is relatively low and generic dominance high.

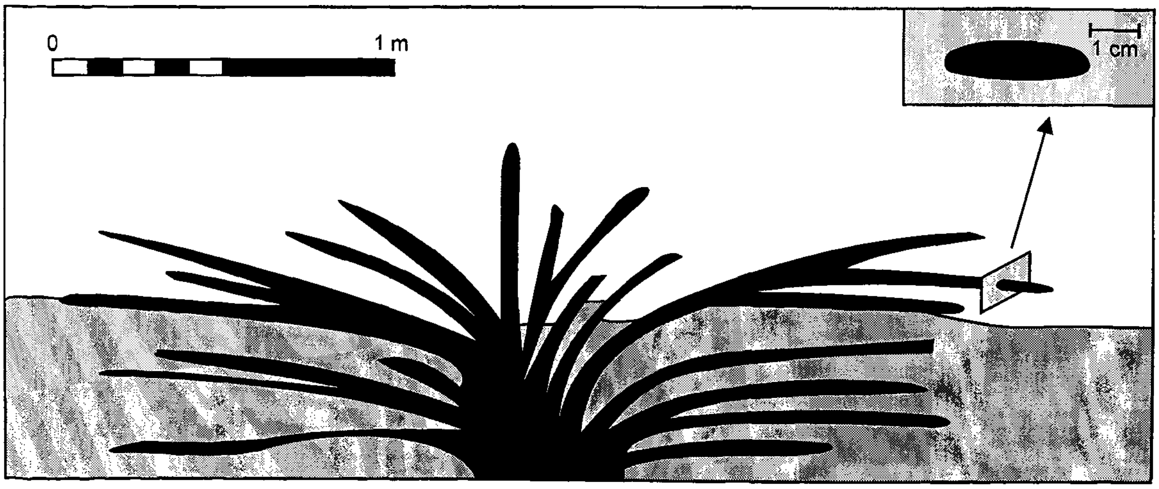


Figure 5.5: Growth habit of the branching ramose coral *Dendaraea* in the Liesberg biostrome.

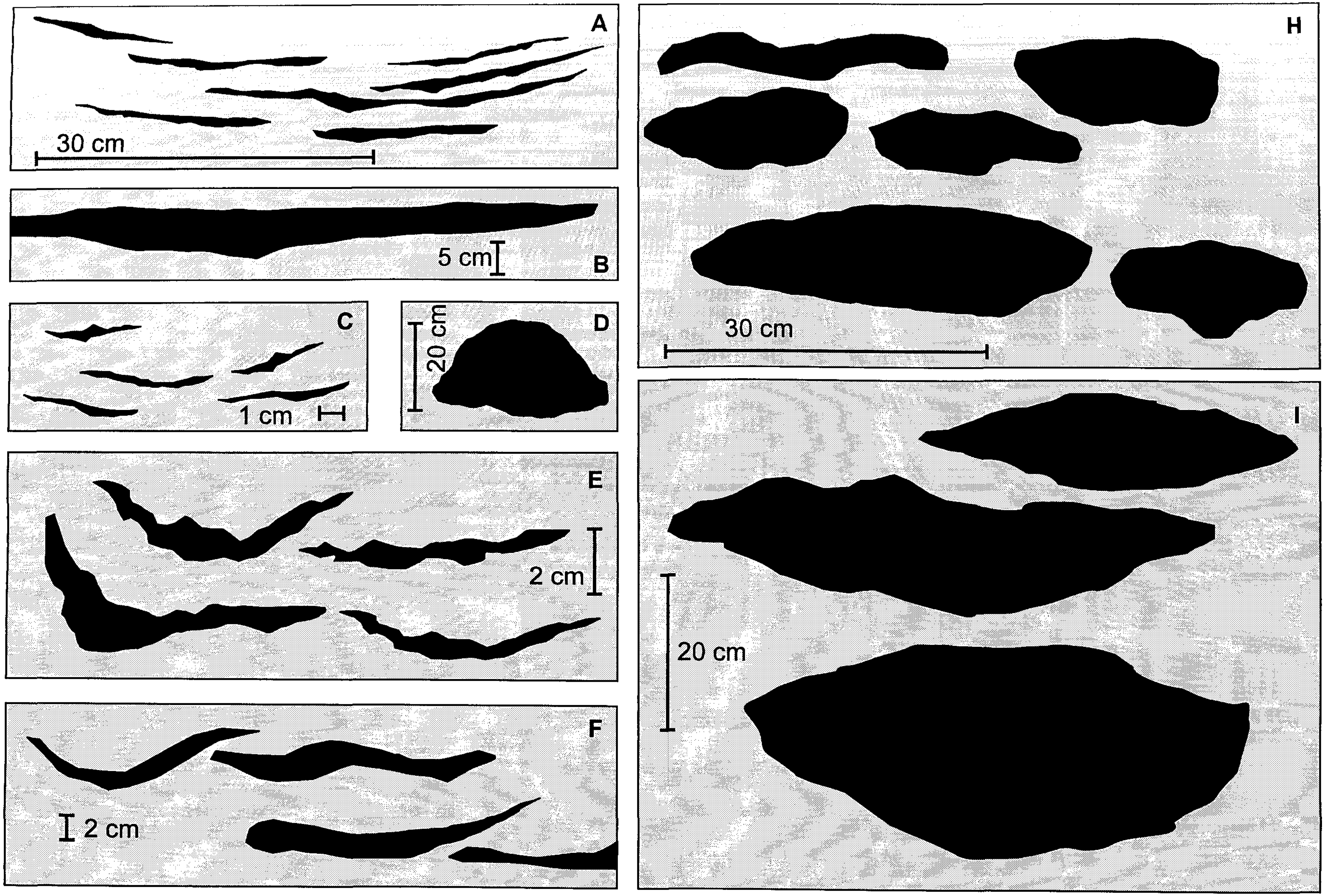


Figure 5.6: Variations in the growth form of the platy and tabular corals in the Liesberg biostrome.

Coral assemblage of the Liesberg biostrome:

Phaceloid branching		**Massive-Lamella**		**Family composition:**	
(9%)		**(80%)**		**Microsolenidae**	**56**
Thecosmilia	8	*Microsolena*	3	**Other**	**44**
Calamophlliopsis	<1	*Dimorpharaea*	50		
Stylosmilia		*Thamnasteria*	4	**Generic richness:**	**15**
Cladophyllia	<1	*Isastraea*	16		
Goniocora		*Comoseris*	3	**Eveness index:**	**0.63**
		Fungiastraea	1		
Branching ramose		*Actinarea*	2	**Diversity indexes:**	
(9%)		*Meandraraea*	<1	Shannon-wiener:	2.47
Dendaraea	9			Simpson:	0.70
Solitary					
(2%)					
Montlivaltia	2				

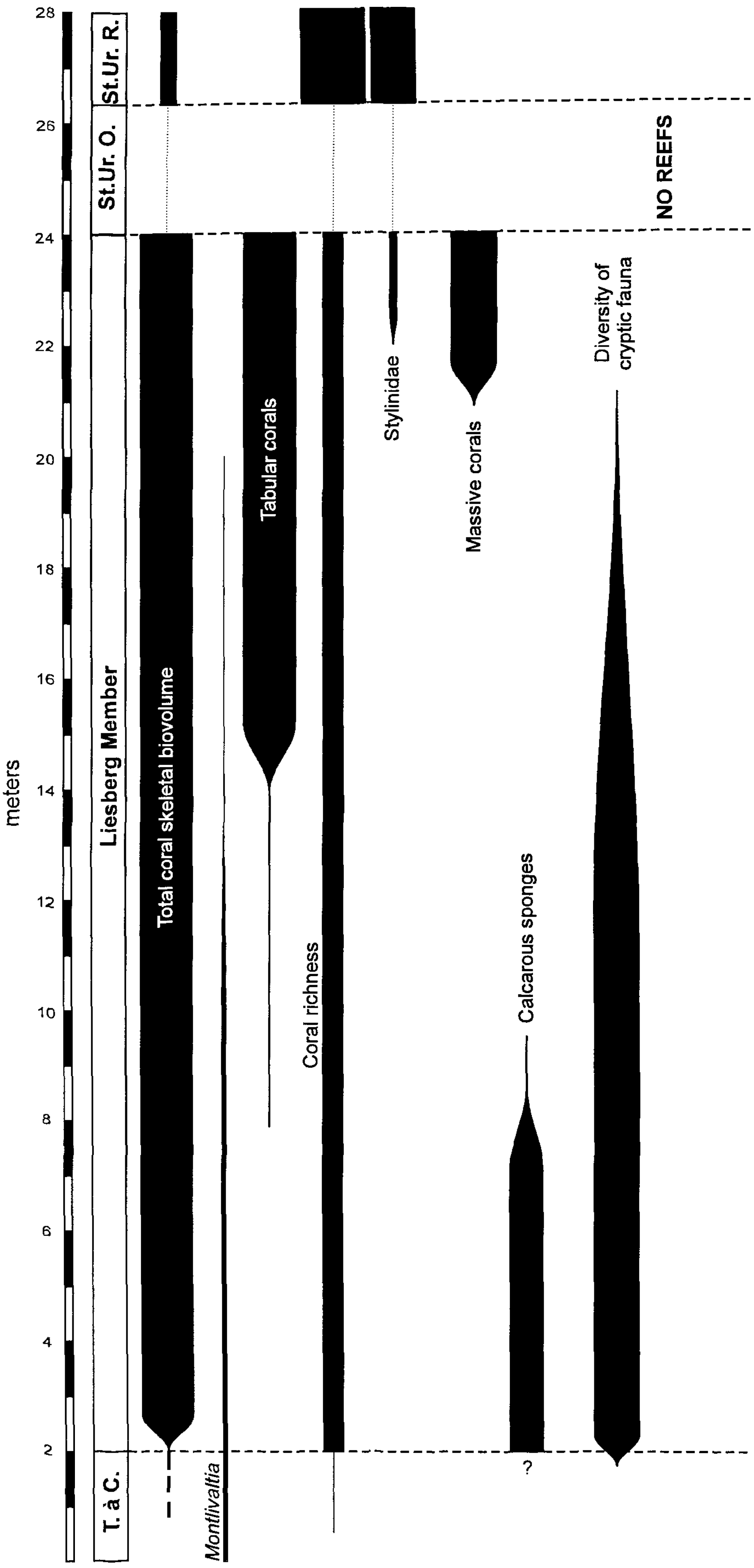
Note: since there appears to be changes in the composition of the biostrome through its vertical development (see section 5.2.2.3 below) the quadrat used to collect these data was placed along one bedding surface (17 m from the base of the unit) and had an area of 10 by 0.5 m (along bedding).

5.2.2.3. Vertical variations in framework composition and development

In order to discern whether there are any changes in framework composition through the vertical extent of the biostrome the section was studied at approximately 2-3 m intervals from a few metre below the base of the Liesberg Member. Due to time constraints this analysis was carried out only qualitatively in the field and is summarised in figure 5.7. The results suggest that:

1. massive and tabular colonies do not become abundant until half way up the unit;
2. *Dimorpharaea* plates appears to get thicker up section;
3. *Stylina* first appears right at the top of the unit, though only one colony was found;
4. *Montlivaltia* was the only coral that was present in any numbers below the Liesberg Member. It persists into the Liesberg Member although becomes less abundant near the top;
5. calcareous sponges, although relatively common in the lower Liesberg Member, appear to diminish in their numbers towards the middle and top of the unit; and
6. the diversity of the cryptic fauna gradually diminishes at the top of the unit.

These up-section changes are likely to be related with the shallowing of the sequence and the development of the biostrome in progressively shallower water. These changes are discussed in detail in chapter 7.



St.Ur. R:
St. Ursanne Formation; reefal facies

St.Ur. O:
St. Ursanne Formation; packstones & grainstones; no reef development

Liesberg Member
Biostromal reefal unit

T. à C:
Terraine à Chailles Member; no reef development

Figure 5.7: Variations in faunal composition and framework development up the Liesberg section. See section 5.3.3 for details of the St. Ursanne reefs.

5.2.2.4. Depositional environment of the Liesberg biostrome

The location of the biostrome low in the shallowing upwards sequence, just above sponge- and ammonite-bearing marls, suggests a relatively deep-water environment (Gygi and Persoz (1986) suggest a palaeodepth of 20 m for the deposition of the Liesberg Member). This inference is substantiated by the lack of wave, current or storm reworking, suggesting a position well below fair weather wave base, in a low energy regime. The microfacies, dominated by bioclastic material of immature nature, and the lack of laminated peloidal fabrics, suggests a relatively high detrital sedimentation rate. It is interesting to note that according to Gygi and Persoz (1986; p. 419-220) there is a minor lateral facies transition from shallow-water limestones to deeper-water marls in the lowermost St. Ursanne Formation near Bärschwil (south-east of Liesberg). Here the lowermost St. Ursanne Formation grades laterally into the Liesberg Member towards the basin in the south-east. This suggests that this type of reefal unit developed on the platform slope contemporaneously with shallower water reefal facies developing on the platform top. The significance of this will become clear in chapter 7, section 7.1 and chapter 8, section 8.1.

5.2.3. Reefal facies of the St. Ursanne Formation at Liesberg

At the top of the section part of the St. Ursanne reefal facies can be observed. This is best studied in a road cutting just outside of the quarry. Here small coral patches with relatively low coral skeletal biovolumes (20-30%) occur within fine bioclastic packstones. The intra-reef sediments are mainly fine, dense, microbial wackestones. The associated fauna is generally very poor, except for terebratulid brachiopods, which are quite common. Conspicuous groups include cidaroid echinoids and pectinids, though both are rare; crinoids are absent. *Lithophaga* borings occur in both the corals and the microbialite. The coral fauna is dominated by massive and branching phaceloid forms (though not all corals are in growth position). The massive domal forms are relatively small (10 cm thick and 15 cm across) and the branching forms are generally less than 1 m high.

Coral assemblage of the St. Ursanne patch reef at the top of the Liesberg section:

Massive	**Branching phaceloid**	**Branching ramose**
(?50%)	(?30%)	(?20%)
Isastraea	*Aplosmilia* (c)	unidentified sp.
Meandaraea (c)	*Calamophylliopsis* (c)	unidentified sp.
Meandrophyllia (c)	*Donacosmilia*	
Microsolena (c)	*Pleurosmilia*	**Solitary**
Stylina (c)	*Stylosmilia*	(insignificant)
Thamnasteria	*Thecosmilia*	*Montlivaltia*

Note the faunal distinctness between this reef and that of the Liesberg Member biostrome .

5.3: ST. URSANNE

5.3.1. Introduction

The St. Ursanne Formation is a shallow-water carbonate platform deposit with a complex association of different limestone facies. The thickness of this formation varies between 35 m near Kleinlützel and 105 m near Vellerat, and it is underlain by the Liesberg Member and overlain by the Vorbourg Member (Gygi and Persoz, 1986). The principal section studied is located adacent to the St. Ursanne railway station and is the type section for the formation (figure 5.8). The section contains 2 distinct reefal units: (1) a lower basal biostrome; and (2) a series of upper patch reefs. For a detailed description of this section see Pümpin & Woltersdorf (1965).

5.3.2. Basal biostrome (lower St. Ursanne Formation)

The St. Ursanne section begins with a 9 m thick biostromal unit. This reefal unit was not studied in detail because of time constraints but the some of the characteristic features of the reef are outlined below. The reefal unit is biostromal with a well developed bedded appearance (plate 5.6-figs 1-2). The intra-reef sediment is a coarse grained bioclastic, slightly oncolitic, packstone and is extremely rich in echinoid fragments. The associated fauna is dominated by echinoids and crinoids, though *Lithophaga* borings (plate 5.6-fig 3) and pectinids are also present. Very large (up to 20 cm across) *Millericrinus* crinoid stems are particularly conspicuous. Also abundant are *Trichites* valves (plate 5.6-fig 4) which become increasingly common and larger towards the top of the section.

At the base of the section coral skeletal biovolume is very low (about 10%) though it increases to 20-30% in the main body of the biostrome, and to approximately 50% at the top of the unit. The coral fauna is dominated by microsolenids, especially *Microsolena* which constitutes over ?70% of the total coral skeletal biovolume. Other corals present are *Isastraea*, *Thamnasteria*, *Thecosmilia* and *Actinararea* and become increasingly common towards the top of the biostrome. The coral assembalge is dominated by platy and tabular corals (>90%) with average dimentions of approximately 4 cm thick and 30 cm across in the main body of the biostrome. Towards the top of the biostrome the corals become thicker (8-15 cm thick), and domal forms (30 cm across and 20 cm thick) appear. Here the sediment becomes more oncolitic and marked storm erosion surfaces are present. According to the depositional scheme proposed by Gygi and Persoz (1986) this basal biostrome is the upper part of the 1b depositional sequence which also includes the upper Terraine à Chailles and the Liesberg Member. The basal biostrome is separated from the upper patch reefs by a series of oolitic and oncolitic grainstones (figure 5.8).

5.3.3. Upper patch reefs (upper St. Ursanne Formation)

Three of these reef patches within the upper St. Ursanne Formation were studied (figure 5.9). These developed contemporaneously with each other and are separated by approximately 100-200 m of inter-

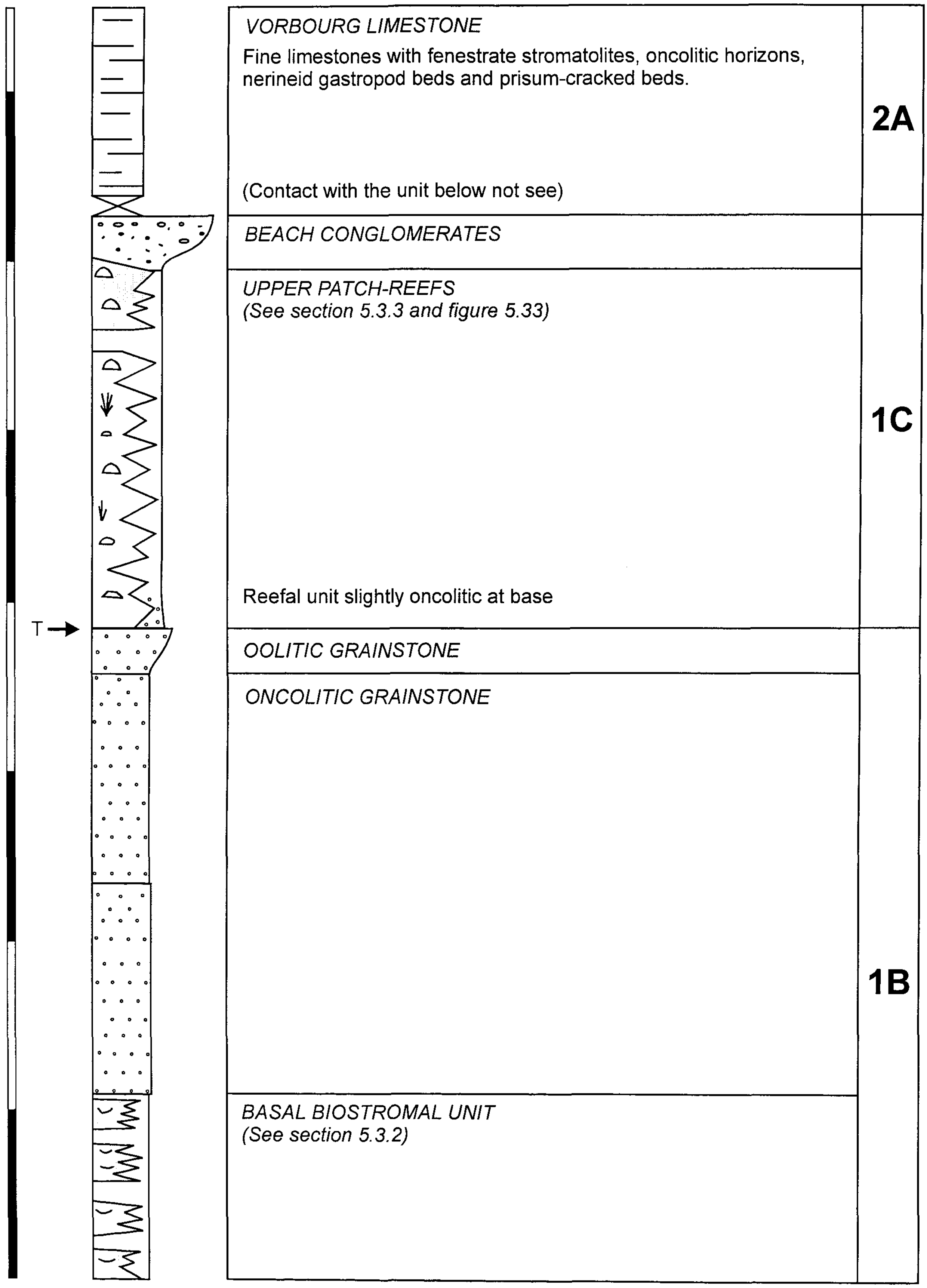


Figure 5.8: Schematic log of the St. Ursanne type section. Sequences according to Gygi and Persoz (1986). T: Trangressive surface.

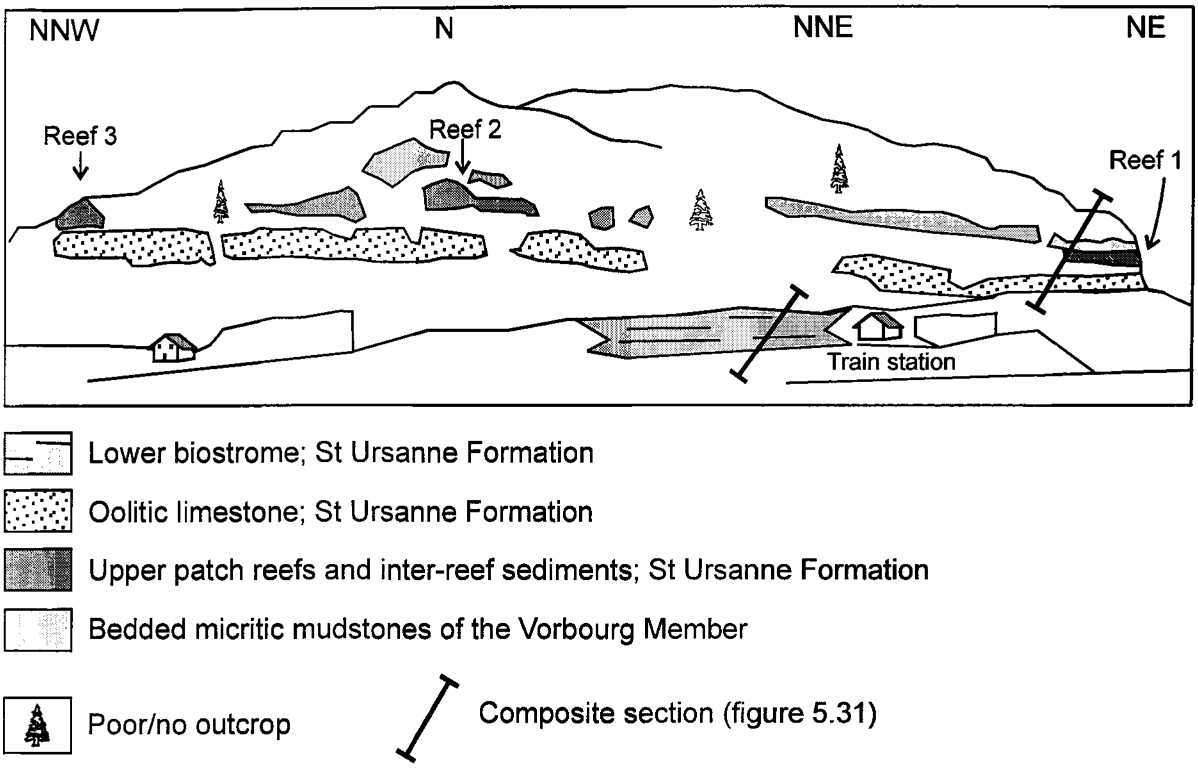


Figure 5.9: Field sketch of the panorama looking north at the face of the Doubs-Tales valley; the field of view is approximately 500 meters.

reef sediment across the platform interior. The inter-reef sediments are mainly arenitic bioclastic limestones in the lower part of the formation but oolitic and oncolitic limestones are more common in the upper part.

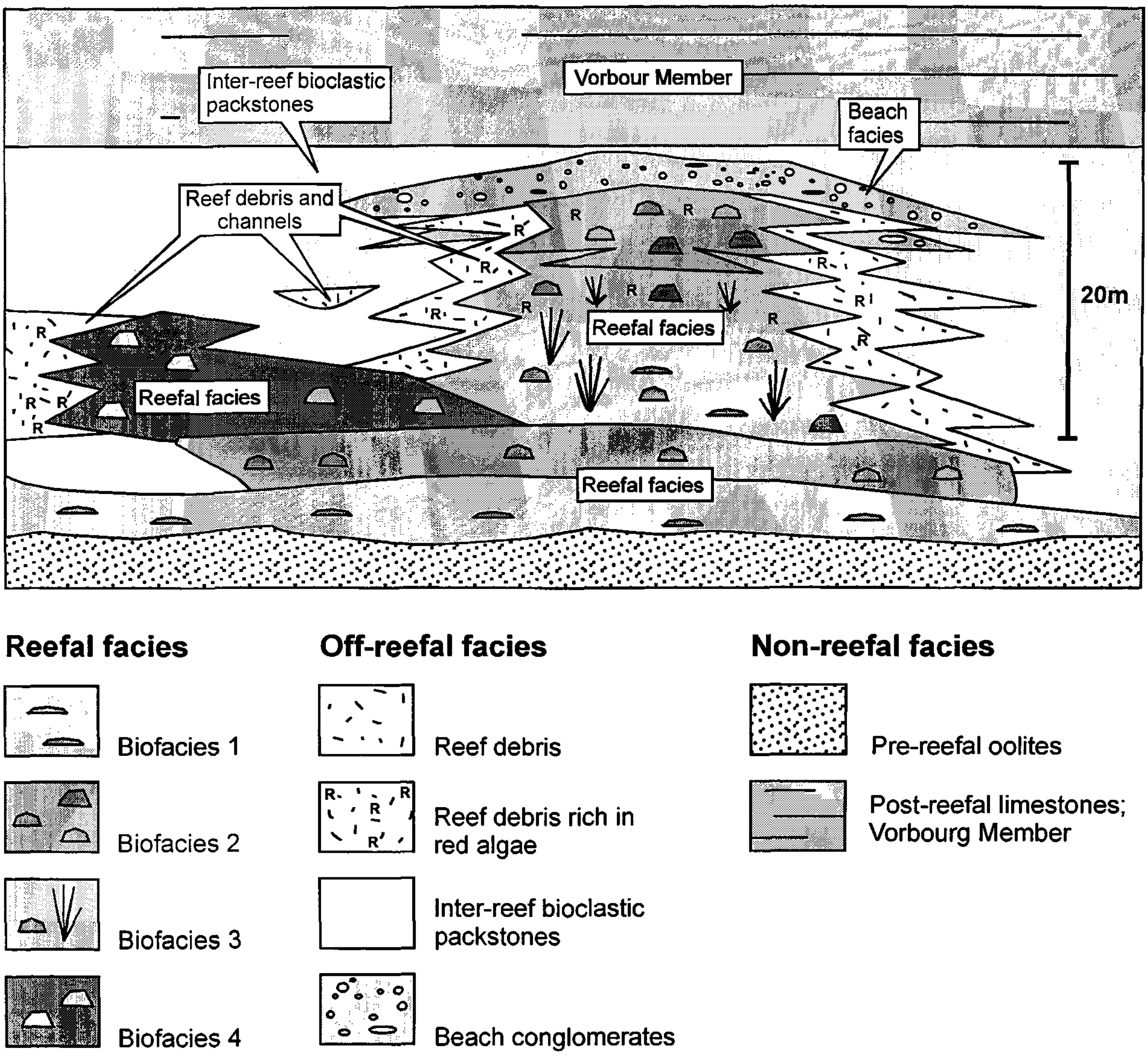
Facies sequence (figure 5.8; plate 5.7-fig 1)

The coral biolithites and bioclastics packstones of the St. Ursanne Formation rest sharply on a thick unit of slightly oncolitic oolite (uppermost 1b sequence of Gygi and Persoz, 1986). The rapid vertical transition from oolite (of the uppermost 1b sequence) to coral biolithites (of the subsequent 1c sequence) documents a rapid increase in water depth. The top of the oolite is therefore interpreted as a trangressive surface (Gygi and Persoz, 1986). One of the patch reefs studied is capped by a beach conglomerate (plate 5.7-fig 2) and they all terminate approximately 3-4 m below the top of the St. Ursanne Formation.

5.3.3.1. Reef structure and facies of patch reef 1

Reef structure and framework development

The vertical extension of this reef is approximately 30 m and has a lateral extent of 30-50 m (figure 5.10). The detailed work of Pümpin & Woltersdorf (1965) suggests that these reefs are circular to oval in plan view, and domal with quite steep sides in cross-section (figure 5.10; Pümpin & Woltersdorf (1965), figures 14 and 15). Low angle bioclastic aprons are present all around the reef and suggest the syn-depositional relief was slight (no more than a few of metres). The framework is constructed



Reefal facies
Pümpin & Woltersdorf (1965) have recongised the 4 coral biofacies characherised by the genera listed below. The present study was not able to clearly identfy all four biofacies. However it was observed that stylinids did dominate the fauna at the top of the reef and which seems to corrispond to their biofacies 2.

Biofacies 1	**Biofacies 2**	**Biofacies 3**	**Biofacies 4**
Aplophyllia	*Aplosmilia*	*Comoseris*	Mixed biofacies.
Cladopyllia	*Calamophlliposis*	*Heliocoenia*	
Comoseris	*Comoseris*	*Stylina*	
Dimorpharea	*Goniocora*		
Goniocora	*Latomeandra*		
Stylina	*Stylina* (common; 3 sp.)		
Thamnasteria	*Thamnasteria*		
	Solenopora (common)		

Off-reefal facies:
These are off-reef coral debris beds but also contain a rich mulluscan fauna, most conspicuous of which are the *Diseras* bivalves and the *Nerinea* gastropods. These facies occur as sheets lateral to the reef or occasionally as channels. Two slightly different facies may be distinguished the main difference being the abundance of red algae. Common elements include:

Bivalves	**Echinoderms**	**Gastropods**	**Brachiopods**
Diseras arietinum	*Acrocidaris nobilis*	*Natica sp. sp.*	*Zeilleria huddlesstoni*
Diseras ursicinum	*Hemicidaris sp. sp.*	*Nerinea laufonensis*	
Diseras sp.	*Psudodiadema sp. sp.*	*Nerinea ursicina*	**Red Algae**
	Rhabdocidaris sp. sp.	*Nerinea sp.sp.*	*Solenopora sp.*
		Purpuroidea sp.sp.	
		Sequania sp.	

Faunal lists from Pümpin & Woltersdorf (1965).

Figure 5.10: Cross-section through patch reef 1; upper patch reefs of the St. Ursanne Formation. Modified From Pümpin and Woltersdorf (1965).

primarily by massive colonies though branching ramose and phaceloid forms are secondarily important. The coral skeletal biovolume is very high, 50-90%, with a very well developed framework. This coral framework was bound together by abundant early cementing microbialite which forms as much as 60% of intra-reef sediment and was important contributor to framework construction. At the top of the reefal unit massive domal colonies of *Stylina* become common (plate 5.7-fig 3-4), and are locally enveloped by abundant red algae which probably also acted as a builder in small parts of the reef. In the upper parts of the reef much of the material is not in growth position. Lateral to the reef are rubble zones with large blocks up to 40 cm across of massive and branching phaceloid colonies which have been overturned. These deposits are a result of particularly violent storms.

Facies and sedimentology (**figure 5.10**)

Intra-reef sediments (plate 5.8). The intra-reef sediments are dominated by rindy peloidal fabrics and are best described as rindy microbialite biopelmicrites (M/S/C ratios are vary variable and range from 80/0/20 to 50/0/50 to 40/10/50). The microfacies is similar to the that documented in the reefs of Quatre Pieux and Bois du Parc, Burgundy (chapter 2, sections 2.3 and 2.4) and Novion-Porcein, Ardennes (chapter 4, section 4.1.3), although the laminated peloidal fabrics are not so well developed. The bioclasts are immature, lacking micritisation and spongiostromate coatings, suggesting that they were rapidly incorporated into the reef framework. The intra-reef sediments appear to have undergone early cementation as suggested by bivalves boring directly into the intra-reef sediment and the presence of peloidal intra-clasts. At the top of the reef some of the peloidal fabrics appear to have birds eye structures within them.

Inter-reef sediments. These are fine to coarse grained bioclastic packstone rich in fragments of red algae and nerineid gastropods. Also common are rubbly bioclastic beds, which contain large diceratids up to 10 cm high and locally developed birds eye textures. In situ corals are generally rare with only a few large stylinid heads being present. *Solenopora* can be common in these beds.

Post-reef sediments; beach rock (plate 5.7-fig 2). This is a poorly sorted conglomeratic unit rich in rounded fragments of corals, *Solenopora* and nerineids. Clasts can range in size from over 10 cm to less than 1 cm in diameter are are set in a gravely matrix dominated by highly micritised bioclastic material. The contact with the reef is sharp, though no colonies are seen to be truncated. The unit coarsens up slightly and has vague planar surfaces within it.

5.3.3.2. Palaeoecology of patch reef 1

(These observations were made from the main body of patch reef 1 and therefore correspond to biofacies 3 of figure 5.10)

Associated fauna

The associated fauna is very poorly developed. The only conspicuous organism within the reef are the red algae, which can be locally common. Other groups represented, albeit rarely, include bryozoans, brachiopods, encrusting bivalves, pectinids, echinoid spines, *Millericrinus* stems and chaetitids. Some of the corals are highly bored by bivalves although the boring intensity is in general is low to moderate.

Coral fauna

The fauna is dominated by massive forms. The dimensions of these massive colonies vary greatly though the modal average is about 20-35 cm thick and 30-40 cm across. Small (3 cm across) spherical colonies are numerically common. The branching ramose colonies, although less common, can be very large, up to 2 m high and 4 m across. Taxonomically these reefs are very rich, with over 31 genera, having been collected from a relatively small collection site. It has not been possible to establish which genera dominate, though porous, plocoid and meandroid forms appear to be relatively common. At the top of the reef massive spherical stylinid colonies (40-50 m across and thick) dominate the fauna and can constitute up to 30% of total coral skeletal biovolume (plate 5.7-fig 3-4). This stylinid-rich facies is biofacies 2 of Pümpin & Woltersdorf (1965).

Coral assemblage of patch reef 1 (biofacies 3 of figure 5.10):

Massive
(50-60 %)
?Mixastraea
Allocoenia\Stephanastraea?
Clausastraea
Comoseris
Cyathophora
Diplocoenia
Heliocoenia
Isastraea
Meandrophyllia (c)
Microphyllia
Microsolena
Myriophyllia
Pseudocoenia (c)
Psudocoeniopsis
Solenocoenia
Stylina (c)
Synastraea
Thamnasteria

Branching phaceloid
(10-15%)
?Dermosmilia
?Donacosmilia
Aplosmilia
Calamophylliopsis (c)
Latomeandra (c)
Stylosmilia
Thecosmilia

Branching ramose
(20%)
?Heliocoenia
Pseudocoenia (c)
Stylina (c)
Thamnasteria

Platy-tabular
(15%)
Isastraea
Microsolena
unidentified sp.
unidentified sp.

Encrusting
(5%)
Microsolena
Stylina (c)
Thamnasteria

Solitary
(insignificant)
Haplaraea
Montlivaltia

5.3.3.3. Depositional environment

The reef developed in a pure limestone regime with no siliciclastic influx. The association of the reefal facies with oolites and oncolites below, and beach facies above, suggests that the reef initially developed in very shallow water, probably less than 5 m in depth, and then aggraded to sea level. At the top of the reef the presence of bioclastic grainstones, the greater proportion of corals not in growth position and local birds eye textures suggest that the upper part of the reef developed very close to the inter-tidal zone in relatively high energy. The bioclastic material was mainly a product of physical erosion and was deposited within the reef but also exported as bioclastic aprons.

5.3.3.4. Other upper St. Ursanne patch reefs (see figure 5.9)

These patch reefs are not easily accessible, being deep in the forest and poorly exposed. Hence the data collected from these reefs is rather limited. The coral skeletal biovolume of patch reef 2 is about 30% and dominated by branching forms, in particular *Aplosmilia*. Spongiostromate crusts are well developed around the phaceloid branches which are also encrusted by bryozoans, *Lithocodium* and other problematic chambered encrusters (plate 5.9-figs 1-4), and bored by clionid sponges and ?forams (plate 5.9-fig 1). The reef appears to be very similar to that examined at Pagny-sur-Meuse, Lorraine (section 3.3). The interesting feature of patch reef 3 is that it exhibits the corrugated internal structure as defined by the reefs in Burgundy (Saussois and Roches aux Poulet; sections 2.5 and 2.6) and Lorraine (St. Mihiel; section 3.5). The coral fauna appears to be generically rich and similar in composition to patch reef 1 (biofacies 3).

5.4: COURTÉTELLE

5.4.1. Introduction and facies sequence

5 km south-west of Delémont is a little known section near the town of Courtételle. The section can be reached by following the road south out of Courtételle up into the forested Jura mountains for about 2 km. The section exposes over 70 m of hitherto unstudied reefal units intercalated with non reef-facies, and forms part of the upper St. Ursanne Formation (pers. comm. R. Gygi, 1992). The facies sequence is summarised in figure 5.11.

5.4.2. Structure, facies and palaeoecology of the reefs

Reef 1

The section begins with a reefal unit which occurs in a coarse grained dark grey bioclastic packstone. The corals appear to be mainly platy microsolenids approximately 2 cm thick and 10 to 20 cm across. The intra-reef sediments are bioclastic packstones with an M/S/C ratio of approximately 50/0/50 and are simialar to those recorded at Châtel-Censoir, Burgundy. The top of this reef grades rapidly into a well sorted and crudely bedded oolitic grainstone where in situ corals are absent (unit A).

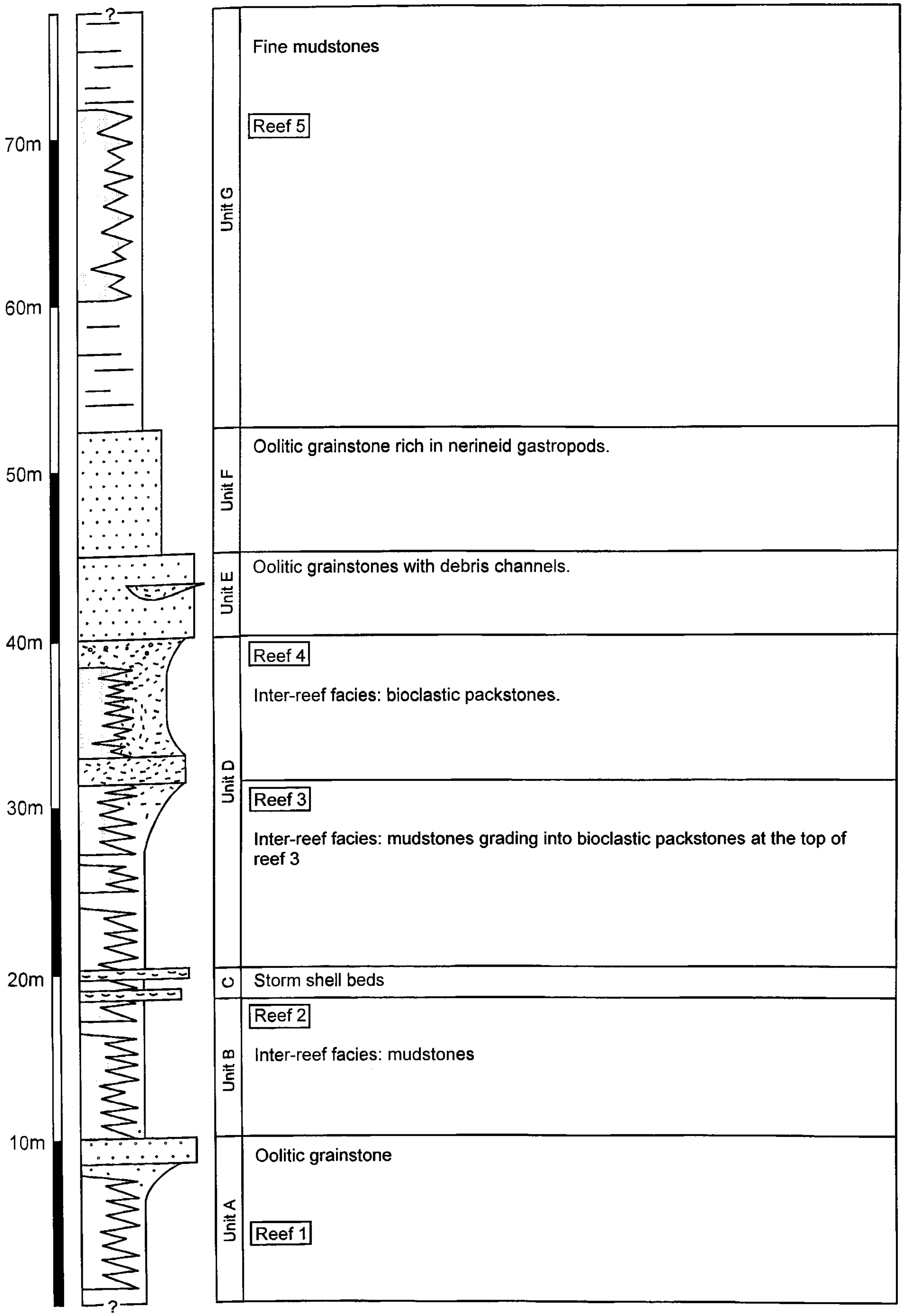


Figure 5.11: Schematic log of the Courtételle section to show facies sequence and location of the reefs within the sequence. Thicknesses of units are only approximate values.

Reef 2

The second reefal unit overlies the oolites of unit A. Isolated oolite grains are present at the base of the reef, though they completely disappear within 10-20 cm of the the contact with unit A. This unit (unit B) can be sub-divided into the hard and massive reef itself (Bi) and the contemporaneous well bedded inter-reef sediments, which are fine biomicrites (Bii) (plate 5.10-fig 1).

Reef and Intra-reef sediment (Bi). The coral skeletal biovolume increases from approximately 10-20% at the base of the reef to 20-30% in its core. The framework is constructed mainly by tabular and platy corals and the intra-reef sediment is dominated by microbialite. The microfacies varies from a rindy microbial biopelmicite to a homogeneous biomicrite with M/S/C ratios of 80-90/0/10-20 (plate 5.10-fig 3). The form of the reef is domal and attains a height 5 m and a width of 27 m. Internal bedding is poorly developed though suggest a syn-depositional relief of 1-2 m (plate 5.10-fig 1). The details of the coral fauna are difficult to assess because of the hard nature of the limestone. Nevertheless it is clear that massive colonies dominate the fauna and are mainly platy forms (3 cm thick and 10-20 cm across) and tabular forms (10 cm thick and 30 cm across). Taxonomically regularly perforate and pennulate forms appear to be abundant.

Coral assemblage of Reef 2:

Branching phaceloid (10%)	**Massive-Platy (90%)**	**Solitary forms (insignificant)**
cf. *Stylosmilia*	*Microsolena*	*Montlivaltia*
cf. *Cladophyllia*	*Isastraea*	
cf. *Rhabdophyllia*	*Thamnasteria*	**Branching ramose**
? *Calamnophylliopsis*	?*Clausastraea*	**(absent)**
	unidentified sp.	
	unidentified sp.	

The associated fauna is generally poorly developed, with only the occasional pectinid being observed. Echinoid spines and red algae are not present and only one crinoid stem was found. However terebratulid brachiopods are exceedingly common (plate 5.10-fig 2). Bioerosion intensity is moderate to high and solely by bivalves.

Inter-reef sediment (Bii). These are fine grained well bedded mudstones rich in terebratulids. Although this is an inter-reef facies in situ corals are present and in areas coral skeletal biovolume can reach 10%. Therefore in terms of coral skeletal biovolume there is not that much difference between the reef and inter-reef facies. What really defines these two units is the very early cementation of the microbialite in the reef. The inter-reef facies does not contain any/much microbialite and consequently has not undergone the early cementation. This is also reflected in the draping and differential compaction of this facies over the reef. The corals in the inter-reef facies are generally around 20 cm across, though some colonies can be quite large (15 cm thick and 40 cm across). A huge colony of ?*Isastraea* 20 cm thick 114 cm across was seen in growth position in this unit. The off-reef thickness of this unit is approximately 3 m. Both the reef (Bi) and inter-reef (Bii) facies are overlain by a series of storm shell beds (unit C).

Reef 3

Between reefs 2 and 3 is a series of storm shell beds and a poorly exposed reefal unit with a total thickness of 8 m. Reef 3 is 5-6 m thick and can be divided into a lower and upper framework which are separated by a bioclastic wackestone-packstone.The lower framework has a low coral skeletal biovolume 20-30% with a coral fauna much like reef 2; *Isastraea* is common. The associated fauna is still poorly developed though the brachiopods are still present. Echinoid spines are present though very rare. The coral assemblage is again dominated by platy and tabular forms with an average size of 4-10 cm thick and 20-30 cm across (these constitute over 80% of the total coral skeletal biovolume). Boring in the corals is solely by bivalves and their intensity is moderate to high. The microfacies of the intra-reef sediment is a pelleted bioclastic mudstone-wackestone with M/S/C ratios around 60-80/0/20-40. The matrix is composed of of pelloids, faecal pellets and fine detrital fragments. Small (0.1-0.2 mm) oval faecal pellets are very common and give the fabric a rather clotted appearance. Laminated peloidal fabrics are absent though rinds are present. The carbonate grains are predominatly bioclasts of corals, echinoids and bivalves, though sponge spicules are numerically abundant; lithoclasts are rare. Crust development is not common though it can be well developed on some larger fragments.

The upper framework has a higher coral skeletal biovolume reaching 40-50%. The coral fauna includes *Microsolena* (common), *Meandaraea* and/or *Meandrophyllia*, *Isastraea*, *Stylosmilia*, *Kobyastraea* and *Stylina*. Only one colony of *Stylina* was observed, however it is significant since it is the first appearance of this coral in the sequence. Within this reef is also the first appearance of a branching ramose plocaoid colony, although this may not be in growth position. The growth forms present are: massive domal (15%); thick platy and tabular (85%). Tabular form (30 cm across and 6 cm thick) dominate, and occasionally reach over 25 cm thick and 50 cm across. Encrusting bivalves and pectinids are more conspicuous, and echinoid spine are present though rare. The microfacies is the same as that of the lower framework, though with much better developed peloidal rinds. Coarse bioclastic material becomes increasingly abundant at the top of the reef.

Reef 4

Reefs 3 and 4 are separated by about 2-3 m of crudely bedded coarse bioclastic material rich in highly micritised and coated coral debris which includes large coral fragments up to 4 cm across. In situ corals are absent from this bioclastic facies and only appear gradually at the top of the unit. This facies contains a rich and abundant bivalve fauna (including *Girvanella*) and one possible nerineid was found.

The reefal unit has a high coral skeletal biovolume (up to 60%) and the coral growth forms composition is similar to reef 3, although domal forms are more abundant (20%) and slightly larger (occasionally reaching 80 cm across and 40 cm thick; plate 5.11-fig 1). Tabular and domal plocoid stylinids such as *Cyathophora*, *Pseudocoenia* and *Stylina* become increasingly abundant towards the top of the unit, and occasionally exhibit mammilated to knobbly top surfaces. Meandroid forms (*Meandaraea* and/or *Meandrophyllia*) are common near the base of the reef and *Microsolena* is rarer than in previous reefs. Other corals present include *Montlivaltia* and ?*Dendraraea*. Brachiopods are still present and common in areas, as are small (less than 1 cm in diameter) nerineids at the top of unit. Pectinids and other bivalves are more abundant than in previous units, though *Cidaris* spines are still rare; large (about 2 cm in diameter) bivalve borings are abundant. The intra-reef sediments are as in previous reefs (rindy pelmicrites; plate 5.11-figs 2-3) and the inter-reef sediments are bioclastic packstones rich in micritized and coated coral and bivalve material (plate 5.11-fig 4). Reef 4 is overlain by 4-5 m of oolitic grainstones (unit E) (plate 5.11-fig 5).

Reef 5

Reef 5 occurs at the top of the section and is the best preserved reefal unit. It sits within a well bedded mudstone facies (unit G) (plate 5.12-fig 1). In terms of composition and style of framework development this reef appears to be very much like the Bois du Parc reef, Burgundy (chapter 2; section 2.4).

Reef structure and framework development

The reef is approximately 10 m high and 11 m across and has domal form (plate 5.13-fig 1). The flanks of reef are composed of a bedded bioclatic wacke- to packstones rich in echinoid, bivalve, red algae and coral fragments. This apron facies is restricted to within 1-2 m of the reef and in-turn grades into mudstone (plate 5.13-figs 2-3). Within the reef vague internal bedding suggests that the maximum syn-depositional relief was about 2-3 m. Coral skeletal biovolume is very low about 20%, although the presence of stylolites may suggest that some coral material may have been dissolved away. Dense early cementing microbialite forms the rest of the reef.

Facies and sedimentology

Intra-reef. The facies and microfacies are identical to those documented at Bois du Parc, Burgundy (see section 2.4.3) and are rindy to laminated microbialite biopelmicrites. Early cementation of the microbialite was very important in the development of this reef and allowed bivalves to bore directly into the microbialite consequently producing numerous geopetal fills.

Pre- and inter-reef. These sediments (unit G) are generally well bedded mudstones. However the bedded materials at the flanks of the reef, the surfaces of which can be clearly traced into the bioclastic apron and then into reef (plate 5.13-fig 3), appear to be bedded microbialites. Thus the only real difference between the reef itself and the bedded microbialites that flank the reef is the presence of corals which gave the reef potential for vertical extension and hence the domal form of the reef. These bedded microbialites in turn grades into non-microbial well bedded mudstones.

Palaeoecology

Associated fauna. Cidaroid spines are very common and occasionally whole echinoids may be recovered. The only other conspicuous groups are bivalves such as *Chlamys* and *Liostrea*, unidentified calcified cyanobacteria and small 6.5 cm high domes of red algae. Bioerosion intensity is high with some of the corals being completely destroyed by bivalves such as *Lithophaga*; only one possible *Entobia* trace was seen.

