# THE HAMPEN MARLY AND WHITE LIMESTONE FORMATIONS: FLORIDA-TYPE CARBONATE LAGOONS IN THE JURASSIC OF CENTRAL ENGLAND

*by* T. J. PALMER

ABSTRACT. The Hampen Marly Formation of central England was laid down on a shallow shelf fringing the shore of the London Landmass to the east. Three principal environments can be recognized: (i) a nearshore lagoonal region, dominated by clastic sediments, with faunal and floral evidence of periodic brackish and freshwater influence; (ii) a shallow marine, more offshore region dominated by oyster reefs, where clastic and carbonate sediments intermix; (iii) a deeper, more fully marine area further offshore, where the carbonate sediments and their marine fauna are identical to those of the overlying White Limestone Formation. The White Limestone Formation of the area studied can be divided lithostratigraphically into three members. These are, in ascending order, the Shipton Member, the Ardley Member, and the Bladon Member. Each member represents a shallowing of the sea by sediment accumulation after an initial deepening that was probably under tectonic control. Eight recurrent assemblages of invertebrates, which are strongly correlated with the nature of the substrate, can be recognized. Close similarities exist between these assemblages, and those found today in comparable habitats, such as those in Florida. A picture of the region's palaeogeography and the distribution of the main habitats is built up from the facies analysis. Some ideas on the tectonic control of the sedimentation are put forward.

THIS paper describes and discusses the depositional environments and the ecological control on the faunas of two stratigraphic units in the Great Oolite Group (Bathonian) over part of central England. It contains a summary of a broader study over a wider area (Palmer 1974, D.Phil. thesis), where the evidence on which the conclusions herein are based is more fully presented. The principal geographic region under consideration runs along the outcrop from Burford (SP 2512) to Buckingham (SP 6933). South-west of this area there is a marked drop in the number of extant exposures in both the Hampen Marly and the White Limestone Formations. There is also a facies change in the White Limestone representing the passage from predominantly marine lagoonal micrites to predominantly well-sorted current-swept lime sands associated with a shelf break at the western limit of the Oxfordshire shallows (Worssam and Bisson 1961). The region chosen for study therefore has both artificial and natural limits.

The study involved the investigation of over thirty extant exposures, some of considerable size. In addition, some information has been taken from the observations and accounts of previous workers particularly in the now poorly exposed Hampen Marly Formation in the region around and to the south-west of Burford. The sections studied are listed in Table 1.

## THE HAMPEN MARLY FORMATION

### *Definition and stratigraphy*

The Hampen Marly Formation (=Hampen Marly Beds of Arkell, Richardson, and Pringle 1933) consists of a variable series of clays, limestones, marls, and sands, which

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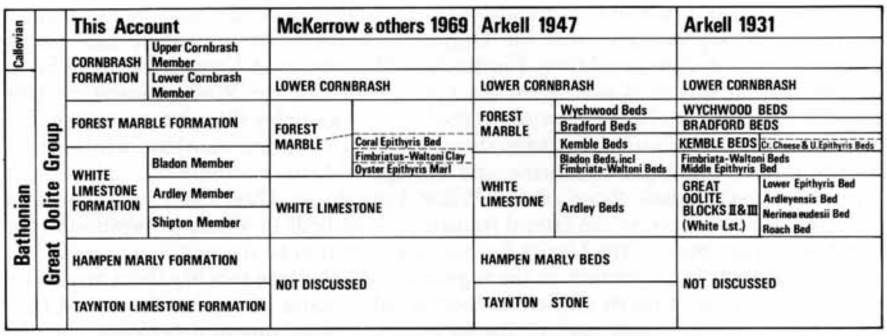
TABLE 1. Map references of the sections in the Hampen Marly Formation and the White Limestone Formation discussed in this account. The principal previous descriptions are also given.