Coral fauna. The coral fauna is dominated by massive and sub-branching ramose forms and there appears to be a complete gradation between the two (i.e. massive forms with knobbly, mammilose top surfaces). Fully developed branching ramose forms are relatively rare. The average size of the massive forms is 20 cm across and 10-20 cm thick, and they generally have an irregular form. The branching phaceloids are dominated by *Calamnophylliopsis* (which constitutes over 50% of the branching phaceloid coral skeletal biovolume) and occur as loose thickets up to 60 cm high.

Coral assemblage of Reef 5:

Branching phaceloid
(40%)
Calamophylliopsis (c)
Pachygyra and/or *Rhidogyra*
Stylosmilia
Phaceloid sp.

Sub-branching ramose
(10%)
Pseudocoenia
Thamnasteria

Massive and tabular
(50%)
Isastraea
Pseudocoenia
Stylina
Synastraea
Unidentified pennular form.

Solitary
(insignificant)
Montlivaltia

Thin lamellar forms
(insignificant)
Unidentified

5.4.3. Interpretation of the sequence and depositional environments

The whole of the section developed in relatively shallow water with no influx of siliciclastic sediments. The main facies variations in the section generally reflect variation in environmental energy:

1. The oolitic grainstones developed as shoals in moderately high energy environments with constant water movement in depths less than 5 m;
2. The bioclastic packstones developed in environments of moderate energy levels. Energy levels were not high enough to allow the constant winnowing and rolling needed for oolitic grainstone

development, though high enough to allow the accumulation and production of significant bioclastic material and prevent excessive mud deposition.

3. The mudstones are indicative of very quiet water conditions.

The change from unit A, an oolitic grainstone, to the reefal facies of reef 2 and 3 documents a rapid decrease in environmental energy since these reefs developed in fine mudstones. The cause of this drop in environmental energy is interpreted to be a result of a rapid rise of sea level (see below). Hence reefs 2 and 3 are believed to have developed between fair weather wave base (FWWB) and storm wave base (SWB) in quiet conditions where muds could accumulate. These reefs were occasionally affected by storms which produced well developed brachiopod storm beds (unit C). The water depth began to shallow at the top of reef 3 where the inter-reef occurrence of bioclastics becomes increasingly important up-section. Reef 4, which occurs within bioclastic packstones, developed in an environment of moderate energy levels just below FWWB. The demise of reef 4 resulted from a continued shallowing of the environment and its accompanying increase in energy levels and water movement. The environment became more conducive for oolite development and the deposition of 10 m of oolites of various types ensued (units E and F). The top of unit F shows a fining of the oolite suggesting a lowering of energy levels. The end of unit F and the beginning of unit G signifies a significant drop in energy levels with the development of a rather protected quiet water lagoon. This is believed to be a result of the development of a protective barrier in the area. Initially within this lagoon well bedded muds were deposited (unit G). Reef development did not occur in unit G, presumably because of the lack of a suitable substrate for coral planulae. Following the deposition of over 10 m of this reefless mud, reef development commences with growth of reef 5. The inter-reef sediments of reef 5 are superficially like unit G suggesting little change in environmental energy. However the microfacies analysis suggest that much of the bedded inter-reef sediment may be, at least in part, microbial in origin. So the development of reef 5 in unit G seem to be initiated by the development of microbialite mats on the micritic muds which, after early cementation provided, a more suitable substrate for reef development. What allowed the development of the microbialite mats in the first place can only be speculated, but a drop in background sedimentation rate would favour their development (Leinfelder *et al.*, 1993b). The growth of reef 5 was short-lived with only 10 m of reef building before a return to the muddy sedimentation of unit G.

In summary the section documents the development of various reefal units within a shallowing-upward sequence:

- After a rapid rise in sea level the sequence begins with reefs that developed within a relatively deep water muddy environment (reefs 2 and 3).
- As water depths decreased reef development occurred in shallower water packstone environments between FWWB and SWB (reef 4).
- As water depth continued to get shallower, above FWWB, constant water movement and grain reworking favoured oolite development and precluded reef building, with the demise of reef 4.

- After the deposition of 10 m of oolite sands, the probable development of a barrier elsewhere on the platform drastically reduced energy levels and a muddy lagoon developed. Initially within this lagoon well bedded lagoonal mud were deposited.
- Finally a slight drop in sedimentation rates allowed the development of microbial mats and the subsequent growth of coral reef 5.

Interestingly the reefal units of reefs 2 - 3 and reef 5 occur within similar lithofacies, bedded mudstones. On the basis of the lithofacies *alone* the two reefs could be incorrectly interpreted as having developed in the same type of low energy environment. However the cause of the low energy in these two reefal environments was different: for reefs 2 - 3 it was their development in relatively deep water; but for reef 5 it was due to the development of a protective barrier, and reef development was in fact in shallow water. This difference in water depth in the two reef environments is clearly reflected in the difference in the reef faunas.

5.5: PÉRY-REUCHENETTE

5.5.1. Introduction

A large Charuque quarry at Péry-Reuchenette provides an excellent outcrop exposing reefs which developed within the Günsberg Member. The Günsberg Member is a belt 10 to 20 km wide with coral reefs at its base and oolites at its top. This member separates the platformal (inter- to supra-tidal) Natica Member from the coeval part of the mainly marly basinal Effingen Member (Gygi and Persoz, 1986). This outcrop is of particular interest in this study since it is a rare Tethyan shallow water coral reef that had developed in a sedimentary regime strongly influenced by siliciclastics. Hence, its composition and framework development can be compared to the Sub-Boreal type coral reefs of southern England which appear to have developed in similarly siliciclastic-influenced environments.

5.5.2. Reef structure and facies

Reef structure and framework development

Reef development is rather patchy and discontinuous and the generally coral skeletal biovolume is low (less than 20%; though can reach 40-50% in small framework patches). Individual framework are 1-3 m high and up to 10 m across, although the change from reef to non-reef facies is very gradational (plate 5.14-fig 1). Large frameworks can reach 10 m thick and 20 m across and are the result of the amalgamation of smaller framework patches. The framework development is primarily by massive, tabular and phaceloid corals (plate 5.14-figs 3-4; plate 5.15-fig 1-2). Not all the corals are in situ and large rounded coral domes are often over-turned (plate 5.15-fig 1). The shape of the reefs is domal and vague ill defined internal bedding within the reefs can distinguished. These surfaces can be followed into the inter-reef sediment and indicate syn-depositional relief of the reef was no more than a couple of metres.

Facies and sedimentology

The two most obvious feature of the reef facies are: (1) the very muddy marly nature of the intra-reef sediments which clearly contain a significant component of siliciclastic sediment (plate 5.14 -15); and (2) the presence of very conspicuous dark crusts which have developed primarily around the corals (plate 5.15-fig 2 and 3). Within the sequence there are a number of small fining upwards beds 2 to 20 cm thick (plate 5.16-fig 1). These contain coarse bioclastic material at their bases which is both autochthonous (echinoderms, rhynchonellid brachiopods, fragments of broken crusts and corals) and autochthonous (nerineids, *Trichites*, terebratulids, ?red algae). The coarser bands are particularly rich in echinoid and coral fragments and the bioclasts in general are texturally very immature. The dark crusts are commonly fragmented, and reincorporated into the intra-reef sediments as peloidal intraclasts (plate 5.15-fig 3; plate 5.16-fig 1). These crustal intraclast are a common constituent of the intra-reef sediments and they themselves acted as a site for further crust development. Rolled and toppled coral heads are common as are brachiopod storm beds. Large patches of the intra-reef sediment are composed of a dark dense microbialite biopelmicrite. The intra-reef microfacies is dominated by microbial fabrics (plate 5.16-figs 1-4). The microfacies is best described as a rindy biopelmicrite with M/S/C ratios of around 90/0/10. The microbialite can develop as concentric layers forming spheres 3-4 mm in diameter and can therefore look oncoidal (plate 5.16-fig 4). Occasionally microbialite columns up to 10 mm high, 4 mm across develop (plate 5.16-figs 2-4). In between such fabrics is a matrix composed of more indistinct microbial pelmicrite, fine clasts and clay material. Also identifiable are quartz grains and pyrite fragments.

Crusts. (plate 5.17-figs 1-4; also see plate 5.15). One of the most conspicuous features of these reefs is the abundant occurrence of dark crusts that have developed particularly around the coral colonies, especially the phaceloid forms. But from the study of the intra-reef microfacies it is found that much of the intra-reef sediment is composed of peloidal fabrics of presumed microbialite origin (plate 5.16-figs 1-4). These dark crusts therefore appear to represent merely a staining of the microbialite during various stages of their development, giving the microbialite a dark colour and hence standing out as a dark crust. This iron mineral (probably pyrite) staining appears to be similar to that occurring in some shallow-water hardgrounds (Wilson and Palmer, 1992). The dark colour may also reflect the presence of some organic matter although it has not been possible to substantiate this. These crusts completely encrust many of the massive corals and may grow up, down or sideways. Empty microbial tubes 30-70 microns in diameter have been documented in these crusts (Gygi, 1992). They were encrusted by organisms such as serpulids and problematic microencrusters (plate 5.17-figs 1, 3 and 4).

5.5.3. Palaeoecology

Associated fauna

The most obvious feature of the associated fauna is the extremely common occurrence of rhynchonellid brachiopods. Also common on the coral branches are small encrusters such as serpulids, *Lithocodium*, forams, bryozoans (plate 5.18-figs 3-4), the problematic encruster *Koshirobulia socialis* (plate 5.17-figs 1 and 4) and other problematic encrusters (plate 5.17-figs 1 and 3). The molluscs are generally oyster-type forms and are encrusted on corals and local hardgrounds. Echinoid spines are common as are 10 cm large domes of red algae, although it has not been possible to establish for certain whether the red algae are definitely in situ. Lithophagan borings are common in both the top surface of corals and in the hardground; boring intensity is moderate to high.

Coral fauna

Tabular forms (approximately 6 cm thick about 20 cm across) and domal forms (over 20 cm thick) dominate the fauna (plate 5.15-fig 1-2). Also present, albeit rare, are very thin crinkly dish-shaped and platy forms (plate 5.14-fig 2). In the massive colonies intra-colony mortality and sediments are common. *Isastraea* is particularly abundant.

Coral assemblage of the Péry-Reuchenette reef:

Branching phaceloid	**Massive and platy**	**Branching ramose**
(20%)	(80%)	(not present)
?*Dermosmilia*	*Fungiastraea* (c)	
?*Placophyllia*	*Isastraea* (c)	**Solitary forms**
Calamophylliopsis (c)	*Meandaraea*	(not present)
Haplaraea	*Microsolena*	
Thecosmilia (c)	*Stylina*	**Thin lamellar forms**
	Thamnasteria (c)	(not significant)
		unidentifyable

5.5.4. Depositional environment

The reef fauna and the reef's association with oolites suggests that these were relatively shallow water coral reefs. They are likely to have developed in sub-tidal water depths just below FWWB. They were clearly well above SWB since they were subject to frequent storm events. General background sedimentation rate can be inferred to be relatively low as indicated by the development of local hard ground formation, the dominance of microbial fabrics and crust formation. Siliciclastic influx was therefore likely to be sporadic, probably introduced during storms events. The source of the siliciclastics can be inferred to be relatively close to the development of these reefs since sand-sized quartz grains are present within the intra-reef sediment.

CHAPTER 6: England and Italy

6.1: ENGLAND

6.1.1. Introduction

The Corallian of England has had a long history of study (Blake & Hudleston, 1877; Arkell, 1933, 1935, 1929-1937; Fürsich, 1976, 1977; Wilson, 1968; Ali, 1978; Negus, 1991, 1983), however only a small number of these works have focused on the palaeoecology and sedimentary dynamics of the coral frameworks. Furthermore none have made detailed comparisons between Corallian reefs of England and their counterparts of continental Europe. This has led to a poor understanding of the relationship between the reefs of these two regions. Therefore this chapter is essentially a literature synthesis for the Coral Rag coupled with the author's own study of a number of key field localities (figure 6.1). More detailed work has been carried out on a new (temporary) section at Haydon Wick (Wiltshire). The chrono- and lithostratigraphic framework for this study is that proposed by Cope *et al.* (1980). This correlation suggests that all the Corallian reefal deposits were deposited contemporaneously during the Middle Oxfordian, *Cardioceras tenuiserratum* Zone (*C. tenuiserratum* to *C. blakei* Subzones) (figure 6.2).

6.1.2. Southern England: the Oxford-Faringdon Ridge

The Oxford-Faringdon Ridge is a ridge of Corallian outcrops that extends from Headington (Oxfordshire) in the northeast, through to Faringdon, and terminates at Calne (Wiltshire) in the southwest. This Corallian unit is composed of two sand and limestone horizons sandwiched between the thick Oxford and Kimmeridge Clays. The Coral Rag and the associated Wheatley Limestone (inter-reef facies) are located at the top of the Corallian succession.

The Coral Rag is composed largely of corals, though not always in growth position. It has a loose, rubbly appearance and contains a large amount of marl and clay in its interstices. The corals that construct the Rag can be up to 1.8 m in diameter but they are rarely greater than 1 m. Only 4 species are common: *Thecosmilia annularis, Thamnasteria concinna, Isastraea explanata* and *Fungastraea arachnoides*, with two secondarily common species, *Rhabdophyllia phillipsi* and *Cladophyllia conybeari*. In addition another four species have been identified but are all very rare. The associated fauna is variably developed and the common elements include *Chlamys, Plagiostoma, Nanogyra, Lopha, Lithophaga* and *Paracidaris*. The associated Wheatley Limestone represents detrital accumulations of bioclastic material from the Rag and is deposited in channels in between the coral frameworks. Two sections through the Corallian of the Oxford-Faringdon Ridge were examined:

(1) Shellingford Cross Roads (Stanford) quarry, Oxfordshire, which is the classic Corallian section of southern England.

(2) Haydon Wick, Wiltshire, a temporary section excavated during a road development scheme (1994).

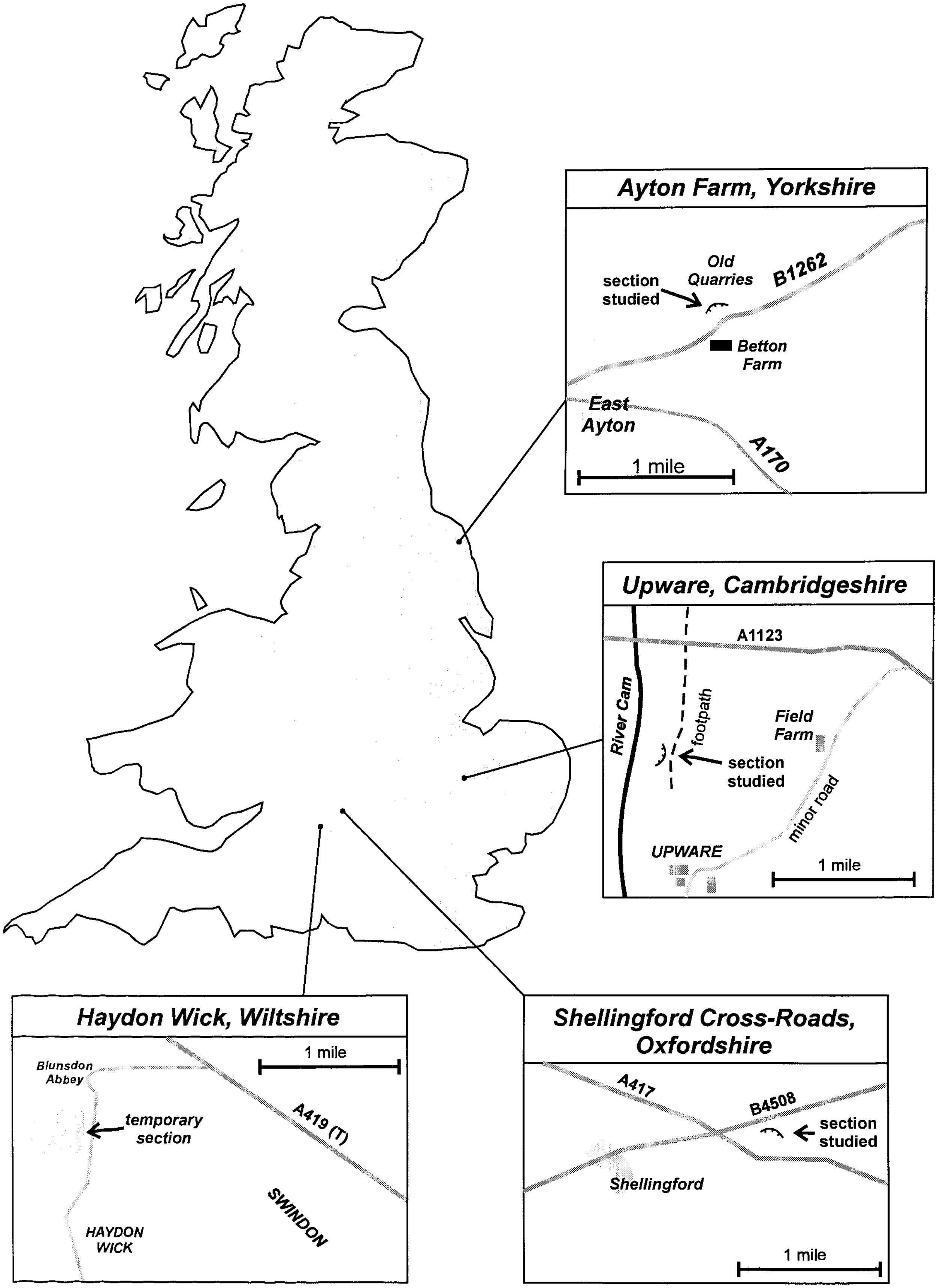


Figure 6.1: Locality map of the sections studied in England.

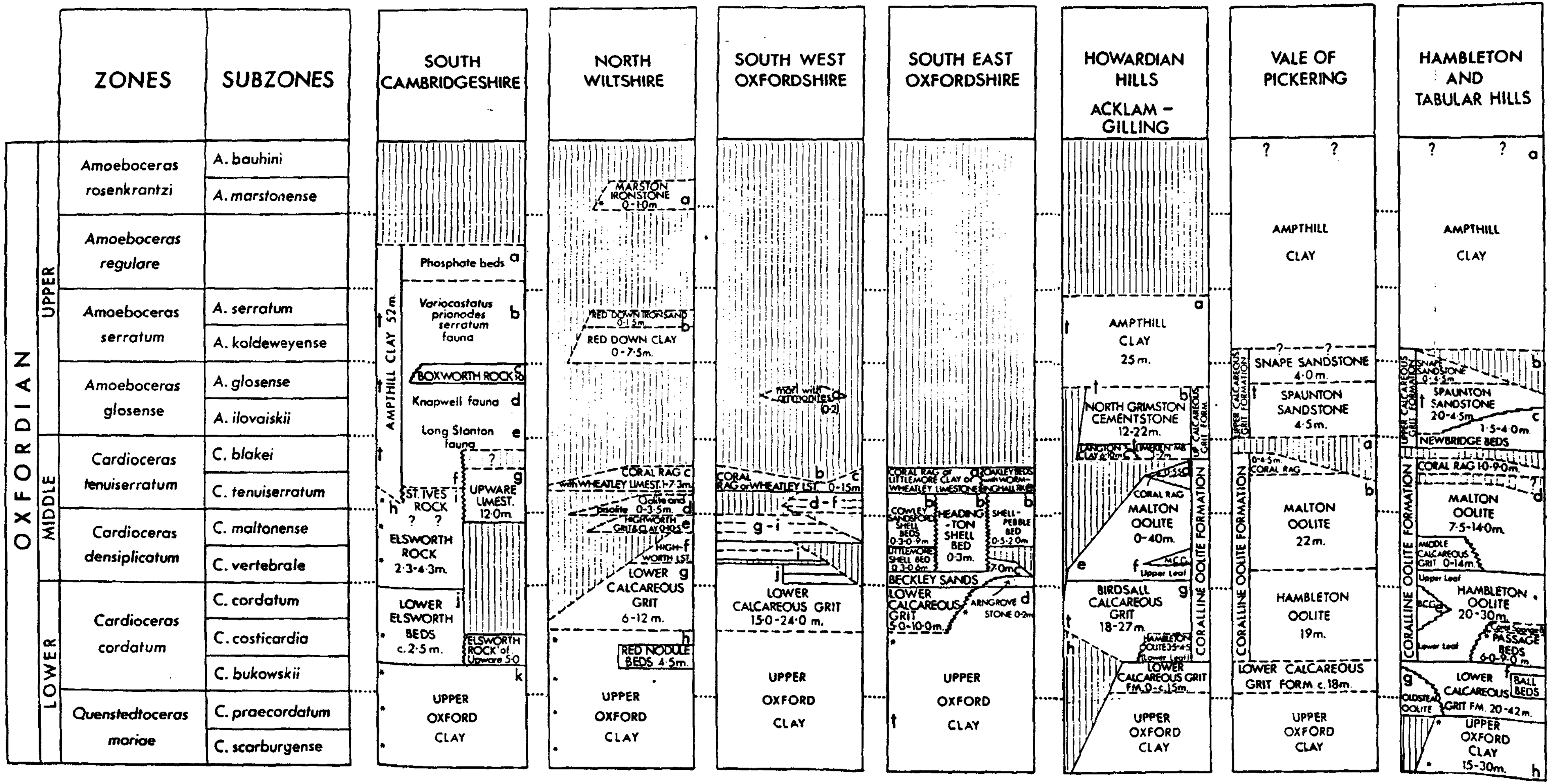


Figure 6.2: Correlation and stratigraphy of the Oxfordian rocks in England (from Cope et. al., 1980).

6.1.3. HAYDON WICK, WILTSHIRE

6.1.3.1. Introduction

A temporary outcrop of the Corallian was exposed during the construction of a new road just north of Haydon Wick. The section corresponded to the southern extension of the Oxford-Faringdon Ridge. The facies exposed were generally similar to other southern England Corallian units, such as those of Shellingford Cross Roads, Oxfordshire though more extensive and better developed. The section also revealed the development of a hitherto undocumented knobbly form of spongiostromate crust.

6.1.3.2. Reef structure and facies

Facies. The main facies in the section are: bioclastic packstones, bioclastic oolites, oncoidal grainstones (plate 6.2-fig 1), *Rhaxella* biomicrites (plate 6.2-fig 2), coral biolithites and clay bands. Due to the patchy nature of the outcrop it is difficult to establish the precise spatial relationship of these facies to each other. Nevertheless they all appear to have been deposited contemporaneously, and most of the packstones and grainstones were deposited within channels around the coral biolithites. Many of the channel sands have a rich bivalve and gastropod fauna. The pack- and grainstones represent the Wheatley Limestone.

Reef structure and framework development

Reef development occurred as small isolated patches of *Thamnasteria* and *Isastraea*, or thickets of *Thecosmilia* approximately 5-10 m across; between individual coral patches corals are rare. The total visible lateral extent of Coral Rag is over 300 m^2 and the thickness of biolithite is about 1 m. The coral-bearing units have a characteristically rubbly appearance (plate 6.1-figs 1-2) and the coral skeletal biovolume within individual patches is about 20-40%. The framework is constructed from domal coral and rather loose branching phaceloid colonies; they may have also been locally bound by knobbly spongiostromate crusts. Some coral colonies are completely encrusted by these knobbly crusts to the extent that the corals themselves are no longer visible (plate 6.3-fig 1). Clay bands can be up to 30 cm thick and occur relatively frequently within the coral frameworks (plate 6.1-figs 2-3). These bands are slightly lensoid in form are laterally extensive (tens of metres across) though difficult to trace. Within these clay bands are large, often whole, echinoid spines and *Nanogyra* valves. These clay bands, where well developed, have clearly interrupted reef growth.

Facies and sedimentology

The intra-reef sediment within the *Thecosmilia*-dominated coral patches (where this is not clay) is a dark grey mudstone-wackestone with M/S/C ratios of 70/5-10/20 (biomicrites). The carbonate grains are mainly bioclasts (90%) and peloidal lithoclasts (i.e. small fragments of spongiostromate crust; 10%). The bioclasts include *Rhaxella* sponge spicules (which can be very abundant: 55% of bioclastic material), corals, bivalves, echinoids, serpulids, thecidean brachiopods and gastropods; grain orientation is present. The bioclasts are generally fine-grained (<0.3 mm), poorly sorted and angular.

Grain micritization is not high and spongiostromate crusts are only present on the large fragments. The matrix is rather homogeneous and composed of an admixture of fine detrital carbonates, fine siliciclastics (mainly clays and quartz), fine opaques (?pyrite), and faecal pellets. Where the matrix is uncompacted well-defined oval faecal pellets are clearly visible (plate 6.2-fig 3). The pellets are generally circular to oval, well-sorted and rather large with a diameter of between 0.3-0.5 mm, and are common, indeed much of the matrix may be composed of compacted, homogenized, faecal pellets. In the more protected microenvironments the amount of bioclasts, other than the sponge spicules, is reduced with the development of patches *Rhaxella* biomicrite (plate 6.2-fig 2).

In areas where the framework is dominated by domal and platy colonies the intra-reef sediment is a grey-brown bioclastic wackestone (M/S/C: 50/0-5/50; biomicrite). The carbonate grains include both bioclasts (80-90%) and fragmented spongiostromate crusts (10-20%). They are coarse-grained (average 1-3 mm; range 0.1-10 mm) and sub-angular to sub-rounded. The bioclasts show a clear preferred orientation. They are not highly micritized and relatively thick (0.3 mm) spongiostromate crusts are quite common on the larger fragments. However, the formation of these crusts is more often pre-bioclast formation. The bioclastic material is dominated by fragments of bivalves (60%), with corals (20%) being the only other main constituent. Other bioclasts include serpulids, thecidean brachiopods, forams, echinoids (common), sponge spicules (numerically very common) and gastropods. The matrix is much the same as the previous microfacies, effectively representing a compacted homogenized admixture of fecal pellets and fine siliciclastic detrital material. These sediments grade laterally into dark grey bioclastic packstone lacking framework; the inter-reef sediments. The microfacies is the same as that described above, though slightly coarser-grained (2-3 mm). The bioclasts are again mainly bivalve fragments with coral and echinoid material being secondarily common. The grains show a well developed preferred orientation. Grain micritization is common though not highly developed. Spongiostromate crusts are common and approximately 0.1-0.3 mm thick.

Spongiostromate crusts. The Haydon Wick reefs possess well developed knobbly spongiostromate crusts which appear to be unique to these reefs and have not been documented from any other British Corallian outcrop. These crusts are extensively developed and pervasive throughout the frameworks, often enveloping whole coral colonies (plate 6.3-figs 1-2). Their thickness ranges from 2-6 mm (average of about 3-4 mm), with individual knobs being 2-4 mm across (plate 6.3-fig 3; plate 6.4-figs 1-2). These knobbly crusts seem to have developed particularly well on the branching phaceloid *Thecosmilia* colonies and are rarer on the massive colonies. The spongiostromate crusts that developed on massive corals are less common and more planar in nature, however they can be thicker, up to 17 mm thick (plate 6.5-figs 1-2). At outcrop and on polished slabs these crusts are a bright white and contrast sharply from the siliciclastic-rich grey-brown intra-reef sediment (plate 6.3-figs 1-2). The white colour of the crust presumably reflects the purer carbonate content of the crust, which generally lacks siliciclastics. In thin section the crusts are darker than the surrounding intra-reef sediment, and are clearly composed of oval, well-sorted precipitated peloids 200-300 µm in diameter (plate 6.6-fig 2). The peloids are generally tightly packed, resulting in a certain degree of homogenization, however in some areas within the crust peloids float in sparite. Bioclastic material within the crust is invariably very fine (<0.1 mm) (plate 6.6-figs 1-3). Growth lamellae, are present though poorly developed (plate 6.6-figs 1-3) and often not visible. These crusts underwent early cementation and were a source of peloidal fragments to the intra-reef sediments. Some early peloidal fragments were themselves incorporated into the growing crust. They are not highly encrusted by organisms but occasional serpulids and thecidean brachiopods can be seen within them (plate 6.2-figs 4-5).

6.1.3.3. Palaeoecology

Associated Fauna. The most conspicuous genera amongst the associated fauna are the oyster *Nanogyra* and the spines of *Paracidaris*, both of which are very common. *Rhanxella* sponge spicules are extremely common in the muddier facies. Other groups present include thecidean brachiopods, stomatoporid bryzoans, calcareous sponges and other cementing and byssally-attached bivalves. The fauna is essentially the same as that documented at Shellingford Cross-Roads (see next section) though more abundant. Bioerosion is common and mainly by bivalves, although *Talpina* borings are frequent in areas.

Coral Fauna. The coral fauna, although rather limited, is dominated by domal and tabular forms of *Isastraea* and *Thamnasteria* (50%), and the loose branching phaceloid *Thecosmilia* (50%). The domal forms can be up to 50 cm across and 30 cm thick. The branching phaceloid colonies of *Thecosmilia* are also relatively large with colonies reaching a height of 55 cm. Less common are thin platy and encrusting forms of *Thamnasteria* which are only 7-12 mm thick and 10-20 cm across (plate 6.5-fig 2). Taxonomically the coral fauna is typical of the British Corallian with only four species present: *Thamnasteria concinna, Isastraea explanata, Thecosmilia annularis* and *Montlivaltia* sp. The fauna is dominated by *Thamnasteria* and *Thecosmilia*, which together constitute about 80% of the total coral skeletal biovolume.

6.1.3.4. Depositional environment

The facies association of bioclastic packstones, oolites, oncoidal grainstones and coral biolithites suggests that the coral thickets and patches had developed in very shallow water. The bioclastic oolites and oncoidal packstones suggest water depths not in excess of 5 m with moderate energy levels, and little siliciclastic influx. The intercalated clay bands within the frameworks suggest that strong siliciclastic influx was likely to have been episodic (at least in intensity) rather than a uniform constant supply (which would have hindered the development of oolites). The well developed clay bands also suggests that the terrigenous source was not far away. These muddy siliciclastic sediments would probably have been introduced during storms which appear to be have been quite frequent. Storms were also responsible for the development of many channel sand deposits rich in bivalve and gastropod material. The storm events terminated reef growth through clay smothering and erosion by storm channels.

The area represents small-scale reef development in a complex environment of sub-tidal sand shoals and channels within a storm-dominated regime. In an area where siliciclastic influx was not strong oolitic and oncoidal grainstones developed in higher energy environments. There were two distinct coral frameworks: (1) the *Thamnasteria/Isastraea-dominated* patches; and (2) *Thecosmilia*-dominated thickets. From the facies association it is clear that both these biolithites developed in very shallow water (less than 5 m), and it can be speculated that the *Thamnasteria/Isastraea* biolithites, dominated by massive colonies, grew in slightly higher energy environments, and the *Thecosmilian* thickets, dominated by branching phaceloid forms, were more abundant in the hydrodynamically protected areas. The development of large volumes of microbialite was probably hindered by the siliciclastic sedimentation. Consequently the microbialite developed as a knobbly spongiostromate crust mainly around the phaceloid branches, which were raised above the depositional surface.

6.1.4. SHELLINGFORD CROSS ROAD

The Shellingford Cross Roads quarry is one of the best known UK Corallian exposures and is a S. S. S. I. It lies about 1 km north of Shellingford village and 4 km ESE of Faringdon.

6.1.4.1. Reef structure and facies

Facies sequence. The coral limestones (Coral Rag) are located at the top of the exposed sequence (figure 6.3). A number of sub-facies are present within the coral-bearing limestones including: framestones (*Thecosmilia*- and *Isastraea/Thamnasteria*-dominated); thecosmilian rudstone, bioclastic grainstone lenses and clay bands (plate 6.7-figs 1-2).

Reef structure and framework development. The maximum thickness of the whole coral-bearing unit is 2 m and is visibly 110 m across. The majority of the coral limestone is parauthochthonous rubble from *Thecosmilia* colonies (Thecosmilian rudstone). The thecosmilian rudstone grade laterally into Thecosmilian biolithite. At the top of the section is a 0.5 m thick unit of *Thamnasteria/Isastraea* biolithite which to the east grades to *Thecosmilia* biolithite. The section is interrupted by a number of biosparitic lenses (0.15 cm thick, 3 m across) which are vaguely cross-bedded and contained small in situ *Thecosmilia* colonies (plate 6.7-fig 2). Thin (1-6 cm thick) clay seams are present though not common (rare compared to Haydon Wick). They are composed of smectite (88-98%; Ali, 1978), silt and sand, and coral material (insoluble residue approximately 65%; Ali, 1978). The total coral skeletal biovolume in the *Thamnasteria/Isastraea* biolithites is 20-40%; 30-60% in the *Thecosmilia* biolithite. In the biolithites most of the corals are in growth position (over 80%). In short these coral limestones represent small thickets approximately 50 cm high of either *Thamnasteria* and *Isastraea* or *Thecosmilia* and grade laterally into storm-generated Thecosmilian rudstones, which volumetrically dominate the section. Individual thickets are 5 m across. Both the coral facies (biolithites and rudstones) have a

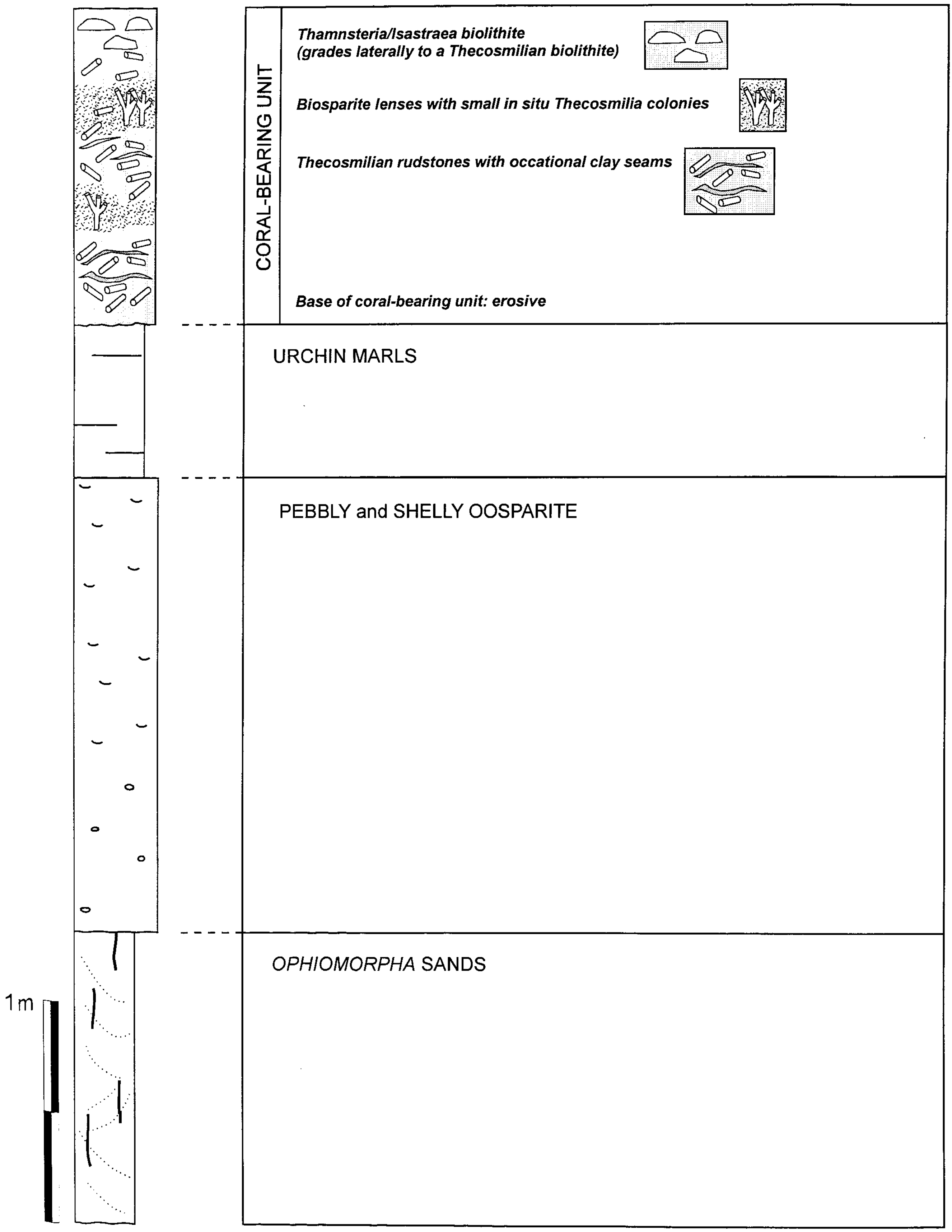


Figure 6.3: Schematic log of the Shellingford Cross-Roads section.

rubbly appearance. Spongiostromate crusts on the corals are rare, though where present are similar to those encountered at Haydon Wick (plate 6.7-fig 3).

Facies and sedimentology. The interstitial sediments of the thecosmilian rudstones are bioclastic grainstones (biosparites) with M/S/C ratios of about 5/50-60/40-50. The carbonate grains are essentially all bioclasts (mainly of bivalves, corals and echinoids). Spongiostromate coatings are common, though thin (about 0.1 mm thick), except on the large fragments where they can reach up to 0.5 mm thick; grain micritization is well developed. The carbonate grains are coarse (0.5-3 mm), barrel-shaped, sub-rounded, moderately well sorted and show a preferred orientation. Also present are areas dominated with muddy material (M/S/C: 50-60/0/40-50) rich in *Rhaxella* spicules and faecal pellets. Occasionally reworked extraclasts of oolitic pisolite can be found in these muddy sediment, an indication of storm activity. There are rapid variations from muddy to clean sediments. The intra-reef sediments of the *Thamnasteria/Isastraea* and *Thecosmilia* biolithites are essentially *Rhaxella* pelmicrites very rich in faecal pellets. The biosparite lenses are concave-up and composed of coarse-grained (up to 5 mm) oyster-type bivalve and coral material which is moderately well sorted.

6.1.4.2. Palaeoecology

Associated fauna. The associated fauna is generally quite rich and abundant. *Nanogyra* is very common, being the commonest species. Epifaunal low-level suspension feeding bivalves are the most diverse group. Boring activity is moderate and solely by bivalves. (For more details on the associated fauna see Ali, 1978).

Faunal list of the associated fauna (from Ali, 1978)

Bysally-attached	Shallow infaunal	Cemented	Other	Echinoderms
Chlamys	*Neocrassina*	*Nanogyra*	*Terebratula*	*Paracidaris*
Modiolus	*Sowerbya*	*Plicatula*	*Stomatopora*	*Diplodia*
Isognomon	*Isocyprina*	*Lopha*	*Enaulofungia*	*Ophiurella*
Camptonectes			*Rhaxella*	
Plagiostoma	Boring	Gastropods	Thecidean brachiopods	
Ctenostreon	*Lithophaga*	*Metriomphalus*	Nubeculinid forams	
Pteroperna	*Gastrochaena*	*Procerithium*		
		Bourgetia		

Coral fauna. The coral assemblage is dominated by *Thamnasteria* and *Thecosmilia* with *Isastraea* being secondarily common. The massive colonies (*Thamnasteria* and *Isastraea*) grew as low domal and tabular forms (plate 6.7-fig 3). The colonies of *Thamnasteria* are generally between 80-150 cm across and 10-40 cm thick; the *Isastraea* colonies are smaller (46 cm across and 25 cm thick). In many of the massive colonies, especially in *Thamnasteria*, there are intra-colony growth discontinuities. These are marked by veneers of sediment (pelmicrites and silty muds), spongiostromate crusts or encrustations (such as nubeculinids, calcified cyanobacteria and serpulids). The branching phaceloid

Thecosmilia generally forms small colonies up to 40 cm high and 10-20 cm across, although in the monospecific *Thecosmilia* biolithites the colonies are considerably larger (1 m high and 30-40 cm across). Some colonies have intergrown and developed as large (3 m across and 51 cm high) composite colonies. The composition of the *Thamnasteria/Isastraea* reef patches is: massive forms: *Thamnasteria* (60%), *Isastraea* (20%), *Fungastraea* (insignificant); branching phaceloid forms: *Thecosmilia* (20%).

6.1.4.3. Depositional environment

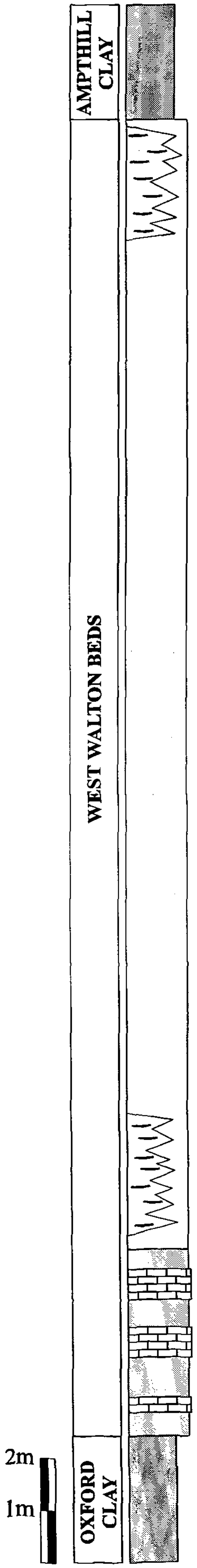
The dominance of the thecosmilian rudstone facies suggests that the majority of the section represents rubble from *Thecosmilia* thickets such as those of Haydon Wick, which were probably storm-generated. Where in situ reef development does occur, such as within the biosparitic lenses, the sediments are clean grainstones suggesting high energies, or *Rhaxella* biomicrites suggesting low energies. Clay bands, although present, are not as frequent as they are in the Haydon Wick section, possibly suggesting a more distal source. The *Thamnasteria/Isastraea* biolithites are essentially the same as those from Haydon Wick and are considered to have developed in a similar environment.

6.1.5. UPWARE, CAMBRIDGESHIRE

6.1.5.1. Introduction

The Upware Limestone forms a ridge extending northwards from Upware village for about 3-4 km. The limestones are exposed as an inlier of Late Jurassic rocks surrounded by Early Cretaceous. The Upware Limestone, which forms the upper part of the West Walton Beds, contains a number of small coral-rich reef-like units (figure 6.4). The geology of the Upware region is best summarized in Kelly (1985) and Gallois & Cox (1977) and references therein. The Upware limestone and the reefal units they contain have been dated as Middle Oxfordian (*Cardioceras maltonese* and *C. tenuiserratum* Subzones) (Cope *et al.*, 1980; Gallois & Cox, 1977), and therefore can be regarded as being broadly contemporaneous with other Corallian outcrops in Britain.

The reefal facies of the area has been commented on by numerous authors (Blake & Hudleston, 1877; Arkell, 1933; Gallois & Cox, 1977; Ali, 1978, 1983; Kelly, 1985). One of the most interesting aspects of the Upware reef is its very distinct faunal composition and structure when compared with other contemporaneous Corallian reefs in Britain. Yet it compares very closely to various biostromal units in continental Europe, for example the reefs at Foug, Lorraine; Chatel-Censoir, Burgundy; and Liesberg, Swiss Jura. The coral reefs of England and continental Europe normally represent extremes in reef development with regard to species richness and the degree of framework construction, hence the similarity of the Upware reef to these Tethyan reefs has been puzzling. In the past this so-called Tethyan aspect to the Upware fauna had been explained by suggesting a connection to Tethys, perhaps via the London Platform shoal (Arkell, 1933; Wright, 1972), but there is little evidence for such a migrational route. A detailed study on the Upware reef was carried out in order to draw more



Reefal facies: Microsolenid biolithite.

Matrix: bioclastic pelmicritic limestones to marls.

Total coral skeletal biovolume 30 - 50%.

Extremely diverse associated fauna including a rich epifaunal suspension-feeding bivalve community, crinoids, echinoids, serpulids, gastropods, brachiopods, bryozoans, sponges and blue-green algae. Stromatolitic crusts present.

Percentage of coral skeletal biovolume					
Genus		Family		Growth-form	
Microsolena	46	Microsolenidea:	66	platy - sub-massive:	80
Dimorpharaea	20	Other:	34	phaceloid:	16
Fungiastraea	2			solitary:	4
Montlivaltia	4				
Thecosmilia	15				
Thamnasteria	5				
Rhabdophyllia	1				
Isastraea	7				

GENERIC RICHNESS:		8
EVENESS:		0.75
DIVERSITY INDEX	[SHANNON-WIENER]:	2.24
	[SIMMPSON]:	0.72

Mudstones and limestones.

Figure 6.4: Schematic log of the Upware section.

qualified comparisons with the reefs of continental Europe, and to get a better understanding of the palaeoecology of this reef.

Commissioners Pit and Bridge Pit North are the only two pits in the area that presently expose the Upware Limestone. The reefal sub-facies of the Upware Limestone has been documented at both these pits by Kelly (1985) and Ali (1978). However, the Bridge Pit North Pit no longer reveals the reef; Commissioners Pit is now the best example of the reef facies in this area.

6.1.5.2. Reef structure and facies

Facies sequence. The total thickness of the Upware Limestone is approximately 17 m (Gallois & Cox, 1977). Only 2 m of it is visible at Commissioners Pit and 7 m at Bridge Pit North. The majority of the limestones exposed today are generally coral-free pelmicrites containing variable amounts of oolites, oncolites, lithoclasts and bioclastic material. The reefal facies of this limestone, the "Coral Rag", makes up only a very small proportion of the limestone and is composed of in situ corals in a biopelmicrite matrix. Within the reef 5-10 cm thick micritic mud seams have been documented (Ali, 1978). These reefs are laterally discontinuous and wedge out or pass laterally into the pelmicrite facies. At Commissioners Pit the exposure consists of about 1.3 m of well-bedded coral-rich reef facies overlying about 1 m of pelmicrite. The following account refers to the work carried out on the reefal facies at Commissioners Pit.

Reef structure and framework development. The reefs occur as sheets and lenses 1-2 m thick and 10-20 m across. Internally they exhibit a well bedded structure on a decimetre scale. The sheet-like, well-bedded nature of these reefal units suggests that they possessed little, if any, relief and hence can be termed biostromes. The framework is well developed and coral skeletal biovolume is approximately 20-50%. The framework is constructed almost totally by platy corals (plate 6.8-fig 1). Micritic mud seams are present within the biostrome but do not terminate coral growth.

Facies and sedimentology. The majority of the intra-reef sediment is a white, coarse-grained bioclastic to oncolitic packstone (M/S/C ratio: 20-30/0/70-80; bio-oncomicrite). The carbonate grains are mainly bioclasts (80%) and fragments of spongiostromate crusts (20%). The average grain size is medium to coarse-grained (generally around 0.5 mm) though large centimetre-sized fragments are present. These grains are poorly sorted and angular. Bioclastic material is composed of bivalves (both as small bioclasts and large shell fragments), corals, echinoids, *Rhaxella* sponge spicules (very common), and encrusting nubeculinid forams (common, especially within oncoids and spongiostromate crusts). The proportions of these constituents are: sponge spicules (30%), bivalves (20%), echinoids (20%) and corals (30%). The grains do not shows a preferred orientation. The grains are not micritized and do not generally posses spongiostromate coatings, although crusts have been observed on some of the larger centimeter-sized material. The large bivalves and coral fragments do have well-developed spongiostromate crusts showing knobbly forms up to 2 mm thick (occasionally up to 10 mm on some coral plates). The matrix is composed of an admixture of very fine detrital material (40%) and precipitated peloids (60%) and is homogeneous, lacking peloidal rinds or laminations. Locally there are small areas of poorly washed bio-oncomicrite which are similar in composition to the microfacies described above, though with a significant sparite component (M/S/C: 50/10-20/30). The grain size is coarser (average grain size is 1 mm, though 3 mm material is common), and large (0.5-3 mm) rounded peloidal fragments are abundant 30% of carbonate grains). The undersides of the coral plates provided a suitable microenvironment for the deposition of peloidal mudstones dominated by precipitated peloids.

6.1.5.3. Palaeoecology

Associated fauna. The associated fauna is diverse and species-abundant, and contrast with other Corallian outcrops which are generally species-poor. Epifaunal suspension-feeding bivalves dominate the assemblage, especially *Nanogyra* and *Chlamys,* and there is a very rich bivalve and echinoid fauna. Bivalve borings are common and in some places they have completely destroyed coral colonies. Other boring traces present are *Trypanites* and *Entobia*, though these are not common. Cementing bivalves, especially *Nanogyra*, cement themselves to the top surface of the corals and are abundant. *Barbatia* and other byssally-attached bivalves occupy the coral overhangs. Much of the bivalve fauna seems to occur near the base of the outcrop as a shell concentration. Serpulids and spongiostromate crusts are common. The associated fauna is as follows (after Ali, 1978, and Kelly, 1985):

Byssally-attached bivalves:..	*Chlamys, Isoarca, Opis, Eonavicula, Hiatella, Arca, Mytilus, Prorokia, Plagiostoma, Barbatia, Modiolus, Praeconia, Parallelodon, Ctenostreon*
Shallow burrowing bivalves:.	*Gervillella, Neocrassina*
Cemented bivalves:	*Nanogyra, Lopha, Plicatula, Liostrea*
Boring bivalves:....................	*Lithophaga, Gastrochaena, Gastrochaenopsis*
Gastropods:..........................	*Metriomphalus, Procerithium, Bourguetia, Nerinella, Pseudomelania*
Echinoderms........................	*Paracidaris, Nucleolites, Isocrinus, Pentacrinus*
Foraminifera	*Nubeculinella, Lenticulina, Ceitharina*
Brachiopods:........................	*Terebratula, Moorellina*
Sponges...............................	*Enaulofungia, Rhaxella*
Other:	*Serpula*, *Stomatopora, Protulophila, Girvanella*, crustacean claw

Coral fauna. The coral fauna is dominated by platy forms averaging a few centimetres thick and 10-20 cm across, though ranging from 5 mm to 8 cm thick and up to 40 cm across. Occasionally large *Isastraea* colonies up to 15 cm thick and 50 cm across can be found. Taxonomically the fauna is dominated by microsolenids. The coral assemblage is summarized below.

Platy		**Branching phaceloid**		**Growth form**	
Microsolena	46	*Rhabdophyllia*	1	Platy	80
Dimorpharaea	20	*Thecosmilia*	15	Branching phaceloid	16
Fungiastraea	2			Solitary	4
Thamnasteria	5	**Solitary**			
Isastraea	7	*Montlivaltia*	4	**Family**	
				Microsolenidae	66
				Other	34
Diversity indices:		**Generic richness**	8		
[Shannon-Wiener]	2.24	**Eveness**	0.75		
[Simpson]	0.72				

6.1.5.4. Depositional environment

The depositional environment of the reef is not easy to establish due to the small size of the outcrop and its isolated nature. The general pelmicritic character of the inter-reef sediments suggest low energy conditions. The oncoids and oolites that occur within the reefal facies do not appear to be autochthonous, but rather represent washed in material. Kelly (1985, page 15) states "The reefal facies with bioclastic debris may indicate marginal regions of the reef adjacent to deeper water conditions."...."inter-digitation of clay of probable West Walton Beds clay facies may indicate fore-reef conditions. This was probably seen at Commissioners Pit.". Kelly (1985, page 21) goes on to say "The presence of clays suggests the close proximity of the basinal clays of the West Walton Beds, and therefore this locality represents the outer margin of the reef with the fore-reef facies.". I agree with these statements, and they are corroborated by a detailed palaeoenvironmental analysis of this type of reef, given in chapter 7, section 7.1. In summary, this reef developed in a low-energy, relatively deep-water environment, in which sediments from shallower-water facies were occasionally washed in.

6.1.6. YORKSHIRE

6.1.6.1. Introduction and general overview of coral reef development in Yorkshire

The coral reefs of Yorkshire have been recently studied by Hitchings (1981). A brief summary of reef development in the area is presented below (mainly after Hitchings, 1981). The litho- and chronostratigraphy of the area is that of Wright (1972) and Cope *et al.* (1980) and shown in figure 6.2. For more details of the geology and stratigraphy of the Corallian in Yorkshire see Wright (1972).

The three main coral-bearing units within the Yorkshire Coralline Oolite Formation are: (1) the Coral Sponge Bed at the top of the Passage beds; (2) Coral horizons associated with the Hambleton and Malton Oolites; and (3) the coral patches of the Coral Rag. Only the latter two are dealt with in this study.

Coral reefs of the Coral Rag and the Hambleton and Malton Oolites: These reefal units possess a number of shallow-water sub-facies including:

(1) *Thamnasteria* biolithite
(2) *Solenopora*-gastropod facies
(4) *Terebratula*-gastropod facies
(3) *Bourguetia* facies
(5) Nerineid facies
(6) phaceloid coral facies;
(7) coral debris biomicrite facies;
(8) rounded biopelsparite facies;
(9) shell beds;

Of interest in this study are the coral-bearing facies (*Thamnasteria* biolithite and phaceloid coral facies) but also the *Solenopora*-gastropod facies and nerineid facies. The latter two facies are of interest since they are: (1) closely associated with the coral-bearing facies, and (2) appear to be very similar to nerineid-bearing facies of many continental European sections.

Thamnasteria biolithite and phaceloid coral facies

The *Thamnasteria* biolithite is exemplified by the reef at Betton Farm, East Ayton. These have been interpreted as high energy shallow water coral patches which developed in and around oolite shoals during periods of bedform stability (see section on the Ayton reef below). The phaceloid coral facies is characterized by the dominance of phaceloids such as *Thecosmilia* and *Rhabdophyllia* and is widely distributed in the area from Ayton to Pocklington and south-eastwards to Langton Wold. A faunal list of the phaceloid coral facies from Hitchings (1981) is shown below. This reefal facies is considered to have developed in low to moderate energy conditions allowing the deposition of micritic and peloidal sediments.

Faunal list from the *Thamnasteria* biolithite and phaceloid facies (from Hitchings, 1981).

Corals
Thecosmilia
Rhabdophyllia
Styliosmilia
Thamnasteria
Isastraea
Comoseris
Stylina
Montlivaltia
Episstreptophyllum
Dermosmilia

Bivalves
Lithophaga
Nanogyra
Ctenostreon
Chlamys
Lopha

Foraminifera
Placopsilina
Textilina
Rosalina
Tentilenticulina

Gastropods
Metriomphalus
Trochotoma
Pseudomelania
Nerineids
Turriform gastropods

Echinoids
Paracidaris

Sponges
Rhaxella
Enaulofungia

Algae
Acicularia
Solenopora

Other
Serpulids

Solenopora-gastropod facies and nerineid facies: These facies, especially the *Solenopora*-gastropod facies, are closely associated with the reefal facies and are deposited in and around the coral biolithites. They are coarse-grained oo-oncobiosparites rich in molluscan material. A faunal list of the *Solenopora*-gastropod facies at Betton Farm Quarry (from Hitchings (1981) corroborated by personal observations) is shown below. This facies is interpreted as having been deposited in a relatively high energy environment as inter-reef sand sheets and channels. This facies is very similar to the carbonate sand shoal facies of Bellême and the Novion-Porcein (see chapter 4).

Faunal list from the Solenopora-gastropod and Nerinacean facies:

Gastropods: *Metriomphalus, Bourguetia, Turbo, Nerinaea,* Turriform gastropods
Bivalves: *Chlamys, Nanogyra*
Brachiopods: *Terebratula,* Zeilleria;
Corals & sponges: *Rhaxella, Rhabdophyllia*
Echinoderms: *Paracidaris, Hemicidaris*
Algae: *Acicularia, Solenopora*

The corals documented from the all the coral-bearing units of the Yorkshire Corallian are:

Thamnasteria *
*Fungastraea**
Isastraea *
Rhabdophyllia
*Thecosmilia**
Stylosmilia
Dermosmilia
Cladophyllia
Montlivaltia
Epistreptophyllum
Stylina
Protoseris
Comoseris
Meandrophyllia

(*principal framebuilding corals. From Hitchings, 1981)

6.1.6.2. Ayton

Due to the lack of time and resources, and the fact that a detailed study of the Corallian reefs of Yorkshire has already been carried out by Hitchings (1981), only one exposure was examined in detail for this thesis. Betton Farm Quarry, East Ayton, was chosen because it is: (1) one of the best exposed reefs in the area; (2) characteristic of the *Thamnasteria* biolithites of the Coral Rag and Hambleton and Malton Oolites; and (3) also exposed is the *Solenopora*-gastropod facies. The coralliferous unit in this section is not the true Coral Rag but a coralliferous sub-facies at the top of the Malton Oolite Member, though is very similar to the *Thamnasteria*-dominated reefs of the true Coral Rag (Hitchings, 1981).

6.1.6.2.1. Reef structure and facies

Reef structure and framework development. The reefs occur as a series of isolated masses up to 2 m across and high, and are lensoid in form (plate 6.8-fig 2 and 4). The total coral skeletal biovolume of individual reefs is very high (90%), however this is because the reefs are small, and constructed by relatively few large individuals. The framework is constructed exclusively by massive corals and there is no internal organization; storm debris beds are present. These reefal units are the *Thamnasteria* biolithites of Hitchings (1982) and have developed around the *Solenopora*-gastropod facies of the Malton Oolite which occurs as pre- and inter-reef sediments (plate 6.8-fig 3). Below the reef patches is a 20 cm thick oobiomicrite-oobiosparite band rich in *Rhabdophyllia* fragments (plate 6.8-fig 3).

Facies and sedimentology. The intra-reef sediments are sparse in these coral patches since their coral skeletal biovolume is very high. What intra-reef sediment is present is effectively imported inter-reef sediment from the adjacent Malton Oolite (*Solenopora*-gastropod facies). This imported sediment was subsequently modified by the intra-reef microenvironment. These sediments are oo-oncobiosparite with M/S/C ratios of 0/50/50. The carbonate grains are coarse (1 mm across), highly micritized and well coated. The bioclasts are mainly fragments of bivalves and echinoids (bioclasts 30-40%; ooliths 60-70%). Within the more protected parts of the reef where ooliths become less dominant, bioclastic material, especially coral fragments, is more abundant and the matrix becomes significantly muddier (M/S/C: 70/0/30; biomicrites). Shell bed biosparites occur throughout the section.

6.1.6.2.2. Palaeoecology

Associated fauna. Within the biolithites the associated fauna is relatively poorly developed. The only groups that are abundant are cementing bivalves (especially *Nanogyra*), boring bivalves and small agglutinating forams. Bioerosion is quite high though only by bivalves.

With regard to the coral fauna the reef patches are effectively monospecific, dominated by *Thamnasteria concinna*. Only one colony of *Isastraea explanata* has been observed. *Rhabdophyllia* is common in a 20 cm horizon below the reef patches, though these are rarely in situ and represent an allochthonous storm deposit. The average size of the domal colonies is 30-40 cm high and up to 1 m across.

6.1.6.2.3. Depositional environment

These *Thamnasteria* biolithites occurred in very shallow water (less than 5 m), clean, relatively high-energy environments, in and around stable oolite shoals and channels.

6.2: FRIULI, NORTHERN ITALY

6.2.1: Introduction and facies

The reefal outcrops are located in the Friuli and eastern Veneto regions of northern Italy (figure 6.5). The reefs studied are situated in the Monte Cavallo and Cansiglio areas, cropping out along a steep hillside road from the town of Polcenigo to the hillside village of Mezzomonte. Reefs occur throughout the Polcenigo-Mezzomonte section and are located about 200 m down section from the Al Faro restaurant, hence these reefs are referred to as the "Al Faro" reefs. There are only two recent works that mention the coral reefs of the of the Friuli platform, Sartorio (1989) and Bosellini *et al.* (1981). However these works deal with the large scale evolution of the Friuli Platform and do not treat the reefs in any detail. There has been hitherto no description of their palaeoecology, reef structure or sedimentology. The chrono- and lithostratigraphic framework is that used by Bosellini *et al.* (1981). The reefs form part of the Polcenigo Limestone (Baldazzi *et al.*, 1966; Sartorio, 1989) and are of Late Oxfordian to Early Kimmeridgian age (figure 6.6).

Palaeogeography and platform evolution (from Bosellini *et al.*, 1981).

The Friuli platform is closely related to the neo-Tethys passive margin and was located on its southern margin. The exposed Mesozoic carbonate sequence in the Cansiglio area represents the north western edge of the Friuli platform from the Upper Jurassic to the Upper Cretaceous. During the Late Liassic the Friuli platform had become a superproducing oolite carbonate "factory". Soon platform overproduction resulted in export of oolite sediments into the adjacent basin in the form of westwards prograding deep-sea fans which infilled the Belluno Trough. In the Callovian, probably as a result of a short sea-level drop, large parts of the Friuli platform were subaerially exposed and subject to vadose zone diagenesis. The ensuing transgression over the substrate resulted in extensive reef

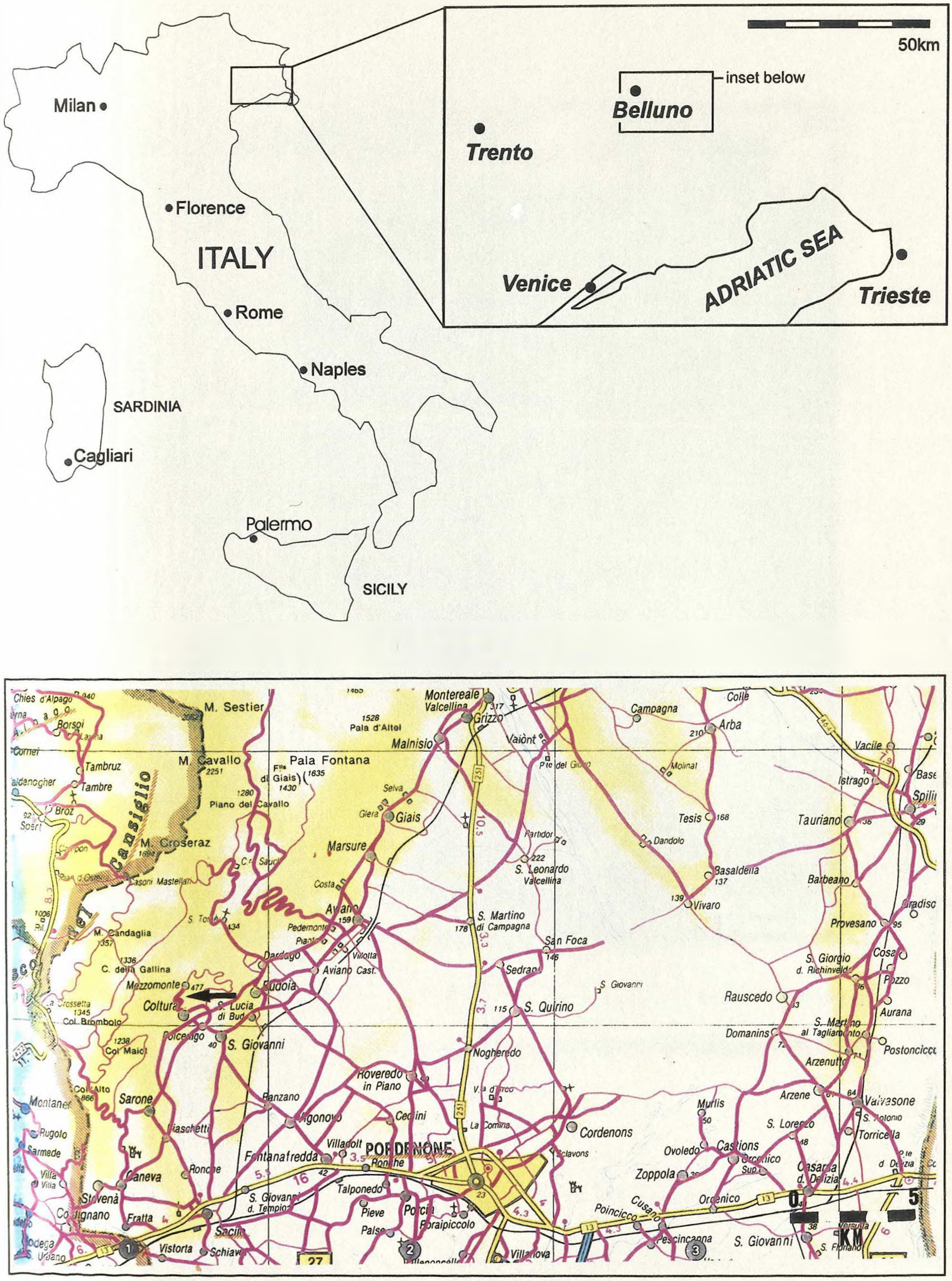


Figure 6.5: Location map of the Italian section studied.

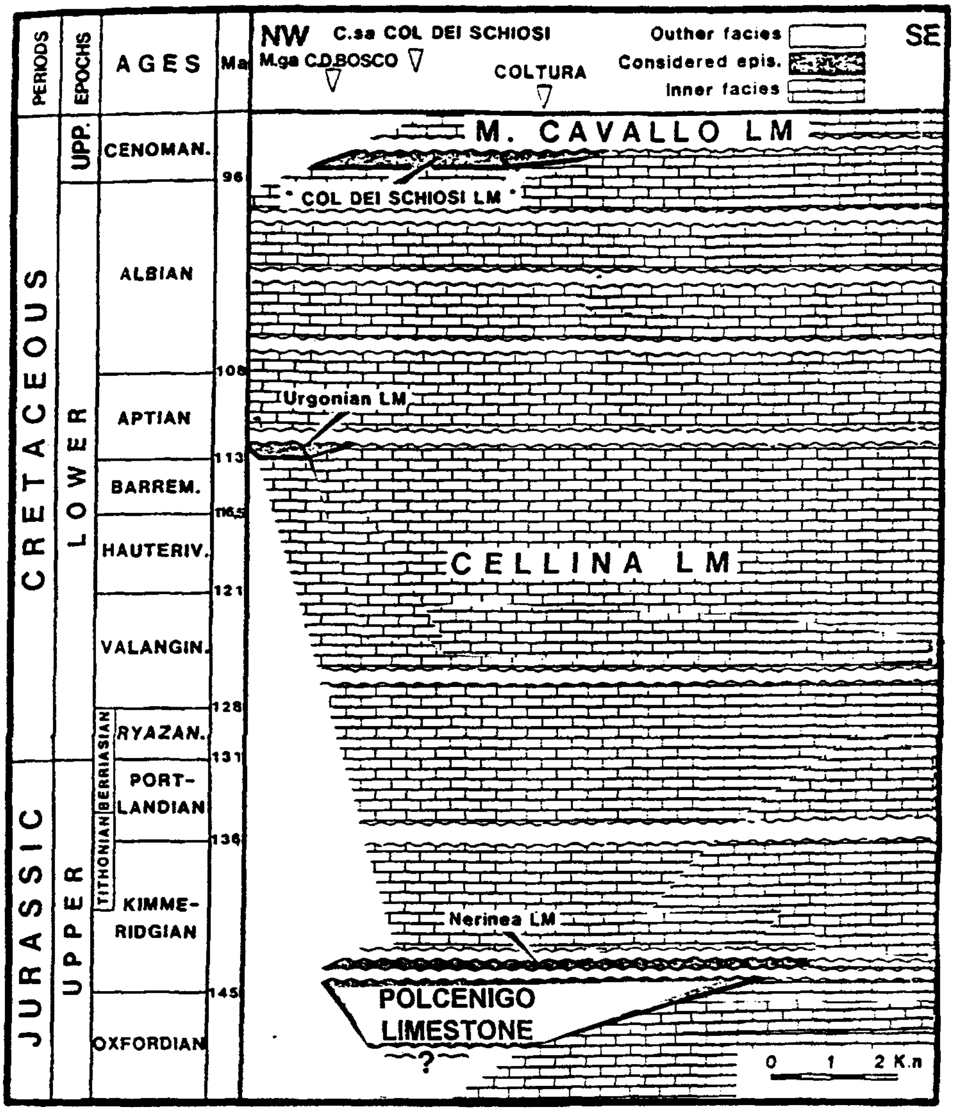


Figure 6.6: Mesozoic stratigraphy of the Cansiglio margin sequence (from Sartorio, 1987).

development which fringed the Friuli platform for the whole of the Upper Jurassic and Cretaceous (figure 6.7).

Facies sequence (figure 6.8). The reefs of the Polcenigo Limestone rest unconformably above the Callovian Ternowaner Oolite, although the unconformity is not seen in this section. The Polcenigo-Mezzomonte section begins with two reefal units, the first 25 m thick the second 15 m thick. The second (upper) can be sub-divided into two distinct zones based on the growth form of the main framebuilders and type intra-reef sediments. The upper reefs have a well developed lateral bioclastic apron and are overlain by approximately 5 m of inter-tidal beach gravels and conglomerates. The beach gravels grade into 5 m of nerineid grainstones deposited as sheets and small channels. These in turn grade into 7 m of coarse-grained biolithoclastic grainstones (plate 6.9-fig 4) which contain small scale channels (less than 1 m across) rich in imported coralline material. This finally grades into a well bedded back-reef "lagoonal" unit (plate 6.9 fig 1) which is at least 40 m thick. These are inter-tidal fine-grained pelmicrites with well developed laminated fenestrate textures (plate 6.9 figs 2-3), desiccation cracks and rip-up clasts.

The outcrop is such that the lateral facies distribution is also visible and follows the same pattern as the vertical succession (i.e. beach conglomerates grade laterally to sands and then to lagoonal limestones). Therefore it appears that once the reef had aggraded to sea level, resulting in the development of beach conglomerate, the back reef facies began to prograde over the previously deposited units. Thus the lower part of the section, up to the beach facies, represents an aggradational sequence, and the upper part of the section (above the beach facies) represents a progradation sequence.

6.2.2. Reef structure and facies of the upper reefal unit

Reef structure and framework development. The second reef can be divided into two distinct zones: a "seaward zone" and a "lagoonward" zone (figure 6.9) which have distinct bio- and lithofacies characteristics. The change from seaward to lagoonward zone appears to be gradational however the outcrop does not allow detailed evaluation of this. The coral skeletal biovolume of both these reefal units is around 50-60% and framework development is continuous. The form of these reefs is not discernible from outcrop and they are internally massive with no internal structure. The two reefal units together are about 80-100 m across and about 15 thick, although these are the limits of the outcrop. The seaward zone is dominated by massive forms, with branching ramose forms being absent. The framework construction in the lagoonward zone is principally by branching forms although massive forms are also important. Early microbially-mediated peloidal cements were also important contributors to the framework construction in terms of their binding and cementing role.

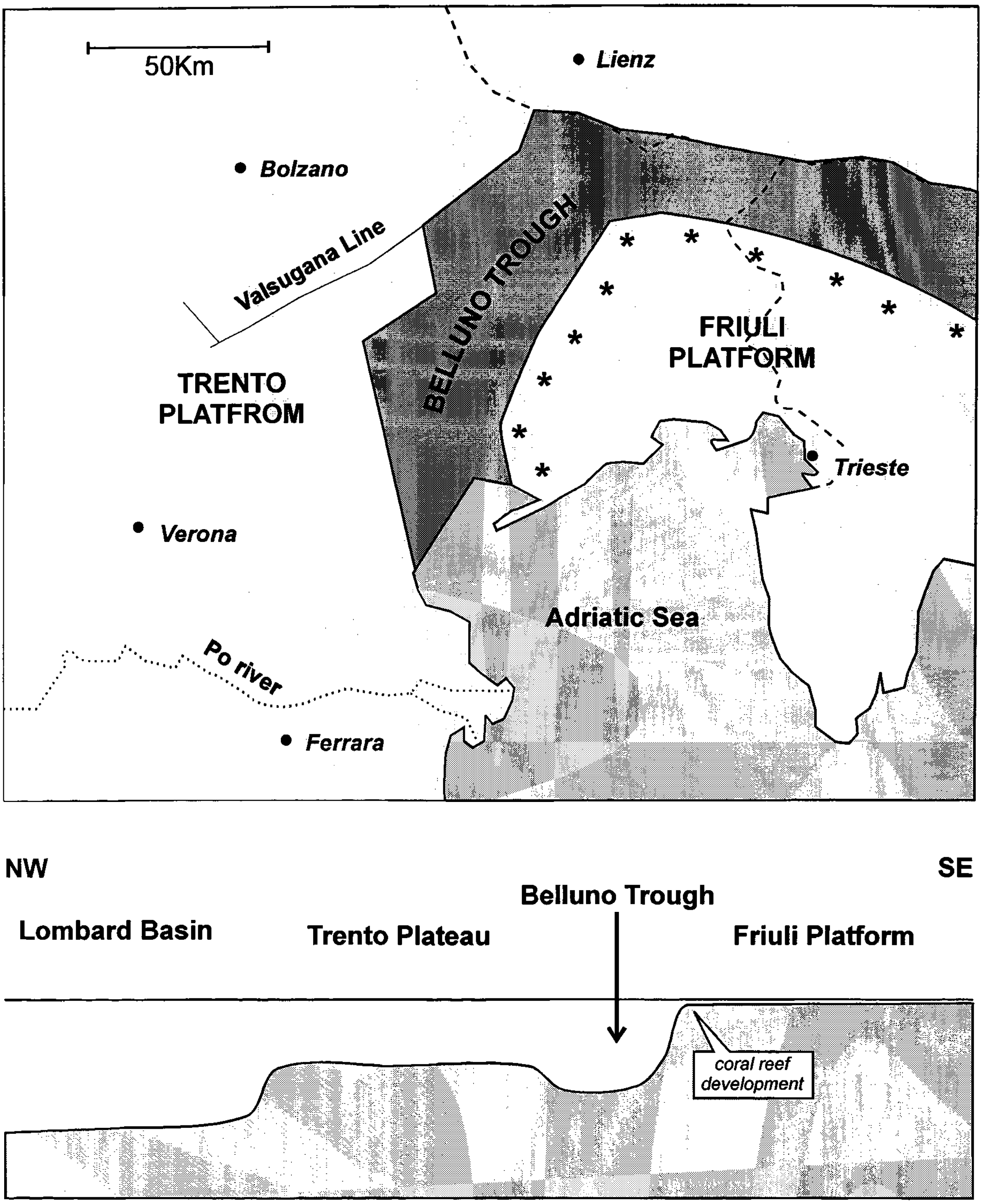
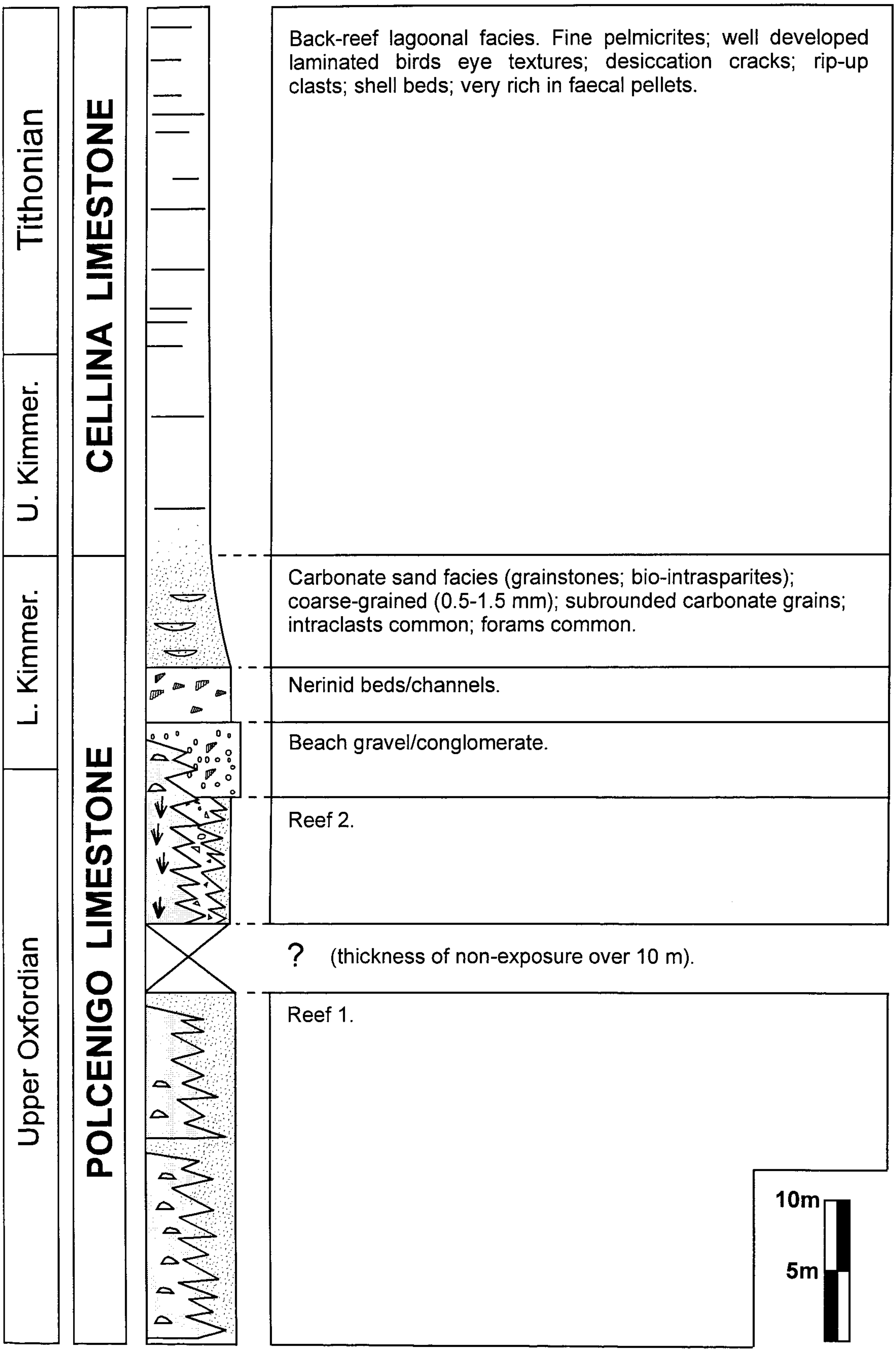


Figure 6.7: Palaeogeogeography of northeast Italy during the Upper Jurassic (Kimmeridgian). Reef development occurred primarily on the northern and western margin of the Friuli platform and prograded into the Belluno trough. In the interior parts of the Friuli platform back reef wackestones with *Clypeina* were deposited. During this time the Trento platform was submerged and red nodular limestones were deposited. Modified from Bossellini *et al.* (1989).



Back-reef lagoonal facies. Fine pelmicrites; well developed laminated birds eye textures; desiccation cracks; rip-up clasts; shell beds; very rich in faecal pellets.

Carbonate sand facies (grainstones; bio-intrasparites); coarse-grained (0.5-1.5 mm); subrounded carbonate grains; intraclasts common; forams common.

Nerinid beds/channels.

Beach gravel/conglomerate.

Reef 2.

? (thickness of non-exposure over 10 m).

Reef 1.

Figure 6.8: Schematic log through the Polcenigo-Mezzomonte section; the "Al Faro" reefs.

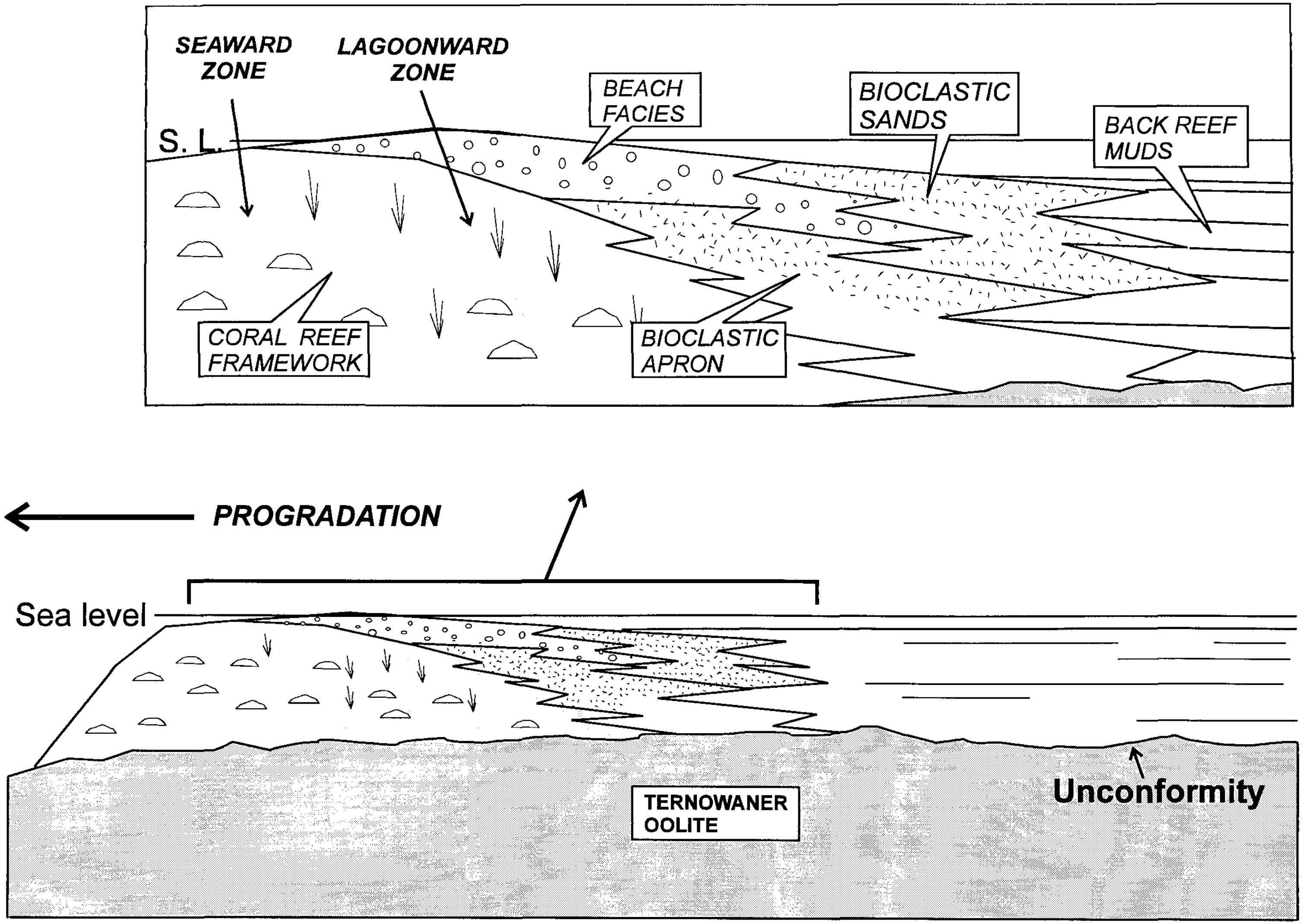


Figure: 6.9: Schematic depositional model for the Al Faro reefs and associated facies.

Facies and sedimentology

Seaward zone. At outcrop the intra-reef sediment is a hard, dense, cream coloured intraclastic grainstone. The microfacies are very similar to those described at Quatre Piexe, Burgundy, and comprises generally angular, medium to coarse-grained (1 cm-0.3 mm) intrasparites (plate 6.10-fig 1). At a microfacies scale the M/S/C ratio is approximately 0/40/50-60, but marked variation is present. The carbonate grains are generally coarse, extremely angular and very poorly sorted. The bioclasts exhibit very little micritization and spongiostromate crusts are poorly developed, and only present on the larger fragments. The carbonate grains are dominated by peloidal intraclasts (60%). The bioclastic material (40%) is mainly coral (80%), but serpulids, forams, calcified cyanbacteria, chaetetids, bryozoan, echinoid and bivalve material is also present; forams can be locally common. The inter-grain spaces are filled by sparite with well developed acicular fibrous fringes around the bioclasts; micritic material is generally very sparse. Large peloids (intraclasts) floating in sparite are common. These features suggest very early cementation. Laminated peloidal fabrics are not as common as the Quatre Piexe reef though some graded fabrics are present. There is no grain orientation. In the upper part of the reef framework local bird's eye textures can be observed within peloidal micrites. Patches of gastropod rich grainstones occur at the top of the reef.

Lagoonward zone. The microfacies is very similar to that described at Bois du Parc, Burgundy. Intra-reef sediments range from coarse-grained grainstones through to wackestones with very rapid variations between the two which can be both gradational and erosive. In outcrop the intra-reef sediment is characteristically hard, dense and cream coloured, signifying a high microbial content of the facies. At a microfacies scale the M/S/C ratio is approximately 70-60/10-15/30-20; microbial biopelmicrites (plate 6.10-fig 2) locally biopelsparites. The microbial biopelmicrites and biopelsparites dominate the intra-reef sediments with the detrital pelmicrites only occurring as local patches. The carbonate grains are peloidal intraclasts (and ?micritized grains) (30-50%) and bioclasts (50%). The bioclastic material is dominated by fragments of corals (70%), calcified cyanobacteria and chaetetids (up to 20%); other (10%). The biopelmicrite-biopelsparite is characterized by very coarse (up to 1 cm), angular to subrounded and unsorted bioclastic material set in a pelmicritic matrix with varying amounts of sparite. Spongiostromate coatings are present on the bioclasts; however they are generally poorly developed and thin (<0.2 mm thick). Thicker (0.5-1 mm) discontinuous crusts are common around the phaceloid coral branches. The bioclasts are only slightly micritized. The matrix is inhomogeneous and made up from precipitated peloid (25%), wavy peloidal fabrics (25%) and very fine bio- and intraclastic material (50%). Free, well developed precipitated peloids are common. The pelmicritic matrix shows well developed laminated fabrics on a sub-mm scale with only small patches of homogenous matrix. These microstromatolitic spongiostromate crusts are 0.1-1.5 mm thick (up to 1 cm) and have a wavy to knobbly form. These peloidal crusts are identical to those described from the Burgundy reefs. Porostromate crusts are common. Near the top of the unit small patches of oncoidal grainstones occur (plate 6.10-fig 3).

6.2.3. Palaeoecology

Associated fauna

1) Lagoonward zone. The associated macro-fauna is not well developed. Hemispherical 10 cm high chaetetid domes are common as well as echinoid spines and pectinids. Small encrusters are abundant especially problematic forms such as *Lithocodium* and *Bacinella* (plate 6.11 and plate 6.12). These occur both as distinct individuals (domal in form; 0.5-1 cm across) and/or indistinct coatings; they are especially abundant around the phaceloid coral branches. Also present are nubeculinid forams, serpulids, *Cayeuxia, Girvanella,* bryozoans and *Neuropora.* The absence of brachiopods is significant since in a stratigraphically lower reef (reef 1 of figure 6.8) brachiopods are common. (Reef 1 was not studied in detail since it has undergone a considerable amount of diagenetic alteration.) Boring intensity is low and boring bivalves are not conspicuous. Small boring organisms are common, especially forams (plate 6.13). The associated fauna of the seaward zone reef seems similar to that of the lagoonward zone though the macrofauna is less common. In the upper part of the reef nerineid gastropods are more frequent. In the nerineid beds the following have been documented (Sartorio, 1987): *Nerinea*, *Ptygmatis* (gastropods) and *Hetrodiceras*, *Plesiodiceras* (diceratids).

Coral fauna (plate 6.14). The corals are very poorly preserved and often completely recrystallised, with only the growth form and corallite integration being discernible. Hence the generic richness is probably greater than what has been documented. In the seaward zone the coral fauna is dominated by massive forms. It is difficult to make out the form and dimensions of the corals, but they appear to be domal and up to 30-50 cm across. Branching ramose forms appear to be absent. In the lagoonward zone the coral fauna is dominated by massive and branching phaceloid forms which together constitute approximately 80% of the coral skeletal biovolume. However in this zone there is a significant appearance of branching ramose forms (20%) which were completely absent from the seaward zone framework. Branching ramose forms occur as dense branching colonies up to 1.5 m high and 1 m across, the branches of these colonies are very thick (3-5 cm thick).

Seaward zone:	
Massive (80%)	**Br. phaceloid** (10-20%)
Stylina	*Calamophylliopsis*
Pseudocoenia	branching phaceloid sp.
Microsolena	branching phaceloid sp.
Isastraea	
?*Meandaraea*	**Br. ramose**
Latomeandrids	(0%)

Lagoonward zone:	
Massive (40%)	**Br. phaceloid** (40%)
Pseudocoenia (c)	*Calamophylliopsis* (c)
?*Isastraea*	*Stylosmilia*
Latomeandrids	*Placophyllia*
Haplaraeids	*Aplosmilia*
Microsolena	?*Dermoseris*
Br. ramose (20%)	?*Complexastraea*
Sylina	*Rhipidogyra*
? *Meandrophyllia*	

6.2.4. Depositional environment (figure 6.9).

The facies associated with the reefs (beach conglomerates with rounded coral clasts, skeletal and peloidal sands and fenestrate pelmicrites) suggests that they developed in very shallow-water and in places probably grew to sea level. An energy gradient can be inferred to exist from the exposed beach facies (high energy) to the protected lagoonal facies (low energy). The seaward zone reef is associated with the beach facies and hence can be assumed to have developed in a high energy environment. The sparseness of peloidal material and the dominance of sparite cements in the seaward zone reef is likely to be a consequence of the high energy levels. The lagoonward zone reef, although onlapped by beach facies, is closely associated with the fenestrate pelmicrites and therefore energy levels were likely to have been significantly lower. This is reflected in the intra-reef microfacies which contains much less sparite cement, less bio- and lithoclastic material and is dominated by peloidal fabrics.

CHAPTER 7:

TYPES OF LATE JURASSIC CORAL REEFS IDENTIFIED IN THE STUDY

Introduction

It is clear from the comparative study of reef-bearing sections in central western Europe (part 2 of this thesis) that there is a diversity in Late Jurassic reef types with regard to their sedimentological, palaeoecological and constructional characteristics. It is also clear that a number of these reefs share broadly similar features and on a descriptive level are very similar. Therefore it is possible to group these reefs which possess similar structural, compositional and framework styles into reef types.

Eight broad reef types and one reef-related facies have been identified. These can in turn can be grouped into two major sets of reefal units depending on their photic setting. These are:

1. reefal units that developed in environments where light was limiting (comparatively deep-water coral reefs); and
2. reefal units that developed in environments where light was not limiting (comparatively shallow-water coral reefs).

The reefal units defined are as follows:

Description of reefal unit	Type	Photic setting
Biostromal units dominated by platy microsolenids developed within clean limestone facies (microsolenid biostrome)	I	Light limiting (deep-water)
Biostromal units dominated by platy microsolenids developed within marly facies (microsolenid biostrome)	II	
Thickets dominated by tall dense phaceloid colonies developed within pure carbonate muds	III	Light not limiting (shallow-water)
Microbial-coral reefs dominated by massive, branching ramose and phaceloid colonies	IV	
Large high diversity reefal units associated with large volumes of bioclastic material	V	
Small species-poor reefs developed within mixed carbonate/siliciclastic facies	VI	
Microbial-coral reefs dominated by massive colonies	VII	
Thickets of branching ramose colonies with widely spaced branches developed amongst sand shoals and coral debris channels	VIII	
Conglomerates rich in rounded coral fagments	IX	

Criteria used in identifying coral reef types

The criteria used in identifying these different reefal units are effectively those used in the summary sheets and are based around four key elements of the reefal unit:

Palaeoecological criteria	*Sedimentological and structural criteria*
1. Characteristics of the coral fauna:	3. Sediment type (intra- and inter-reef):
(a) degree of richness and diversity	(a) presence of a siliciclastic component
(b) growth form composition	(b) carbonates: M/S/C ratio
(c) coral biovolume relative to: intra-reef sediment	type of allochems
microbialite	allochem maturity
other organisms	microfabrics
d) type and degree of framework construction	
2. Characteristics of the associated fauna	4. Reef shape, dimensions and internal structure.

The reef types identified are based solely on their physical and biological characteristics as seen in outcrop, hand specimen and thin-section studies; the depositional environment in which the reef had developed is not a criterion for reef-type recognition. The characteristics of the coral fauna are generally the main criteria for identifying the different reef types since they are the main framebuilders and show the most marked compositional variations between different reef types; the other criteria vary in their diagnostic value from reef to reef.

The following sections deal with the two major reef groups in greater detail. Particular attention has been given to the deep-water reefs since they showed a number of very clear palaeoecological and sedimentological patterns which had previously not been investigated.

7.1: DEEP-WATER CORAL REEFS: MICROSOLENID BIOSTROMES (TYPE I AND II REEFS)

7.1.1: Study examples and general characteristics

Study examples: Type I reefs: Upware, Cambridgeshire (section 6.1.5): [abbreviation: UP].
Châtel-Censoir, Burgundy (section 2.2): [abbreviation: CC].
Foug, coral limestone, Lorraine (section 3.2): [abbreviation: F1].

Type II reefs: Foug, coral marl, Lorraine (section 3.2): [abbreviation: F2].
Liesberg, Swiss Jura (section 5.2): [abbreviation: LI].

General characteristics:

- The biostromes are characterised by a coral community of relatively low generic diversity, being dominated by the Microsolenidae. In type I reefs *Microsolena* dominates; in type II reefs *Dimorpharaea* dominates.
- The coral skeletal biovolume is generally very high (40-80%) and is overwhelmingly dominated by platy ecomorphotypes.
- Sedimentologically these biostromes developed in low energy marl and limestone regimes which were subject to low sedimentation rates and varying degrees of siliciclastic influx. Type I reefs develop in siliciclastic-free regiemes; type II reefs develop in siliciclastic-rich regimes.
- The associated fauna of these reefs shows a high generic diversity, in particular a rich assemblage of echinoids and bivalves. The coral plates provide an ideal habitat for a well developed and strongly polarised encrusting and boring fauna. Top surfaces show limited post-mortem encrustation by serpulids and cementing bivalves, and are also bored by lithophagan bivalves. The undersides of the plates show a highly developed and diverse cryptic fauna of serpulids, thecidean brachiopods, bryozoans, calcareous sponges and sclerosponges.

7.1.2. Stratigraphy, sedimentology and facies

1. Stratigraphy. From comparison of the stratigraphies of the microsolenid-bearing sections it becomes clear that with the exception of the Burgundy section they range from the Plicatilis Zone, Antecedens Sub-zone to the Tranversarium Zone, Parandieri Sub-zone, and therefore can be regarded as essentially chronostratigraphic equivalents (see figures 2.3; 3.2; 5.2 and 6.2). The Burgundy section, although identical in its sequence of reefal units to the sections in Lorraine and Swiss Jura, is younger, with its biostromal unit appearing at the top of the Tranversarium Zone, Schilli Sub-zone and terminating at the top of the Bifurcatus Zone, Grossouverei Sub-zone. From this, the synchroneity of these shallowing upward events, in particular the timing of the appearance of these microsolenid biostromes, is very noticeable. Even when taking into account the auto-shallowing (aggradational) effect of reefal growth, these sections would suggest a significant shallowing event during the Middle to Upper Oxfordian over much of western Europe. This would signify either a eustatic sea level fall or, though less likely, widespread tectonic movements independent of local intrabasinal tectonics. A reasonable approximation to the curves of Hallam (1988) and Haq *et al.* (1987) points to a eustatic control of this shallowing event.

The lithostratigraphy of the French and Swiss sections may be simplified into 4 sequential units from base up as follows:

1) Pre-reefal deep-water marls and micritic limestones often with a rich ammonite and sponge fauna;
2) Initial reefal phase: microsolenid biostromes (type I and II reefs);
3) Second reefal phase: variety of reef types from high diversity patch-reefs to mono-specific thickets (type III-VIII reefs); and

4) Post-reefal unit: generally extremely shallow-water facies often with the develoment of beach (type IX facies) and/or restricted muddy lagoon deposits.

This sequence of sedimentary phases represents a shallowing-upwards sequence from below the euphotic zone through to, in some cases, sea level. Hence, through this succession, the parameter that would have shown the most marked variation is light intensity. This would have been especially pronounced at shallower depths since according to the equation, $I_x/I_0=e^{-cx}$, (where I_0 is incident light intensity at the surface, I_x is light intensity at a depth x, and c the extinction coefficient) (Houck *et al.*, 1977), light intensity decreases exponentially with depth. Therefore at some point along this succession a critical depth is reached where the light intensity will be just sufficient to allow photosynthesis of the species with the lowest compensation irradiance (Done, 1983), and thus allow the growth of certain zooxanthellate corals and the subsequent potential for reef development. This point is marked by the appearance of microsolenid corals and the development of microsolenid biostromes, and they are therefore characteristic of the base of comparatively deep-water shallowing upwards sequences.

In regions of high siliciclastic influx the stratigraphically pre-reefal units consist of ammonite-bearing marls and muddy limestones with a high siliciclastic component (the Terrain à Chailles at Foug and Liesberg). Where siliciclastic influx is low, pre-reefal units are pure micritic limestones, often with a significant ammonite and sponge fauna (Châtel-Censoir). Above these pre-reefal units appear the first reefal units, the microsolenid biostromes. The boundary between the pre-reefal limestone and these biostromal units is conformable and is marked by a sudden and abundant appearance of corals (Liesberg). At Foug the boundary, although still conformable, is marked by a prominent secondary hardground constructed by a band of superimposed valves of the oyster *Deltoideum delta*. Where these biostromes developed on isolated platforms with little siliciclastic influx the boundary between these two units is of a more gradational nature, with siliceous sponge-bearing micritic limestones grading into microsolenid-bearing micritic limestone over a vertical distance of a few metres. This transition is the result of a progressive replacement of the hexactinellid and lithistid sponges by microsolenid corals. The degree to which siliciclastics entered these areas of biostromal development would also have strongly governed the depth at which the euphotic zone would be reached. In areas where siliciclastic input was high (i.e. type II reefs), especially where the clay fraction was large, turbidity would have been significantly higher and thus the critical depth for the deepest water reef development would have been shallower (Hallock and Schlager, 1986; Loya, 1976). It is therefore likely that the depth at which type II reefs developed (e.g. LI and F2) was considerably less than that for type I reefs (e.g. CC and UP). The lower turbidity experienced by the Châtel-Censoir biostrome would have had the effect of reducing the photic gradient, thus expanding the photic window within which these biostromes could develop, hence the larger time-slice represented by the Châtel-Censoir biostrome (figure 7.1). Continuing up these shallowing-upwards sequences a second reefal phase is invariably reached which is clearly distinct from the microsolenid biostromes in terms of its coral and associated faunas, reefal fabric and reefal structure.

The Upware section is different from the sections in France and the Swiss Jura. The Upware type I reef is located at the top of the West Walton beds which themselves are sandwiched between two clay

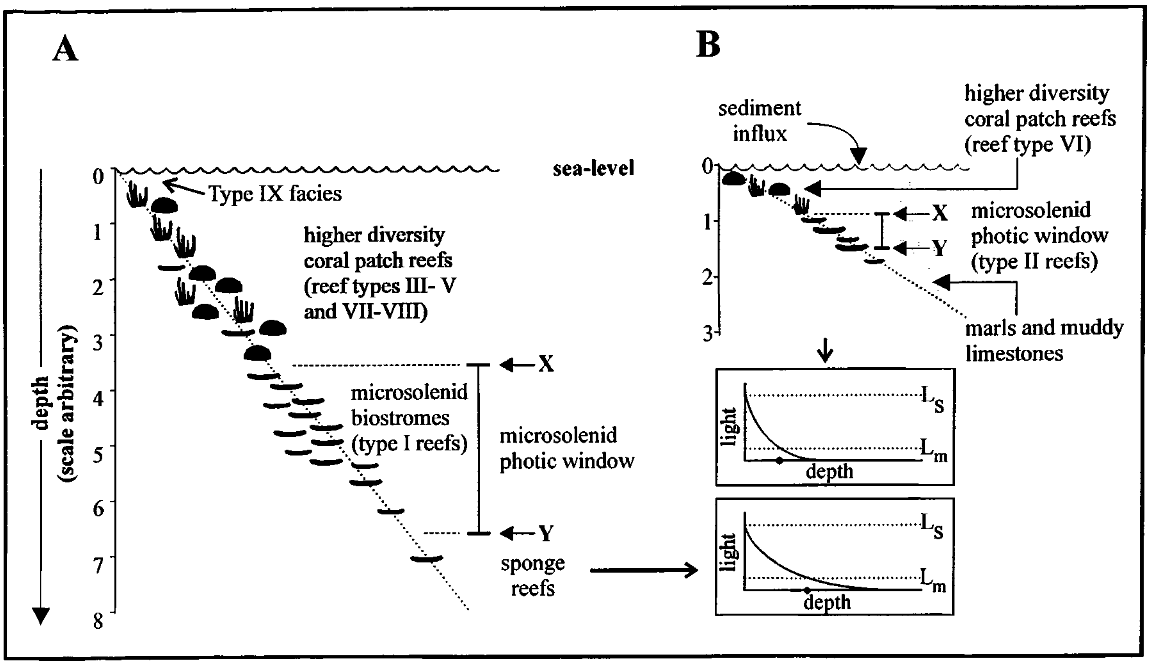


Figure 7.1. Schematic diagram illustrating the location of microsolenid biostromes relative to other reef and reef related units. (A) Water clarity high, low photic gradient, resulting in expanded zonation and the development of type I reefs within the microsolenid photic window (e.g. Châtel-Censoir). (B) Water turbidity high, photic gradient much steeper; zonation less extensive and nearer the surface. Within the microsolenid photic window type II reefs developed (e.g. Liesberg). Point X represents the top of the microsolenid photic window where illumination is sufficient for many other zooxanthellate corals, with a variety of growth-forms to colonise the substrate in considerable numbers. Above point X microsolenids generally subordinate to other corals. Point Y represents the minimum level of illumination for zooxanthellate corals to survive; appearance of the microsolenids in substantial numbers with the development of microsolenid biostromes. In clear waters below point Y are sponge-bearing units and sponge reefs (e.g. Châtel-Censoir; also see section 7.1.5). Where turbidity is high below point Y marly muddy limestones are deposited (e.g. Foug and Liesberg). Ls: Light intensity at sea-level; Lm: Minimum light intensity needed for biostrome development. Dots on X-axis mark the relative depth at which microsolenid biostromes develop. (For discussion of other reef types see section 7.2).

units, the Oxford Clay below and the Ampthill Clay above. So although stratigraphically unlike the French and Swiss sections, there again seems to be a stratigraphic association of the biostrome to ammonite-bearing deeper water clays and marls.