| LOCALITY | MAP REFERENCE | PRINCIPAL PREVIOUS ACCOUNT |
|---|---|---|
| *Boreholes* | | |
| Stony Stratford | SP 785405 | Woodward 1894 |
| Calvert | SP 689247 | Davies and Pringle 1913 |
| Oxford | SP 505063 | Pringle 1926 |
| Witney | SP 344147 | Poole 1969 |
| Stowell Park | SP 088128 | Green and Melville 1956 |
| Latton | SU 093957 | Arkell 1933*c* |
| Charlton | ST 963888 | Geological Survey field notes |
| Ready Token | SP 105044 | Richardson 1932 |
| *Quarries and Cuttings* | | |
| Deanshanger | SP 753395 | Woodward 1894 |
| Brackley | SP 757377 | Walford 1912 |
| Aynhoe | SP 516335 | Woodward 1894 |
| Croughton* | SP 563336 | Palmer 1974 |
| Stratton Audley* | SP 6025 | Palmer 1973 |
| Blackthorn Hill* | SP 616211 | Arkell 1931 |
| Ardley* | SP 543264 | Palmer 1973 |
| Ardley Railway Cutting* | SP 518287–531276 | Arkell *et al.* 1933 |
| Northbrook Farm* | SP 497222 | Palmer 1974 |
| Kirtlington* | SP 494199 | McKerrow *et al.* 1969 |
| Shipton* | SP 4717 | Arkell 1931 |
| Whitehill Quarry, Gibralter* | SP 497187 | Palmer 1974 |
| Greenhill* | SP 486178 | Arkell 1931 |
| Wood Eaton* | SP 534123 | Palmer 1973 |
| Tolley's New Quarry, Bladon* | SP 450150 | Arkell 1933*b* |
| Old White House Quarry, Bladon* | SP 448150 | Arkell 1933*b* |
| Long Hanborough Station* | SP 436142 | Arkell 1931 |
| Layshill Wood* | SP 418147 | Richardson 1946 |
| Whitehill Wood* | SP 388153 | Richardson 1946 |
| Whitehill Wood Railway Cutting | SP 395157 | Arkell 1931 |
| Fisher's Gate, North Leigh* | SP 391142 | Richardson 1946 |
| Stonesfield | SP 389169 | Walford 1896 |
| Minster Lovell War Memorial* | SP 316109 | Arkell 1931 |
| Astall* | SP 300118 | Worssam and Bisson 1961 |
| Eton College* | SP 297102 | Worssam and Bisson 1961 |
| Whitehill (Sturt Farm)* | SP 271109 | Palmer 1974 |
| Swinbrook | SP 278124 | Woodwood 1894 |
| Stonelands* | SP 278098 | Palmer 1974 |
| Milton* | SP 257157 | Richardson 1910 |
| Taynton | SP 236155 | Richardson 1933 |
| Little Barrington | SP 205121 | Richardson 1933 |
| Windrush | SP 190125 | Richardson 1933 |
| Slape Hill* | SP 423196 | Palmer 1973 |
| Whiteways, Middle Barton* | SP 420246 | Palmer 1974 |
| Great Rollright* | SP 322304 | Palmer 1974 |
| Temple Mills* | SP 345361 | Whitehead and Arkell 1946 |
| Hampen* | SP 062205 | Richardson 1929 |
| Pinswell | SP 035126 | Richardson 1933 |
| North Cerney | SP 023080 | Richardson 1933 |
| Chedworth Cutting | SP 061019 | Richardson 1933 |
| Foss Cross* | SP 056091 | Torrens 1969 |
| Dagham Downs* | SP 003060 | Torrens 1967 |

An asterisk indicates that the section is extant, and has been examined by the author.



TEXT-FIG. 1. Scheme of stratigraphic subdivision of the Upper Great Oolite Group adopted in this account, compared with selected previous divisions.

occur between the Taynton Limestone Formation (where present), and the overlying White Limestone Formation (text-fig. 1). The 8·7-m-thick type section is at Hampen Railway Cutting, west of Salperton, Gloucestershire (Table 1), and has been described by Woodward (1894), and Richardson (1929). Within the main study area the Hampen Marly Formation is only well exposed at Wood Eaton Quarry (Palmer 1973). The locations of former exposures are shown in text-fig. 2, and listed in Table 1.

To the south-west of the type section the Hampen Marly Formation seems to disappear, and is replaced laterally by beds of the White Limestone Formation. In the railway cutting at Chedworth (Richardson 1911) it is barely distinguishable from the latter, being represented only by thin marl beds in a predominantly limestone sequence. Similarly in the Stowell Park borehole, 2·5 km north-east of the Chedworth cutting (Green and Melville 1956), there is doubt about the development of the formation, which is probably represented only by an uncored 2·6-m interval immediately overlying the Taynton Limestone Formation. This was inferred to be marly from the gamma-ray log. At Latton, 10 km south-west of Cirencester, the formation appears to be entirely absent (Arkell 1933*c*; Richardson 1933), having passed laterally into expanded White Limestone (Arkell 1947; Arkell and Donovan 1952). At Charlton, 15 km south-south-west of Cirencester, 3 m of doubtful Hampen Marly Formation were recorded in the Geological Survey borehole. All these beds, however, were limestones, and their inclusion in the Hampen Marly Formation seems to have been based on the presence of local wisps of mudstone. Otherwise they seem to have been identical to what was referred to as White Limestone in the Latton section.