2. Intra-reef sediments. These sediments are essentially bioclastic wackestones and packstones with varying amounts of siliciclastics, mostly in the form of detrital clay. The skeletal fragments are set in a micritic matrix, with sparite cements being localised to intra-skeletal cavities. Bedding is generally well developed, and when differential compaction is taken into account, suggests that these biostromes lacked significant relief, perhaps no more than 2m at most.

The bioclastic component to the intra-reef sediment varies from approximately 1% (micritic mudstones) to greater than 50% (bioclastic packstones). The bioclastic material represents in situ fragmentation of the nearby reef biota with little evidence of bioclastic material entering the reef complex from adjacent areas. The bioclasts themselves represent a wide variety of taxa; the most abundant fragments are of corals, bivalves, echinoids, serpulids, siliceous sponge spicules and foraminifera, though fragments of bryozoans, brachiopods and calcareous sponges may also be identified. The bioclasts, which are angular and extremely poorly sorted, show a considerable range in size from less than 1mm to greater than 22 mm. The grains show little evidence of being mechanically reworked, with even the most delicate of coral structures remaining intact. The abundance of bioclastic material is significant in the light of the fact there is little evidence of either current reworking or storm activity; clearly these deposits were deposited below normal wave base. This, together with the volume of bioclastics and their poorly sorted nature, would seem to imply that the bioclastics are in fact a result of intense bioerosion. Palaeoecological analysis of the reef fauna corroborates this inference with an abundant and well represented bioerosive element in the reef biota.

A number of skeletal fragments, in particular of corals, echinoids and bivalves, show well developed micritic rims with recognisable microborings, suggesting micritzation as a result of algal/cyanobacterial activity. In fact, locally abundant are coarse (1 mm) angular peloids which are a likely result of post-micritisation fragmentation of skeletal material. Evidence of microbial activity is provided by micritic spongiostromate oncoids which are locally abundant within the reefs. These coated grains are embedded in a micritic matrix which is markedly lighter in colour. Similar structures, again seemingly of microbial origin, have developed on many of the coral plates showing thin (1-6 mm) indistinct stromatolitic textures with poorly developed laminations. Compositionally these are again micritic, though in areas a clotted microfabrics is preserved.

On first inspection the matrix appears as an amorphous though inhomogeneous micrite. However closer examination of this micrite reveals a rather clotted, thrombolitic, fabric, and where protected from compaction, for example within shells, coral calices and geopetal structure, the fabric is distinctly peloidal. The peloids are approximately 10μm to 70μm in size and extremely well rounded and sorted. The micrite that forms these peloids is distinct from the majority of the matrix micrite in its darker colour. Although peloidal fabrics are widespread in many modern and ancient reefs their origin remains controversial (Macintyre, 1985 and references therein). However in these reefal units the association of the peloids with stromatolitic structures and the abundant evidence of microbial activity suggest that they are microbial precipitates, either directly or indirectly (Leinfelder *et al.*, 1993b; Sun and Wright, 1989; Sun *et al*, 1992). Nevertheless some of the larger rounded peloids are clearly of faecal origin, which should be expected considering the strong filter-feeding component of the reef fauna (see below), whilst the larger, angular, peloids are a result of fragmentation of heavily micritised grains.

Early lithification of these intra-reef sediments can be inferred from the pronounced platy growth form of the corals. This has in the past been interpreted as a response to a soft substrate, with the coral spreading its weight over a wider surface, thus preventing it from sinking; the snow-shoe effect. In these biostromes this was clearly not the case since in fact only a small proportion of the coral plate was in contact with the sediment surface whilst the rest was raised sufficiently above the sediments to allow dense under-encrustation by a cryptic fauna. This could only have been achieved if the sediment were adequately firm. Firmness of substrate is also suggested by the associated fauna which clearly lacks infaunal and semi-infaunal elements and is dominated by epifaunal groups.

A number of these biostromes developed in areas of high argillaceous influx (the type II reefs of F2 and LI). Consequently their intra-reef facies has a substantially higher siliciclastic component with solid insoluble residue values reaching 60%, mainly in the form of clays. The sedimentation rate of these biostromes seems to have been relatively high, for example the Liesberg biostrome, which measures a thickness of approximately 22m, was deposited during a fraction of the duration of the Antecedens sub-zone (Gygi, 1986, Gygi and Persoz, 1986).

In summary, these biostromes represent reefal units that developed below normal wave base. Furthermore the lack of any clear indications of storm deposits or erosive horizons suggests a position around or below storm wave-base, especially considering the fact that contemporaneous shallower reefal units within the same region show frequent and well developed storm horizons. Sedimentation rates were generally very low as indicated by the presence of stromatolitic crusts and other microbial fabrics (Leinfelder *et al.*, 1993b, Leinfelder, pers. commun., 1995). However where these biostromes developed in areas of siliciclastic influx, such as the type II reefs of F2 and LI, sedimentation rates were significantly increased. In terms of their microfacies the intra-reef sediments range from micritic mudstones to bioclastic wacke- and packstones. The bioclasts represent in situ bioerosion of the reef fauna and comprise a wide variety of taxa. The matrix has a poorly preserved peloidal fabric, though in areas where protected from compaction peloids are clearly visible. This peloidal fabric is interpreted as microbially induced.

7.1.3. Associated fauna: palaeontology, palaeoecology and trophic structure

1. Assemblage composition and structure. One of the most striking aspects of many of the diverse coral reefs in the Upper Jurassic is the sparseness of the intra-reef associated fauna (e.g. type III, IV and VII reefs; see section 7.2). However in these biostromal units the associated fauna is relatively rich and abundant (figure 7.2). It shows a high generic diversity, in particular a rich assemblage of echinoids and bivalves. In addition the coral plates provided an ideal habitat for a strongly polarised encrusting and

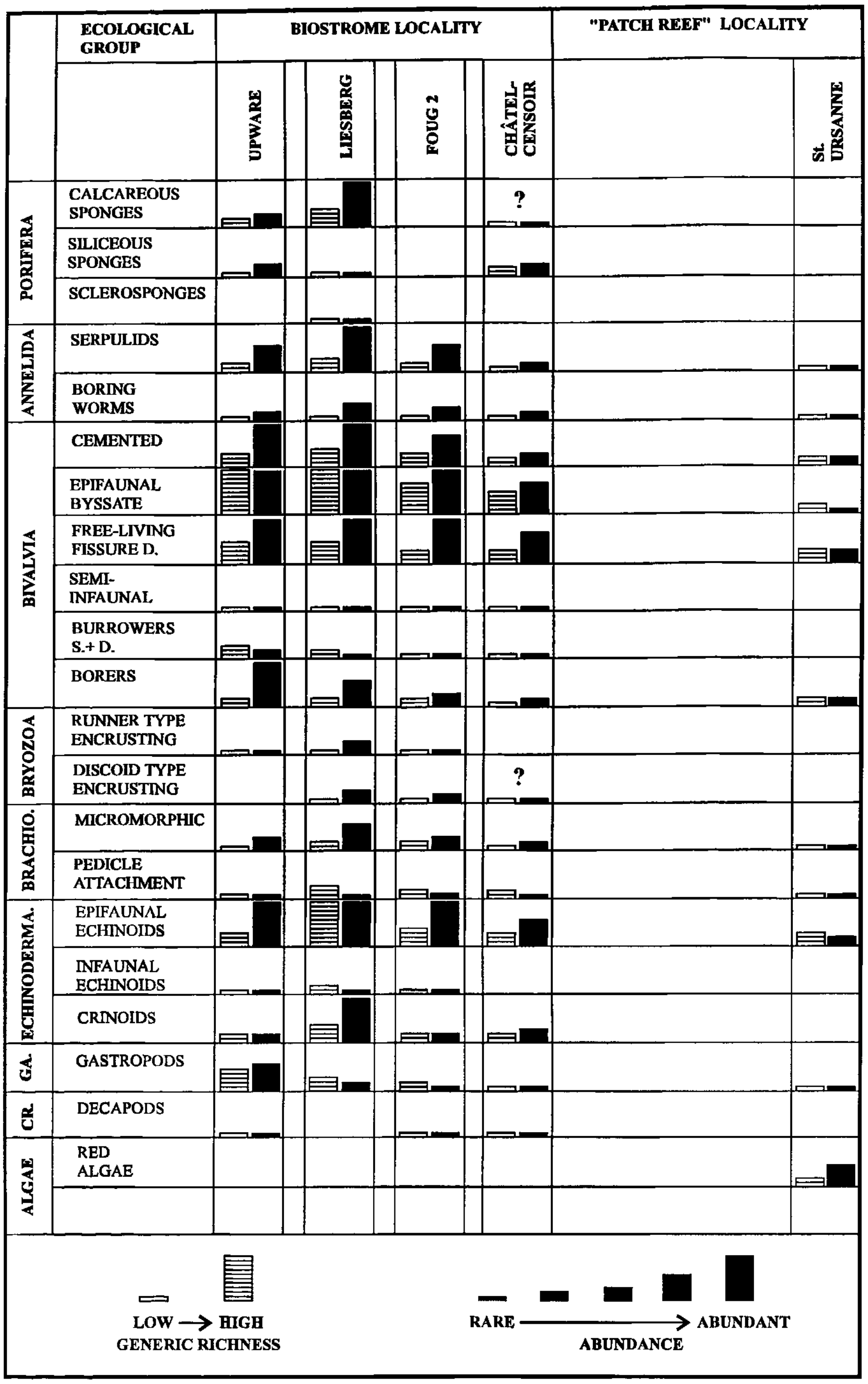


Figure 7.2: Relative generic richness and abundance of the main ecological groups present within the microsolenid biostromes (excluding corals). Also shown are data from a shallow-water patch reef from the Swiss Jura (St. Ursanne, patch reef 1) to illustrate the contrast in the diversity of the associated fauna between these two reef types. Abundance values are based on the frequency of occurrence of a particular group. This ranged from **rare** (in total only a few individuals identified) to **abundant** (found throughout the biostrome and being an obvious faunal element). These subjective categories are based on field observations and subsequent examination of 1020 Kg of samples. Generic richness gives an approximate indication of the number of genera within each ecological group. The diagram is designed to give only an impression of the *relative* faunal richness and abundance of the associated fauna rather than a detailed breakdown of the faunal composition of the reef fauna. (Abbreviations: Fissure D. - fissure dwelling, S.+D. - shallow and deep burrowers, CR. - Crustacaea, GA - gastropods, Echinoderma. -Echinodermata, Brachio. - Brachiopoda.)

boring fauna. Top surfaces show limited post-mortem encrustation by serpulids, cementing bivalves and in some cases stromatolitic crusts, and are also heavily bored by lithophagan bivalves. However the undersides of the plates have a highly developed and diverse cryptic fauna of serpulids, thecidean brachiopods, bryozoans, calcareous sponges and sclerosponges. In extreme cases these epibiogenic undercrusts can reach 15mm thick, representing the superposition of several generations of encrusters. The cryptic fauna in these biostromes is exceptionally well developed with many taxa represented. The development of this fauna is clearly associated with the platy form of these corals which created large overhangs available for colonisation. The most abundant cryptobionts, in terms of the number of individuals, are the serpulids which may completely cover the under surfaces of the coral plates and include both *Cyclo-* and *Dorsoserpulid* forms. Sponges, usually rare in coral reefs, are relatively common including small knob-shaped calcareous sponges like *Enaulofungia* and *Corynella* and sclerosponges such as *Neuropora*. Evidence of siliceous sponges comes from common *Rhaxella* spicules. Bryozoans, again normally rare in the Upper Jurassic (see Taylor and Larwood, 1990, figure 10.3) are unusually common, in particular *Berenicia-* and *Stomatopora*-type forms. Brachiopods, apart from the abundant micromorphic brachiopods such as *Rioultina* and *Moorenella*, are poorly represented, and are invariably terabratulid forms with well developed fold and sulcus.

The most important group of essentially sessile epibenthos are the Bivalvia, being both abundant and generically rich. This include cemented forms such *Nanogyra, Lopha* and *Plicatula*; free-living and fissure-dwelling forms, such as *Chlamys* and *Spondylopecten*; and the byssally-attached forms, such as *Isoarca, Barbatia, Plagiostoma, Opis* and *Isognomon*, this last group being the most abundant and species-rich. Significantly, burrowing and semi-infaunal forms are very rare and taxonomically poorly represented. Also present and locally important are crinoids such as *Millericrinus* and *Pentacrinus* which are particularly common at Liesberg.

Bioerosion by a variety of taxa was intense in these biostromes with some coral colonies being almost completely destroyed. The borers are essentially confined to the top surface of the coral plates and the most abundant of these is the boring bivalve *Lithophaga*. Less common are clionid sponge borings and evidence of small boring worms. Regular echinoids such the cidaroids are extremely abundant. These cidaroids would have rasped away at microbial material on the corals and hence would have been responsible for a considerable amount of fine, silt-grade bioclastics.

2. Trophic structure. The microsolenid biostromes seem trophically quite unlike modern coral reefs. Analysis of the associated fauna in terms of trophic structure and nutritional requirement reveals a clear dominance in the benthic community of uniserial heterotrophs. These include low-level suspension feeders, such as the bivalves and calcareous sponges (which presumably subsisted on zoo- and phytoplankton, and organic detritus) and grazing herbivores and scavengers, such as the echinoids and gastropods (which fed on the algal/cyanobacterial mats). Clearly to sustain such a rich and abundant community of benthic heterotrophs, ambient nutrient levels must have been relatively high. Further biotic evidence of relatively high eutrophic conditions is provided by the inferred presence of

microbial films which are again characteristic of these trophic conditions (Hallock and Schlager, 1986; Wood, 1993). This rich source of nutrients, which is likely to have been of terrestrial origin, would have been introduced to these areas with the high siliciclastic influx from adjacent landmasses. Moreover, the effects of nutrient influx would extend beyond the range of active siliciclastic sedimentation (Livingstone, 1963; Birkeland, 1977; Crossland, 1983; Hallock and Schlager, 1986), thus the fact that there may not be evidence of siliciclastic sediment within the intra-reefal sediment, such as in type I reefs, does not necessarily imply that nutrients were not being introduced into the ecosystem from a terrestrial source.

Trophic analysis of present day coral reefs strongly suggests that they commonly develop in oligotrophic regimes (Hallock and Schlager, 1986; Hallock *et al.*, 1988; Birkeland, 1988; Molfino and McIntyre, 1990; Wood, 1993; Vogt, 1989). Indirect evidence in the form of very pure carbonates and extraordinarily poorly developed associated fauna (e.g. reef types III, IV, V, VII and VIII; see section 7.2), suggests that many of the diverse coral reefs of the Upper Jurassic also thrived in nutrient-poor waters. If so, then the microsolenid biostromes appear paradoxical. On the one hand the rich and abundant associated fauna of filter- and suspension-feeding heterotrophs is suggestive of raised eutrophic conditions. Yet in terms of coral skeletal biovolume and framework construction these biostromes are possibly some of the best developed coral reefs in the Upper Jurassic. Clearly a reassessment of the nutrient limitation model for these microsolenid biostromes is needed. In particular, one must address the question of whether the microsolenids had similar trophic requirements to present day reef building corals, or whether a significant part of their energy budget was supplied from heterotrophic feeding. Possible explanations are discussed below.

7.1.4. Microsolenid coral assemblage

1. Growth form. Platy corals overwhelmingly dominate the assemblages, constituting atleast 80% of the total coral skeletal biovolume and form of a coherent, well developed framework. The coral plates vary only slightly in form and dimensions from thin foliaceous plates less than 2cm thick and 40cm across (CC), to larger, more tabular forms up to 6cm thick (F1). The relatively small thickness of the corals in these units suggests that the longevity of the compound forms was extremely low. From well preserved growth bands average "life spans" for *Thamnasteria* and *Isastraea* within the LI biostrome have been calculated to be approximately 17 and 18 years respectively, with similar results obtained from the other biostrome localities (see section 8.2.4.3; Insalaco, 1996b). It seems clear that the corals in these biostromal units died after a relatively short time, and that coral faunas in general had a high faunal turnover. It is very probable that the low longevity experienced by the corals in these assemblages is a consequence of the adverse conditions in which these biostromes developed. However the precise mechanism that caused the mortality remains unclear. Abiotic factors such as low light levels and relatively high sedimentation rate, although having adverse effects on coral growth, should not affect general longevity since neither of these factors would show periodic increases in their intensity on this frequency. Nevertheless, low longevity and high faunal turnover are characteristic of pioneer stages in

reef successions (Copper, 1988) and also eutrophic environments (Wood, 1993), both of which these microsolenid biostromes are thought to represent.

The corals vary from more or less flat tabular forms to strongly concave, cuspate forms, both of which resemble very closely the growth forms of present-day deep-water agiricids such as *Leptoseris*. The platy growth form is interpreted as a response to poor illumination. In deep or turbid environments the majority of the light energy is received essentially from above. Therefore to catch all the available light the most efficient growth form a coral can develop is a flat plate shape exposing the largest possible surface area to the incoming light. On present day reefs such platy forms develop where light levels are approximately 4% of that of the surface (Yamazato, 1972; Lang, 1974; Falkowski and Dubinsky 1981, Titlyanov *et al.*, 1981; Titlyanov and Latypov, 1991; Fricke and Schuhmacher, 1983; Porter *et al.*, 1984; Fricke and Meischner, 1985). This contrasts with shallow, clear water environments where light is received from all directions and hence domed and branched forms can develop. Here, light levels are in excess of 40% of that of the surface (Goreau,1959; Goreau and Wells, 1967; Barnes, 1973; Dustan 1975).

2. Taxonomy. Taxonomically the biostromal units are dominated by microsolenids which constitute at least 60% of the family level coral skeletal biovolume. At generic level the biostromes are relatively low in richness. At LI (Swiss Jura), considered to be the "metropolis of coral growth" (Arkell, 1935), 15 genera is an unusually low number compared with other reefs in the same region. Comparing the coral fauna of these different biostromes it is immediately apparent that the reefal units were constructed by essentially the same coral assemblage. The typical microsolenid assemblage is characterised by a dominance of the microsolenid genera *Microsolena, Dimorpharaea* and *Comoseris* but also consistently present, though of secondary importance in terms of their contribution to the reef framework, are the genera *Actinaraea, Dendaraea, Thecosmilia, Montlivaltia, Isastraea, Thamnasteria, Fungiastraea and Stylosmilia.* However it is not only that the same corals occur in these different biostromes, but they also occur in very similar proportions, thus true ecological diversity of these reefs is relatively constant (figure 7.3). Shannon-Wiener diversity indexes were found to range from 2.24 at UP to 2.48 at LI. Such a small range between these two localities is surprising considering that these two regions are generally considered to represent extremes in reef development. What is clearly shown in figure 7.3 however is that there is a shift in which genus of microsolenid dominates. In the type II reefs of LI, and F2, where the facies has a high siliciclastic component, *Dimorpharaea* dominates, whereas in the type I reefs of UP, CC and F1, where the limestones are purer, *Microsolena* dominates. This may reflects the better sediment-dispelling capabilities of *Dimorpharaea* and is consistent with the structural aspects of Hubbard and Pocock's (1972) model which suggests that corals with deeper, larger and more "v" shaped corallites (such as the corallites of *Dimorpharaea*) are more efficient sediment rejecters.

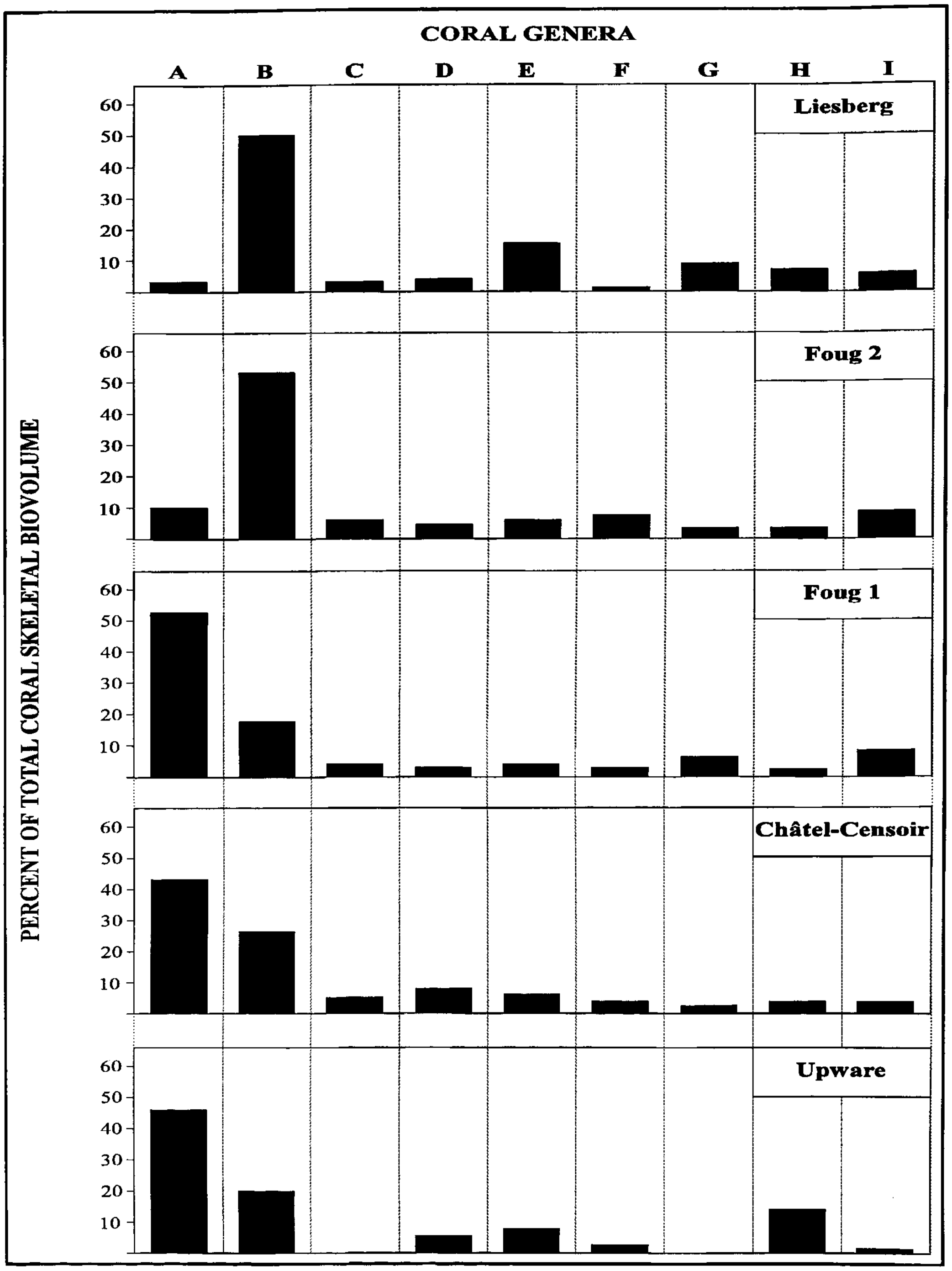


Figure 7.3. Generic composition of the coral fauna in the microsolenid biostromes. (A) *Microsolena*; (B) *Dimorpharaea*; (C) *Comoseris*; (D) *Thamnasteria*; (E) *Isastraea*; (F) *Fungiastraea*; (G) *Dendraraea*; (H) *Thecosmilia*; (I) Other.

Liesberg and Foug 2 (coral marl): type II reefs.

Foug 1 (coral limestone), Châtel-Censoir and Upware: type I reefs.

7.1.5. Depositional environment

The sedimentological, stratigraphical and paleoecological evidence all suggest that the microsolenid biostromes developed where light intensities, sedimentation rates and energy levels were extremely low, well below normal below wave base in the region of the lower photic zone. In type II reefs (F2 and LI) high siliciclastic influx from adjacent landmasses increased sedimentation rates and turbidity significantly. So microsolenid biostromes appear to be deep-water reefs, but how deep? Objectively and without relying too heavily on the principle of uniformitarianism this question is irritatingly difficult to answer. Accurate palaeobathymetry of reef facies has always been a problem in reefal studies, with a dependence on qualitative terms such as "shallow" and "deep" water. Water depth has usually been derived from hydrodynamic datums such as normal wave base and storm wave base, which themselves vary in absolute depth according to palaeogeographic and climatic settings. More recently this question has been addressed by detailed comparative palaeoecological work carried out on the Upper Jurassic metazoans and micro-encruster associations of Iberia (Werner *et al.* 1994; Leinfelder 1994; Leinfelder *et al.* 1993b; Werner, 1986). These studies have identified a number of trends in various groups relating to increasing water depths. With regard to the microsolenid biostromes, the platy microsolenid growth-form and relative abundance of siliceous sponges are most significant and suggest a water depth between 60 and 80 m. However not all the trends identified in the Iberian associations can be directly applied to these biostromes. For example boring bivalves are often very abundant in the microsolenid biostomes but in the Iberian associations boring bivalves decrease with increasing water depth. Clearly other local factors must also be taken into account.

A uniformitarian approach is another, albeit less satisfactory, way of addressing this question of water depth. At present in the Red Sea, coral-dominated structures can occur down to depths of 160m (Kaiser, *et al.*, 1993). These reefal structures show many similarities to the microsolenid biostromes both in terms of reefal morphology and in the nature of the frame builders, being dominated by platy agariciids, in particular *Leptoseris*, which show a number of significant similarities to microsolenids (below; J. Darrell, pers. comm., 1994). These are obviously extreme depths, but illustrates that where conditions are right, certain zooxanthellate corals can grow at great depth and in extremely low light levels. It is unlikely however that the Late Jurassic microsolenid biostromes extended down to these depths for two reasons. Firstly, palaeogeographically, the northern margin of Tethys was a shallow epicontinental sea and hence even in the deepest areas depths probably did not exceed 200m and were dominated by ammonite-bearing marls or sponge reefs. Secondly in many biostrome localities turbidity must have been high (e.g. type II reefs) and hence this would have substantially reduced the possible depth these reefs could grow. Taking this into account one could tentatively suggest depths of between 80m to 20m where turbidity was high, but until more quantitative approaches to palaeobathymetry are available for the Jurassic more accurate absolute depth estimation is not possible.

The proposed depositional model for these biostromes suggests that low light level is the overriding ecological control on the development of this type of microsolenid-dominated assemblage. If this is the case then this type of coral assemblage should occur in two other situations: (a) capping deep-water biogenic structures such as sponge reefs as they grew into shallower water; (b) occurring in shallow water environments in cave-dwelling crypts. During the Oxfordian and Kimmeridgian, south-west Germany was dominated by sponge reefs which during this time grew progressively into shallower water. These sponge reefs have been traditionally interpreted as deeper water structures when compared to coral reefs, with depositional depths generally greater than 100m (Gwinner, 1976; pages 64-65). However by the Tithonian these reefs had reached a point where poor illumination no longer excluded zooxanthellate corals, and the first corals to appear are indeed platy microsolenids (Paulsen, 1964; Barthel, 1977).

Shallow water cave environments provide the ideal setting to test the importance of light relative to other environmental factors in controlling the distribution of microsolenids. Taylor and Palmer (1994) have recently documented a series of remarkable palaeocaves developed within a Kimmeridgian reefal complex. These palaeocaves occur in the Lower Kimmeridgian of the Chay Peninsula south of La Rochelle, in western France. The framework of these reefs is built from corals heavily bound together by masses of thrombolite. The coral fauna comprises the branching phaceloid form *Calamophylliopsis* and branching ramose forms of the genera *Thamnasteria, Microphyllia, Stylina* and *Microsolena*. This coral fauna, in particular the dominance of branching ramose forms, is indicative of relatively shallow well illuminated waters, an interpretation corroborated by the fauna in general. Detailed examination of the paleocaves reveals a spectacular cave-dwelling fauna encrusting the roofs and walls of the caves which includes calcified demosponges, calcisponges, thecideidine brachiopods, serpulid worms and cyclostome bryozoans, in fact very similar in faunal composition to modern cave-dwelling communities. In theory one might expect zooxanthellate corals to be completely absent within these caves, and indeed they are extremely rare, however one form is seen to consistently extend much further into these palaeocaves than other forms. This coral was found to be an encrusting microsolenid. Occasionally these microsolenids are found to extend well into the palaeocaves. These two examples clearly demonstrate that it is light, as opposed to other abiotic factors, that has controlled the development of these assemblages. They also indicate that the relationship between poor illumination and the microsolenid structure is not confined to the Oxfordian, negating the possibility that these microsolenid biostromes simply represent a phase in Mesozoic reef evolution. In fact Scott (1981) has also interpreted platy microsolenids in early Cretaceous coral-algal-rudist reefs from Arizona as a reponse to low light intensity.

The trophic environment in which these biostromes developed is less easy to evaluate with the same degree of confidence. Much can be inferred from the presumed effects that eutrophication has on the reef biota, but many of these cause and effect relationships are of a qualitative nature and have not been rigorously tested. Furthermore the limiting effects of excess nutrients on zooxanthellate corals is suggested to be temperature-dependent, with its effects being more significant at lower temperatures (Hallock, 1981). Hence application of a nutrient-limitation model to fossil reefs is still limited until better understood nutrient correlatives are found. Nevertheless there can be no doubt that in areas of high siliciclastic influx, such as the areas studied, nutrients would have been significantly higher than other areas. Therefore from this point of view it is pertinent to examine the reef biota for any signs of eutrophication. By far the most significant of these is the rich and abundant associated fauna dominated by filter- and suspension-feeding heterotrophs. The abundant evidence of microbial activity, and the large amounts of bioerosion, are also indicative of a shift from phototrophy to heterotrophy (Hallock, 1988). But how has the eutrophication process affected the coral fauna, which is generally assumed to deteriorate under raised eutrophic conditions? Initial analysis would suggest that the coral fauna flourished, as reflected by the high coral skeletal biovolume. However, as previously explained, the longevity of these corals was in fact very short, though showing an ability for rapid colonisation. Both of these behavioural patterns are again characteristic of eutrophic conditions (Wood, 1993). Moreover the microsolenids, which dominate the coral fauna, seem to show unique structural adaptations to improve heterotrophic feeding (see below). There would therefore seem to be a substantial body of speculative evidence to suggest that the microsolenid biostromes grew under conditions of eutrophication, which, if related to terrestrial run-off, would probably have been seasonal. The case for higher nutrients is further strengthened by the fact that many of the biotic characteristics of eutrophication outlined above disappear when the coral diversities increase.

7.1.6. Why Microsolenids?

The natural questions to be asked are then "why should this assemblage of corals, in particular the microsolenids, dominate low light level environments ?" and, "is it possible to explain the ecological distribution of the microsolenids with a functional morphological approach to their skeletal structure ?".

The family Microsolenidae (Koby, 1880), is characterised by the following features (plate 7.1; plate 7.2-figs. 1-2):

1. Corallite walls absent or marked by a synaptular ring.
2. Septa thin, formed by one fan system of simple, or more rarely composite, trabeculae. The septal structure is fenestrate and extremely porous.
3. Synaptulae simple, abundant between septa.
4. In compound taxa corallite integration is high with thamnasteroid forms dominating.
5. Dissepiments feebly developed.
6. Columella trabecular, feeble if developed.
7. Pennulae well developed and regularly arranged.

For more detailed descriptions on the structure and systematics of the Microsolenidae see Gill, (1967, 1968, 1982) and Roniewicz, (1982, 1976)

Pennular development was until relatively recently considered a dominantly Mesozoic character, and indeed it is. However it was recently realised that it is also present in the extant agariciid, *Leptoseris* (J. Darrell, pers. commun., 1994; R. Lathuilière, pers. commun., 1993; E. Roniewicz, pers. commun., 1993). Comparison of the septal structure of *Microsolena* with that of *Leptoseris* shows that they are surprisingly similar (compare plate 7.1 to plate 7.2-fig 3). The intriguing aspect of this is that the ecological distribution of *Leptoseris* is one of a deep fore-reef coral, thriving as foliacecous plates down to depths of 160m (Red Sea, Kaiser *et al.*, 1993). Equally significant is recent work on the cryptic reefal environments of Lizard Island (Great Barrier Reef, Australia) (Reitner, 1993). Within these shallow-water Holocene caves there exists a cave dwelling community of encrusting organisms such as bryozoans, serpulids, thecidean brachiopods, sponges, foraminifera and microbial films. Zooxanthellate corals were found to be generally absent apart from *Leptoseris.* This assemblage would seem to be a modern analogue to the palaeocave fauna reported by Taylor and Palmer (1994), with *Leptoseris* occupying a similar habitat to that of *Microsolena*. Therefore although *Leptoseris* and *Microsolena* are not thought to be closely related, their similar ecological distribution coupled with their similar septal structure invites a comparison of these two corals with regard to their palaeobiology and palaeoecology.

Recent physiological and histological work on *Leptoseris fragilis* has shown that it adapts to low light in two ways (Kaiser, *et al.*, 1993, Schlichter, 1991):

(1) Ecophysiological photoadaptations. In a detailed study of *Leptoseris fragilis* in the Red Sea it was shown that with increasing depth the coral decreased its zooxanthellae density and volume, though the content of its pigments increased. Both chlorophyll a and especially c_2 concentrations per cell wall were enhanced at lower light intensities. These changes are interpreted as a chromatic adaptation to low light level environments. In these environments light of short wavelengths (the violet end of the visible spectrum) predominates. This light can be directly absorbed with pigments such as chl a and chl c_2. These pigments then transform these wavelengths, less suitable for photosynthesis, into longer ones by means of autoflorescence. The emitted longer wavelengths correspond to the absorption maxima of the symbiont algal pigments. Thus the host supports photosynthesis of its symbionts. Although not directly observable it can be speculated that a similar process may have occurred in microsolenids.

(2) Morphological and structural adaptations. The fact that pennulae are characteristic of both *Microsolena* and *Leptoseris*, and in general extremely rare in other extant corals, would suggest that these pennulae may be a structural adaptation to low light levels. In *Leptoseris* the energetic requirements of the host and algal symbionts can be satisfied by a combination of photo- and heterotrophy (mixotrophy), as it is in many other corals (Porter, 1976). Although *Leptoseris* shows some unique photoadaptations, as outlined above, during periods of lowered solar radiation or in extremely poorly illuminated waters, the energy requirements of this symbiosis are met by a shift in feeding strategy with a significant increase in the heterotrophic component (Kaiser, *et al.*, 1993). This is achieved by the development of an unusual non-blind-ended, through flowing, gastrovascular system which aids suspension feeding. Anatomically this consists of a system of gastric ducts radiating from the pharynx. These gastric ducts are supported by the upper surfaces of the pennulae. Thus considering that *Leptoseris* and *Microsolena* both have these pennular structures, and share similar ecological habitats, and in the absence of any other plausible functional interpretation of the pennulae, it seems reasonable to suggest that their function was the same in both corals. Hence they probably

both showed a more heterotrophic feeding habit. This would be consistent with reduced photic potential and higher nutrient flux in typical microsolenid environments. Hence, returning to trophic considerations of these reefs, the paradoxical situation seem to have been resolved. The development of a heterotrophic bias in the feeding strategy of the microsolenids allowed these corals to optimise their available resources. Indeed where microsolenid biostromes develop in areas of siliciclastic influx (type II reefs), biostrome development tends to be greater with a more diverse associated fauna, denser framework, higher coral skeletal biovolume and more abundant microsolenids. This is unusual since in most cases siliciclastic sediment stress leads to coral reef deterioration, lower coral diversities and reduced coral cover (Acevedo *et al.*, 1989). These increases in microsolenid population must be met a corresponding increase in food supply. Clearly increased siliciclastic sedimentation has not improved photic conditions, therefore it is unlikely that this increase in population is a response to increased phototrophy. The resource that would have most markedly increased in such situations is that utilised by heterotrophic feeders. It seems therefore that the increased population of microsolenids is sustained by a increased potential for heterotrophic feeding, which provides further evidence to suggest that microsolenid have a strong heterotrophic component to their energy budget. For other corals more dependent on phototrophy the extremely low light levels in these environments were probably insufficient for their survival.

The other characteristic feature of the microsolenids that is of key importance in trying to explain their dominance in poorly illuminated waters is their extremely porous skeleton. Many of the normal skeletal elements found in compound corals are either absent or very poorly developed, for example the calicinal wall, dissepiments and columella. The septa in particular are extremely thin and entirely porous. It is known from studies on present day corals that with decreasing light intensities the amount of algal symbionts held in the gastrodermal tissue decreases (R. Day, pers. commun., 1993; Kaiser, *et al.*, 1993). It is also known from early physiological work that the presence of algal symbionts enhances calcification by a factor of 10 (Goreau, 1959, 1963; Goreau and Goreau, 1959). Therefore as light levels decrease so do calcification rates. It is suggested in this work that in the environments that the microsolenid biostromes developed, light intensities were at, or close to, a minimum that can still sustain substantial zooxanthellate populations. Since in these environments calcification would have been severely reduced by the low light levels, corals that did not rely on producing densely calcified skeleton, such as the microsolenids, would predominate. Hence these biostromes are dominated by porous forms. It should be noted that *Actinaraea*, which is also a member of the microsolenid assemblage, has a similarly porous skeleton. If this calcification-limitation model is accepted, it could be argued that *Actinaraea* should also be abundant in these assemblages. However *Actinaraea* rarely constitutes more that 10% of the total coral skeletal biovolume, compared with more than 50% for *Microsolena* in the same biostromes. The dominance of *Microsolena* over *Actinarea* may be a consequence of the higher recruitment colonisation rate of *Microsolena,* which, in environments where space is limiting, is essential to be successful. Also significant is the lack of pennulae in *Actinarea*, which as it has been suggested is a means of enhancing heterotrophic feeding in poorly illuminated water.

This suppression in calcification has also manifested itself in decreased coral growth rates. If we assume that the density banding present in many of the massive corals is indeed growth-related then it is found that for a given species in a given region growth rates decreased by up to a factor of two between shallow water reefs and microsolenid biostromes (see section 8.2.4.3, figure 8.10; Insalaco, 1996b and c). This would be consistent with modern studies that also show that growth rates decrease with increasing depth (Hudson, 1981; Baker and Weber, 1975). The particularly low L/H ratios of the coral bands is also suggestive of coral growth in poorly illuminated waters (see section 8.2.4.3, figure 8.11; Highsmith, 1979; Insalaco, 1996b and c). Furthermore in microsolenid biostomes all the compound corals, with one exception, are thamnasteroid forms lacking corallite walls, and having relatively few, thin septa. The exception, *Isastraea*, has a corallite wall; however the wall structure of *Isastraea* in these biostromal units is unusually poorly developed, with a accompanying reduction in the number and density of the dissepiments. Together, this evidence suggests that the corals in the biostromes found it difficult to produce their $CaCO_3$ skeleton, consequently relatively light skeletons tended to be constructed. A similar response to reduced light levels has been demonstrated in the Bajocian coral *Kobyastrea* (Lathuilière, 1984). In this study *Kobyastrea* was inferred to adapt to low light levels by not only changing its colony morphology, developing the characteristic plate-shaped form, but also its calicinal structure. Detailed measurements of the dimensions and extent of development of a number of calical elements revealed that with decreasing illumination general skeletal density decreased. This was found to be a result of a decrease in the extent of wall development, the number of septa, their thickness and their density. Similarly detailed autecological work on *Thamnasteria concinna* (Bertling, 1993a, 1993b) from Upper Jurassic reefs in northern Germany has demonstrated similar adaptations to decreased illumination, turbidity and sedimentation. These observations are qualitatively identical to the skeletonization trends that have been identified in the microsolenid biostromes. Another possible mechanism for the reduced deposition of $CaCo_3$ may relate to eutrophication of these environments. It has been suggested that abundant nutrients can result in orthophosphatic poisoning of $CaCo_3$ crystal formation (Hallock and Schlager, 1986; Simkiss, 1964). Kinsey and Davies (1979) suggest phosphate poisoning as a partial explanation for the 50% reduction in calcification rates on a lagoon patch reef at One Tree Island in the Australian Great Barrier Reef that was fertilised by Kinsey and Domm (1974). The evidence for the suppression of the calcification process in these biostromes is strong and while it is highly probable that poor light availability played a large part in this, this trophically related process may also have played a significant role. What is interesting is that apart from the microsolenids this typical microsolenid assemblage is composed of corals such as: *Thecosmilia, Montlivaltia, Isastraea, Thamnasteria, Fungiastraea, Stylosmilia and Dendaraea.* This association of corals is essentially that of the English Oxfordian reefs, the so-called Corallian of Yorkshire and Oxfordshire. This eurytopic coral fauna was able to survive in the unstable environments of the sub-boreal province (Fürsich and Sykes, 1977) and in conditions where annual solar radiation is reduced as a consequence of high palaeolatitude (Ziegler *et al.*, 1984) (also see dicussion of type VI reefs; section 7.2.4.3). Thus the consistent presence of these secondary corals in these biostromes is unsurprising.

7.1.7. Comparison with other coral reefs

Very similar, if not identical, reefal units to the microsolenid biostromes described above have been documented from the Late Jurassic of the following regions: Celtiberian ranges (Errenst, 1990a, 1990b); Central Polish Uplands (Poland) (Roniewicz and Roniewicz, 1971); Central Dobrogea (Romania) (Roniewicz,1976); Khoba-Kaia Massif (Crimea) (Bendukidze, 1972); Rocky Range (Georgia) (Bendukidze, 1982); western Uzbekistan and Turkmenistan (Khusanov, 1980, 1987). It therefore appears that these microsolenid biostromes are a distinct and common reef type in Late Jurassic reefal successions.

A comparison of the microsolenid biostromes with other contemporaneous reef types reveals few similarities. On a reefal scale the biggest difference between these biostromes and other reefal units is the style of reef building. The microsolenid biostromes grew as thin, well bedded sheet-like units whereas the patch reefs tended to be more massive with internal isochrons poorly defined. However the more fundamental differences are in the faunal composition of the various reefs. Many of the Oxfordian reefs of Lorraine, Burgundy and the Swiss Jura show high coral richness both in terms of taxonomic composition (up to 30 genera at St. Ursanne, Swiss Jura) but also growth form and styles of corallite integration. It could be expected therefore that where coral diversities are high with a rich coral fauna the subsequent sketetal biovolume produced would be accordingly high, and vice-versa. However this seems not to be the case since in many of these high diversity patch reefs coral skeletal biovolume rarely exceeds 40% in terms of the whole volume of the reef. Yet as has been shown in these low diversity biostromes, which developed at the environmental limits of coral reef development, coral skeletal biovolume was extremely high, locally reaching 80% of the total reef volume. This clearly suggests that carbonate production was higher in these reefs than in shallower areas more suitable for coral growth. This rather paradoxical situation has arisen from the unusually low calcification requirements and feeding strategy of the microsolenidids which, in the apparent absence of the competition pressures of other reef environments, completely dominated and flourished.

Equally striking is the contrast between the associated fauna of the biostromes and patch reefs. In many of the more diverse patch reefs the associated fauna seems extremely restricted, with many of the taxa present in microsolenid biostromes being absent, or if present their abundances are extremely low (figure 7.2). As previously discussed this could reflect differences in nutrient flux in these differing reef environments. However there are some notable exceptions, for example red algae. The Solenoporacea can be common within the shallow-water patch reefs, and in some reefs actively bind small areas of the framework (St. Ursanne, patch reef 1, Swiss Jura; Bellême, Normandy). Red algae, despite an extensive search, were not found in any of the biostromes and evidently were not present. Presumably light intensities were too low and in some regions siliciclastic influx too high for these algae to survive. Within the shallow water patch reefs, the only locally abundant groups, apart from the corals and algae, are the cidaroid echinoids and pectinid bivalves. These are the only two groups that are common in both reef types, though far more abundant in the biostromes. The abundance of cidaroid echinoids is likely to be a response to the abundant algae and/or cyanobacterial mats on which they could graze. The abundance of pectinid bivalves in the patch reefs is less easy to explain. If the trophic analysis of these reefs is accepted the persistence of these pectinids into the upper high diversity coral reefs is significant. In most of the other groups there is a very sharp decrease in diversity and abundance in the upper high diversity reefs. This may suggest that these pectinid bivalves have different nutritional requirements from other forms, perhaps being able to live in nutrient poorer waters.

7.1.8. Summary of type I and II reefs

Detailed comparative palaeoecology of Oxfordian reefal units across Europe has led to recognition of a very distinctive reefal unit referred to here as "microsolenid biostromes". These reefal units show little significant relief though they are laterally very extensive. Intra-reef sediments are characterised by wackestones and to packstone textures essentially of angular unsorted bioclasts set in a micritic matrix with peloids and peloidal fabrics being common. However it is the biotic composition of these reefs that sets them apart from other Oxfordian reefal structures, and it is this that gives the biostromes their distinctive character. The coral fauna, of relatively low generic diversity, is dominated by microsolenids such as *Microsolena, Dimorpharaea* and *Comoseris*. The associated fauna is extremely rich and abundant with many taxonomic groups being represented.

The main control on the development of the biostromes is thought to be, primarily, low light intensity, apparently the minimum light intensity needed for the development of coral reefs in the Oxfordian. However other factors were also important such as low background sedimentation rates, low energy levels, the degree to which siliciclastics entered the environment and possibly the degree of eutrophication. These factors not only controlled the style of reef building and their biotic composition but also the behavioural patterns of the corals. The corals in the biostromes adapted to these conditions by ecomorphological plasticity, adopting a platy form, but also by showing ecophysiological adaptations such as reducing their growth rates. *Microsolena* shows many structural and ecological similarities with the modern agariciid, *Leptoseris* enabling, to a limited extent, a uniformitarian approach to be taken to unravel its autoecology. The microsolenids dominated the coral fauna in these environments because they were well adapted to the prevailing conditions in two ways: (1) They have an extremely porous skeleton which in environments where the calcification rates in corals are reduced, such as poorly illuminated water, gave them a competitive advantage over other corals.; (2) In poorly illuminated water a feeding strategy relying heavily on phototropy with the utilisation of photoassimilates produced by algal symbionts is of less value. From analogy with *Leptoseris*, it is speculated that the microsolenids enhanced their energy supply by possessing a specialized heterotrophic feeding process. This second point, that some zooxanthellate corals can gain most of their energy demands from other than phototrophy, is of fundamental significance. Current ideas relating the demise of coral reefs through eutrophication do not appear to hold for microsolenid biostromes. In this case the difficulty with the model is that it is under-pinned by the assumption that zooxanthellate corals that build reefs rely heavily on phototrophy as their main source of energy. However if this is not always the case the applicability of the model is weakened.

7.2: SHALLOW-WATER CORAL REEFS

Introduction and general setting

Six types of shallow-water coral reefs have been identified (reef types: III to VII) and one reef associated facies (facies IX). Where the temporal evolution of the platform is seen these reefs always form part of the second reefal complex during the aggradational sequence (eg. Burgundy, see section 2.1; Lorraine see section 3.1; Ardennes, see section 4.1.1; and the Swiss Jura see section 5.2). These reefs are associated with shallow water lithofacies such as oolites, bioclastic packstones and grainstones, fenestraal pelmicrites and conglomerates which often contain sedimentary structures indicative of relatively shallow water (such as storm horizons, grain reworking, cross bedding and birds eye textures). The following account briefly describes the sedimentological and palaeoecological characteristics of these different reefs and the depositional environment they have developed in. For more detailed descriptions of their facies and fauna see the description of the study examples in the relevant chapters to which cross references are made.

7.2.1. Type III reefs:
Thickets dominated by tall dense phaceloid colonies within pure carbonate muds.

7.2.1.1. Study examples and general characteristics:

Study examples: Pagny-sur-Meuse, Lorraine (section 3.3): [abbreviation: PA].
St Ursanne, patch reef 2, Swiss Jura (section 5.3.3.4): [abbreviation: UR2].

General characteristics:

- Dominated by phaceloid forms especially *Aplosmilia*.
- Muddy intra- and inter-reef sediments composed pure micritic material.
- Encrustation of coral branches by spongiostromate crust and small encrusters.

This reef type is essentially defined one from study example (PA). To a lesser extent the limited data available from the UR2 study example suggests that it is of very a similar type. The Pagny outcrop is sufficiently distinct with regard to its palaeoecology and sedimentology to warrant being defined as a separate reef type.

7.2.1.2. Reef structure and facies

Reef structure and architecture. These types of reef appears to have developed as small thickets of branching phaceloid forms 5-10 m across and high surrounded by fine chalky sediment. Vague metre scale bedding can be present and suggests than syn-depositional relief was slight (about 1 m). The coral skeletal biovolume within individual thickets can be high (60%) though within the reefal unit as a whole it is very low (20%) because of the discontinuous nature of the framework. Large amounts of intra-reef microbialite are absent, and microbialite is only present as small crusts around branches. Storm-produced shell beds and erosive surfaces are present.

Facies and sedimentology. The intra and inter-reef facies is a chalky wackestone-mudstone. The microfacies of the intra-reef sediment is micrite dominated with M/S/C ratios of approximately 70/5/15 (pelmicritic to pelbiomicritic). The carbonate grains are fine grained, very immature and dominantly bioclasts. Spongiostromate coatings are not developed on the bioclasts and only the fine material appears to be micritized. The matrix is composed mainly of very fine detrital material and peloids (mainly lithoclasts and small fragments of micritized grains), and lacks laminated peloidal fabrics. The fabric is blotchy, possibly a result of bioturbation, and rather loose with frequent primary open space structures which may be fenestrae. Spongiostromate peloidal crusts are well developed on branching phaceloid corals.

7.2.1.3. Fauna and palaeoecology

Associated fauna. The associated fauna is poorly developed. Red algae are the most conspicuous macrofaunal organism though they played no part in reef construction. The associated fauna is mainly represented by small encrusters around the coral branches which can be relatively numerous and include nubeculinid forams, serpulids, encrusting bivalves, *Lithocodium*, porostromate crusts and other problematic chambered encrusters of uncertain affinity. In areas dominated by fine sediment there is evidence of bioturbation suggesting a relatively soft sediment. Bioerosion is by forams and sponges which are common although volume of bored material is low to very low; boring bivalves appear to be absent. Spongiostromate crusts are abundant around coral branches though restricted to thin crusts only a few mm thick. The small encrusters are commonly incorporated in to the spongiostromate crust resulting in *Tubiphytes*-like associations.

Coral assemblage. Branching phaceloid colonies completely dominate the fauna, constituting approximately 80% of the total coral skeletal biovolume. The coral assemblage shows a very high dominance pattern and is dominated by branching phaceloid *Aplosmilia* which constitute 60% of the total coral skeletal biovolume. Coral taxonomic richness is low to moderate with 10-?14 genera having been identified. Other framebuilders include the thin branching phaceloid *Stylosmilia*, massive to columnar forms (in particular of *Stylina* and *Pseudocoenia*) and branching ramose stylinids, but these are only minor contributors to the framework.

Palaeoecology. As explained earlier (section 3.3.3 and 3.3.4; also see below) these coral thickets developed in turbid environments with relatively high mud sedimentation rates. This appears to have favoured fast growing branching phaceloid forms, such as *Aplosmilia* which has a growth rate of approximately 1.3 cm/yr. The advantage branching phaceloid forms have other over fast growing forms (such as branching ramose colonies) is that their calices are located at the top of each branch and hence are positioned closer to the surface where light penetration is greater and where they were not vulnerable to smothering by mud.

These reefs have been compared with the present day reefs of Gulf of Guacanayabo of Cuba where reefs of very similar sedimentological and palaeoecological character thrive in a turbid environment (Geister and Lathuilière, 1991). Here water visibility can be reduced to 20-30 cm (Zlatarski, 1980; page 394), hence it is likely that these *Aplosmilia* reefs grew close to sea level. The slower growing massive forms were not adapted to these environments and therefore poorly represented. The few massive forms that are present are fast growing; the growth rate of a *Stylina* colony at PA was measured at 1.1 cm/yr, which is very fast for massive forms (see section 8.2.4.3; Ali, 1984). These colonial forms also developed as large columnar colonies which would be better suited to relatively high mud sedimentation rates compared with broader domal colonies which would have been prone to smothering by mud. Their columnar form may also be a response to a lack of suitably firm substrate which would have encouraged colonies to grow vertically rather than laterally. The lack of firm substrate is also reflected in the relative paucity in epifauna (epibenthos is only represented by small encrusters on the coral branches) and the presence of bioturbation. The relatively high sedimentation rates precluded the development of large volumes of intra-reef microbialite which is only present as thin crusts on the coral branches.

7.2.1.4. Depositional environment

These reefs developed in a protected platform interior setting where energy levels were low (as suggested by the muddy nature of the intra- and inter-reef sediments). Water depths were comparatively shallow (a few metres maximum) and the environment was prone to storms. Very rapid allochthonous mud sedimentation resulted in a turbid environment with probably reduced visibility, but not to the extent of favouring corals adapted to low-light intensities (i.e. microsolenid biostromes; section 7.1). Sediment supply to the reef was predominately by sediment import; auto-sedimentation (see chapter 8, section 8.1 for definition) was very low since physical and biological erosion of the reef was negligible. The muddy sediments introduced to the reef environment were effectively trapped there because of the lack of sediment export mechanisms and the low energy levels. Hence the reefs that developed are those constructed by corals with high sediment accommodation space (see chapter 8, section 8.1 for definition).

7.2.1.5. Comparisons with reefal units elsewhere

From the literature the only comparable reefal units are the *Calamophylliopsis/Stylosmilia Tubiphytes* bafflestones which developed in the muddy lagoon behind the reef of the Ota reef complex, Portugal (Leinfelder, 1994 pages 77-79; also see Leinfelder, 1993; page 11 and references therein). In terms of framework development, palaeoecology and depositional setting these thickets appear to be very similar to the *Aplosmilia* thickets described in this study, although constructed by the branching phaceloid *Calamophylliopsis*. The form and dimensions of these two corals appear to be very similar and evidently played a similar role in the development of these reefs. The reason for this compositional difference is puzzling since *Aplosmilia* and *Calamophylliopsis* are present in both biogeographical pools and therefore available for reef construction. To resolve this problem a detailed comparative study of these two reefs is needed.

7.2.2. Type IV reefs:

Microbial-coral reefs dominated by massive, branching ramose and phaceloid colonies

7.2.2.1. Study examples and general characteristics:

Study examples: Bois du Park, Burgundy (section 2.4): [abbreviation: BP]
Al Faro reefs, lagoonward zone, Italy (section 6.2): [abbreviation: ALL]
Courtételle; reef 5, Swiss Jura (section 5.4): [abbreviation: CO]
St. Ursanne patch reef at Liesberg, Swiss Jura (section 5.2.3): [abbreviation: URL]

General characteristics:

- Abundance of dense intra-reef microbialite.
- Relative abundance of branching ramose and sub-branching ramose forms.
- Early cementation of the intra-reef microbial pelmicrite.
- Abundance of porostromate crusts and other problematic encrusting organisms.
- Common association with type VII reefs.

7.2.2.2. Reef structure and facies

Reef structure and architecture. The reef form and dimensions of this type of reef appear to very variable, ranging from small domal structures 10 m high and 11 m across (CO) to more extensive structures at least 40 m high and over 100 m across (BP). Where syn-depositional relief can be estimated from facies relationships (such as at CO) this evidence suggests that it was never greater than 2-3 m, but this may vary from reef to reef. These reefs lack internal architecture and have a massive appearance, although storm surfaces are present. Framework construction is mainly by massive and phaceloid forms though branching ramose and sub-branching ramose forms also played a significant role in framework development. Coral skeletal biovolume is variable and ranges from 20% (CO) to 60% (BP, ALL). The intra-reef sediment is dominated by early cementing microbialite, which, considering the low coral skeletal biovolumes, was important for framework development. Geopetal fills are common.

Facies and sedimentology. Where the inter-, pre- and post-reef facies are seen they are invariably well bedded fine grained peloidal micrites (CO, ALL), which may possess features such as laminated fenestrae suggesting inter-tidal deposition (ALL). These are interpreted as lagoonal mudstones and microbialites.The intra-reef sediment is exemplified by that observed at BP (see section 2.4.2.). They are mainly bioclastic packstones although can range from wackestones through to small areas of coarse grained grainstones. In outcrop the intra-reef sediments are characteristically hard, dense and creamy coloured, commonly signifying a high microbial content of the facies. At a microfacies scale the sediments are rindy to laminated microbial biopelmicrite-pelmicrite with local variation in the amount of bioclastic material and spar cement (M/S/C ratios are around 40/10-20/40); peloidal fabrics common. The bioclasts, which are dominated by coral fragments, are very immature and intraclasts are abundant. Early cementation microbial biopelmicrite-pelmicrite has resulted in the abundance of peloidal intraclasts and has allowed boring bivalves to bore directly into the pelmicite.

7.2.23. Fauna and palaeoecology

Coral assemblage. Coral generic richness is moderate to high (BP: 21; ALL: 15; CO: 14) as are dominance patterns (only 4-5 genera dominate). The relatively low generic richness at ALL and CO is primarily a function of the poor coral preservation (ALL) and small outcrop size (CO). The fauna is mainly dominated by massive forms although branching phaceloid and ramose are also abundant. A characteristic feature of the coral fauna is the presence of the branching ramose colonies that show a sub-branching form (see section 2.4.2 for definition and examples). Transitional forms between massive and sub-branching ramose are also present. Massive and ramose stylinids (sub-order Stylinina) and fungids (sub-order Fungiina) are dominant.

	Coral fauna characteristics of type IV reefs:		
	Coral growth form		
	Massive	Ramose	Phaceloid
Colony dimensions	10-30 cm thick; 30-40 cm across	1-1.5 m high, 1 m across.	1-1.5 m high, 1 m across.
Branch thickness	———	4 cm	2 cm
BP:	40%	40%	20%
CO:	50%	10%	40%
AL:	40%	20%	40%
General values for type IV reefs:	**43%**	**24%**	**33%**
Common type IV reef coral taxa:	*Pseudocoenia, Stylina, Isastraea, Cyathophora, Meandrophyllia*	*Pseudocoenia, Meandrophyllia*	*Dermoseris*

Associated fauna. The intra-reef macrofauna fauna of type IV reefs is particularly poorly developed, being species-poor and having low abundances. Conspicuous groups are red algae (can be common though volumetrically insignificant), chaetetids and echinoids. Small encrusters are more abundant and include serpulids, bryozoans, forams and problematic encrusters such as *Bacinella*, *Lithocodium*, *Girvenella* and *Cayeuxia*. Bioerosion intensity is moderate to high and primarily by bivalves, although boring forams were common in the ALL reef, and *Entobia* was seen in the CO reef. The relative abundance of boring bivalves and porostromate crusts is notable since they are both absent or very rare in similar, though higher energy reefs (eg. type VII reefs).

Microbialite. Three types of microbialite can be identified in type IV reefs: 1) massive, macroscopically structureless, microscopically laminated microbialite (very abundant and dominates the intra-reef sediment); 2) spongiostromate crusts (generally poorly developed); and 3) porostromate crusts (relatively common). (See section 2.4.2 for their description).

Palaeoecology. The inferred depositional environment (see below) presented an ideal situation for coral growth: shallow, well lit water, energy levels not excessively high or low, and low sedimentation rates. The relative abundance of branching forms (especially branching ramose colonies) is likely to be a reflection of the relatively low energy levels in which these reefs developed. This is corroborated by the fact that in the similar though higher energy type VII reefs, branching forms are comparatively rare, and branching ramose forms are absent.

The presence of these branching morphotypes of genera which commonly occur as massive domal forms is significant since they are absent from type VII reefs. The three common massive forms in type VII reefs (*Meandrophyllia*, *Pseudocoenia* and *Microsolena*) also occur as branching ramose colonies in type IV reefs. Changes from massive to branching growth forms (both by species replacement and/or ecophenotypic plasticity) can be attributed to changes in light and/or energy levels (Stearn, 1982; also see section 8.2.4.5). In this case the presence of branching morphotypes in type IV reefs is unlikely to be correlated with variations in light levels since there is no evidence to suggest that light levels were different in the two reef types (i.e. light was not limiting in either type IV or VII reefs). It appears therefore that in these genera the appearance of branching ramose forms (possibly ecophenotypic morphotypes) is correlated with lower energy conditions in non-light limiting environments.

7.2.2.4. Depositional environment

These reefs developed in two low to moderate energy settings: (1) protected proximal back-reef setting platformward of higher energy type VII reefs (eg. BP and ALL.); and (2) low energy lagoonal settings (e.g. CO). Low energies are inferred by the position of these reef types on the platform, general lack of rubble and grainstone facies and the fact that even fragile thinly branching colonies such as *Cladophyllia* and *Stylosmilia* (which would be vulnerable in high energies) are found in situ and not fragmented. In the BP and ALL type IV reefs the presence of local grainstones and their association with high energy type VII reefs suggests that energy levels were higher than type IV reefs that developed within lagoonal muds such as the CO reef. The association of these reefs with inter-tidal facies (e.g. ALL.) and local isopachous cements (e.g. BP) suggests that they developed in very shallow water probably around the upper sub-tidal zone. Sediment supply to the reef was low, as suggested by the abundance of early cementing microbialite and the lack of major bioclastic dominated areas. Sediments were supplied to the reef primarily by bioerosive auto-sedimentation (physical erosion of the reef was negligible because of the low energy levels) and sediment import mechanisms appear to have been absent. This sediment appears to have been rapidly incorporated into the reef framework as suggested by the immature nature of the allochems. Since there is no indication of turbidity, light levels are unlikely to have been limiting.

7.2.2.5. Comparisons with reefal units elsewhere

- *Lower Kimmeridgian reefs of the Chay Peninsula south of La Rochelle* (*Charente Maritime*), *western France* (Taylor and Palmer, 1994). Personal observations of this reef complex reveals a number of similarities with the type IV reefs described above, which include:
    1. the growth form characteristics of the coral assemblage, especially the abundance and richness of branching ramose forms including stylinids, fungids and microsolenids;
    2. high levels of bioerosion, especially by bivalves, and the presence of red algae;
    3. the dominance of intra-reef microbial pelmicrite;
    4. the presence of well-bedded lagoonal muds as inter-reef sediments; and
    5. the domal form of the reefs.

- The *porostromatoporoid zone of the Oxfordian and Lower Kimmeridgian Slovenia reef complex* (Turnšek, *et al.*, 1981; pers. comm., D. Turnšek, 1994; and personal observations). The observations on this reef complex revealed a number of similarities with the type IV reefs described above which include:
    1. the relative abundance of branching ramose stylinids and [1]fungids;
    2. the location of this reef zone platformward of the high energy actinostromariid zone (which is similar to type VII reefs);
    3. its association with lagoonal deposits; and
    4. abundance of intra-reef microbialite.

([1] *In this paper the authors state that there is a dominance of stylinids and faviids. However the genera listed in this paper together with those listed in Turnšek (1972), and personal observations suggest the dominance of stylinids and fungids. It is believed this is a typographical error in the Turnšek, et al., 1981 paper.*)

7.2.3. Type V reefs:
Large high coral diversity reefal associated with large volumes of bioclastics

7.2.3.1. Study examples and general characteristics

Study examples: Saussois, Burgundy (section 2.5): [abbreviation: SA].
Roches aux Poulets, Burgundy (section 2.6): [abbreviation: RP].
St. Mihiel, Lorraine (section 3.5): [abbreviation: MI].
St Ursanne patch reef 3, Swiss Jura (section 5.3.3.4): [abbreviation: UR3].

General characteristics:

- Internal facies organisation: corrugated structure.
- High coral richness and diversity with regard to both growth form and taxa; low coral dominance patterns
- Poor framework development; large areas of bioclastic piles and accumulations.
- Lack of intra-reef microbialite.

7.2.3.2. Reef structure and facies

Reef structure and architecture. One of the most characteristic features of this reef type is the development of an internal facies organisation (corrugated structure) described in section 2.5.2. which is well developed in all the study outcrops of this reef type. The coral skeletal biovolume is generally very low (20%) with bands completely devoid of in situ corals (bioclastic piles). However in zones of better framework construction coral skeletal biovolume can reach 60%, though this is only local. Taking the reefal unit as a whole (including areas of poor framework construction) these types of reefs are quite extensive, being at least 50 m thick and 400 m across, though framework development is very discontinuous. Individual zones of high framework development are up to 10 m thick and many tens of metres across and have tabular form. Syn-depositional relief is difficult to assess since relationships with inter-reef facies are not seen. Storm truncation surfaces are common.

Facies and sedimentology. The intra-reef sediments are coarse grained (1.5-3 mm) chalky bioclastic packstones with M/S/C ratios of around 25-35/25-35/30-50 (packed biomicrites-poorly washed biosparites). The carbonate grains are mainly bioclasts though lithoclastic material is abundant. The bioclasts are not dominated by corals but bivalve and echinoid material can also be very abundant. The carbonate grains are generally texturally mature, possessing spongiostromate coatings and being well micritized. The matrix is rather homogeneous and composed of a mixture of fine detrital carbonate and peloids. Microbialite is only present as spongiostromate coatings and crusts on bioclasts; it played no part in reef building and large volumes of intra-reef microbialite are absent. These is no evidence of early cementation of these reefs, in fact the maturity of the allochems suggests that they underwent considerable reworking on the sediment surface before inclusion within the reef framework and cementation. (The RP example shows a slightly different microfacies (see section 2.6.2) being slightly finer grained and possessing immature grains. This is thought to represent local changes in the depositional environment at the top of the RP section as discussed in section 2.7.)

7.2.3.3. Fauna and palaeoecology

Associated fauna. The intra-reef fauna is generally low to moderately well developed. The conspicuous groups are oyster type and byssally-attached bivalves (especially *Chlamys*), although *Trichites*, terebratulid brachiopods, gastropods, calcified cyanobacteria and cidaroid echinoids are also present; red algae appear to be absent. This fauna tends to be concentrated in framework-poor, bioclastic-rich zones (in particular the *Trichites* and gastropods). Bioerosion intensity is low and predominately due to bivalves.

Coral assemblage. Growth form composition of these reefs is particularly rich and diverse, though the most abundant colonies are various massive forms (varying from platy to domal). Branching phaceloid and ramose forms vary in their importance but generally neither constitutes more than about 20% of the total coral skeletal biovolume. Massive forms vary from domal colonies 40 cm across and 30 cm thick, to tabular and sub domal colonies 15-35 cm across and 3-30 cm thick. Occasionally very large colonies over 60 cm across and 30 cm thick are present. Platy forms 1-3 cm thick, and small domes 10 cm high can be common. Branching forms can be up to 2 m high and across.

The generic richness of these reefs is high (SA: 22; MI: 19; RP: 20; UR3: not quantified but rich) and dominance patterns are low (10 or so genera in each assemblage can be common; though not necessarily the same genera occur in the different assemblages). *Meandraraea, Stylina, Meandrophyllia, Microsolena, Pseudocoenia, Isastraea, Thamnasteria dendroidea* and *Aplosmilia* can be common. No one taxon was consistently common at all three study localities.

Coral taxa invariably present in type V reefs

Branching phaceloid
(up to 20 %)
Stylosmilia
Aplosmilia
Calamophylliopsis
Dermoseris

Solitary
(insignificant)
Montlivaltia

Massive
(up to 75%)
Meandraraea+
Stylina
Meandrophyllia
Microsolena
Pseudocoenia
Thamnasteria
Isastraea
*Actinaraea**+

Branching ramose
(up to 20%)
*Dendraraea**+
*Thamnasteria dendroidea**
Pseudocoenia limbata

Faunal list for UR3 was not made however the fauna appeared to be similar to UR1. If this is the case all but 3 of the corals listed here occur at UR3. * not at RP; + not at UR3 as suggested form faunal composition of UR1.

Palaeoecology. The depositional environments of type V reef were not ideal for reef development since they underwent episodic periods of high sediment supply, which locally drowned reef frameworks and produced bioclastic piles. Nevertheless in terms of true ecological diversity these reefal units have the highest coral diversity of all the reefs studied. Why are there such high coral diversities?

Paradoxically it may be that these episodic periods of high sedimentation provide a mechanism for developing high coral diversity in these units. The reasoning behind such a suggestion stems from the

"Intermediate disturbance hypothesis" of Connell (1978) which states that seasonal and episodic disturbances reduce the number of strong and weak competitors, thereby diminishing competition effects. No one species is completely excluded nor is able to dominate; instead fluctuations in population densities favour the inclusion of opportunists and species with high propogation rates (r-strategists), all leading to a significant increase in diversity. The community never reaches climax, and several stages of succession are present synchronously in slightly different areas.

Applying this concept to the type V reefal units it appears that local frameworks within the reefal units as a whole may represent different stages of ecological succession from stabilisation through to pioneer and diversification stages, depending on the length of time since the last sediment burial event. Thus type V reefs can be viewed as a stacked section of individual frameworks of various size and varying stages of ecological succession. Hence some frameworks may represent early stages of colonisation dominated by platy and encrusting forms whereas other frameworks of the section may represent better developed frameworks with branching and massive forms. The reef environment was not stable for long enough to allow one association (both in terms of growth form and taxonomy) to dominate the reefs; before this could be achieved the frameworks were buried by sediment and the reef initiation process had to resume all over again and perhaps by different taxa.

This can be tested by comparing the diversity patterns of type V with those of type IV reefs. The only major difference between type IV and V reefs is that type IV reefs did not experience episodic periods of high sedimentation. Type IV environments are therefore more stable and lack "intermediate disturbance", thereby allowing type IV reefs to reach climax. In terms of coral composition this should manifest itself in higher dominance and lower coral diversity (with regard to both taxonomic and growth form composition). This is consistent with what is seen in type IV reefs.

7.2.3.4. Depositional environment

The evidence of frequent storm beds and the lack of evidence for current or wave reworking suggests energy levels were not high and that these reefal units were deposited somewhere between storm- and normal wave-base. The palaeobathymetry of platform interior deposits is problematic since the depth of hydrodynamic datums will vary according to the local palaeogeography and oceanography. Since these deposits were deposited in the platform interior, normal wave base was likely to have been at a shallower depth than in more exposed areas. Bearing this in mind one can speculate on a depth of around 5-10 m. There is no evidence to suggest than light was limiting (such as light-restricted coral fauna dominated by platy microsolenid corals) and relatively well lit waters are envisaged. The tops of some type V reefs can possess slightly higher energy facies (coarser grains, cleaner sediments, lower micrite/sparite ratios and more abundant massive corals) suggesting that these reefal units can aggrade to, or near, normal wave-base (e.g. MI and SA). The large volumes of bioclastic material which dominate areas of the reefal unit suggest high sediment production. However the mature nature of the allochems implies that they were not rapidly incorporated into the reef framework but were subject to micritization and spongiostromate crust development. The low levels of bioerosion imply that much of the material was produced by physical erosion of reef frameworks. Within the reef environment this was predominately by storms but sediment may also have been imported into the type V reef system from adjacent higher energy reefs. Locally type V reefs that had aggraded to higher energy environments would also have produced large volumes of bioclastic material which would have been deposited in other areas of the reef. These processes, together with the lack of sediment export mechanisms, produced large bioclastic accumulations which episodically led to local burial of reef frameworks.

7.2.3.5. Comparisons with reefal units elsewhere

From the literature it has not been possible to evaluate whether this type of reef occurs elsewhere. Both Crevello and Harris (1984) and Leinfelder (1993) refer to reefs with little framework and dominated by bioclastic piles, but both suggest that these were deposited in high energy environments rich in grainstones, and therefore unlikely to represents type V reefs. It is more likely that these authors are referring to the type VIII reef described in this work (see section 7.2.6. below).

7.2.4: Type VI reefs:

Small reef patches associated with siliciclastic deposits

7.2.4.1. Study examples and general characteristics

Study examples: Shellingford Cross Roads, Oxfordshire, England (section 6.1.4): [abbreviation: SH].
Haden Wick, Wiltshire, England (section 6.1.3): [abbreviation: HW].
Péry-Reuchenette, Swiss Jura (section 5.5): [abbreviation: PR].

General characteristics:

- Low coral generic richness.
- Characteristic coral assemblage; common genera include *Isastraea*, *Thamnasteria*, *Fungiastraea*, and *Thecosmilia*.
- Siliciclastics within the inter- and intra-reef sediments; intra-reef clay seams common.
- Knobbly and planar spongiostromate crusts.
- Associated coral rubble deposits.

7.2.4.2. Reef structure and facies

Reef structure and architecture. Reef development is patchy and discontinuous and generally occurs as individual patches 0.5-3 m high and up to 10 m across, although these can coalesce to form discontinuous frameworks many tens of metres across. Framework construction was predominantely by massive forms, though loose branching phaceloids forms are secondarily important; coral skeletal biovolumes are generally very low (around 20%). Knobbly and planar spongiostromate crusts are abundant and may have had a local binding effect in some reefs. Where sedimentation rates where temporally very variable with protracted periods of very low sedimentation, some type VI reefs can have more extensive intra-reef microbialite (e.g. PR). Coral rolling and toppling is common, and rudstone beds are frequent. Storm horizons are common and the frameworks are frequently interrupted by clay seams. Syn-depsitional relief was very slight if present at all (1-2 m max.).

Facies and sedimentology. The inter-reef sediments vary from marls (wackestone-packstones) through to bioclastic and oncoidal grainstones, molluscan-rich debris deposits, bioclastic packstones and rudstones. The grainstones and molluscan-rich debris beds were often deposited as sheets and channels. As with the inter-reef sediments the intra-reef sediments show a considerable variation in textural fabric ranging from dark grey mudstone (such as the *Rhaxella* biomicrite at HW; see section 6.1.3.2.) through to wackestone and packstones, and occasionally grainstones (such as the biosparite lenses at SH; see section 6.1.4.2.) and microbial biointramicrites (PE; see section 5.5.2). In fact the only common component in the inter- and intra-reef sediments is the variable presence of siliciclastics. The variety in textural fabrics and composition of both these facies reflects the broad environmental conditions, particularly in environmental energy, in which this reef type could develop.

7.2.4.3. Fauna and palaeoecology

Associated fauna. The associated fauna of these reefs can be species-rich (see relevant sections for faunal composition) but it is only dominated by a few groups which can be very abundant. Oysters, especially *Nanogyra,* dominate, though cidaroid echinoids, *Chlamys*, thecidean brachiopods, *Stomatopora*, *Rhaxella,* nubeculinid forams and other small encrusters can be common; red algae are absent. At PE the abundance of rhynchonellid brachiopods with coarse ribs probably reflects the more arenaceous environment of this reef. The coarse ribbing is a means of providing efficient water flow in and out of the valves with minimal valve opening; thus reducing the possibility of damage to the lophophore by sediment grains. Boring intensity is moderate and almost solely due to bivalves. Knobbly and planar spongiostromate crusts are characteristic of this reef type and particularly well developed in the HW and PE examples (see section 6.1.3.2 and 5.5.2. for the description of these crusts). However large amounts of intra-reef microbialite (as in type IV and VII reefs) are generally absent.

Coral assemblage. The coral fauna in these reefs is poorly developed, with low generic richness (usually less than 7 genera present) and moderate to high dominance patterns. In terms of growth forms they tend to be dominated by tabular and domal colonies (30-100 cm across and 10-30 cm high), though branching phaceloid forms can be common. Platy to lamellar forms can also be present though rarely abundant; branching ramose forms are absent. Taxonomically the fauna has a characteristic assemblage which is dominated by four consistently present taxa: *Fungiastraea*, *Thamnasteria*, *Isastraea* and *Thecosmilia*.

Palaeoecology. The faunal richness patterns of Oxfordian sub-Boreal realm faunas were studied by Fürsich and Sykes (1977). They suggest that the paucity in species was not a function of any single environmental factor but rather the fluctuations (episodic and seasonal) of many such as temperature, salinity and sediment influx (their so-called "environmental instability model"). This is probably the case, and is strengthened by the fact that richness increases both to the north in the Boreal Realm and to the South in the Tethys when environmental stability increased.

The abundance of siliciclastics and the inferred proximity to a palaeolandmass suggests that salinity levels may have been reduced. Salinity stress has previously been suggested as a possible cause of the low species richness in the sub-Boreal of England (Gorden, 1975; Hallam, 1969). However using the criteria set out by Fürsich (1994) to identify salinity-controlled benthic faunas, constant brachyhaline conditions seem unlikely considering the presence of traditionally interpreted stenohaline organisms (including corals, echinoids, brachiopods and the richness in bivalves and gastropods). Nevertheless there may have been periods during exceptionally high influxes from the palaeolandmass when salinity may have been reduced but this is difficult to assess.

The proximity to palaeoland masses and the strong influx of siliciclastics provide evidence for raised nutrient levels in these areas. The dominance and abundance of low-level suspension feeders in the associated fauna suggests that nutrient levels were sufficient to sustain such populations and clearly the waters were not strongly oligotrophic. These eutrophic conditions may also have been responsible for the abundance of the knobbly form of spongiostromate crust so abundant in the clay rich type VI reefs (e.g. HW and PE). It can be speculated that a eutrophic environment caused "blooms" of heterotrophic bacteria which developed the microbial micrites by direct metabolic action such as the concentration of Ca^{++} and Mg^{++} ions in the cell walls (Chafetz and Buczynski, 1991). This situation may be similar to what has happened in the present-day eutrophication of the Florida keys, reefs which has resulted in blooms of blue-green algae. These have increased coral disease and led to coral overgrowth by benthic macroalgae (Lapointe, *et al.*, 1993).

The environmental instability model can also be used to explain the paucity in the coral fauna; clearly most reef corals were not suited to such fluctuations and conditions would have favoured eurytopic taxa. The eurytopy of this coral fauna is substantiated by the occurrence of these corals (*Fungiastraea*, *Thamnasteria*, *Isastraea* and *Thecosmilia*) in two other situations:

1. High palaeolatitude assemblages. The Yorkshire Corallian and the Helmsdale corals represent the northern latitudinal limits of Late Jurassic coral growth and are dominated by these corals (Yorkshire: Hitchings, 1981; Helmsdale: P. B. Wignall, pers. comm., 1992). This is especially significant since this assemblage occurs in a wide variety of facies (from mudstones through to oolitic grainstones). This suggests that the environmental controls on the development of this fauna in these areas were independent of local sedimentary regime (i.e. latitudinal related factors such as temperature and solar radiation). This situation is paralleled in present-day coral biogeography where latitudinal species attenuation, which has been correlated with decreases in mean annual water temperature, results in high latitude faunas (dominated by eurytopic coral species) tending to be very similar regardless of local environment (Veron, 1995).

2. Deep water coral assemblages at the photic limits of reef development. These corals are common members of the microsolenid assemblage which dominate deep water, very low light level environments (as discussed in section 7.2).

Thus it appears that these eurytopic corals are able to cope with significant variations in light intensity, energy levels, sedimentary regime, and possibly also high nutrient levels and lowered salinity. Thus is seems that it was not so much that this fauna was particularly adapted to these type VI reef environments but rather that most other stenotopic corals were excluded. These eurytopic corals are present in other reef types though never particularly common, since they appear to have been outcompeted by more specialised, stenotopic forms. Similar conclusions were arrived at by Bertling (1993b) from a synecological study of Late Oxfordian coral faunas around Hannover, Northern Germany and from an autoecological study of *Thamnasteria concinna* in northern Europe (Bertling 1993a).

In terms of growth form and corallite type there is no obvious reasons to suggest that they were especially adapted to such broad environmental conditions. Besides, other taxa with similar growth forms and corallites were evidently absent. Therefore the palaeoecological reasons for the eurytopy of this fauna are likely to have been ecophysiological adaptations which were not expressed as morphological features, and hence are difficult to evaluate.

7.2.4.4. Depositional environment

From the above description and discussion it is clear that these reefs can occur in quite a broad environmental range, particularly in environmental energy. However by definition, true type VI reefs develop in areas of significant siliciclastic influx and hence proximal to palaeoland masses. The paleobathmetry of these reefs will vary according to local conditions but are likely to range from below normal wave base through to very shallow water. Local turbidity may have reduced light levels. However the lack of a low light-intensity adapted coral fauna, which can also occur in areas of high siliciclastic influx (e.g. type II reefs; see section 7.1) suggests light attenuation is unlikely to have been severe. Sedimentation, in particular siliciclastic influx, appears to have undergone temporal variations in its intensity throughout the development of these reefs. This is most clearly shown by the presence of clay bands within the reefs. The PE reef appears to have undergone sporadic periods of marked siliciclastic influx between which were considerable periods of little or no sedimentation. In this reef such periods allowed: (1) more intra-reef microbialite to form; (2) a greater degree of encrustation on crusts; (3) the development of local hardgrounds; and (4) iron staining of crusts.

7.2.4.5. Comparisons with other reefal units

Other study outcrops

The presence of bioclastic, oolitic and oncoidal grainstones, molluscan-rich deposits and rudstones at the English localities suggests that these reefal units also developed in agitated water above normal wave base. Indeed in terms of a reefal environment they appear to be similar to type VIII reefal units (see section 7.2.6 below) though with a high siliciclastic component. Hence these type VI reefs can be viewed as siliciclastic versions of type VIII reefs.

Reefal units outside study area:

1. The *Late Oxfordian to Middle Kimmeridgian coral faunas around Hannover* (Bertling, 1993a; Bertling pers. comm., 1993; personal observation, 1993). A number of these coral faunas share similar features to type VI reefs such as: (1) the development of these reefs within siliciclastic regimes; (2) small size of buildups; and (3) the importance of *Thamnasteria* and *Isastraea* (although other characteristic corals of type VI reefs are uncommon (*Thecosmilia*) or absent (*Fungastraea*).
2. The *Corallian of the Weald subsurface* (Sun and Wright, 1989; Sun *et al.*, 1992; personal observations, 1992). The upper part of unit 3 and unit 4 of the Palmers Wood 1 core reveals reefal units very similar to the type VI reefs of HW and SH with regard to the coral fauna, intra-reef sediments and the importance of peloidal crusts. (See Sun and Wright (1989) for the details of the unit sub-division of the core.)

7.2.5. Type VII reefs:
Microbial-coral reefs dominated by massive colonies

7.2.5.1. Study examples and general characteristics

Study examples: Quatre Pieux, Burgundy (section 2.3): [abbreviation: QP].
Al Faro reef, seaward zone, Italy (section 6.2): [abbreviation: ALS].

General characteristics:

- Dominance of massive colonies and phaceloid amphiastraeids.
- Abundance of dense intra-reef microbialite and local bio-intrasparites.
- *Absence* of branching ramose forms.
- Early cementation of intra-reef sediment.
- Laterally associated with type IV reefs and often overlain by beach (type IX) facies.

7.2.5.2. Reef structure and facies

Reef structure and architecture. The shape, form and dimensions of this reef type was not obtainable from outcrop, but they were at least 15 m thick and 50 to 200 m across. They do not possess any internal architecture and have a massive appearance. Framework construction was predominately by massive forms, though phaceloid forms also contribute. Coral skeletal biovolumes are generally high (QP: 60-85%; ALS: 50-60%) and framework development is continuous. All the colonies are in situ and there is no evidence of rolling. Early cementing microbialite played a significant role in the framework construction of these reefs by binding the colonies together and giving these reefs structural rigidity. This was especially important considering the high energy environment these reefs developed in.

Facies and sedimentology

Inter- and post-reef facies. At QP the type VII reef grades to the north to fore-reef slope rubble deposits and to the south to the type IV reef of the Bois du Park section. At ALS the type VII reef grades to the north east into the type IV reef of the Al Faro lagoonward zone; the south-westward gradation is not exposed. (In both cases the lateral transition to the type IV reefs was towards the platform interior). The post reef facies at both locations are inter-tidal deposits (at QP: fenestral pelmicrites, see sections 2.3.1. and 2.7.; and at ALS: beach facies, see section 6.2.1.).

Intra-reef facies. The intra-reef facies are exemplified by the microbial biopelmicrites and biopelsparites with well developed peloidal fabrics described from QP (see section 2.3.2). The intra-reef facies from ALS is virtually identical to those found at a QP although bio-intrapelsparites are slightly more abundant (see section 6.2.2.). At a microfacies scale the M/S/C ratios are very variable though approximately 50 (down to 0) /10-20 (up to 50)/40%. In the upper part of the reef framework, local bird's eye textures can be observed. A number of microfacies and sedimentological criteria suggest very early cementation of this sediment (see sections 2.3.2 and 6.2.2.).

7.2.5.3. Fauna and palaeoecology

Associated fauna. The macrofauna of these reefs is generally very poorly developed, with only a few individuals of various groups being present. Red algae, bryozoans, chaetetids and porostromate crusts are present though not common. The only evidence of bioerosion was by forams (cf. *Bullopora*) and annelids. Bioerosion intensity is very low and there is a notable absence of boring bivalves. This is consistent with a particularly high energy interpretation of this environment (see below).

The microbialites present are essentially the same as those encountered in type IV reefs. They include:

1) massive, macroscopically structureless, microscopically laminated microbialites. This type of microbialite dominates large areas of the intra-reef sediment. Early cementation of microbialite bound the skeletal framework giving the reef structural rigidity;
2) spongiostromate crusts. These are generally poorly developed though common around the phaceloid branches; and
3) porostromate crusts. These are not common (in contrast to type IV reefs where porostromate crusts are abundant).

Coral assemblage

Characterisation of the coral assemblage for the type VII reefs is mainly based on the QP outcrop since the corals at the ALS outcrop are very poorly preserved and generally only growth form data was retrievable. The coral fauna is dominated by massive forms although branching phaceloid forms are also abundant. Branching ramose forms are notably absent.

Growth form composition of type VII reefs.			
Reef	**Coral growth form**		
	Domal	Phaceloid	Ramose
QP	65%	35%	absent
ALS	80-90%	10-20%	absent
Approximate values for type VII reefs	**75%**	**25%**	**absent**

The common branching phaceloid coral forms are *Mitrodendron*, *Dermosmilia*, *Donacosmilia* and *Calamophylliopsis*, and form thickets approximately 1 m in height. Many of the unidentified phaceloids from the ALS reef have same dimensions and form to the phaceloid amphiastraeids described from the QP reef and therefore it is possible that they are also phaceloid amphiastraeids.

The common massive forms include *Stylina, Pseudocoenia, Microsolena* and *Meandrophyllia*, and develop as domal colonies 30 cm high and across. Encrusting corals, although volumetrically insignificant, can be abundant and include forms of *Microsolena* and *Stylina.* These coral crusts are 3-4 mm, rarely up to 1 cm, thick, and up to 10 cm across.

The dominance patterns are moderate with no one genus clearly dominating the fauna, and generic richness is high (QP: 21; ALS: 9; the low richness at ALS reflects the poor preservation of the corals rather than true taxonomic richness). An interesting and characteristic feature of the coral assemblage is the relative abundance of amphiastraeids (such as *Mitrodendron, Donacosmilia* and *Pleurophyllia*) which make up over 11% of total coral skeletal biovolume at QP. Although amphiastraeids cannot be said to dominate the assemblage their occurrence is significant since this group of corals is virtually absent in the other coral reef types studied.

Characteristic coral taxa in type VII reefs		
Phaceloid (35%)	**Massive (75%)**	**Lamellar/encrusting**
Mitrodendron	*Meandrophyllia*	(% Insignificant)
Donacosmilia	*Pseudocoenia*	*Stylina*
Dermosmilia	*Microsolena*	*Microsolena*
Calamophylliopsis	*Isastraea*	
Thecosmilia	*Stylina*	
Stylosmilia	*Solenocoenia*	
Pleurophyllia		

(Mainly compiled from the QP study example though corroborated from data retrieved from ALS and Slovenia; see below.)

Coral palaeoecology

The dominance of massive forms, the presence of thin encrusting forms and the absence of branching ramose forms in this reef type can be best interpreted as a response to the inferred high energy (Stearn, 1982). This is corroborated by the fact that branching ramose forms are common in similar, though lower energy, type IV reefs. If high energy levels have controlled the growth form composition of type VII reefs the presence of branching phaceloids in these reefs is problematic. The branching phaceloid fauna in type VII reefs is distinct from the phaceloid fauna of other reef types by the dominance of amphiastraeids. These phaceloid amphiastraeids may have been structurally adapted to higher energy conditions relative to other phaceloid genera by possessing: 1) heavily calcified branches with thick walls; and 2) densely packed branches. Moreover, presumed epithecal growth banding in *Donacosmilia* revealed growth rates of approximately 0.5-0.8 cm/yr, which is very slow for a branching form. In fact it can be speculated that all these heavily calcified phaceloid amphiastraeids were relatively slow growing since there appears to be a general inverse relationship between skeletal density and growth rate (Goreau, 1959; see chapter 8, section 8.2.4.3). This suggests that *Donacosmilia* in particular and perhaps the other phaceloid amphiastraeids grew at a similar rate to the massive forms, which rarely show growth rates in excess of 10 mm/yr. Therefore it is unlikely that the phaceloid branches of these colonies were significantly elevated over the surrounding framework, which would otherwise have made them prone to wave breakage. Thus it is envisaged that these slow-growing phaceloids derived hydrodynamic protection by growing at a similar rate to the massive forms. This is corroborated by the absence of rolled or toppled branching colonies which might have been expected in such high energy environments. This growth rate argument can be applied in reverse to account for the absence of branching ramose corals since these are faster-growing (with growth rates generally over 1.5 cm; see chapter 8, section 8.2.4.3; Buddemeier and Kinzie, 1976) thus were likely to outpace the growth of massive corals and hence expose themselves to hydrodynamic stress.

7.2.5.4. Depositional environment

The association of type VII reefs with inter-tidal deposits indicates a particularly shallow water depth for reef formation and light levels were not limiting. The presence of local birds eye textures in the upper parts of the reef suggest that the reef itself may have undergone episodic emergence. Therefore it is likely these reefs developed in relatively shallow water, probably around the upper sub-tidal zone. Particularly high energies can be inferred from the presence of intraclastic and bioclastic grainstones, and the reefs association with beach facies. This is consistent with the exposed, reef front, position of these reefs. The abiotic effects of this high energy on the reef were to: 1) pump water through the framework, increasing cementation rates and hence producing rapid, early cementation and the development of sparite-dominated textures. This process was of utmost importance since it increased the rigidity of the reef structure; 2) produced reef debris especially of intraclastic and bioclastic material; and 3) prevented the deposition of detrital lime mud hence producing clean intra-reef sediments. The biotic effects of this high energy were to 1) favour reef development primarily by massive forms and to a lesser extent phaceloid amphiastraeids; 2) exclude branching ramose forms; and 3) restrict the development of the associated fauna and exclude boring bivalves.

Bioclastic sedimentation rates within the reef do not appear to have been high as indicated by the relatively small proportion of bioclastic material present in the intra-reef sediment and the abundance of microbial peloidal fabrics. Reef auto-sedimentation was almost solely produced by mechanical erosion (bioerosive auto-sedimentation was insignificant). The immature nature of the bioclasts suggests that the bioclastic material that was produced was rapidly incorporated into the reef framework.

7.2.5.5. Comparisons with reefal units elsewhere

- The actionostromatoporoid zone of the Oxfordian and Lower Kimmeridgian Slovenia reef complex (Turnšek, *et al.*, 1981; pers. comm. D. Turnšek, 1994; and personal observations). Observations on this reef reveal significant similarities with the type VII reefs described above. These include:
    1. Decrease in the dominance of branching ramose stylinids and fungids and a corresponding increase in the importance of massive stylinids and fungids compared with the parastromatoporoid zone (which is analogous with type IV reefs).
    2. The importance of phaceloid amphiastraeids (such as *Mitrodendron* and *Donacosmilia*) and other phaceloids (such as *Dermosmilia, Calamophylliopsis, Thecosmilia* and *Stylosmilia*).
    3. Abundant intra-reef microbialite.
    4. The location of this reef on the outer platform margin just behind the fore-reef slopes covered with reef rubble deposits.
    5. In the highest part of the reef it is associated with deposits rich in nerineids and diceratids.

- *Kimmeridgian Ota reef complex, Portugal* (Leinfelder, 1992, 1994) and the Oxfordian coral bioherms of the Upper Calcaires de Mem Martins, (*Epidiceras* assemblage) (Ellis, 1984). Both these units appear to show some features in common type VII reefs (points 1,3,4,5 of above) and possibly represent similar types of reefal units.

7.2.6: Type VIII reefs:
Thickets of branching ramose colonies with widely spaced branches developed amongst sand shoals and channels

7.2.6.1. Study examples and general characteristics

Study examples: Novion-Porcien, Ardennes (section 4.1): [abbreviation: NP]
Bellême, Normandy (section 4.2): [abbreviation: BEL]

General charateristics:

- The dominance of branching ramose colonies with widely spaced branches in framework construction. Especially characteristic of this reef type are the thinly branching ramose *Thamnasteria dendroidea* (type A) and the thickly branching ramose stylinid *Dendrohelia* *coalescens*. Secondarily common are small dome-shaped colonies of *Thamnasteria*, *Diplocoenia* and *Stephanastraea* and phaceloid forms such as *Latomeandra*, *Stylosmilia* and *Goniocora* which also have widely spaced branches.

- Association of the reefs with mobile grainstones, channels and coral-rich debris sheets.
- Diverse molluscan fauna (especially nerineids and diceratids) in the inter-reef sediments.
- High levels of bioerosion.

7.2.6.2. Reef structure and facies

Reef structure and architecture

The reefs tend to develop as small patches and thickets of variable size and form, ranging from small lensoid bodies 2 m high and 40 m (e.g. BEL) across to more domal structures 11 m high and 20 m across (e.g. NP). They lack any internal architecture except for storm-produced erosive surfaces. Framework construction is almost solely by branching ramose corals, although locally large massive corals and red algae may contribute if conditions are suitable (e.g. BEL). Coral skeletal biovolumes are generally very low (10-30%) with the intra-reef sediment being composed of a variable mixture of detritus and microbialite. Microbialite is generally present though its abundance is highly variable (70-20% of intra-reef sediment). In type VIII reefs with abundant microbialite (e.g. NP) it contributed significantly to framework construction. Reef development could be interrupted by rubble facies, sandwave encroachment and storm deposits. A secondary, though characteristic, feature of these reefs is the mouldic preservation of the corals by the leaching of their aragonite skeletons giving these reefs a very high mouldic porosity. Dissolution probably occurred soon after deposition when these deposits were within the meteoric realm. These types of reefs are particularly prone to this since they were deposited in very shallow water and hence could be moved to within the meteoric realm very early. Also important was their occurrence within porous grainstone, hence downward flow of meteoric waters was relatively unhindered. The presence of plant material and lignites above these deposits in the BEL example (Enay and Mangold, 1980), suggests that were moved to within the meteoric realm soon after deposition.

Facies and sedimentology

Inter-, pre- and post-reef facies are dominated by: (1) oolitic, oncolitic and peloidal grainstones deposited as sandwaves, sand sheets and channels; and (2) reef debris facies deposited as sheets and channels. Hence these reefs appear to have developed within a complex and dynamic sedimentary environment. The intra-reef facies vary both spatially and temporally depending on the local sedimentary dynamics. These sediments may vary from dense white microbial pelmicrites with M/S/C ratios of approximately 70/0-10/20-30 (NP; see section 4.1.3) to biomicrites with M/S/C ratios of approximately 40-60/0-10/30-50 (BEL; see section 4.2.3). Small patches of biopelsparites are also present. The carbonate grains are generally fine grained, angular, poorly sorted and largely composed of coral fragments and lithoclasts.

7.2.6.3. Fauna and palaeoecology

Associated fauna

Inter-reef fauna. The inter-reef fauna is dominated by gastropods, in particular the Nerineacea such as *Nerinea*, *Ptygmatis* and *Cryptoplocus*. Other common gastropods include *Bourguetia*, *Neritopsis*, *Purpuroidea*, Trochacea and Cerithiacea. These occupied the sandy grainstones facies and were mainly infaunal or semi-infaunal. Bivalves are less abundant but include shallow infaunal forms such as *Pteroperna*, *Ceratomyopsis* and the Crassatellacea, and deep infaunal forms such as *Fimbria*. In more stable areas and local hard substrates (such as hardgrounds and coral debris sheets) Megalodontacea (such as *Petrocardia* and *Isocardium*) and Hippuritacea (diceratids) can be abundant. The above fauna is often mixed together with coral material in rubble facies (spatially averaged deposits).

Intra-reef fauna. The intra-reef fauna is dominated by bivalves which include nestling and crevice-dwelling forms such as Aracacea, Limacea, and Mytilacea; and cementing forms such as Pteriacea and Ostreacea. Gastropods are less common within the reef itself but include typical reef dwelling Pleurotomariacea (such as *Conotomaria* and *Trochotoma*). Red algae can be common and could grow to a large size (30 cm high and across; e.g. BEL). Hemicidaroid echinoids can be common in areas with an abundance of microbialite (such as the NP reefs) where the extensive microbial mats were perhaps able to sustain a larger population of echinoids. Bioerosion in these types of reefs is both very intense and diverse, with a rich assemblage of boring ichnotaxa. These include *Gastrochaenolites Entobia*, *Meandropolydora*, *Caulostrepsis*, *Conchotrema*, *Rogerella*, *Trypanites* and *Talpina*. This reef type possesses the highest bioerosion diversity and intensity of all the reefs studied. Particularly common are *Gastrochaenolites*, *Entobia* and *Talpina*. The presence of *Gastrochaenolites* is significant since they are typical of shallow water, mainly upper sub-tidal environments; however they avoid extremely high energies (Bromley, 1994; Bromley and D'Alessandro, 1990, Peyrot-Clausade and Brunel, 1990). Thus although these reefs are interpreted as relatively high energy (when compared with reef types I-VI) energy levels were not as high as in type VII reefs where *Gastrochaenolites* are absent.

Coral assemblage

The coral fauna of these reefs is dominated by branching ramose colonies which had very widly spaced branches (approximately 70%), in particular *Thamnasteria dendroidea* (type A) and *Dendrohelia coalescens*. The abundance of these two corals (usually greater than 60%) is significant since in this study they have not been documented in any other reef. Their growth form, habit and dimensions have been described in section 4.1.5 and 4.2.3. Taxonomically these reefs can be quite rich with over 25 genera having been identified in the NP example. The apparent paucity in coral genera in the BEL example is likely to reflect the smaller outcrop and hence sample size, rather than any palaeoecological controls. *Thamnasteria dendroidea* (type A) dominates over *Dendrohelia coalescens* (*T. dendroidea* (type A): approximately 40-50% of the total coral skeletal biovolume; *D. coalescens:* approximately 10-20%, although *Dendrohelia coalescens* dominated frameworks have been inferred to have occurred in more exposed areas see section 4.1.2.-4.1.5). Branching phaceloid forms, although volumetrically much less dominant, still contribute to framework construction and include forms such as *Calamophylliopsis*, *Cladophyllia*, *Thecosmilia*, *Goniocora* and *Stylosmilia*. As with the branching ramose forms these develop as loosely packed thickets occasionally reaching 60 cm in height.

The massive forms contributed very little to framework construction (<10%) and are interpreted as secondary framebuilders and dwellers. These are generally small dome-shaped forms rarely exceeding 5 cm in height and 7 cm across. Although these forms constitute a small proportion of the coral skeletal biovolume as a consequence of there small size, they are numerically abundant and taxonomically rich. Indeed the relatively high taxonomic richness of the coral fauna is mainly a consequence of the high richness of these small forms. *Diplocoenia*, *Fungastraea*, *Stylina*, *Latomeandra*, *Thamnasteria* and *Stephanastraea* are particularly abundant and characteristic of the fauna. Occasionally larger forms (especially of *Stylina* and *Pseudocoenia*; see section 4.2.3) can occur, though these are not common. Richness and dominance patterns are high and coral taxonomic diversity is low.

Coral palaeoecology

Two forms of *Thamnasteria dendroidea* have been recognised in the course of this work:

1. *T. dendroidea* form A, which is by far the more abundant of the two. This form is very thinly branched, with branch thickness generally less than 0.8 cm. It generally occurs as very loose thickets with sinuous branches reaching a height of 1.5 m.
2. *T. dendroidea* form B has far thicker branches, generally greater than 15 mm and a significantly higher branch packing density. It developed colonies of similar height to form A.

(See section 4.1.5. for further descriptions of the two forms and their differences).

As stated above, *T. dendroidea* form A has only been documented in type VIII reefs, whereas form B has also been documented in other shallow-water reefs types (e.g. type IV and V reefs). The peculiar growth form of *T. dendroidea* has been noted by Beauvais *et al.*, (1974) although no reasons for the development of these colonies were suggested. The unusual growth form of *T. dendroidea* type A may be related to its growth rates and calcification of its skeleton. In these moderately high energy environments, mobile carbonate sands and shifting channels were an important feature, so the ability to cope with mobile sediments and episodic periods of rapid sedimentation must have been important. If it is assumed that it would have been an advantage for this coral to increase its growth rate in such environments then this could have been achieved in two ways: (1) by retaining the same growth form and habit though having increased the rate at which it could produce calcium carbonate, which would have gone directly toward increasing its linear growth rate; or (2) by retaining the same rate of calcium carbonate production but having concentrating deposition in a linear direction thereby making the branches long and thin.

There is no obvious way for *Thamnasteria dendroidea* to have increased the rate at which it could deposit $CaCO_3$ from environments where type B occured to where type A occured since light levels (which are one of the main controles on calcification; Goreau, 1959) were not significantly different in the two areas (i.e. mechanism (1) of above). Therefore it can be speculated that the thin branches of this type A form represents a vertically faster growing form than type B (mechanism (2) of above). However due to the fact that the preservation of *Thamnasteria dendroidea* type A is usually mouldic, no growth bands have been retrieved to corroborate this. Nevertheless high growth rates are typical of modern pioneer species, which may compensate for unstable substrates in this way (Sheppard, 1982) and coral assemblages in such environments are often rich in thin ramose corals. Indeed all the branching corals (including the phaceloid forms) in type VIII reefs develop very loosely branched colonies, which would also be better suited to higher sedimentation rates.

Large massive forms are rare, though small dome-shaped forms are abundant. This suggests that the corals died before they could grow to a large size. This may be a consequence of their comparatively slower growth rates as a result of which they were not able to cope with periods of high sedimentation rates and mobile substrates.

Dendrohelia coalescens forms dense thickets of robustly branching colonies which can reach 1.7m in height. They possess relatively thick branches, generally greater than 2 cm thick. The inferred presence of *Dendrohelia coalescens*-dominated frameworks and rubble units in the more exposed areas of the NP reef complex (see section 4.1.4 and 4.1.5) suggests that they were adapted to higher energy environments by their thicker branches (in a similar fashion to *Acropora*-dominated frameworks of the present-day Florida shelf; see below).

In summary the development of this coral fauna appears to have been governed primarily by the highly mobile nature of the substrate, with episodic periods of very high sedimentation rates (activation of bedloads). This coral fauna could rapidly colonise stabilised sands, and it constructed reef frameworks dominated by loose branching ramose forms which had capabilities of very rapid vertical growth. The loose nature of the branching colonies and low coral skeletal biovolumes (together developing a very open framework) gave these reefs the potential to continue to grow during raised levels of sedimentation. This rapid framework growth and periods of high sedimentation precluded the development of large massive forms but resulted in a high turnover of small forms which where short lived since they could not keep up with the rapidly growing framework and sedimentation rates.

7.2.6.4. Depositional environment

The facies were deposited on a clean carbonate platform dominated by active, constantly shifting sub-tidal sand shoals. Reef development occurred amongst more stable sediments in quiet areas protected by shoals; and during periods of sand shoal stability. Sediments between isolated reef frameworks developed a rich mollusc fauna. Storm and ?tidal channels were abundant and shifted across the depositional environment. Debris sheets rich in reefal material were well developed and resulted from storm erosion and surf disintegration of frameworks in the more exposed areas. Energy levels were moderately high and generally strong enough to drive sand dune migration, develop tidal channels and prevent deposition of mud and silt, hence a position well above normal wave base is envisaged. However energy levels were not so high as to prohibit the development of branching ramose corals and exclude boring bivalves. Water depths were shallow sub-tidal, no more than a few metres, and hence light levels were not limiting with regard to the corals. In these sedimentologically dynamic environments the reefs were prone to sandwave encroachment and burial under sand and debris sheets. The main controlling factor with regard to sediments was the general high productivity of the environment and the potential for periods of very high levels of sediment mobility. Intra-reef sediments were introduced principally by auto-sedimentation (physical and biological erosion of the reef) and sediment import. The coral frameworks appear to be have been able to colonise such environments by developing as fast growing open frameworks which have high sediment accommodation space (see chapter 8, section 8.1 for definition) but also through sediments being locally exported away via numerous channels. Sediment production in the environment was so high that much of the environment dominated by shoals and channels (which accommodated the high production) rather than reefs.

The depositional environment therefore appears to be very similar to the back-reef and reef flat environments of the Florida shelf. Here the shelf can be sub-divided into a number of broadly zoned sub-environments (Enos, 1977; Multer, 1977 and Shinn, 1980) including:

(1) a deep seaward coral rubble zone;
(2) spur and groove zone;
(3) a zone of landward orientated *Acropora palmata,* constructing the reef crest;
(4) the reef flat, composed of unorientated *A. palmata* with much reef rubble;
(5) back-reef zone, consisting of scattered colonies of *A. Palmata*, thickets of *A. cervicornis,* and large heads of *Montastrea annularis* and *Diploria*. Reef rubble and lime sand are locally abundant; and
(6) back-reef lime sands with local patch reefs and cut by tidal channels.

The zones (5) and (6) of the Florida shelf therefore provides a good recent analogy for these type VIII reefal carbonates where as zones (3) and (4) provide a possible analogy for the inferred *Dendrohelia coalescens* dominated frameworks and rubble units in the more exposed areas of NP reef complex (see sections 4.1.4 and 4.1.5).

7.2.6.5. Comparison with other reefal units

Other study outcrops.

Dompcervin, Lorraine, France (see section 3.7). In general terms the inferred depositional environment of the Dompcervin section very similar to the type VIII depositional environments, although in situ reefs have not been observed. It might have been expected that the coral debris in this section would include fragments of type VIII reef corals such as *Thamnasteria dendroidea* (type A) and *Dendrohelia coalescens*, but these were not recorded. This may be related to the fact that the depositional environment at Dompcervin appears to have been less agitated, as suggested by the fine nature of the grainstones and the presence of lithographic limestones at the top of the section. Thus sediment mobility was likely to have been less marked, allowing other taxa to form the reefs that sourced the debris channels.

Reefal units outside the study area. From the literature, a number of reefs have been inferred to have developed in similar environments to type VIII reef described above. However the descriptions of the coral fauna are detailed enough to evaluate how similar these reefs are to the reef type described above. Nevertheless the following literature examples appear to be similar, at least at a superficial level, to type VIII reefs:

1. *Back-reef shoals; nerineid facies of the Montejunto platform, Portugal* (Leinfelder, 1994) Here "coral patch reefs developed in front of, within and behind these shoals" (Leinfelder, 1994, page 104) and hence have developed in similar environments to type VIII reefs. No details of the corals fauna are given apart from them being "bushy" forms dominated by branching ramose thamnasteroid colonies and the phaceloid *Calamophylliopsis*. Similar reefs have developed in the Oxfordian Upper Calcaires de Mem Martins, *Epidiceras* assemblage, of the Ramalhal buildup (Ellis, 1984, pages 97-101).
2. *Upper Jurassic coraliferous limestones from the Holy Cross Mountains, Poland.* (Roniewicz, 1975). This paper describes reefs that had developed in "....very shallow water with a lower energy and in which branching colonies would predominate. These concentrations are a few metres to km across. In one case, the assemblage of corals of 1.5 m in thickness developed on shoals which after the necrosis of the colonies, the branches were dissolved by chemically active surface waters" (Roniewicz, 1975, page 214).
3. Type 3 reefal unit of Beauvais, 1975 in which corals are found in "rubble deposits where the corals are rolled, broken, turned upside down, scattered in a detrital, gravely, sandy or oolitic sediment which often shows cross bedding".
4. The type 2b reefal unit of Crevello and Harris, 1982. These are coral-dominated patch reefs associated with bioclastic, oolitic and oncolitic grainstones and packstones.

7.2.7: Type IX facies:
Conglomerates rich in well rounded coral fragments

7.2.7.1. Study examples, facies and depositional environment

Study examples of this unit are the facies that cap the reefs at Al Faro, Italy (section 3.5; see figure 6.8) and St Ursanne (section 5.3.3.4; see figure 5.8), and the facies present at the top of the Quatre Pieux (section 2.5; see figure 2.6) and Rochers aux Poulets (section 2.6; see figure 2.7) sections.

Reefal unit IX represents wave destruction of reef frameworks at sealevel leading to the development of inter-tidal coral and nerineid-rich beach deposits (coral keys). They occur at the top of shallowing upward successions and are closely associated with type VII. This facies has been defined as a reef-associated unit since they can contain large amounts of reef-derived coral material, and because they can be used as an indicator of sea-level from which palaeobathymetric interpretations of other reef types can be made. Associated with this facies can be laminated fenestrate mudstones deposited in protected, lower energy inter- to supra-tidal environments (e.g. the Al Faro pelmicrites).

CHAPTER 8:
LATE JURASSIC CORAL REEF DEVELOPMENT: DEPOSITIONAL MODEL, TRENDS AND SYNTHESIS

Chapter 7 has identified a number of broad reef types and has outlined their characteristic features and the depositional environments they had developed in. This chapter will develop a depositional model for these reefs which is then used as a framework for a sedimentological and palaeoecological synthesis.

8.1: DEPOSITIONAL MODEL

8.1.1. Environmental controls on coral reef development

The main abiotic controls on coral reef development on an ecological time scale are: 1) hydrodynamic energy levels; 2) light intensity; 3) sedimentary regime; 3) temperature; 4) suitable substrate availability; 5) oxygenation and circulation; 6) salinity levels; and 7) nutrient levels. Of these, hydrodynamic energy levels, light intensity and the sedimentary regime are considered to be the three main determinants on the development of coral reefs and their ecological zonation (Done, 1983). Indeed many zonal schemes for present-day reefs are based on the spatial variation of water energy levels and light intensity (see Done, 1983 for review of present-day coral reef zonation; Giester, 1977; Pichon, 1978; Rosen, 1975; Dana, 1979; Perrin *et al.*, 1995). The effects of the sedimentary regime on reef development are less easy to evaluate, hence few zonation schemes incorporate this parameter into their model. Nevertheless this will exert a strong control on the type and extent of reef development and needs evaluating. Assuming that these three factors (hydrodynamic energy levels, light intensity and the type of sedimentary regime) have also controlled the development of Late Jurassic coral reefs, reef environments of this time can be discussed in terms of these three environmental components.

Evaluation of light and hydrodynamic energy levels, and the type of sedimentary regime

Light (L) and hydrodynamic energy levels (E) are parameters which are relatively easy to evaluate. Hydrodynamic energy is best inferred from microfacies analysis, such as relative importance of micrite- and sparite-dominated textures, and sedimentological criteria, such as presence of storm beds and evidence for wave and current reworking. Light levels are best established from palaeoecological criteria and the inference of palaeobathymetry from facies relationships, as discussed in chapter 7, section 7.1. The sedimentary regime and dynamics of the reef environment is less easy to quantify since the interplay of sediment supply and sediment removal processes must evaluated.

The sediment supply processes are: (1) import of allochthonous sediment into the reef system (reef import, I); and (2) sediment produced from the reef itself (auto-sedimentation, P). Sediment import is an important process where reef development occurs: (a) close to palaeolandmasses and where there is a significant influx of siliciclastic sediment into the reef system; (b) in low energy, but turbid, environments where large volumes micritic material can settle out; and (c) above fair weather wave base in highly productive environments where sediment mobility via channel and bedform activity can be very high. The volume of sediment produced by reef auto-sedimentation can also be significant and will be a function of three factors: (a) the gross $CaCO_3$ production of the reef; (b) the intensity of biological and physical erosion; and (c) whether or not the reef has undergone early cementation.

These two processes (reef import and reef auto-sedimentation) are the sediment suppliers to the reef system; however it is important to evaluate how much of this sediment supply is offset by the sediment removal processes. The main sediment removal processes are sediment export mechanisms (Ex). These are especially important where reef development has occurred close to by-pass type platform margins. Here the sweeping action of wind and tidally driven waves, as well as gravitational basinward transport of sediment, can all effectively remove sediments from the actively growing reef system. Export-type sediment removal can also be achieved in environments where reef development is closely associated with channels which can funnel sediments away from the reef frameworks.

The net result of this interplay of sediment supply and sediment export can be termed sediment balance (S), which is defined as the relative importance of sediment export to sediment import processes. Sediment balance (S) can be expresses by the following equation: $S=(I+P)/Ex$. Clearly this equation is only of conceptual importance since in practice, quantification of the factors is extremely difficult, if at all possible. In practice, this function can be simplified and used to look at two extremes such as reef environments with low S as compared with those with high S. Low S environments are those where little sediment is being supplied to the reef and/or sediment is being efficiently removed from the growing framework, whereas high S environments are those where a considerable amount of sediment is being introduced to the reef and relatively little sediment is being exported away.

Micro- and macrofacies analysis of the intra- and inter-reef sediments is the best way of evaluating sediment balance. The abundance of intra-reef laminated and rinded peloidal fabrics of presumed microbial origin are good indicators of very low sedimentation rates (Leinfelder *et al.*, 1993b) as are the presence of local hardgrounds and syn-depositional cements. The type and nature of the carbonate grains is also important since it can reveal the relative importance of import processes. For example, relatively high sediment import can be inferred from microfacies with a high component of non-reefal allochems (e.g. siliciclastics, ooliths, fragments of non-reef biota), whereas microfacies dominated by carbonate grains of reefal origin tend to occur within environments where reef auto-sedimentation is dominant. Where allochem-dominated fabrics occur in quiet water regimes it can be inferred that much of the material is of bioerosional origin, which is corroborated by analysis of the associated fauna. Conversely, in higher energy environments early cementation of the reef sediment and its subsequent physical erosion produces significant amounts of bio- and intraclastic material. The character of the allochems also provides valuable information on sedimentation rates and grain histories. Very immature allochems (poorly sorted, angular and lacking micritization and spongiostromate coatings) suggest that the grains were rapidly incorporated into the reef framework and not subject to reworking, but may also be a result of high sedimentation rates and storm deposition. On the other hand texturally mature allochems, especially grains that show well developed micrite envelopes and spongiostromate coatings, suggest that they were not rapidly incorporated into the framework but were subject to these post-depositional processes. Extensive grain coating, micritization and rounding is more likely to be produced in open depositional systems where grains are easily reworked on the depositional surface. Hence intra-reef microfabrics dominated by well-coated and micritized grains suggests that sediment import was significant. On a reef scale, the identification of reefal units with large volumes of intra-reef sediments, bioclastic piles and low coral skeletal biovolumes can often be used to infer comparatively high sediment balance.

Framework sediment accommodation space

The rate at which sediment can be incorporated in the reef framework is also important in trying to understand the relationship between reef composition and sedimentation. This will be dependent on two factors: (a) the framework style of the reef; and (b) the rate of framework growth. Framework style would have dictated how much primary space there was available for sediment at any given time within the reef (the reef's sediment capacity). Frameworks dominated by branching forms which possessed widely spaced branches, and which had low coral skeletal biovolumes, were potentially capable of providing more space for sediment than frameworks dominated by domal, platy or tabular forms with high coral skeletal biovolumes. The rate of framework growth is also important since faster growing frameworks were likely to have coped better with increased sedimentation when compared to slow growing frameworks, all other factors being equal. Even if reef frameworks had a high sediment capacity (either by virtue of their low coral skeletal biovolume and/or construction by branching corals) if their average growth rate was slow, these primary spaces for sediment would have been quickly infilled during periods of high sedimentation rates. In reality the fastest growing frameworks are usually dominated by branching ramose and phaceloid forms and therefore there is an inherent relationship between framework growth rate and sediment capacity. Reefs with high sediment accommodation space (i.e. fast growing open frameworks) coped with increased sedimentation rates better than reefs with lower accommodation space.

8.1.2. Environmental axes and depositional model

Figure 8.1 shows the three environmental axes used in the model. The Z-axis pertains to light levels (L) which for the purpose of this analysis can be either "Low" or "High". "Low" L refers to reef environments where light levels were limiting with regard to coral reef development, that is just above euphotic zone. Such low light levels prevailed in relatively deep-water environments but also shallower turbid settings. "High" L refers to reef environments where light levels were not limiting with regard to coral reef development, which prevailed in clear, well lit, shallow-water settings. The Y-axis pertains to hydrodynamic energy levels (E) which can be "Low", "Moderate" or "High". Low E conditions prevailed in relatively deep-water environments, well below normal wave base, but also in very shallow water, though in protected platform interior settings (lagoonal conditions). The facies and microfacies

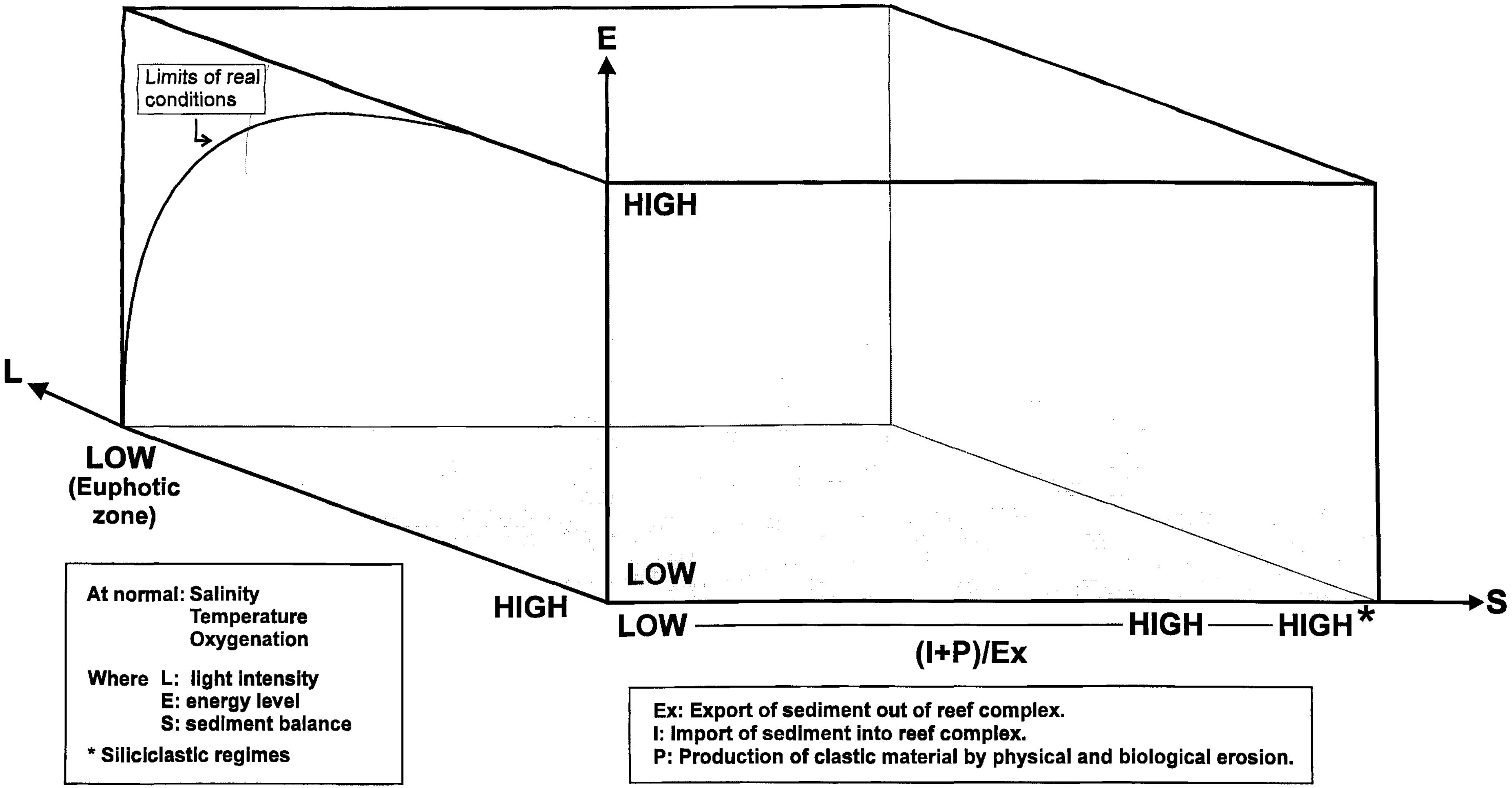


Figure 8.1: Environmental axes for a conceptual model of Late Jurassic reef development. The volume defined by the three axes is referred to a LES space within which different types of Late Jurassic coral reef types can be plotted. See text for definition and discussion of axes. (Note that there is a relationship between L and E indicated by the "limits of real conditions" curve. Under normal conditions light levels are highest at sea level where energy levels are highest and decrease exponentially in deeper water as energy levels decrease (Houck *et al.*, 1977)).

deposited in such environments are dominated by mudstones and wackestones, and lack sedimentological features associated with environments above normal wave base. "High" E conditions prevailed in depositional environments between normal wave base and sea level in exposed settings. The facies and microfacies deposited in such environments are dominated by sparite textures and the reefs are closely associated with high energy facies such as beach deposits, grainstone sandwaves and debris channels; intraclastic grainstones are also common in the intra-reef sediments. "Moderate" E conditions prevailed in open platform settings between storm and normal wave base. Facies tend to be packstone-dominated and develop in environments between the two extremes outlined above. The X-axis pertains to sediment balance (S) which can be "Low", "High" or "High*". Low S environments are those where little sediment is being supplied to the reef and/or sediment is being efficiently removed from the growing framework, whereas high S environments are those where a considerable amount of sediment is being introduced to the reef and relatively little sediment is being export away. The right hand side of the S axis in figure 8.1 is reserved for reef environments with a high siliciclastic influx and is indicated by "High*".

Using the foregoing model, the relative importance of these three parameters for the nine reef facies can inferred from examination of their litho- and biofacies (see chapter 7) and is summarised below.

Reef type	Light levels (L)	Energy levels (E)	Sediment balance (S)
I	LOW	LOW	LOW
II	LOW	LOW	HIGH*
III	HIGH	LOW	HIGH
IV	HIGH	MODERATE (-LOW)	LOW
V	HIGH	MODERATE	HIGH
VI	HIGH	MODERATE (-HIGH)	HIGH*
VII	HIGH	HIGH	LOW
VIII	HIGH	HIGH	HIGH
IX	HIGH	HIGH	LOW-HIGH

Figure 8.2 shows where the different reef types plot within the LES space. The reef boxes represent the approximate position occupied by the different reef types in LES space and the model illustrates how the different reef types relate to each other with regard to these parameters. It will be noted that although the reefs were initially plotted as having 3 components of L, E and S, each of which can be low, moderate or high, the position of the type VIII, VI and III reef boxes have been adjusted to give a better representation of their true relative valves of L, E and S. Thus the type VIII reef box has been shifted slightly down the energy axis since, although it has been interpreted as a high energy reef, the environments they had developed in were not as high as type VII reefs environments (though considerably higher than type V reef environments). The type VI and III reef boxes have been shifted along the L axis slightly since although light has not been interpreted as being "low", local turbidity may

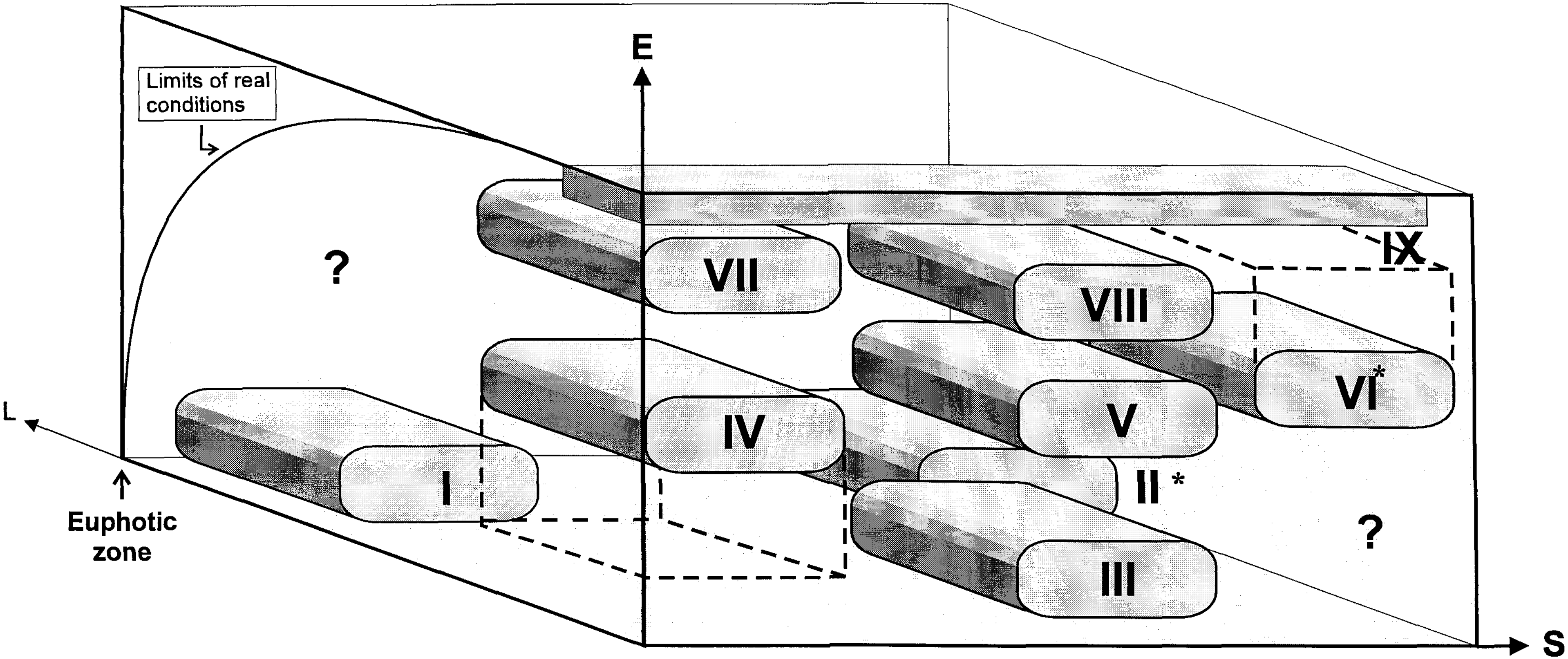


Figure 8.2: Conceptual depositional model for Late Jurassic reef development illustrating how the different reef types relate to each other within a conceptual environmental framework. The dashed extensions to reef types IV and VI* reflect the broader limits in environmental energy levels in which these reefs can develop (see section 7.2). Areas with a question mark (?) indicate areas where no data is available. (Axes as figure 8.1).

have reduced light levels slightly. With the exception of the volume occupied by the type IX beach facies the whole of LES space within the "limits of real conditions" can be occupied by reef faunas, and hence the plotted reef types probably represent end-members in a complete spectrum of possible reef types.

8.1.3. Study reefs that cannot be placed within the reef types defined

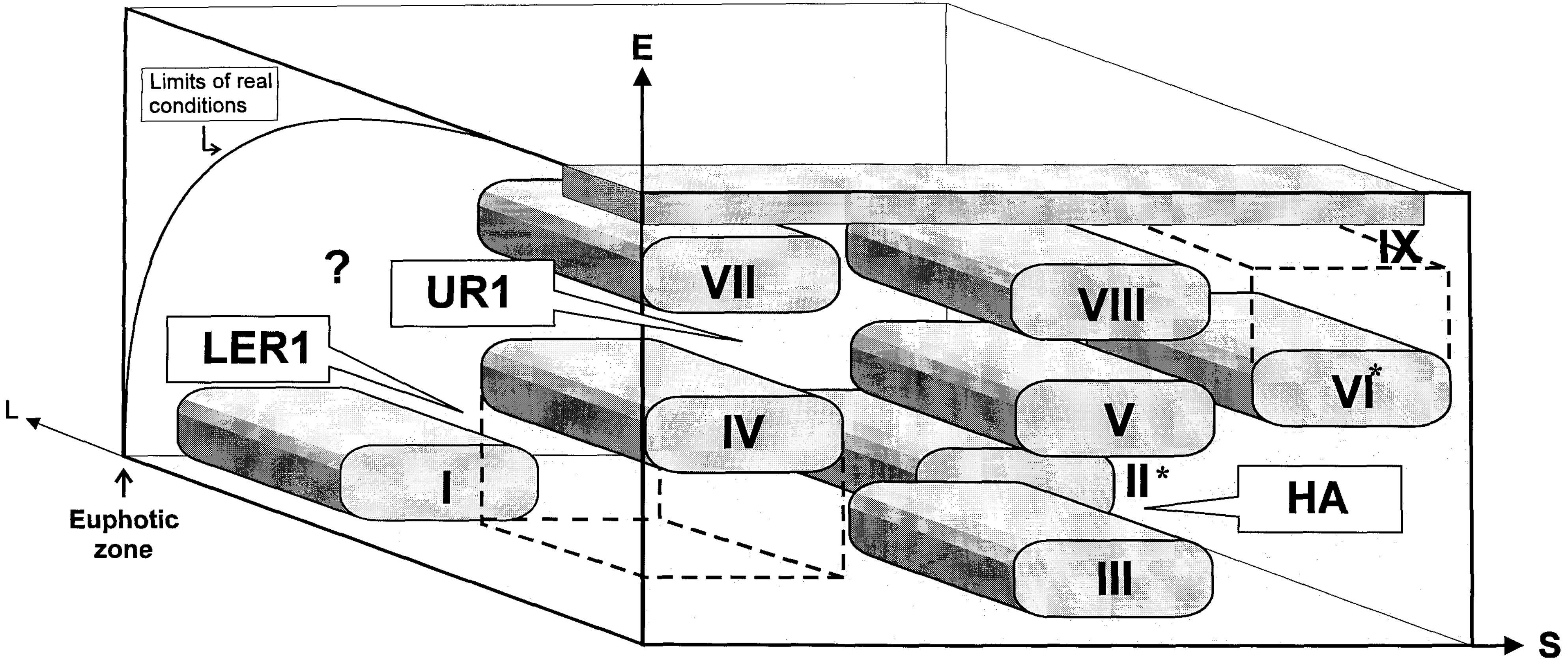
It will be noted that in the description of the different reef types (chapter 7) not all the reefs studied in section two of this thesis (chapters 2-6) were included as type examples of the reef types defined. Those reefs that do not fit comfortably into the reef types defined are believed to represent either: (1) transitional forms between end-member reef types (see below for examples); (2) reefs whose development has been influenced by factors in addition to light intensity, energy levels and sediment balance (see below for examples); or (3) reef outcrops that do not provide enough data to confidently assign them to a reef type (Courtételle reefs 1-4, Swiss Jura).

Transitional reefs

The following reefs probably reflect intermediate-type reefs that have developed in environmental conditions between those of the end-member reefs plotted in figure 8.2.

Haudainville, Lorraine (see section 3.6). This reef could not be satisfactorily assigned to one single reef type but rather showed similarities with both type III and V type reefs. Aspects of the Haudainville reef which suggest an affinity with type III reefs include: (1) abundance of phaceloid forms, especially *Aplosmilia*; (2) relative abundance of micritic material producing chalky bioclastic pack- and wackestones; (3) the relative abundance of red algae; and (4) the burrowing of the inter-reef sediments. Aspects of the Haudainville reef which suggest an affinity with type V reefs include: (1) diversity of the coral assemblage with regard to both taxa and growth form; (2) discontinuous nature of the framework development with large volumes of inter-reef bioclastics; (3) frequent storm erosive surfaces; and (4) the type of intra-reef sediments. It is envisaged that the Haudainville reef represents a transitional form between the type III and V reefs (figure 8.3). The termination of this reef by onlapping bioclastic sediments at the top of the Haudainville section signifies the onset of environments which were likely to have been dominated by more typical type V reefs, such as those of the St. Mihiel study example. This may suggest that the Haudainville reef is stratigrapically older than the St. Mihiel reef.

Lérouville, reef 1, lower reef complex, Lorraine (see section 3.4.2). In terms of fauna and framework development the limited data available from the outcrop suggest that it is very similar to type I reefs. The problem with such an interpretation is that the unit at Lérouville had developed a very significant palaeorelief of approximately 20 m, and therefore can hardly be called biostromal. Moreover the reef had grown into shallow water, as indicated by onlapping crinoidal sandwaves and rippled surfaces, and therefore had developed in a significantly different environment to type I reefs. The development of



LER1: Lerouville, Lorraine (section 3.4.2)
UR1: St. Ursanne; patch reef, Swiss Jura (section 5.3.3.1)
HA: Haudainville, Lorraine, (section 3.6)

Figure 8.3: Location in LES space of study reefs of intermediate reef type. (Axes as figure 8.1).

significant relief and the growth of the reefal unit into shallow water argue against a type I interpretation for this reef. However, as was initially noted by Humbert (1971), the Lérouville reef is located in a stratigraphically intermediate position between the lower and the upper reef complex (see figure 3.3). Thus the lower reefal unit at Lérouville may represent a reef intermediate between type I reefs and type IV or V reefs (i.e. a transitional reefal unit between deep- and shallow-water reefal units; figure 8.3). This also implies that once type I reefs had established themselves they could grow into environments which would have otherwise been occupied by other reef types. One might have expected in such intermediate-type reef a higher proportion of domal and branching ramose forms, other than *Dendrarea* which is a member of the microsolenid assemblage, and a decline in the dominance of microsolenids; this does not appear to be the case. Indeed, in all the conformable aggradational sequences from deeper to shallower water (such as the sequences in Burgundy, see section 2.1; Lorraine see section 3.1; and the Swiss Jura see section 5.2) the type I and II reefs and the shallow water reefs are very distinct, with no compositionally intermediate reefs being present.

<u>St. Ursanne patch reef 1, Swiss Jura (see section 5.3.3.1).</u> This outcrop revealed a reef-bearing section that aggraded to sea level. The main body of the reef (biofacies 3 in figure 5.10) shows a number of similarities with type IV reefs, such as: (1) the abundance of early cementing intra-reef microbialite; (2) growth form and taxonomic composition of the coral fauna; and (3) the relative abundance of boring bivalves. However this biofacies also shows some similarites with type VII reefs, for instance: (1) the presence of two possible phaceloid amphiastaerids (*Dermosmilia* and *Donacosmilia*); (2) the abundance of *Meandrophyllia* and *Pseudocoenia*; (3) and the presence of encrusting forms. As the reef continued to aggrade to sea level the character of the biofacies changes (biofacies 2 in figure 5.10) and begins to show more similarities with type VII reefs, including: (1) the dominance of large domal and encrusting stylinids and a reduction in the number of branching ramose forms; (2) the abundance of early cementing intra-reef microbialite; and (3) the association of the reef with beach facies. It therefore appears that this reef had aggraded from a type IV to a type VII reef environment and that the whole of patch reef 3 can be viewed as a transitional form between these two reef types (figure 8.3).

Reefs that do not fit the model

<u>Ayton, Yorkshire (section 6.1.6.2).</u> This reef does not fit the model developed above since palaeoenvironmental and sedimentological analysis suggests that it should plot in the region of the model occupied by type VIII reefs. Indeed, in terms of the general depositional environment, the Ayton reef developed in a very similar environment to the type VIII reefs of Bellême and Novion-Porcien. The problem with this is that with regard to coral assemblage and framework development the Ayton reef bears no similarities to type VIII reefs. This apparent discrepancy in the model suggests that the development of the Ayton reef was controlled by factors in addition to S, L and E. Thus in order to account for the distinctness of the Ayton reef, additional controls need to be invoked. There is no indication that the Ayton reef developed in an environment that had abnormal levels of nutrients,

salinity or oxygenation and these can be ruled out. However what is significant is the geographical position of the Ayton reef; it is located at the northerly palaeolatitudinal limits of Late Jurassic reef development. Thus, latitudinally-related controls, such as decreases in temperature and/or solar radiation, may be responsible for the departure from typical type reef VIII composition and framework styles. This inference is corroborated by: (1) the fact that all Late Jurassic high palaeolatitude coral reef faunas possess similar coral assemblages regardless of facies and depositional environment, and are dominated by eurytopic forms (as discussed in chapter 7 section 7.5.3; also see section 8.2.4.2 on latitudinal control); and (2) growth rate data (see section 8.2.4.3). It is interesting to note that characteristic features of type VIII reefs which would be less affected by high latitude controls such as sedimentation styles, high intensity of bioerosion and the abundance of nerineid gastropods in the inter-reef sediments, are also a feature of the Ayton reef outcrop.

Lérouville reefs 2 and 3, Lorraine. Reef 2 (*Meandraraea* biofacies; see section 3.4.3.) and reef 3 (*Isastraea* biofacies; see section 3.4.4) of the Lérouville section are very distinct with regard to coral composition and to a lesser extent framework development, and they are unlike any other reefal unit studied. They show no significant similarities to the eight reef types defined and are unlikely to represent transitional forms between end-member reef types. The inferred depositional environments of these reefs suggests that they developed in relatively shallow, but calm water environments within the topographic lows of the underlying crinoidal sandwaves (see section 3.4.5). However they bear no similarity to type I, IV or V reefs which the model would suggest. The dominance of platy and tabular growth forms possibly suggests either soft substrate or low light intensity. Underencrustation of the coral plates in the *Meandraraea* biofacies and to a lesser extent the *Isastraea* biofacies suggests that soft substrate was not the cause of the platy form. Thus low light levels may have been responsible for the development of these reefs, perhaps resulting from their location in the lows of the crinoid sandwaves. However until more detailed litho- and biofacies analysis is carried out the reasons for the development of these unusual faunas can only be speculated on.

8.1.4. The use of the model as a predictive tool for the distribution of different reef types

By having an understanding of the relative values of L, E and S the model can be used to predict the types of reefal units expected for particular environments. In a spatial context the model can be used to predict the type and character of the reefal carbonates across various types of carbonate platform. Figures 8.4-8.6 show how the model can be used to predict the spatial distribution of reefal carbonates across various idealised types of platform margins.

Figure 8.4 A shows a typical high energy rimmed carbonate platform developing in a siliciclastic-free regime, and the expected distribution of reef types across the platform. This has been predicted by constructing an LES path of the likely variations in L, E and S across the platform (figure 8.4 B). This can then be transferred to the model which suggests which types of reefal carbonates can be expected

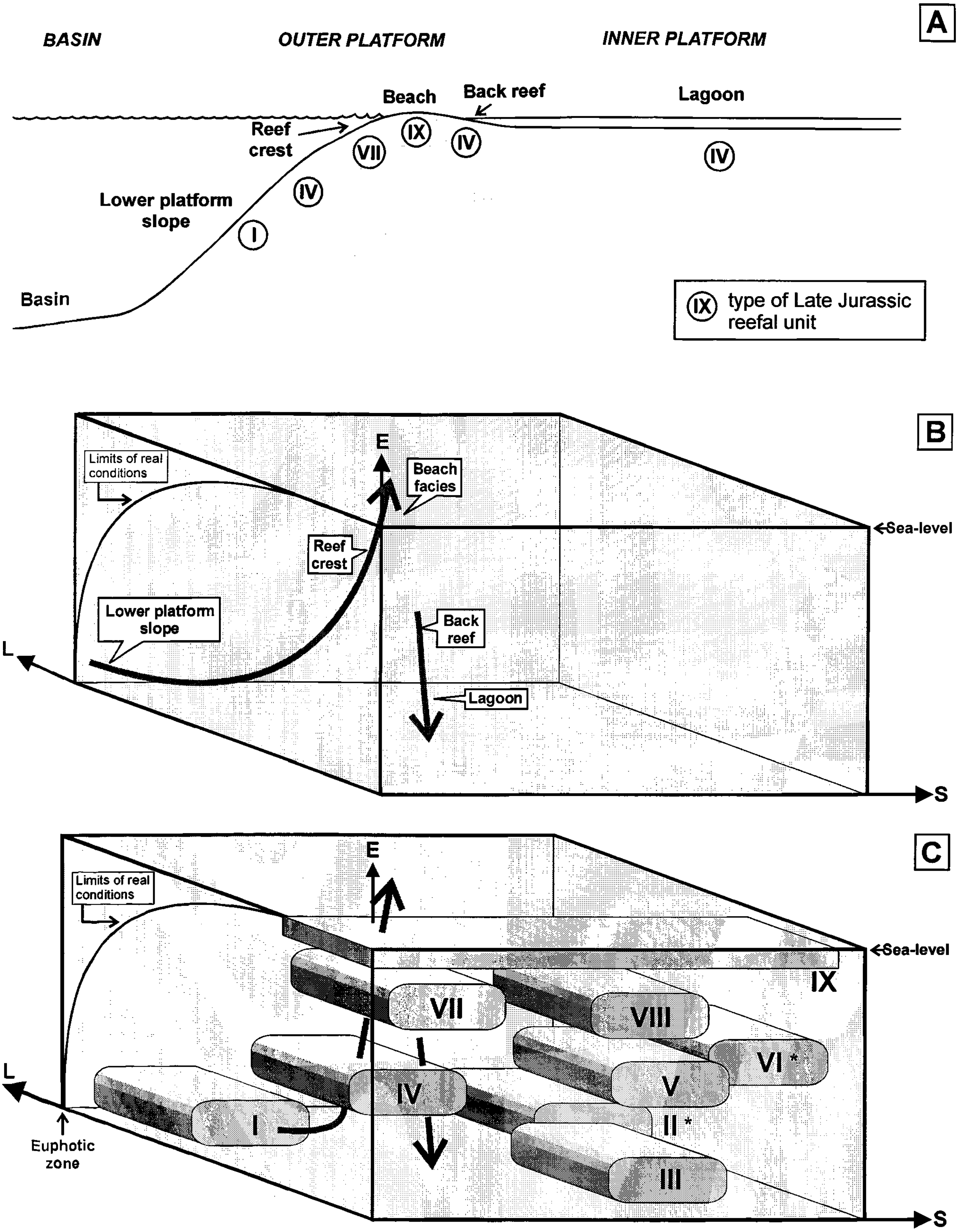


Figure 8.4: Application of model in predicting the spatial distribution of reefal carbonates across a rimmed carbonate platform.

A: Simplified geomorphological profile of a rimmed platform margin with the predicted spatial distribution of Late Jurassic reef types (from figure 8.4 C).

B: Inferred environmental path through LES space.

C: Environmental path transferred to the model to predict the types of reefal carbonates to be expected along the path as shown in 8.4 A. (See figure 8.2 for the model details).

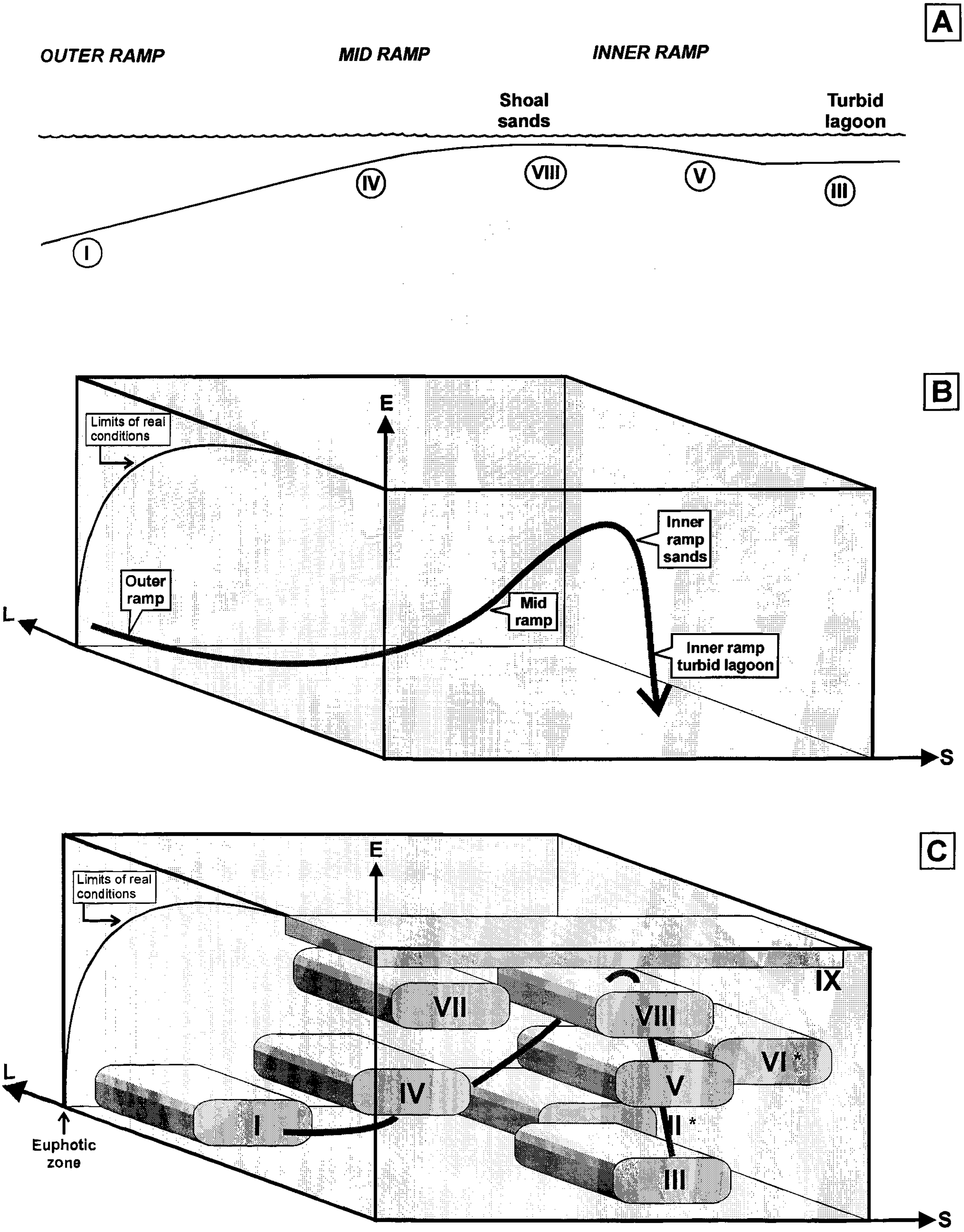


Figure 8.5: Application of model in predicting the spatial distribution of reefal carbonates across a ramp style carbonate platform.

A: Simplified geomorphological profile of a ramp platform margin with the predicted spatial distribution of reef types (see figure 8.5 C).

B: Inferred environmental path through LES space.

C: Environmental path transferred to the model to predict the types of reefal carbonates to be expected along the path as shown in figure 8.5 A. (See figure 8.2 for model details).

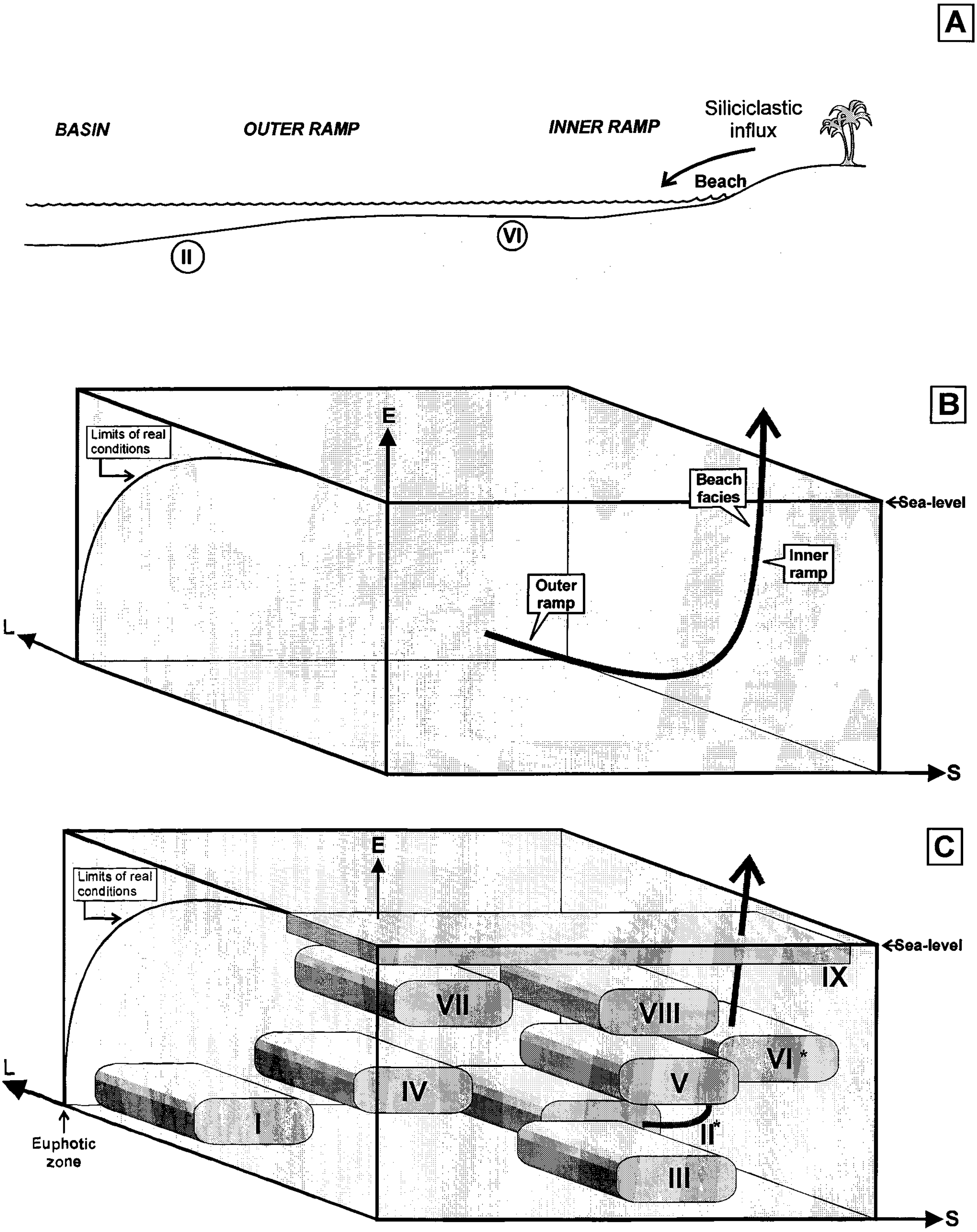


Figure 8.6: Application of model in predicting the spatial distribution of reefal carbonates across a siliciclastic influenced carbonate ramp.
A: Simplified geomorphological profile of a shelf platform margin and predicted spatial distribution of reef types (see 8.6 C).
B: Inferred environmental path through LES space.
C: Environmental path transferred to the model to predict the types of reefal carbonates to be expected along the path as shown in figure 8.6 A. (See figure 8.2 for model details).

along the path (figure 8.4 C). Thus for a Late Jurassic rimmed carbonate platform the following reefal distributions across the platform can be expected:

Position on basin platform profile	***Expected Late Jurassic reef type***
Basin	*Sponge reefs; ammonitic mudstones
Lower platform slope	Type I reefs
Mid platform slope	Type IV reefs
Crest	Type VII reefs
Beach	Type IX facies
Proximal back-reef	Type VI
Distal back-reef (lagoon)	Type VI reefs

(*not shown in model; see chapter 7 section 7.1.)

It will be noticed that the model predicts that type IV reefs will develop in three locations: (1) the mid-platform slope; (2) the proximal back reef setting (just behind the outer type VII reef crest); and (3) in lagoonal settings. The latter two are consistent with the interpretations of Al Faro and Bois du Parc type IV reefs as having developed in proximal back reef settings, and the Courtételle (reef 5) type IV reef as having developed within lagoonal muds. This may also explain the variations in the size and form of the type IV reefs at these different localities. The Bois du Park and Al Faro type IV reefs having grown in proximal back reef locations are more likely to have developed massive and larger scale structures since suitable substrate would have been plentiful. Conversely, suitable substrates would have been less extensive within inner platform lagoonal settings where muddy sediments would have dominated. Hence type IV reefs that developed in these settings, such as the Courtételle type IV reef, were likely to have been more localised and developed as small patches. Outcrops corresponding to the mid-platform slope have yet to be identified and thus the presence of type IV reefs in this setting has yet to be confirmed.

Figure 8.5 A shows a typical ramp type platform developing in a siliciclastic-free regime, and the expected distribution of reef types across the platform as predicted by the model (figure 8.5 B & C). For a Late Jurassic ramp type carbonate platform the following reefal distributions across the platform can be expected:

Position on basin platform profile	**Expected Late Jurassic reef type**
Basin	*Sponge reefs; ammonitic mudstones
Outer ramp	Type I reefs
Mid ramp	Type IV reefs
Inner ramp sand shoals	Type VIII reefs
Inner ramp packstone settings	Type V
Inner ramp turbid lagoon	Type III reef

(*not shown in model; see chapter 7 section 7.1.)

The presence of type III and V reefs is dependent on local palaeogeography and the sedimentary regime. Type V reefs would have occurred if local energy levels had decreased and the sediments were not being constantly reworked, and hence were likely to have developed in slightly deeper water. Type III reefs would have developed where energy levels were very low. Thus this reef type may not have developed until an outer ramp barrier had emerged, thus inducing low energy mudstone environments in the inner ramp settings. If large amounts of mud were being produced and deposited in the platform interior, type III reefs were likely to have developed.

Figure 8.6 A shows a carbonate ramp type platform developing in a siliciclastic influenced regime, and the expected distribution of reef types across the platform as predicted by the model (figure 8.6 B & C). The model predicts the following distributions of reef types across the platform:

Position on basin platform profile	**Expected Late Jurassic reef type**
Basin	*Ammonitic marls
Outer ramp	Type II reefs
Inner ramp	Type VI reefs
Beach	Type IX facies

(*not shown in model; see chapter 7 section 7.1.)

Finally, using a similar approach to that outlined above, the model can be used to predict the temporal distribution of Late Jurassic reef carbonates, in particular, the appearance and disappearance of different reefal units during the development of carbonate platforms. During the evolution of a carbonate platform the depositional environment changes from a deep-water setting without coral reefs (early in the evolution of the platform) through to sea level when the platform is fully developed (platform aggradation). With regard to the L, E and S, the platform progresses from a low E and L setting to a high E and L setting, for a given S. This platform evolution can be represented by aggradational pathways through LES space as show in figure 8.7 A. This can be transferred to the model to predict the expected succession of facies and depositional sequence as shown in figure 8.7 B.

8.2. SEDIMENTOLOGICAL AND PALAEOECOLOGICAL SYNTHESIS

The following account summarises the main facies and faunal characteristics of the reefs studied and then uses the depositional model developed in section 8.1 to highlight the principal sedimentological and palaeoecological trends within Late Jurassic reef development.

8.2.1. Reef form, scale and internal architecture

Where reef form could be established the reefs were either biostromal, domal or tabular. However the main problem with the identification of reef form was that in many of the reefal units framework

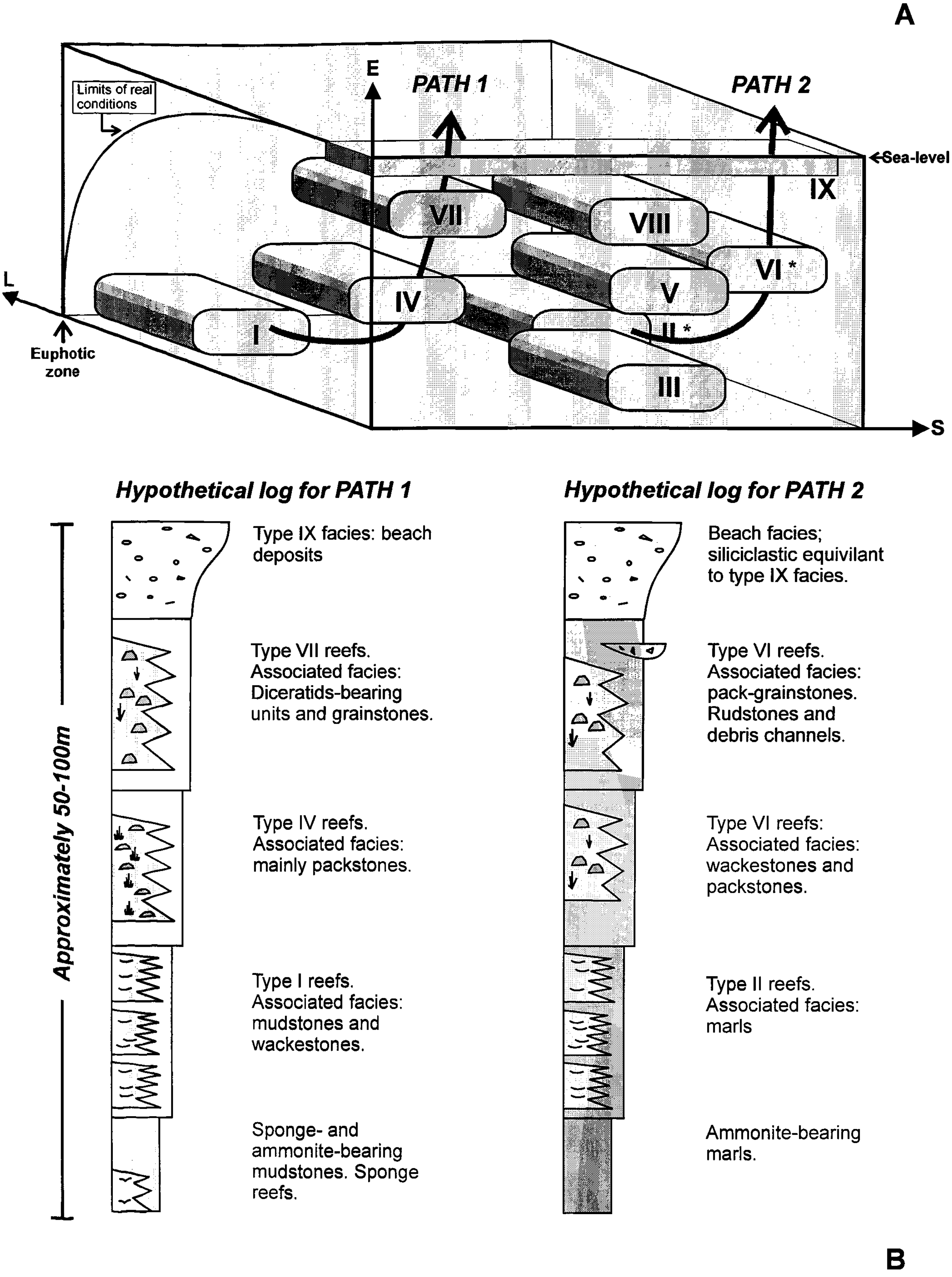


Figure 8.7: Diagram showing the use of the model to predict the temporal distribution of reefal units during the evolution of an isolated carbonate platform with low S (path 1), and a carbonate platform undergoing siliciclastic influx (path 2).

development was very patchy and discontinuous, hence distinction between reef and inter-reef facies was rather arbitrary (see discussion on framework development below). The scale of the domal and tabular reefs was very variable and ranged from 1 m thick and a few m across to at least 15 m thick and 200 m across The biostromal units (type I and II reefs) can be up to 25 m thick and can have a platformwide distribution with an almost continuous framework development; biostromal units were found to be very common in the study area. Where syn-depositional relief could be established it was rarely more than 3 m, the exception being the type VIII reef at Novion-Porcien which had a relief of 5-8 m. The only reef types that possessed clear internal architecture were the type I and II reefs which show internal bedding, and V reefs which possessed a corrugated structure. Accretionary surfaces, such as clinoforms, are absent, although storm surfaces can be common in shallow water reefs.

8.2.2. Framework development

In this thesis the manner in which corals have constructed reefal facies has been broadly referred to as framework and framework development. A retrospective analysis, discussion and synthesis of Late Jurassic reef frameworks is necessary in order to address two important questions: (1) what type of frameworks did Late Jurassic coral reefs possess?; and (2) did Late Jurassic coral reefs possess rigid frameworks? Before these questions can be adequately addressed a brief discussion of the terminology and concepts of framework is needed. The problem with classifying frameworks is twofold. Firstly, it has been rigorously defined from the study of present day reefs (see Rosen, 1991 for definition), and according to this definition the growth fabric of a reef is either a rigid framework or not a framework at all; it does not take into account the gradational nature of frameworks. This is a problem when studying reefs in cross-sections where what is seen is a growth fabric of in situ corals which constitute a considerable part of the reefal facies. These corals do construct a framework around which sediment may accumulate and other organisms can encrust; nevertheless this may not be consistent with the definition of true framework since the corals may not necessarily be intergrowing. Hence there is a considerable diversity of growth fabrics, "framework types", which lack a descriptive terminology. Secondly, no universally accepted description system exists to cover such complex fabrics. Embry and Klovan (1971) proposed a modification of Durham's (1962) classification to describe simple reef rock and included allochthonous facies such as rudstones and floatstones, and autochonous facies which were divided into framestones, bindstones and bafflestones. The problem with these terms is that they do not cover the wide variety of facies encountered, and that the latter two are rather interpretive and subjective.

To resolve these problems two aspects of reef construction and framework need to be evaluated: (1) the framework petrography (the type, style and degree of framework development); and (2) the spatial variation in framework development (framework continuity and uniformity). The type of framework refers to whether the growth fabric of the reef conforms to the rigid framework model. As has already been mentioned a reef either has or has not a rigid framework. A useful distinction of framework types has been made by Geister (1983) based on observations on modern unlithified reef sediments in the Caribbean (also see McCall *et al.,* 1994). In this work two different framework types are identified: (1) *starr* (translated from German as "rigid"; see his figure 24); and (2) *locker* (translated from German as "loose"; see his figure 25). Geister's "rigid frameworks" correspond to framestones and bindstones and therefore conforms to standard usage. Geister's "loose frameworks" refer to corals colonising unconsolidated sediments though not necessarily fusing together. This is attractive since is acknowledges that, although in situ corals may not have fused or been bound together, they nevertheless construct a type of framework. A rigid framework can develop as a result of the abundance and densely packed nature of the skeletal framebuilders and/or by the involvement of binding organisms such as algae, sheet-like encrusters and/or microbialite (secondary framebuilders). Loose frameworks by definition lack significant contributions by binding organisms. Although the distinction between rigid and loose frameworks is rather interpretative, in most cases it is self-evident. Thus the first step in classifying reef frameworks is to identify whether the framework was loose or rigid.

The degree of framework construction refers to how much skeletal framework is present, and thus refers to the in situ coral skeletal biovolume (CSB). The style of framework construction refers to the skeletal constructional fabric of the framework and is essentially defined by the growth forms of the corals. Four purely descriptive terms can be introduced: 1. platestones; 2. branchstones; 3. domestones; and 4. mixstones. These are simply defined by which growth form constructs the majority of the reef framework; over 50% of the coral skeletal biovolume must be constituted by one growth form for it to be classified as that stone; mixstone are frameworks constructed by a variety of framework styles. Any skeletal framework, whether it be a branchstone, platestone or domestone, can be further bound by algae, sheet-like encrusters or microbialite. Thus any reef fabric can be a bindstone, and only reefal fabrics overwhelmingly dominated by binders, and with very little vertical skeletal component, can be truly described as bindstones. Thus the presence or absence of binding organisms should be addressed in parallel with the style of framework rather than being defined as a separate fabric in itself. It is also important to evaluate the degree of framework continuity and uniformity. Framework continuity refers to the spatial variations in the presence of framework within a reefal unit. Commonly a reefal unit can be defined, but within that unit the degree of framework development may vary considerably. Thus within these units framework patches may be identified but which are interspaced with framework-poor, sediment-rich zones. The transition between these zones may be very gradational and hence the identification of distinct frameworks within these units becomes rather arbitrary. Similarly framework uniformity refers to spatial variations in the style of framework development; reef frameworks may be continuous but their style may vary considerably. For simplicity in this study framework continuity and uniformity has been described as either high or low.

Classification of the reef types studied.

The terms explained and discussed above can be used to develop a guide to classifying coral-dominated frameworks (table 8.1), which in turn can be applied to the classification of the frameworks studied (table 8.2). Seventeen out of the twenty-seven classified frameworks were rigid and therefore conform to the classic definition of framework. These were equally split between bound and unbound rigid frameworks. The rigid-bound frameworks were bound exclusively by microbialite; red algae and sheet-like encrusters made no contribution. The role of secondary binders, with the exception of microbialite, appears to be insignificant in the construction of Late Jurassic coral reefs. Of the eight unbound rigid frameworks six of these were platestones. This is presumably because platy and lamellar corals have a large lateral component to their growth and therefore are more likely to inter-grow and hence develop a rigid framework. Other framework styles rarely produced rigid frameworks unless they were secondarily bound by microbialite. The uniformity of framework style in the reefs studied was generally low; consequently the commonest framework style were mixstones. The most abundant single growth form dominated frameworks were platestones.

FRAMEWORK ELEMENT			
Type	***CSB***	***Binding***	***Style***
Rigid	Estimated CSB percentage	Unbound	
			Platestone
			Domestone
			Branchstone
			Mixstone
		Bound	
			Platestone
			Domestone
			Branchstone
			Mixstone
Loose	Estimated CSB percentage	Unbound	
			Platestone
			Domestone
			Branchstone
			Mixstone

Table 8.1: Guide to the description of coral dominated frameworks (see table 8.2 for examples).

Reef study locality	Type	Framework classification	Continuity	Uniformity
Châtel-Censoir	I	Rigid 50-60% unbound platestone	H	H
Quatre Pieux	VII	Rigid 60-85% bound domestone	H	H
Bois du Parc	IV	Rigid 30-65% bound mixstone	H	L
Saussois	V	Loose 20-60% mixstone	L	L
Roche aux Poulets	V	Loose 30% mixstone	L	L
Foug: coral marl	II	Rigid 60-80% unbound platestone	H	H
Foug coral limestone	I	Rigid 50% unbound platestone	L	H
Pagn-sur-Meuse	III	Rigid 20-60% unbound branchstone	L	H
Lérouville Reef 1	?I-V	Cross-section not seen	____	H
Lérouville Reef 2	?	Loose 30-50% platestone	H	H
Lérouville Reef 3	?	Rigid 50-60% unbound platestone	H	H
St. Mihiel	V	Loose 20-60% mixstone	L	L
Haudainville	III-V	Loose 20-50% mixstone	L	L
Dompcervin	____	No in situ reef: rudstone	____	____
Novion-Porcein	VIII	Rigid 10-15% bound branchstone	H	H
Bellême	VIII	Loose 30% branchstone	H	H
Liesburg	II	Rigid-loose 20-70% unbound platestone	H	H
St. Ursanne patch reef	IV	Rigid 20-30% bound mixstone	H	L
St. Ursanne Basal Biostrome	I	Rigid-loose 20-50% unbound platestone	H	H
St. Ursanne (biofacies 3)	IV	Rigid 50-90% bound mixstone	H	L
St. Ursanne (biofacies 2)	VII	Rigid 50-90% bound domestones	H	H
St. Ursanne patch reef 2	III	Too little data	____	____
St. Ursanne patch reef 3	V	Too little data	____	____
Courtételle reef 1	?	Too little data	____	____
Courtételle reef 2	?	Too little data	____	____
Courtételle reef 3	?	Too little data	____	____
Courtételle reef 4	?	Too little data	____	____
Courtételle reef 5	IV	Rigid 20% bound mixstone	H	L
Péry-Reuchenette	VI	Loose 20-50% domestone	L	H
Haydon Wick, Wiltshire	VI	Loose 20-40% mixstone	L	L
Shellingford Cross Road	VI	Loose 20-40% mixstone	L	L
Upware, Cambridgeshire	I	Loose 20-50% platestone	H	H
Ayton	?	Rigid 90% unbound domestone	H	H
"Al Faro" laggonward zone	IV	Rigid 50-60% bound mixstone	H	L
"Al Faro" seaward zone	VII	Rigid 50-60% bound domestone	H	H

Summary: Number of classified frameworks: 27
Rigid frameworks: 17 (bound: 9; unbound 8, of these 6 are platestones)
Loose frameworks: 10
Platestones: 8; Branchstones: 3; Domestones: 5; Mixstones: 11

Table 8.2: Classification of the frameworks studied.

8.2.3. Intra-reef microfacies and microbialite

Microfacies

A considerable number of intra-reef microfacies types have been identified which can be broadly grouped into four standard intra-reef microfacies: (1) bio-intraclastic pack-grainstones; microbial biopelmicrites to sparites (common in type VII and IV reefs); (2) bioclastic packstones; biomicrites ± siliciclastics (common in type I and II reefs); (3) coarse-grained bioclastic packstones; poorly washed biosparites and biomicrites rich in highly micritized and coated allochems (common in type V reefs); and (4) mudstones, biomicrites (common in type III reefs). In general these microfacies are reef specific and therefore useful in reef type identification from cores where other data is limited. (For detailed decriptions of these microfacies see chapter 7.)

Microbialite

The importance of intra-reef microbialite in the reefs studied has previously gone unnoticed. The presence and abundance of different types of microbialites has been found to be an important feature, indeed it is characteristic of many of the reef types identified and fundamental to the construction of type IV and VII reefs. It appears that these microbial crusts have played a similar role to encrusting coralline red algae in present-day reefs, especially in the high energy type VII reefs. Four main types of microbialite have been recognised in the study: (1) spongiostromate crust; (2) macroscopically massive and dense, microscopically laminated and rinded microbialite (leiolites of Braga *et. al.*, 1995); and (3) porostromate crusts and other encrusting microproblematica. The distribution and abundance of these microbialites with regard to the different reef types is summarised in table 8.3.

1. Spongiostromate crusts. These are particularly common as coatings on bioclasts and as crusts on coral branches, in particular of phaceloid forms. These can be sub-divided into (a) planar; and (b) knobbly crusts. The knobbly crusts appear to be especially well developed in reefs that had experienced a high degree of siliciclastic influx, especially of clays. They are distinguished from planar crusts and leiolites by having a very distinct knobbly form as described in sections 5.5.2 (Péry-Reuchenette, Swiss Jura) and 6.1.3.2 (Haydon Wick, England).

2. Macroscopically massive and dense, microscopically laminated and rinded, microbialite (leiolites). These occur in large volumes within the intra-reef sediment of type IV and VII reefs (see section 2.3.3 and 2.4.2 for their description). They possess a variety of peloidal fabrics from domal, knobbly and cauliflower-shaped structures, to more laminated and rinded microfabrics. Where the microbialites have been able to grow down into large primary cavities in the reef framework they developed a macroscopically clotted fabric as described from Novion-Porcein reef (see section 4.1.3). These macroscopically clotted microbialites (thrombolites) develop pseudostalactite and pillow structures, although the reason for the development of the two different structures remains unclear.

The above types of microbialite are non-skeletal and algal/cyanobacterial filaments are not preserved, hence they can both be described as spongiostromate. Internally these microbial fabrics are composed of a variable mixture of precipitated peloids and micrite. They are interpreted as microbialites because they show cryptic evidence of microbial communities as reflected by gravity-defying growths of the micritic and peloidal material. These spongiostromate microbialites are identical to other peloidal fabrics of presumed cyanobacterial origin described from Portugal, Spain and Germany (Leinfelder *et al.*, 1993b), the Swiss Jura (Gygi, 1992) and south-west France (Taylor and Palmer, 1994), and it is likely that they have the same origins. It is probable that these different types of spongiostromate microbialites are a manifestation of different cyanobacterial communities. In this context, the knobbly spongiostromate crusts common in type VI reefs have been speculated to have been formed by heterotrophic cyanobacteria (see section 7.2.4.3). The leiolites common in type IV and VII reefs were possibly formed by autotrophic cyanobacteria since in these reefs the very low diversity of the associated fauna, and the reefs' isolation from the influence of palaeolandmasses, may suggest, more oligotrophic conditions.

3. *Porostromate crusts and other microproblematica. Cayeuxia*, *Ortonella* and *Girvanella* (porostromate crusts) and *Bacinella*, *Lithocodium*, *Thaumatoporella* and *Koskinobullina* (microproblematica) were documented in the study. The microproblematica may or may not be cyanobacterial in affinity but they nevertheless form sheet-like encrustations and are commonly found intergrowing with both poro- and spongiostromate crusts. These crusts are particularly common in type IV reefs.

Reef type	Type of microbialite				Volume of microbialite	Reef binder?
	1 (a)	1 (b)	2	3		
I	•	—	—	—	Can be common	No
II	•	•	—	—	Rare to common	No
III	•	—	—	•	Both are common around branches	No
IV	•	—	•	•	2. Very abundant; 3. Common	Yes
V	•	—	—	•	Rare	No
VI	•	•	—	—	Abundant	Perhaps local
VII	•	—	•	•	2. Very abundant; 3. rare	Yes
VIII	•	—	± •	•	2. Can be very abundant if present	Yes

Table 8.3: Distribution and abundance of the different types of microbialite.

8.2.4. Coral fauna

8.2.4.1. Richness and diversity patterns

This study has identified 52 genera from the study area. However only a relatively small number of these are common (table 8.4). The "common framebuilders" are important contributors to most reef frameworks; they constitute 23% of the total number of corals identified. The "auxiliary framebuilders" are corals which can be the dominant framebuilders in some reef types but are generally uncommon;

they constitute 13% of the total number of corals identified. The "minor framebuilders" are genera that never constitute much of the coral skeletal biovolume and are generally rare. Nevertheless when present, they can contribute, albeit in a small way, to framework construction; they constitute 13% of the total number of corals identified. The "rare framebuilders and dwellers" are very rare, numbering only few colonies/individuals in any given reef, though in terms of richness these are by far the richest group and constitute 50% of the total number of corals identified. They are small in size or solitary and contribute very little, if at all, to framework construction.

Rare framebuilders	***Minor framebuilders***	***Auxiliary framebuilders***	***Common framebulders***
Allocoenia (ma) [ra]	*Actinaraea* (pl, ma)	*Comoseris* (pl, ma)	*Aplosmilia* (ph)
Cheilosmilia (sol)	*Clausastraea* (pl, ma)	*Dermoseris* (ph)	*Calamophylliopsis* (ph)
Cladophyllia (ph)	*Cyathophora* (ma)	*Dermosmilia* (ph)	*Dendraraea* (ra)
Complexastraea (ma)	*Fungiastraea* (pl, ma)	*Donacosmilia* (ph)	*Dendrohelia* (ra)
Epistreptophyllum (sol)	*Latomeandra* (ph)	*Mitrodendron* (ph)	*Dimorpharaea* (ma, pl)
Enallhelia (ph)	*Microphyllia* (pl, ma)	*Stylosmilia* (ph)	*Isastraea* (ma, pl)
Goniocora (ph)	*Diplocoenia* (ma)	*Thecosmilia* (ph)	*Stylina* (ma) [ra]
Haplarea (sol)			*Meandraraea* (ma, pl)
Heliocoenia (ma)			*Meandrophyllia* (ma, pl)
Kobyastraea (ma)			*Microsolena* (ma, pl), [ra]
Latiastraea (pl, ma)			*Pseudocoenia* (ma, ra)
Mesomorpha (ma)			*Thamnasteria* (pl, ma, ra)
Mixastraea (ma)			
Montlivaltia (sol)			
Myriophyllia (ma)			
Ovalastraea (ma)			
Pachygyra (ma)			
Placophyllia (ph)			
Pleurosmilia (ph)			
Pseudocoeniopsis (ma)			
Rhabdophyllia (ph)			
Rhipidogyra (ma)			
Solenocoenia (ma)			
Stephanastraea (ma)			
Stephanocoenia (ma)			
Synastrea (pl, ma)			

Growth form abbreviations:

ra: branching ramose	ma massive-domal	pl: platy-lamellar
ph: branching phaceloid	en: encrusting	sol: solitary

(growth form): frequently occurs in this growth form.
[growth form]: only occasionally occurs in this growth form.

Table 8.4: List of genera identified in the study.

The Swiss Jura and Burgundy regions have the highest regional richnesses of the study area with approximately 40 genera (table 8.5). However as table 8.5 shows this is probably a consequence of the greater number of different reef types and thus the greater environmental heterogeneity in these regions. Also significant is the greater number of reefal units studied which again will increase the total number of genera recorded.

The regional richnesses in England are the lowest in the study (see table 8.5). This is mainly a consequence of the fact that only low-richness type VI reefs are present in southern England, and to a lesser extent the small number and size of outcrops. The low richness in Yorkshire is more intriguing since the Ayton reef developed in an environment usually associated with type VIII reefs, so generic richness may have been expected to be high. The low generic richness in the Ayton reef seems to be related to latitudinal factors (see section 8.1.3. and section 8.2.4.2. below). The exception to the general low richness in the English reefs is the enigmatic Steeple Ashton fauna in Wiltshire, which is of Upper Oxfordian age (Dichotomoceras birfurcatum zone, D. stenocycloides sub-zone). This coral fauna which was studied by Negus and Beauvais (1979), is very rich, with 23 genera recorded. These corals are not found in situ but occur in a rubble deposit which had a "reef front slope character" (Negus and Beauvais, 1979). The high richness may be accounted for, at least in part, by Beauvais's tendency to split taxa, but also by the fact that the coral deposit could represent the net accumulation from a number of reefs, perhaps of different types (i.e. the deposit could be a spatially and temporally averaged fauna). From the documented fauna it is difficult to establish which reef type or types were the source for this deposit since it is difficult to evaluate for a possible taphonomic bias. However it seems unlikely that corals were derived from type VIII or III reefs since the characteristic corals of these reefs types are absent. They are also unlikely to have come solely from type VI reefs since the Steeple Ashton fauna contains many genera not normally associated with this reef type.

Study region	YO	CA	OX	WI	AR	NO	LO	BU	SJ	IT
N° of reefal units studied	1	1	1	1	2*	1	9*	5	12	2
N° of reef types	1	1	1	1	2*	1	5*	4	7	2
Number of genera	3	8	4	4	26	15	33	40	41	13

Table 8.5: Summary of regional coral richness. Abbreviations: YO Yorkshire; CA: Cambridgeshire; OX: Oxfordshire; WI: Wiltshire; AR: Ardennes; NO: Normandy; LO: Lorraine; BU: Burgundy; SJ: Swiss Jura; IT: Italy. (* Includes one coral rubble facies.)

For a given reef locality the maximum generic richness appears to be approximately 18-25 genera. These high coral richnesses are associated with siliciclastic-free shallow water reefs (types IV, V, VII and VIII) which was to be expected. The richest reef was the St. Ursanne patch reef 1 where 31 genera were recorded. This unusually high generic richness can be accounted for, at least in part, by the transitional nature of this reef (see section 8.1.3) which contains genera common to both type IV and VII reefs.

8.2.4.2. Latitudinal patterns in coral richness

Two of the most characteristic features of present-day coral reefs are their latitudinal restriction to within approximately 35° N and S of the equator, and the latitudinal taxonomic gradients within this belt

(Veron, 1995). Can similar latitudinal patterns in reef development and coral assemblages be discerned from Late Jurassic coral reefs? The data collected for this synthesis provide an ideal opportunity to try and address this question for three reasons:

1. Data have been collected from a wide geographical area spanning a palaeolatitude of approximately 7° (from Swiss Jura at 32°N to Yorkshire, 39°N; palaeolatitudes from Smith *et al.*, 1980). This broadly Tethyan to Boreal transect runs from one of the Late Jurassic high diversity zones (Swiss Jura) to the northern latitudinal limits of reef development (Britain), and is more or less continuous. (Italy and Slovenia, which were located at approximately 26°N, have been ignored in this analysis since reliable richness data are not available for them due to poor outcrops and coral preservation.)
2. Data collection has been standardised and collected solely by the author (i.e. these are primary data; literature data are not used). Hence it is possible to try to evaluate the effects of outcrop size and quality, and collecting intensity, on taxonomic richness.
3. Broad reef types have been identified in the present study and their depositional environments evaluated. This therefore allows the possibility to normalise (i.e. correct) for local environmental effects on reef development and hence try to isolate latitudinal and climatic factors from them.

Present-day distribution of coral reefs

At generic level the broad features of reef coral distribution are well known (Rosen, 1988, figures 1 and 2). The distribution can be described as broadly tropical, but with notable extensions into subtropical latitudes. Coral generic richness rises rapidly between the latitudes of 40° and 35° except in the South Atlantic where their southernmost limit is about 20° S. Generic richness is relatively constant between 20° N and S, and hence the generic richness-latitude plots have a "step-and-plateau" form (Rosen, 1988, figure 2). Global data at species level is still insufficient to make such generalisations. However, detailed distribution studies on the three Indo-Pacific latitudinal contiguous distribution sequences (Veron, 1995) shows that there is a marked decline in species richness from tropical to non-tropical and temperate reefs at the latitudinal limits of reef coral distribution. From these detailed studies came the general observation that species compositions of high-latitude subtropical reefs are relatively similar irrespective of local environment because they are populated by species with very broad ranges in all directions (eurytopic species).

Factors controlling the latitudinal distribution of Recent coral reefs and their coral richness

1. *Temperature*. The present-day distribution of coral reefs is essentially ecophysiologically determined by latitudinal temperature gradients (Rosen, 1984; Veron, 1995). There is a consensus view that temperature is the paramount factor controlling both the absolute latitudinal limits of present-day reef coral distribution and for the latitudinal taxonomic gradients within this belt. There is a considerable body of empirical evidence that suggests that 18°C, sustained over protracted periods of time, is the minimum sea-surface temperature at which functional coral reefs (not necessarily reef

corals) survive (Veron, 1995 and references therein). Nevertheless the ecophysiological reasons for this temperature control remains poorly understood.

2. *Solar radiation.* The ability of algal-symbiotic corals to build reefs using the energy from the sun, is the key to the existence of all modern reefs and probably their counterparts in the Mesozoic. However at present there is little evidence to suggest that it causes latitudinal boundaries in the distribution of Recent coral reefs (Veron, 1995). This is strange since it is well established that it is light, not temperature, that is by far the most ecologically limiting of all physical-environmental parameters. It is likely that light availability as a limiting factor will depend on the species of coral as well as the species of zooxanthellae.

Late Jurassic latitudinal patterns in coral generic richness

To establish whether Late Jurassic reefs show taxonomic attenuation with increasing palaeolatitude similar to that observed in present-day reefs, generic coral richness was compared for a given reef type (thereby correcting for local environmental effects) in different regions. Only reefs where comparable and reliable data were available were compared. Thus only reefs with similar outcrop extent and quality were compared. Regrettably this meant the data from the Slovenian and Italian reefs could not be used in this study.

Results and interpretation

Table 8.6 and figure 8.8 summarises the richness data for the different reef types in the different regions. The results clearly show that for a given reef type generic richness decreased with increasing palaeolatitude (figure 8.8). Considering the more equitable Late Jurassic climate this is surprising since the increase in palaeolatitude between the sample site limits is only 7°. However the sample area of this study is located at the latitudinal limits of reef development, where generic richness is likely to drop rapidly. For example, the present day Indo-Pacific maximum generic richness profile shows a drop of 19 genera in only 6° at its northerly latitudinal limits (see Rosen, 1984, figure 11.4). It is reasonable to assume that the decline in Late Jurassic generic richness is also correlated with temperature, as it is in Recent reefs.

The steepness of the type VIII reef gradient is notable. Although the Ayton reef is not classed as a type VIII reef on a descriptive level the environments the two reefs had grown in are identical. Indeed it has been argued here that the reason the Ayton reefs are dissimilar to the other type VIII reefs is due to a latitudinal control. The generic richness of these type VIII reefs drops from 22 at Novion-Porcien (34.5°N) to 3 at Ayton (39°N). So why is there such a marked drop in generic richness? One possible explanation for the low generic richness in the Ayton reef is the reduction in annual solar radiation as a consequence of its relatively high palaeolatitude. In this respect it is interesting to note that it has been shown that most Mesozoic and Cainozoic shallow shelf carbonates occur within the sub-tropics, 5-35° N and S (Ziegler *et al.,* 1984). Evidently the carbonate belt did not shift northwards during warmer periods such as the Jurassic, suggesting that simple climatic considerations are not enough to explain their distribution. However year-round solar radiation falls markedly at about 35° from the equator

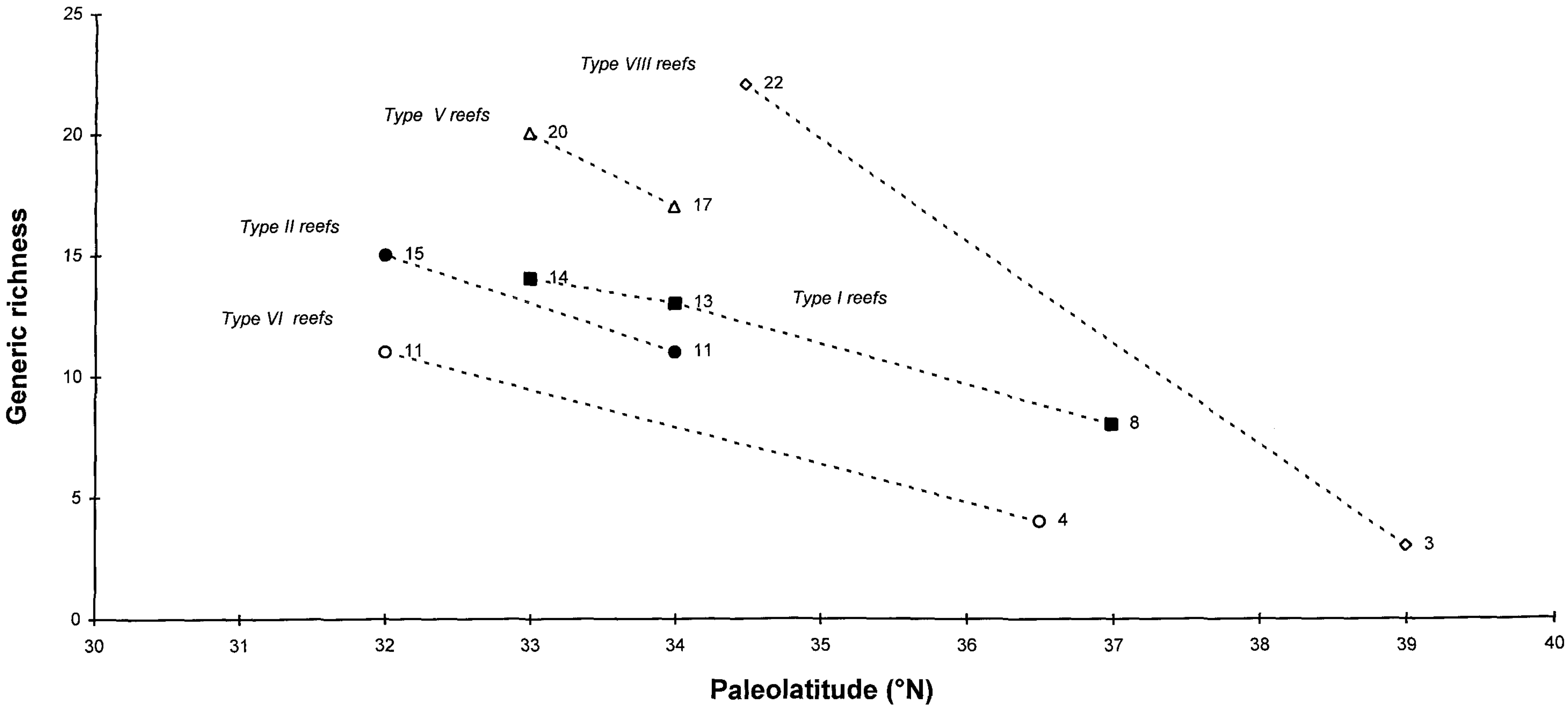


Figure 8.8: Variations in generic richness with palaeolatitute for different reef types.

(Ziegler *et al.*, 1984, figure 1.1 A), this latitude being the present poleward limit of Bahamian-type environments. Ziegler *et al.* (1984) suggest that it is this latitudinally induced drop in light intensity that limits depositional systems that rely on algal-symbiotic fixation of calcium carbonate, either directly or indirectly, to within these latitudes. It is likely that this decrease in solar radiation adversely affected the development of the Yorkshire coral reefs in general, and the richness of these reefs in particular, which lay approximately 39° N (Smith *et al.* 1980). Thus it appears that the temperature-controlled latitudinal decrease in generic richness is accentuated at high palaeolatitudes by the effects of decreased solar radiation. This latitudinally-related solar radiation control on high latitude Late Jurassic reefs is corroborated by the coral growth banding study in section 8.2.4.3. (see below; Insalaco 1996b and c). This effect is not seen in present day reefs since the 18°C critical temperature is at present within 35° N and S, i.e. within the latitudinal limits where solar radiation decreases rapidly.

Type I reefs		
Locality	Palaeolat.	Richness
Upware	37°N	8
Foug (coral limestone)	34°N	13
Châtel-Censoir	33°N	14

Type II reefs		
Locality	Palaeolat.	Richness
Foug (coral marl)	34°N	11
Liesberg	32°N	15

Type V reefs		
Locality	Palaeolat.	Richness
St. Mihiel	34°N	17
Saussois	33°N	20

Type VI reefs		
Locality	Palaeolat.	Richness
Haydon Wick	36.5°N	4
Péry-Reuchenette	32°N	11

Type VIII reefs		
Locality	Palaeolat.	Richness
Ayton	39 °N	3
Novion-Porcien	34.5°N	22

Table 8.6: Summery of coral richness data from comparable reefs. (Palaeolatitude data from Smith *et al.*, 1980.)

8.2.4.3. The use of coral growth bands as palaeoenvironmental indicators

8.2.4.3.1. Introduction

A detailed Pan-European sclerochronological study was carried out on two Jurassic corals, *Thamnasteria concinna* (Goldfuss) and *Isastraea explanata* (Goldfuss). The aim of this study was firstly to identify the controls on the deposition of the growth bands, on both a regional and local scale, and secondly to assess the potential value of Mesozoic sclerochronology as a tool for palaeoenvironmental, in particular palaeoclimatic, interpretations.

The approach of the study was to compare the nature of the growth banding and the growth rates of *Thamnasteria concinna* and *Isastraea explanata*, in two situations:

1. Between different geographic regions though within the same reef type, thereby normalising for local environmental effects such as water depth and sedimentary influx on growth rate. Any difference in growth rates should therefore represent regional differences in factors controlling coral growth, such as temperature, seasonality and solar radiation.
2. Between different reef types such as deep and shallow-water reefs within the same region. Differences in growth rates should be influenced only by differences in the local environment. In particular the study aimed to evaluate the effects of water depth (light intensity) and siliciclastic influx on the growth rates and patterns of these two corals.

The material on which this study is based came from the following regions:

Region	Reef sampled
Swiss Jura	Liesberg (LIE); St. Ursanne patch reef 1, biofacies 3 (UR), Courtetélle, reef 5 (CO).
Burgundy	Saussois (SA), Châtel-Censoir (CC).
Lorraine	Haudainville (HA), the coral marl at Foug (F1), the coral limestone at Foug (F2), St. Mihiel (MI).
Oxfordshire	Shellingford Cross Roads (OX).
Cambridgeshire	Upware (UP).
Yorkshire	Ayton (YO).

The reefs that were sampled for this study can be placed into four broad categories with regard to siliciclastic influx and water depth:

(1) Deep-water reefs with a low siliciclastic influx: study examples: UP, F2, CC (type I reefs);

(2) Deep-water reefs with a high siliciclastic influx: study examples: F1, LI (type II reefs);

(3) Shallow-water reefs with a low siliciclastic influx: study examples: MI, SS (type V reefs); CO (type IV reef); HA (type III-V reef); UR (type IV-VII reef); YO (type VIII reef); and

(4) Shallow-water reefs with a high siliciclastic influx: study example: OX (type VI reefs).

8.2.4.3.2. Nature of the growth banding and methods

Thamnasteria concinna and *Isastraea explanata* were chosen for this study since they are almost ubiquitous in Late Jurassic reefs but, more importantly, consistently show pronounced, well preserved growth banding; thus the large numbers of specimens needed for such a study were available. Furthermore, the quality of the growth banding was such that accurate measurements could be taken in the field by using silicon carbon grinding paper to grind down the surface to 800 grade. This method proved very successful on the soft limestones and increased the total size of the data set considerably.

More detailed analysis of the banding regarding septal thickness and dissepiment distribution was carried out on selected polished slabs and thin sections with the use of optical microscopes. All growth rate measurements were measured in millimetres (mm) and were estimated to 1 decimal place.

Distinct growth banding is visible in longitudinal section of many of specimens studied and is identical to the seasonal high- (H) and low- (L) density bands present in many modern corals and assumed to have developed in the same way (Knutson *et al.*, 1972; Ali, 1984; Geister, 1989; Le Tissier and Scrutton, 1993). The annual (seasonal) nature of these pairs of bands has been thoroughly confirmed by comparison with chronologies from radioactivity labelled environments (Knutson *et al.*, 1972; Knutson and Buddemeier, 1973; Buddemeier *et al.*, 1974; Moore and Krishnaswami, 1974; Noshkin *et al.*, 1975), by the general agreement between radiographically determined growth rates and those from conventional radiometric dating (Moore and Krishnaswami, 1974; Dodge and Thomson, 1974) and by the general agreement with real-time measurements (Buddemeier and Kinzie, 1976, see their table II). The banding is depicted by alternating regions of thicker septa with more numerous dissepiments (high density band), and a band of thinner, less well developed septa with fewer dissepiments (low density band) (plate 8.1-figs 1-3; plate 8.2-figs 1-2; plate 8.3-figs 1-3).

On each colony the following measurements were recorded from five consecutive L/H density couplets: 1) spacing of the L/H density couplet (growth rate); and 2) the L/H thickness ratio. For each sample site the arithmetical mean of the growth rate and L/H ratio for each species was calculated. The standard deviation for the growth rate was also calculated in order to indicate the degree of growth rate variability for a given species at each locality.

Two problems are encountered when measuring the growth rate on individual colonies. Firstly, there can be variations in growth rate along the section. Care is needed to ensure that the orientation of the section is truly vertical. Oblique sections give erroneously high measurements. This problem is compounded in some colonies by the fact that the corallites do not show straight vertical growth. This is especially pronounced in colonies that show mammilose growth surfaces. This results in sections that are in part vertical and in part oblique. This is illustrated in plate 8.2-fig. 2 where the bottom left of the figure shows an almost transverse section whereas the rest of the section is effectively vertical. The growth forms of the two species chosen for the study are tabular to domal with planar top surfaces, which suggests that divergent corallite growth was not marked. However where this was marked, with a resultant development of axial growth, the axial rate was taken. Marked axiallity was very rare and only encountered in three colonies (plate 8.1-fig 3).

Another problem is one of the continuity in the definition of the low and high density bands. Even in colonies that are generally well preserved there are often small areas of the colony that have undergone greater recrystallisation than others, with a resultant loss in the sharpness of the bands. These areas are avoided when taking measurements. For example, in plate 8.2-fig. 2 the area which would be measured is the far right and top of the specimen. The central area, which has experienced a greater amount of recrystallisation, is not measured.

For each species, per sample locality, the distinctness of the L- and H- density was also recorded. This is an indication of the visual contrast in a L/H density couplet between the low density band and the high density band. Where the visual contrast between the two bands is high (high distinctness) the L/H couplets are easier to distinguish. The distinctness was recorded using an arbitrary scale of 1 to 5 (1= low, 5= high). This is based on a general assessment of all the colonies for each species per sample locality.

In none of the reefs studied were there any lateral or vertical changes in litho- or biofacies that could be attributed to changes in water depth or siliciclastic influx, therefore an indiscriminate sampling procedure, over total exposure of each reef facies, was used to select colonies for measurement. Only well preserved colonies, where at least five consecutive L/H density couplets could be measured, were selected. The whole study is based on measurements of 875 L/H density couplets from 175 colonies. However it should be noted that although, with one exception, both species were present in all the reefs studied, they are not equally present in these different reefs. For example, the reef at Ayton Quarry, Yorkshire, is almost a monospecific patch of *Thamnasteria concinna* with only one colony of *Isastraea explanata* found (which has been excluded from the analysis because of the small sample size). Hence, at this locality, the analysis of *Thamnasteria concinna* is based on a large sample size (twenty colonies). Conversely, in many of the reefs in France and Switzerland these two corals are rare and generally less than eight well preserved colonies could be measured. In general, *Isastraea explanata* and especially *Thamnasteria concinna* became less dominant in the more southerly reefs.

8.2.4.3.3. Results

<u>1. Growth rates</u>. Figures 8.9-8.10 and table 8.7 summarise the results of the study. Figure 8.9 shows the growth rates of the corals in the same reef type in different regions. In both plots there is a weak trend, in both species, of decreasing growth rate with increasing palaeolatitude. The highest values were encountered in the Swiss Jura and the lowest in England. In both species this trend is more marked in the shallower water facies where values range from 4 mm/yr (Swiss Jura) to 2.5 mm/yr (British Corallian) in *I. explanata*; and 2.8 mm/yr (Swiss Jura) to 0.8 mm/yr (British Corallian) in *T. concinna*. In the deeper water facies this variation is less pronounced with values ranging from 2.8 mm/yr (Swiss Jura) to 2.2 mm/yr (British Corallian) in *Isastraea explanata* and 1.5 mm/yr (Swiss Jura) to 0.8 mm/yr (British Corallian) in *Thamnasteria concinna*. However these decreases in growth rate are not significant at the 95 per cent. confidence level since the difference between adjacent points is less than 1.96 standard deviations. Also evident on the shallow-water plot (figure 8.9A) is a sharp decrease in the growth rate, again in both species, between the continental and the English localities. This shift from 3.6 to 2.5 mm/yr for *Isastraea explanata* and 2.7 mm/yr to 1.3 mm/yr for *Thamnasteria concinna* between Haudainville (Lorraine, France) and Oxfordshire (England) is well above 1.96 standard deviations and therefore significant at the 95 per cent. confidence level. This feature is not visible the deeper water facies. Figure 8.9B also shows that the difference in growth rate, for a given region, between *Thamnasteria* and *Isastraea* is greater in the deeper water facies.

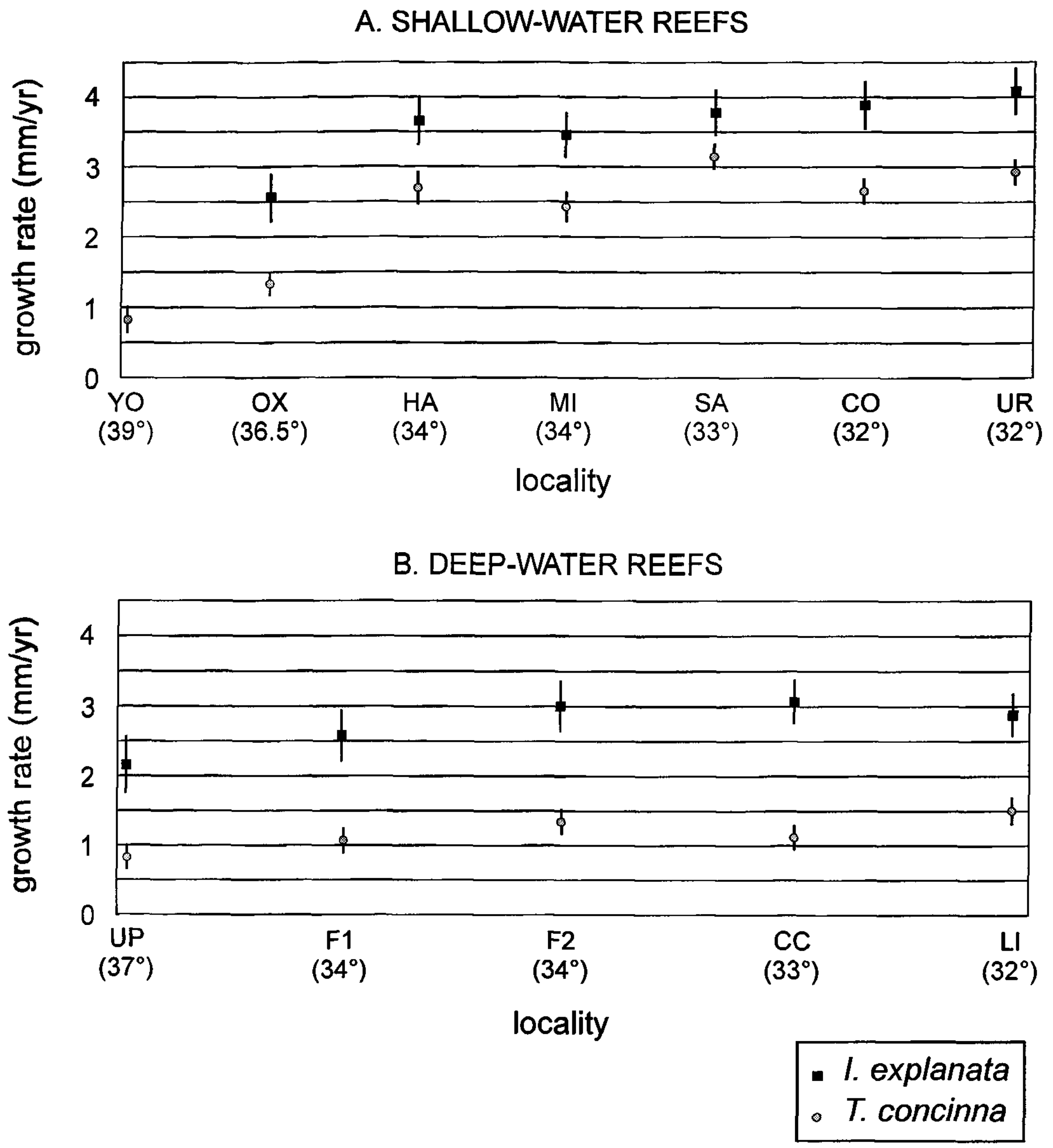


Figure: 8.9: Variation in growth rate (mm/yr) between *Thamnasteria concinna* and *Isastraea explanata* in shallow-water (figure 8.9 A) and deep-water (figure 8.9 B) reefs. The points plotted are the arithmetical means of all the measurements collected for each species per locality. Vertical line represents 1 standard deviation. Also indicated in parentheses is the approximate palaeolatitude of each location in °N. (See section 8.2.4.3.1 for locality abbreviations.)

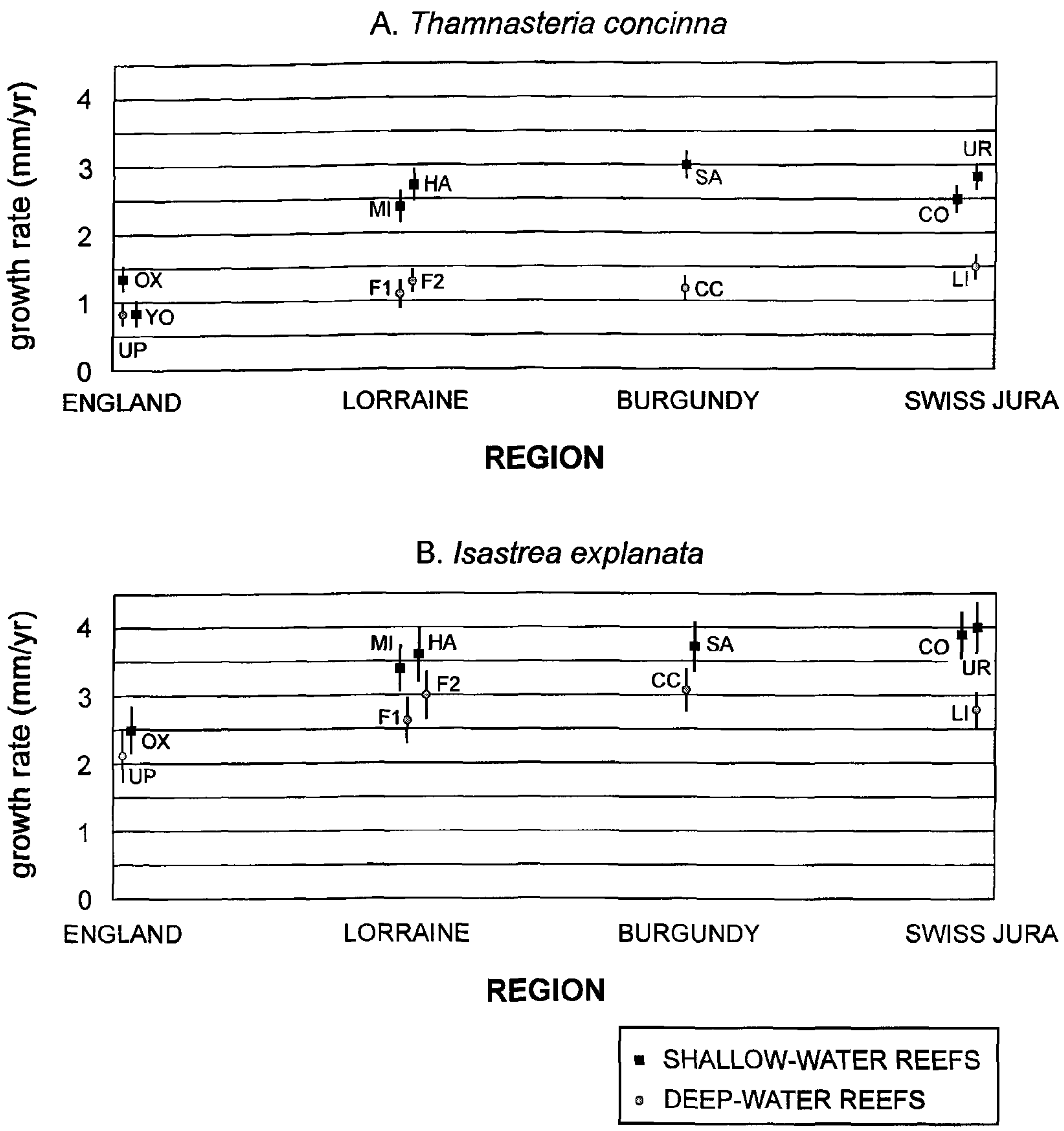


Figure 8.10: Variation in growth rate (mm/yr) between shallow and deep water reefs for *Thamnasteria concinna* (figure 8.10 A) *and Isastraea explanata* (figure 8.10 B). The points plotted are the arithmetical means of all the measurements collected for each species per locality. Vertical line represents 1 standard deviation. (See section 8.2.4.3.1 for locality abbreviations.)

Figures 8.10A and B illustrate the variation in the growth rates in the two corals between shallow and deeper water facies. Comparing figure 8.10A with 8.10B it is immediately apparent that in general *Thamnasteria concinna* shows a greater variability in growth rate than *Isastraea explanata* between extreme reef types. It is also clear from figure 8.10A, and to a lesser extent 8.10B, that the difference in growth rate between shallow and deeper water reefal units is much greater in Lorraine, Burgundy and the Swiss Jura, than in England, this being especially pronounced in *Thamnasteria concinna* (figure 8.10A).

Location	***Thamnasteria concinna***					***Isastraea explanata***				
	G.R.	**L/H**	**DIST.**	**SD.**	**NO.**	**G.R.**	**L/H**	**DIST.**	**SD.**	**NO.**
Yorkshire (YO; 39° N)	0.8	0.4	5	0.12	20	—	—	—	—	—
Oxfordshire (OX; 36.5° N)	1.3	0.6	5	0.11	11	2.5	0.5	5	0.28	8
Cambridgeshire (UP; 37° N)	0.8	0.5	5	0.11	8	2.2	0.5	5	0.35	4
Foug 1 (F1; 34° N)	1.1	0.4	5	0.15	13	2.6	0.6	5	0.29	7
Foug 2 (F2; 34° N)	1.3	0.5	5	0.11	10	3	0.7	4	0.31	5
Haudainville (HA; 34° N)	2.7	1.4	2	0.18	4	3.6	1.3	1	0.32	3
St. Mihiel (MI; 34° N)	2.4	1.2	2	0.17	5	3.4	1.3	3	0.27	3
Châtel-Censoir (CC; 33° N)	1.2	0.7	1	0.13	7	3.1	0.5	1	0.27	5
Saussois (SA; 33° N)	3	1.4	1	0.12	6	3.7	1.6	1	0.29	4
Liesberg (LI; 32° N)	1.5	0.5	5	0.14	17	2.8	0.5	5	0.26	14
Courtételle (CO; 32° N)	2.5	1.7	1	0.12	8	3.8	1.4	2	0.3	3
St. Ursanne (UR; 32° N)	2.8	1.3	2	0.12	6	4	1.5	2	0.31	4

Table 8.7. Summary of results. G.R. - arithmetical mean growth rate (mm/yr), L/H - low/high density ratio, DIST. - distinctness value, SD. - standard deviation of the mean growth rate. NO. - number of colonies measured. Approximate palaeolatitude of each location is indicated in parentheses (in °N).

<u>2. Low / High (L/H) density band ratio.</u> The L/H ratios of the corals studied are shown on figure 8.11. L/H ratios range from 0.4 in Yorkshire to 1.7 in the Swiss Jura. L/H ratios of *Thamnasteria concinna* and *Isastraea explanata* do not seem to be significantly different, nor do they show any significant regional variations. The L/H ratio results can be grouped into three clusters:

1. Colonies that show L/H ratios greater than 1.2 occurring in the shallow-water facies (Lorraine, Burgundy, Swiss Jura);
2. Colonies that show L/H ratios less than 0.7 occurring in the deep-water facies (Upware, Foug, Châtel-Censoir, and Liesberg);
3. Colonies occurring in shallow water though having a L/H ratio of less 0.7 (Yorkshire and Oxfordshire).

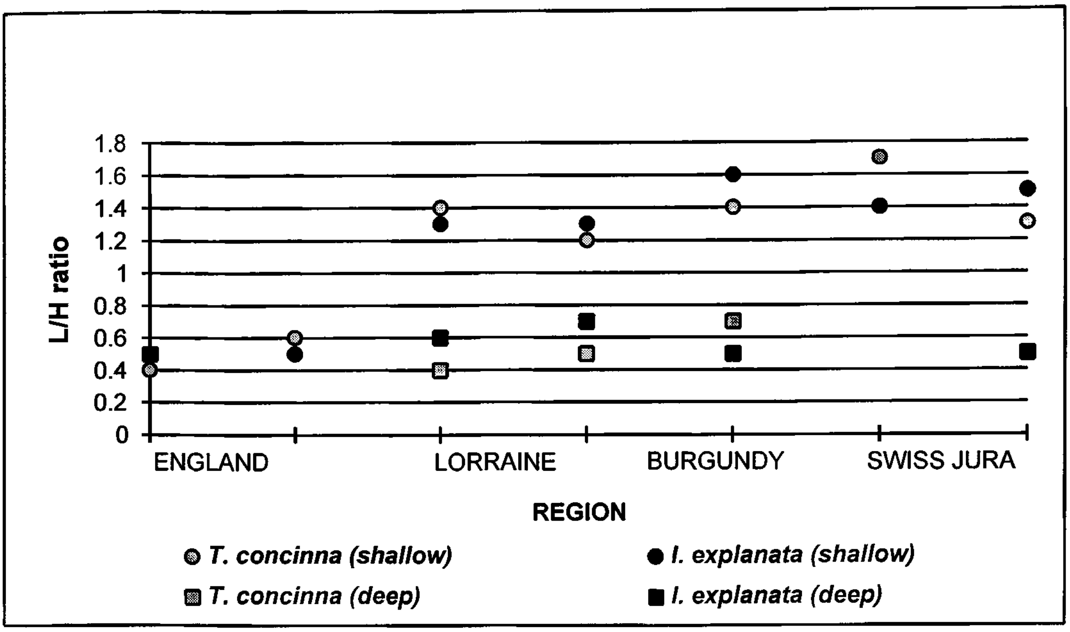


Figure 8.11: Low/high density ratios for all reef types and all localies, for both species. The points plotted are the arithmetical means of all the measurements collected for each species per locality.

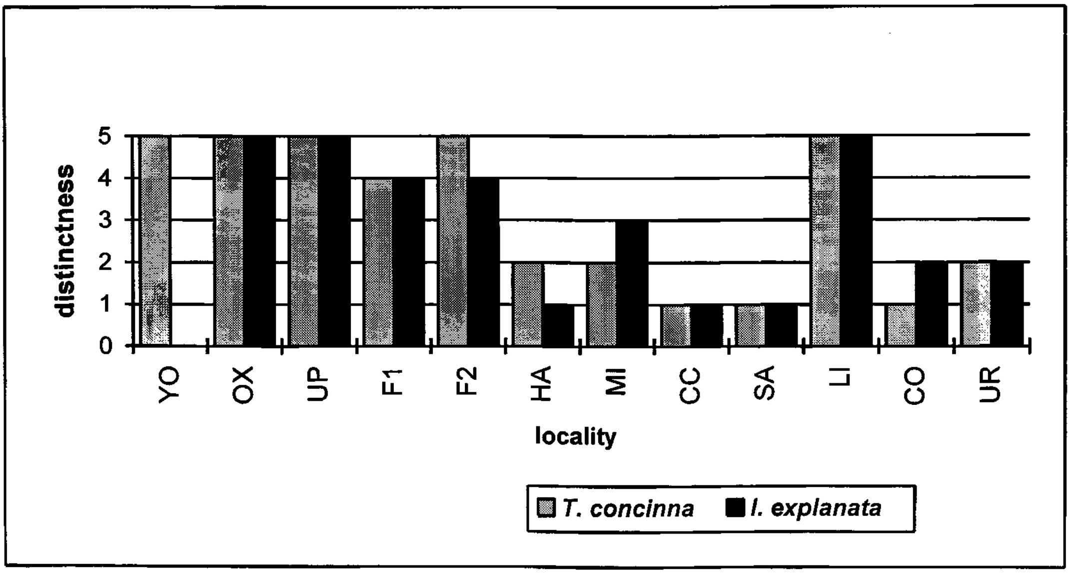


Figure 8.12: Distinctness values for the low- and high- density couplets. (See section 8.2.4.3.1 for locality abbreviations.)

3. Distinctness, D. D does not seem to vary systematically between the two species. Not all the colonies showed distinct growth banding; however this phenomenon is also encountered in modern corals (Weber and White 1974; Huston 1985). Diagenesis has probably altered the natural distinctness to an unknown extent, but since these reefs have undergone similar diagenetic histories it seems probable that the relative distinctness has remained similar to the original values. D was extremely high (5, 4) in all the English localities with only Liesberg showing a similarly high value outside England (plate 1, fig. 3). The European localities generally show low D values (2, 1) (figure 8.12).

8.2.4.3.4. Discussion

1. Growth rates. The weak general trends shown on Figures 8.9A and 8.9B are notable for their insignificance at the 95% confidence level. Since these plots are comparing corals from the same reef type across different regions (8.9A for shallow-water reefs and 8.9B for deep-water reefs), differences in growth rate should be independent of local environmental controls and should reflect more regional changes in climatic (temperature, solar radiation and seasonality) and/or oceanographic factors (Glynn, 1977). One might therefore speculate that with an increase in palaeolatitude, there would be a decrease in regional average temperature and solar radiation consequently resulting in a decrease in growth rate. This is not revealed in the data. However it has been well established that the Jurassic climate was more equable than at present and therefore environmental gradients not as steep (Hallam, 1975, 1984, 1993). This allowed a general spread of coral reefs as far north as Scotland which lay at approximately 43°N, which strongly contrasts with the present-day limits of reef growth which lie approximately 35° N and S of the equator (Rosen, 1981). Hence the lack of large variations in growth rates between the regions studied, all of which lie within a broad mid-latitude climatic belt, might be accounted for by the small difference in palaeolatitude between adjacent localities, and the equable palaeoclimatic regime. Growth rate data are not yet available for reefs located further south (such as the Portuguese and Slovenian reefs) or further north (such as the Helmsdale corals in north Scotland). These areas would provide corals that grew outside this climatic regime and therefore differences in their growth rate may reflect climatic differences. What is now clear is that this climatic signal would be best searched for in corals such as *Thamnasteria concinna* and in shallow-water reefs with low siliciclastic influx since these were evidently the most sensitive to environmental changes (see below).

The low growth rates recorded in the Yorkshire reefs (YO) are however significant. The difference in growth rate between the Yorkshire and the continental European reefs, which developed in similar shallow-water siliciclastic free environments, is very marked (approximately 1.5 mm/yr). As explained above there is clear evidence to suggest that climatic gradients between these regions were not steep, hence unlikely to be responsible for the difference in growth rate. One possible explanation for the reduced growth rates of the corals form the Yorkshire reefs is the reduction in annual solar radiation as a consequence of their relatively high palaeolatitude (Ziegler *et al.*, 1984). It is likely that this decrease in solar radiation adversely affected growth band development in the corals of Yorkshire, which lay approximately 39° N, resulting in low growth rates (Smith *et al.*, 1980).

Another interesting feature of figure 8.9A is the sharp decrease in the growth rate between Haudainville and Oxfordshire. This decrease in growth rate in the English localities is likely to be due to the increase of seasonal runoff and the adverse effects that this has on coral growth (increased sedimentation, increased turbidity and possibly the adverse effects of increased nutrient flux). This feature is absent in the deeper water reefs since all of these reefs shared similar ambient conditions. Figure 8.9B shows that growth rates in deeper water reefs show little variation between locations. This lack of regional variation may be explained by the fact that these deep-water biostromes developed in conditions of low light and in some cases high sedimentation with its associated high turbidity, hence any regional signal is probably masked by the strong local environmental overprint.

Figures 8.10A and 8.10B illustrate the variation in the growth rates in the two corals between shallow and deeper water facies. Growth rates in the deep-water biostromes are likely to represent the slowest possible growth rates for these corals since these reefs developed in comparatively stressful environments. Any further deterioration in environment, such as increases in sedimentary influx, turbidity and hence decreases in light, are likely to have resulted in coral mortality rather than a further reduction in growth rate. On the other hand, growth rates in the shallow-water reefs, especially on the clean carbonate platforms of Burgundy and the Swiss Jura which provided near optimal conditions for coral growth, are likely to represent values close to the maximum linear extension possible for these corals. This contrast is reflected by a dramatic decrease in growth rate from shallow to deep-water in all regions and in both species (figures 8.10A and 8.10B). The decrease in growth rate is accompanied by a change in growth form from dome-shaped colonies in shallow-water settings to flat platy forms in deep water. These results are analogous to those of studies carried out at Discovery Bay, Jamaica (Huston, 1985), in which 4 out of 6 coral species (*Porites astreoides, Montastrea annularis, Colpophyllia natans* and *Siderastrea siderea*) significantly decreased their growth rate over a 1 - 30m depth interval. Also documented in these corals were changes in growth form from dome- to plate-shaped colonies along the same depth gradient. This was especially pronounced in *Montastrea annularis* as was the change in growth rate. Huston concluded that the major control over both these changes (form and growth rate) is decreasing light levels, which reduces calcification rates significantly. Other studies on the relationship between depth and growth rate on present-day reefs come to similar conclusions (Dustan, 1975, 1979; Goreau, 1959, 1963; Goreau and Goreau, 1959; Goreau and Wells, 1967; Baker and Weber, 1975; Highsmith, 1979). In the Jurassic deeper-water, low light intensity reefs further evidence of the suppression of the coral calcification process comes from: 1) a poorly developed wall structure in *Isastraea explanata* resulting from a reduction in the number and density of dissepiments; 2) the dominance of microsolenids in these reefs which are well adapted to environments where calcification is hindered (see chapter 7, section 7.1; Insalaco, 1996 a).

Figures 8.10A and 8.10B also clearly show that the difference in growth rate, in both corals, between shallow- and deep-water facies is greater in continental European localities than in the England. This simply reflects the fact that the environmental contrast between the shallow- and deep-water facies was much greater in the European areas. In Europe the shallow-water reefs developed in near ideal conditions for intense reef growth, i.e. warm well lit water on clean shallow-water carbonate platforms. The deep-water reefs on the other hand grew at the environmental limits of reef growth in conditions of extreme low light and in some cases high turbidity. The situation in England was clearly different, although the deep-water reefs developed in equally poor conditions resulting in equally low growth rates, the shallow-water reefs did not develop in the same ideal environments as their European counterparts due to sedimentary influx and, in the more northerly locations (such as Yorkshire), the possible effects of reduced solar radiation; as a result their growth rates are not as high.

What is also clear from Figures 8.10A and 8.10B is that *Thamnasteria concinna* shows greater variability in its growth rate than *Isastraea explanata* (though *Isastraea explanata* shows more intra-colony variability as reflected by its larger standard deviation), both between different reef types but also between different regions. This is consistent with the evidence that *Thamnasteria concinna* is ecophenotypically very plastic (Geister and Lathuilière, 1991; Bertling, 1993a). In deeper water environments, such as the deep-water microsolenid reefs studied, this coral develops a marked platy growth form. In shallower water it exhibits a much more massive appearance. Furthermore, if one accepts that *Thamnasteria dendroidea* (Lamouroux) is simply a branching morphotype of *Thamnasteria concinna*, as is now believed (Geister and Lathuilière, 1991; B. Lathuilière pers. comm, 1993), then it developed its branching habit in very shallow, quiet, water. What this study seems to show is that this plasticity in the growth form of *Thamnasteria concinna* is paralleled by a plasticity in its growth rate. *Thamnasteria concinna* seems to have varied its growth rate considerably in response to a wide variety of different reef environments. This high degree of ecomorphic and ecophysiological plasticity suggests that *Thamnasteria concinna* was an r-strategist, hence its domination in the unstable reef environments of the sub-boreal province (Bertling, 1993a). In fact, there would appear to be an intimate relationship between plasticity in growth form and plasticity in growth rate, since differences in growth forms are a function of synchronous intra-colonial differences in growth rate, though localisation of sites is also important. Thus platy forms developed when all the corallites on the surface of the coral grew at the same rate, whereas in dome-shaped forms the corallites axial to the dome grew faster than the peripheral corallites. In extreme cases branching colonies developed where there are a number of very localised "hot spots" in coral growth which subsequently grew extremely fast and form branches. In the case of *Thamnasteria concinna* (type "dendroidea"), branch growth rate could reach 13 mm/yr. (approximately ten times the growth rate of their deeper water platy counterparts) (plate 3.1-fig 4). A similar relationship seems to exist in present day corals, for example *Montastrea annularis* shows the highest variation in growth rate between deep and shallow-water environments, but also shows the most marked variation in growth form between these extreme water depths (Huston, 1985). It is interesting to note in this respect that although *Isastraea explanata* shows a higher growth rate of the two species studied, its inter-colony variation is relatively small, which is paralleled by its limited ecomorphic plasticity (*Isastraea* never develops a branching ramose form and only shows moderate morphological variation between thick plates and large heads). What this suggests therefore is that the ability for a coral to vary its growth rate substantially goes hand-in-hand with the coral's capacity for ecomorphic plasticity.

1. Low/high density ratio. The results of the L/H ratio clearly indicate that they fall into three groups. Ali's (1984) study of growth banding in the English Oxfordian showed that the corals from the reefs of the sub-boreal province had relatively low L/H values (generally less than 1.0), compared with the values of present day shallow-water corals in the Indo-Pacific and the Caribbean which are generally greater than 2.0 (Weber *et. al.*, 1975; Buddemeier and Kinzie, 1976). The present study corroborates Ali's (1984) observation with observed L/H ratios between 0.4 - 0.6. The argument put forward by Ali suggests that the reason for these low values is reduced light levels resulting from high local turbidity. This is probably a very significant factor, however one must not discount increased cloud cover for a reduction in solar radiation, especially for the more northerly location such as Yorkshire. This has been shown to be of importance by a study on present day growth rates in corals from the tropical Pacific (Buddemeier, 1974). In Buddemeier's (1974) study a positive correlation between the high density bands and lowered light levels (resulting from high cloud cover) was identified. The latitude-related reduction in solar radiation as implied by Ziegler *et al.* (1984) is also likely to have affected growth band development in the corals of the Yorkshire reefs.

This study also demonstrates that where strong siliciclastic influx is not present, such as the shallow-water reefs of Lorraine, Burgundy and the Swiss Jura, L/H ratios increased (larger low density band) and approach the value of present day corals, though still persistently and considerably lower. One explanation for this inconsistency between modern and Mesozoic values is again related to the relatively high palaeolatitudinal location of these reefs (lying approximately between 32° and 39°N). This would have had two adverse effects on coral growth: 1) although temperature gradients were not as steep as at present, temperatures in these high palaeolatitudes may still have been lower than those in present day tropical reef-growing areas; 2) latitude-related reduction in solar radiation. These two factors would have inhibited extensive growth of the low density bands. More data from around the palaeoequator are needed to confirm this. From these low palaeolatitudes it is predicted that L/H ratios will be significantly greater than found in the present study and would compare well with present day values.

The third cluster of values is from the deep-water reef with values below 0.7. This again may be explained by applying a model which invokes a negative correlation between density and light levels. Although it is still unclear which factors control the density variations there is strong evidence to suggest that the density bands negatively correlate with light level as well as temperature. Indeed, it has been demonstrated that L/H ratios decreased with depth in a study of the present day corals of the Enewetak Atoll (Highsmith, 1979). This suggests that it is light that is the more important factor governing the deposition of these density bands, rather than temperature which does not decrease as rapidly with depth.

3. Distinctness. It has been established that in modern corals the low density band is deposited during the summer when the linear extension is greater and consequently the skeletal structure more open, and the high density band is produced during the winter when the process is reversed (Buddemeier, 1974). Although it is clear that the above process is the cause of the low and high density couplet, there is still debate on what precise aspect of the seasonality is driving the process. It seems likely that it is a result of a complex interplay of factors, such as temperature, light and reproductive state, making accurate environmental deductions solely on band distinctness more difficult (Tudhope, 1994). Nevertheless the model implies that where the difference between the summer and winter seasons is large (i.e. a highly seasonal climate) the gross difference between the density bands, and consequently their visual appearance, should also be correspondingly large, i.e. the greater the seasonality the greater the distinctness, all other factors being equal. If one accepts this model for the production of growth bands for Mesozoic corals the data would suggest that at this time the study area was in a highly seasonal climatic belt, as reflected by pronounced growth bands. This would be consistent with both computer models and empirically based models for Late Jurassic climates that suggest that northern Tethys experienced a strongly seasonal climatic regime (Moore *et al.*, 1992a, 1992b, Valdes and Sellwood, 1992; Hallam, 1993). This reasoning is similar to that used by Ma (1934, 1958) who applied this technique to Palaeozoic corals to locate the position of the equator, using this as evidence for drifting continents during various times of the Palaeozoic. A subsequent reinterpretation of Ma's (1934) data in the light of continental drift theory by Fischer (1964) shows that the method is reliable. In a similar study, though on Lower Jurassic to Lower Tertiary fossil tree trunks, Creber and Chaloner (1984) were able to recognise a broad equatorial zone ranging in latitude from approximately 30° N to 30° S, in which annual growth rings are either absent or very poorly developed. Either side of this zone annual growth bands were more pronounced and well developed and were interpreted as suggesting a strongly seasonal climate.

However, figure 8.12 clearly shows that values of D not only varied between different areas but also between different reef types within the same region. This pattern cannot be explained by applying a simple seasonality model. Looking at the data in more detail one finds that the following regions have high D values: Ayton Farm, Stanford quarry, Upware, Foug, and Liesberg, whereas at St. Mihiel, Haudainville, Châtel-Censoir, Saussois, St. Ursanne, and Courtételle, distinctness is low. Taking account of the lithofacies and palaeogeography a very clear pattern emerges; the localities with high values of D are those that have a high siliciclastic component and/or strongly influenced by nearby land masses; localities with low D values occur in very pure carbonate environments with very little influence from land masses. So, although seasonality does not seem to influence the degree of distinctness directly, its indirect influence is nevertheless considerable. Seasonal increases in precipitation and wind energy produced high runoff resulting in large influxes of sediments, and possibly nutrients, into the surrounding sea. Where this coincides with areas of reef development the corals show greater contrast in their high and low density bands, resulting in higher D values. Further evidence for such a pronounced seasonal process is provided by thin veneers of sediment found at the top of the low density bands in a number of specimens from the English Oxfordian. A similar process was invoked for the corals of the Great Barrier Reef (Boto and Isdale, 1985). They suggested that there was a strong correlation between the intensity of the fluorescence in the coral skeleton, and the seasonal pattern of rainfall and runoff from the adjacent Australian landmass. They suggest that the fluorescence in the coral skeleton is caused by organic acids of terrestrial origin that are washed in during periods of high runoff.

8.2.4.3.5. Conclusions from growth band study

Palaeogeographic and palaeoenvironmental settings in combination with the palaeoclimatic regime were found to exert a strong control on the nature of the growth banding, and also the rates at which these bands were deposited. The combination of strong seasonal rainfall and proximity to land masses resulted in lowered growth rates and L/H ratios though increased distinctness values. Where reef development was distal to sediment source areas the effect of seasonality was much less marked, consequently distinctness values decreased but L/H ratios and growth rates increased. All these changes were more pronounced in the shallow-water reefs which seemed to have been more sensitive to environmental change. Growth rates also markedly decreased from shallow to deeper water, as they do in present day coral reefs. This decrease in growth rate is in response to the decreased intensity and quality of light which adversely affects the calcification process in corals.

Due to the more equable Jurassic climate no systematic regional changes in the nature of the growth banding or the growth rate were seen. Data from outside this broad mid-latitude climatic belt could provide suitable material to assess the effect of regional changes in temperature and seasonality on the production of these growth bands. Such areas would include reefs developed further south, for example in Portugal and North Africa, and to the north into the sub-boreal province such as the corals from the Helmsdale region of northern Scotland. The low growth rates and L/H ratios recorded from the corals in Yorkshire are likely to be a response to the low solar radiation received at high palaeolatitudes, and is consistent with the Ziegler *et al.* (1984) model for the distribution of Bahamian-type carbonates.

Marked differences between the two study species can be inferred in the ecophysiological behaviour, as reflected by variations in growth rate. Although *Isastraea explanata* had a greater growth rate, it shows little variation between different reef environments. *Thamnasteria concinna* on the other hand had a smaller growth rate, though it shows a considerable variation between different reef types. It is suggested that this may be related to its strongly plastic ecomorphic behaviour.

This preliminary study has shown that it is possible to apply the methodology developed for present day sclerochronology, to Mesozoic Scleractinia. Moreover the current concepts and ideas about the growth of present day corals seem also to apply to Mesozoic corals which show similar growth patterns to modern forms. Thus Mesozoic sclerochronology is potentially an important tool for interpreting past environments and climates.

8.2.4.4. Comparison of richness and growth rate data sets

The richness data set showed a clear palaeolatitudinal trend of decreasing generic richness with increasing palaeolatitude, which was assumed to be correlated with a temperature gradient. The growth rate data set did not show a trend, which was assumed to reflect the more equable climate at the time. Can these two data sets be reconciled? The two corals which were used for the growth rate study were *Isastraea explanata* and *Thamnasteria concinna*. The evaluation of type VI reefs (see section 7.2.4) has shown that these two corals appear to be eurytopic forms, which is why they are present in such a wide variety of different reef types and geographical regions. Therefore the most parsimonious explanation is that the species richness data reflects a filtering out of stenotopic corals which may have been more sensitive to temperature changes. The growth rates of *Isastraea explanata* and *Thamnasteria concinna*, being eurytopic species, may have been less affected by temperature and hence no trend is present.

8.2.4.5. Coral assemblages

Growth form assemblages

The study has shown that the ecological distribution of different growth form assemblages is clearly environmentally controlled and is summarised in table 8.8 and figure 8.13. The reasons for environmental distribution of different growth forms have been discussed in chapter 7.

	Environment		
Dominant growth form	**Light**	**Energy**	**Sedimentary regime**
Platy	Low	Low	Variable
Encrusting	High	High	Low sedimentation rates
Massive domal forms	High	High	Variable
Branching ramose	High	Moderate-Low	Variable
Loose branching ramose	High	High-Moderate	Mobile sand shoals
Branching phaceloid	High	Low	High mud sedimentation rates

Table 8.8: Coral growth forms and their relationship with environmental parameters

The study has also revealed an interesting relationship between genera that can occur as both branching ramose and massive domal forms (ecomorphic plastic genera), and the optimality of the environment for their branching ramose ecomorph. If it is assumed that greater environmental optimality for ecomorphic branching ramose genera is reflected in an increase in their diversity then the data suggest that the optimal environmental conditions for the appearance of ecomorphic branching ramose genera were: high light levels; low to moderate energy levels and low sediment balance (i.e. where the "branching ramose and sub-branching ramose colonies" plot in figure 8.13). The data also suggest that there is an orderly appearance of various branching ramose ecomorphs of ecomorphically

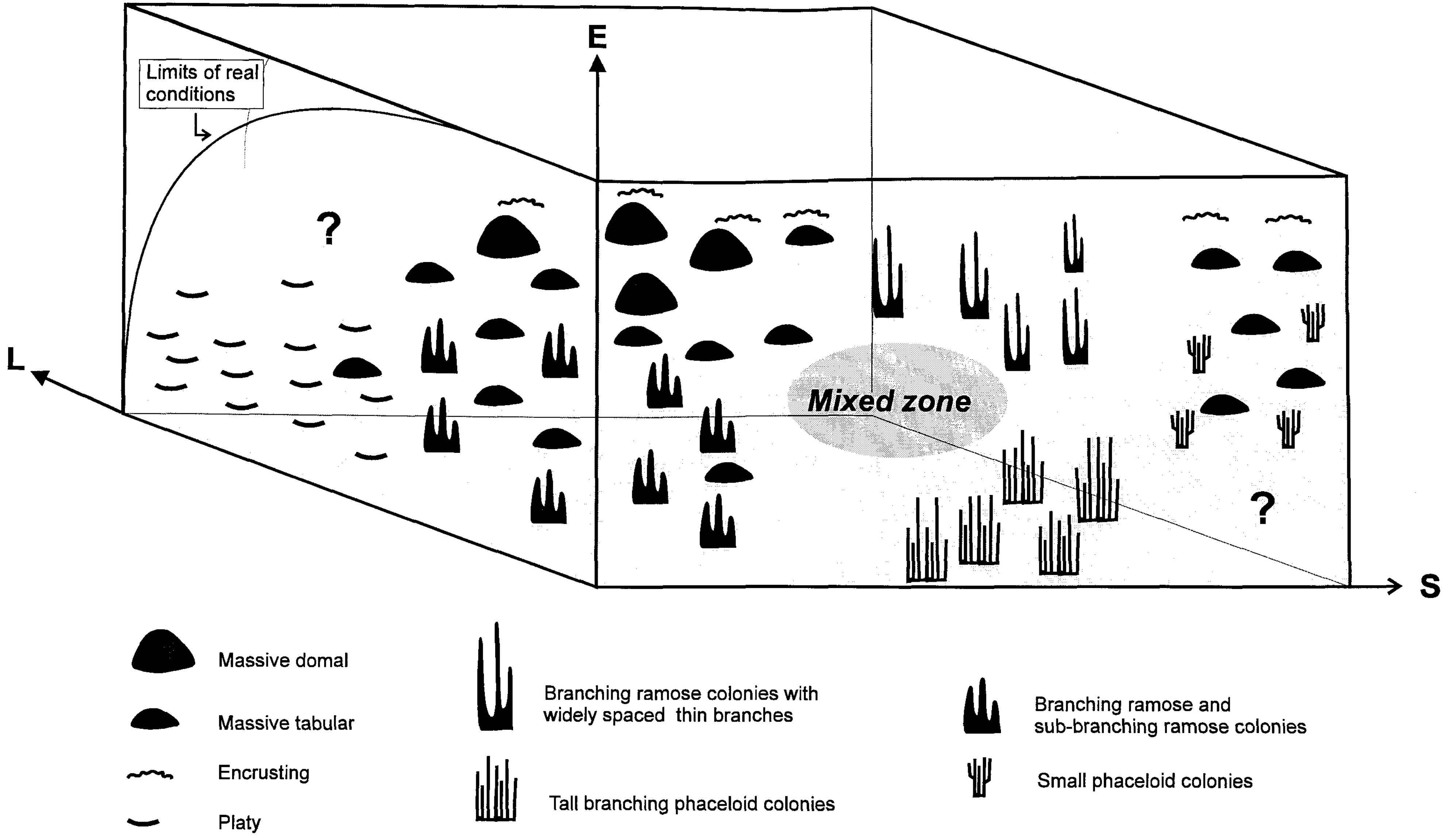


Figure 8.13: Distribution of different coral growth forms in LES space. (Axes as in figure 8.1.)

plastic genera (BRES) with increasing environmental optimality. Thus where the environment was unfavourable for BRES (as inferred from their low diversity) the only branching ramose genera that were present are *Thamnasteria dendroidea* and/or *Pseudocoenia*. With increasing environmental favourability for BRES (as inferred from an increase in their diversity) the sequence of their appearance is as follows: *Thamnasteria* and/or *Pseudocoenia* followed by *Stylina* and finally by *Meandrophyllia*, *Latiastrea*, and *Microsolena* (figure 8.14). Thus it appears that the environmental threshold for the appearance of BRES is different for different genera. In *Thamnasteria* and *Pseudocoenia* this environmental threshold was relatively low and these were the first branching ramose genera to appear (which, with regard to *Thamnasteria concinna*, may be related to the fact that it could vary its growth rate substantially as discussed in section 8.2.4.3.4). Conversely, genera such as *Microsolena, Meandrophyllia* and *Latiastrea* appear to have had a high environmental threshold and branching ramose forms of these genera only occur in the most optimal environments for BRES.

The one branching ramose genus that does not conform to the pattern outlined above is *Dendraraea*, since it is present even in environments which were very unfavourable for BRES (such as type I and II reefs). This suggests that the ecophysiological controls on the distribution of this genus were different to BRES. This can be explained with reference to two distinct features of *Dendraraea,* which are: (1) it only occurs in a branching ramose growth form (i.e. it is not a BRES); and (2) it possesses pennulae. The presence of pennulae is particularly significant since pennulae appear to have been a structural adaptation to low light levels by increasing the filter feeding capabilities of penulae bearing-corals (as discussed in chapter 7.1). Thus it can be speculated that the presence of pennulae in *Dendraraea* had allowed it to colonise a variety of photic regimes which BRES could not.

Taxonomic associations

Five coral assemblages have been identified: (1) microsolenid assemblage (type I and II reefs); (2) *Thamnasteria/Isastraea/Fungiastraea/Thecosmilia* assemblage (type VI reefs); (3) *Dendrohelia coalescens/Thamnasteria dendroidea* (type A) assemblage (type VIII reefs); (4) fungiid, stylinid and phaceloid amphiastaerid assemblage (type VII reefs); and (5) *Aplosmilia* assemblage (type III reefs). The palaeoecology of these assemblages has been discussed in chapter 7.

8.2.5. Associated fauna and bioerosion

This was not the focus of the study and therefore only some broad observations and comments on selected groups are outlined below.

General development. In general the diversity of the associated fauna was low. This was particularly the case for the uniserial benthic suspension feeders (mainly the bivalves) although their diversity was considerably higher in type II and VI reefs; i.e. siliciclastic influenced reefs. This suggests that there may have been a nutrient control on the development of this fauna (as discussed in section 7.1). Other groups, such as the echinoids, bivalves and sponges, are variably common and a clear pattern with regard to reef type specificity did not emerge.

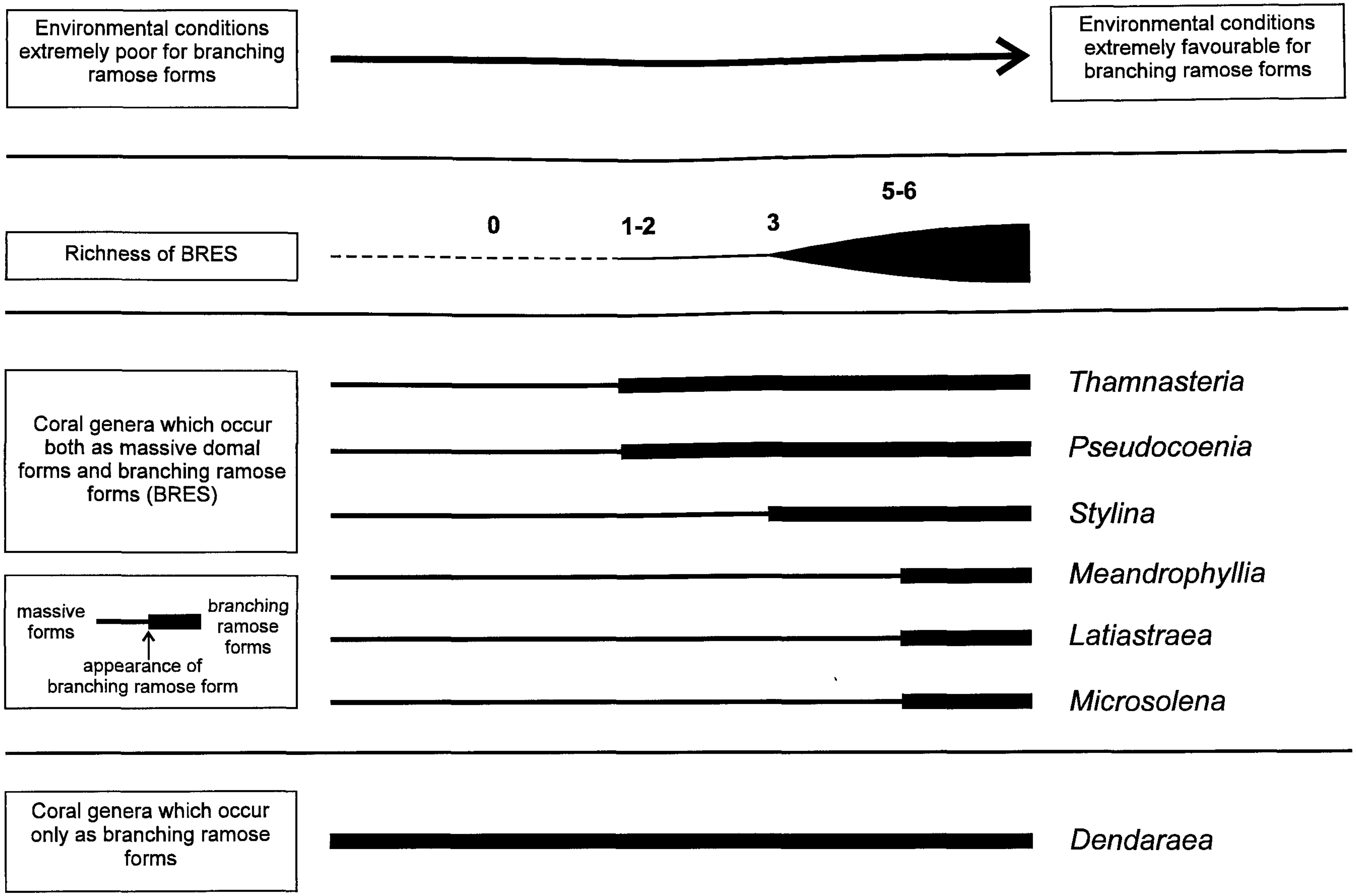


Figure 8.14: Conceptual diagram to illustrate the change from massive to branching ramose forms for different genera in different environmental conditions. (See text for details).

Nerineids and diceratids. In situ nerineids do not occur as an intra-reef faunal element and were only rarely washed in to the reefs. However they are common within the associated facies of type VII, VIII and high energy type VI reefs. These facies are: oolitic and peloidal grainstones, beach conglomerates and debris channels. This suggests that a relatively high level of water agitation was an important control on the distribution of these gastropods, and this is consistent with other studies (Wieczorek, 1979). The diceratids are generally scarce in Late Jurassic coral reefs, but they can be abundant and consistently present within facies associated with type VII and VIII reefs, and type IX facies; they are absent from all other reef types. During the Late Jurassic these reef types were comparatively uncommon, hence the general paucity of diceratids in the Late Jurassic reflects the paucity of these types of reef environments, rather than some factor associated with palaeobiogeography.

Other molluscs. The commonest group of bivalves in these reefs are nestling and crevice-dwelling forms (such as arcids, limids, and mytilids); followed by cementing forms (especially oysters); however both groups are generally never abundant. Of these the only truly ubiquitous group are the pectinids, which were found in all reefs, though never common. The gastropods generally have an off-reef distribution and can be quite numerous in the high energy grainstone facies. Gastropods are rare within the reef itself and if present are invariably typical reef dwelling pleurotomariids.

Red Algae. Red algae are not ubiquitous in Late Jurassic reefs but appear to be restricted to the siliciclastic-free shallow-water reefs (reefal types: III, IV, VII, VIII and type IX facies; see table 8.9). The absence of red algae from type V reefs is less easy to explain, though it may be related to the episodic environmental disturbance associated with this reef type. Generally red algae did not contribute to framework construction, although their abundance in some reefs (e.g. Bellême; the upper parts of the St Ursanne Formation of patch reef 1) suggests that it may have locally bound small areas of coral framework, but this is rare. This contrasts with present-day coral reefs, where coralline algae can play an important constructional and binding role; in the Late Jurassic this was not the case and the binding of framework was almost exclusively carried out by microbialite.

Reef type	Red algae present?	Abundance	Role in reef building
I	NO	______	______
II	NO	______	______
III	YES	Abundant	None
IV	YES	Common	None
V	NO	______	______
VI	NO	______	______
VII	YES	Rare	None
VIII	YES	Can be very abundant	Perhaps locally
IX	YES (though not in situ)	Common	No reef

Table 8.9: Distribution and abundance of red algae in different the reef types.

Bioerosion

The following ichnogenera have been identified in this study, with the organisms thought to be responsible given in parentheses: *Entobia* (clionid sponges), *Talpina* (phoronids), *Cunctichnus* (polychaetes), *Spirichnus* (polychaetes), *Meandropolydora* (spionids), *Caulostrepsis* (eunicids), *Conchotrema* (eunicids?), *Rogerella* (acrothoracids), *Gastrochaenolites* (*Lithophaga; Gastrochaena), Trypanites* (sipunculids?) and the unknown ichnogenus produced by a boring foram. The variation in the type and intensity of bioerosion in the different reef types is summarised in table 8.10. The highest richness of borings occurs in the type VIII reef of Novion-Porcien, where all of the above ichnotaxa were recorded. Boring forams and sponges appear to have preferred frameworks dominated by branching corals, especially phaceloid forms; they were rarely found in massive colonies. The opposite is true for the boring bivalves, which are very rarely seen boring into branching corals. *Gastrochaenolites* was the most abundant ichnogenus and is present in all reef types except type VII and III reefs. Bioerosion intensity is highest in type VIII reefs (e.g. Novion-Porcien, Bellême and Ayton) and lowest in type III and VII reefs where boring bivalves appear to be absent. The extent of bioerosion is increased in reefs which possessed large amounts of early cementing microbialite (such as type IV reefs and some type VIII reefs) which allowed borers, in particular the bivalves, to bore directly into the microbialite.

R. T.	B. I.	Dominant type of boring	Other borings present
I	2-3	*Gastrochaenolites*	*Entobia* can be present
II	3	*Gastrochaenolites*	*Entobia* can be present
III	1-2	*Entobia* and Boring forams	Note: *Gastrochaenolites* absent
IV	3-4	*Gastrochaenolites*	*Entobia* and boring forams can be present
V	1	*Gastrochaenolites*	
VI	3	*Gastrochaenolites*	Talpina can be present
VII	1	Forams, annelids	Note: *Gastrochaenolites* absent
VIII	4-5	*Entobia, Gastrochaenolites, Talpina*	Diverse assemblage of inchnogenera.
Where: R. T: reef type; B. I.: boring intensity; 1: very low ; 2: Low 3: moderate; 4: high; 5: very high			

Table 8.10: Variations in the type and intensity of bioerosion in the different reef types.

General importance of bioerosion in the reefs studied

The intensity and type of bioerosion within Portlandian bivalve-dominated patch reefs in southern England has recently been been studied in detail (Fürsich *et al.*, 1994). The type and intensity of the bioerosion in these reefs is similar to that encountered in the type VIII reef at Novion-Porcien (pers. obs., 1995). Although not quantified, the amount of material removed from the Novion-Porcien reef appears to be comparable with that removed from the Portlandian bivalve reefs where, up to 40% of the reef volume has been removed. As with the Portlandian reefs it is the intensity of bioerosion in general, and the abundance of *Entobia* in particular, in type VIII reefs that give these reefs their modern aspect with regard to bioerosion. The Novion-Porcien reef, which is of Middle Oxfordian age, is the earliest known record of such intense clionid attack on coral reefs. The general paucity in reef bioerosion in the Late Jurassic, and in particular the comparative rarity of clionid borings, appears to be more a reflection of the relative scarcity of type VIII reefs than any other factor. Interestingly, if the Portlandian bivalve reefs were to be placed into the depositional model developed in section 8.1, they would plot in the same space as type VIII reef environments. This further substantiates the suggestion of a strong environmental control of the distribution and abundance of reef bioeroders.

CHAPTER 9: SUMMARY AND PRINCIPAL CONCLUSIONS

[1] From comparative facies and palaeoecological analysis it has been possible to recognize eight broad reef types and one associated facies. These have distinct sedimentological and palaeoecological characteristics, which have been described and discussed in detail. The depositional environment in which these reefs have grown has also been evaluated (chapter 7). From this a conceptual depositional model has been developed which can be used to understand how these different reef types related to each other with regard to light intensity, hydrodynamic energy levels and sediment balance. This model can also be used to gain a fuller understanding of the spatial and temporal distribution of coral-dominated reefal carbonates (chapter 8, section 8.1), and to investigate sedimentological and palaeoecological trends within Late Jurassic reef development (chapter 8, section 8.2). Future work should include an attempt to identify the eight reef types defined in this thesis in other areas of Late Jurassic coral reef development (such as Portugal, the Middle East and South America). This would provide a valuable test to the general validity of the model developed.

[2] Late Jurassic coral reef development was in general small scale (rarely greater than a few tens of metres across and tens of metres high) and syndepositional relief where present was very modest (rarely greater than a few metres); biostromal platestones are a common type of reef and can be laterally extensive (hundreds of metres across). Framework development in these reefs is highly variable in terms of style, type and uniformity. Where these reefs possessed a rigid framework this was a consequence of high coral skeletal biovolume and/or the binding effect of microbialite; other secondary framebuilders such as sheet-like encrusters and red algae played no part in framework development.

[3] The study has revealed that there is a considerable variation in the type of intra-reef sediment present in different reef types which is generally reef-type specific (see section 8.2.3). The study has also documented for the first time the importance of intra-reef microbialite in framework development in the reefs studied. Various types of microbialite have been identified and their distribution and abundance was found to vary according to local environmental conditions and hence reef type. Microbialite also played an important constructional role in a number reefs and acted as an early cementing secondary reef binder (see section 8.2.3).

[4] The study has documented a decrease in coral generic richness with increasing palaeolatitude. It is assumed that this latitudinal generic attenuation is correlated with temperature and a result of the "filtering-out" of stenotopic genera northwards. It has emerged that all high palaeolatitude coral

faunas are of similar composition, regardless of facies, and the corals that dominated these faunas are eurytopic (section 8.2.4.2).

[5] A growth rate study on two corals (*Thamnasteria concinna* and *Isastraea explanata*) revealed that these corals show marked variations in their growth rate and other growth characteristics between reef types. However the study did not record a gradual latitudinal decrease in coral growth rates with increasing palaeolatitude. This is assumed to be a consequence of the more equable Late Jurassic climate and the eurytopic nature of the two corals used in the study. However significant decreases in growth rates were recorded in the Yorkshire reefs; this is interpreted to be latitudinally controlled and thought to be a consequence of lower temperatures and lower amounts of solar radiation that were experienced in higher palaeolatitudes (section 8.2.4.3).

[6] Clear patterns with regard to coral growth forms and environment have emerged from the study (see section 8.2.4.5). Taxonomic patterns have also emerged but are less clear than the growth form trends. Five taxonomic assemblages have been defined which are all reef-type specific (see section 8.2.4.5). Whether more, and clearer, coral assemblages would emerge from a species-level study remains unanswered. However before this can be addressed a detailed pan-European taxonomic study must be carried out. This would also help to evaluate whether different growth forms of the same genera represent different species or ecophenotypic variation.

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