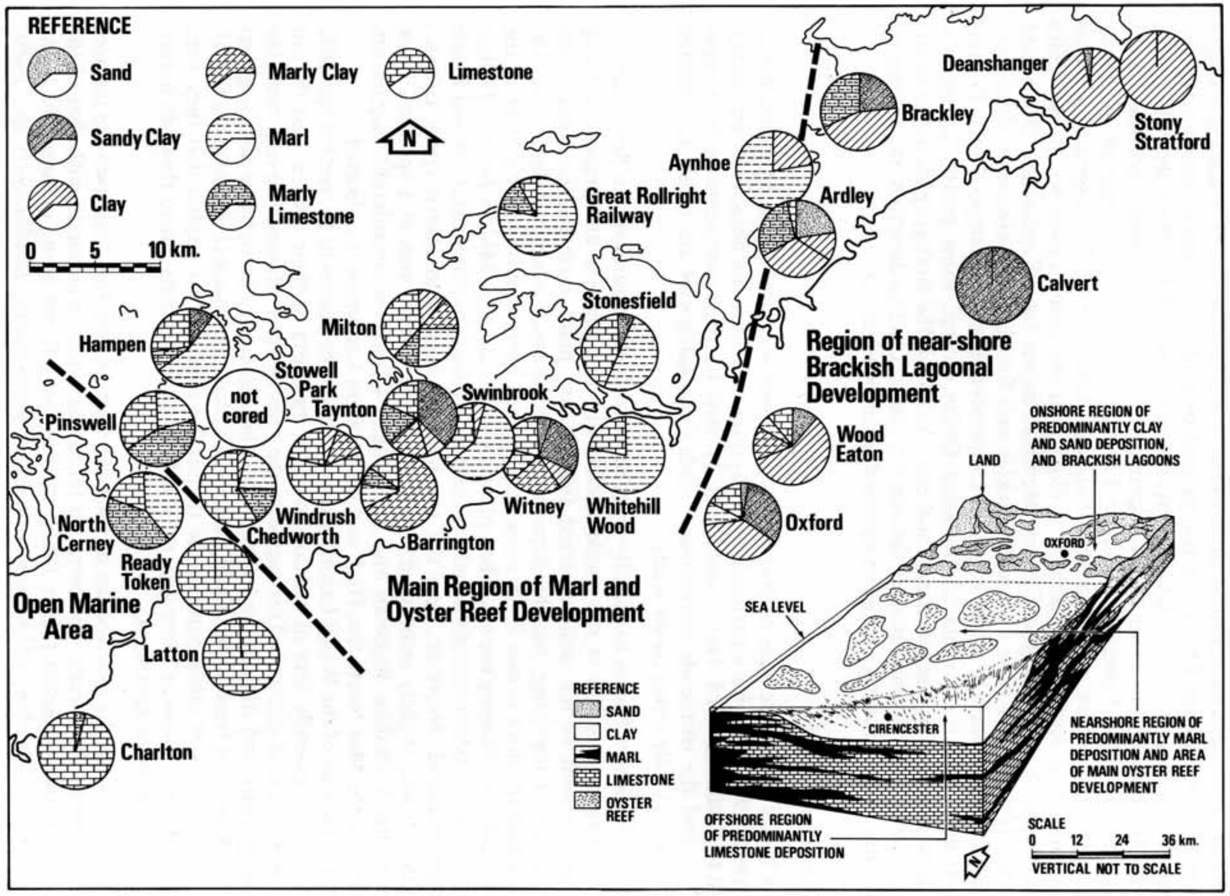
To the north-east of the study area the formation shows another change in facies into the clays of the Upper Estuarine Formation (Arkell 1951–1958, p. 14), although the precise relationship between the two formations is not entirely clear. Only one ammonite has ever been recorded from the Hampen Marly Formation—*Procerites imitator* (S. Buckman) from the base in the Ardley–Fritwell railway cutting—and none have been found in the Upper Estuarine Formation. However, the base of the overlying Great Oolite Limestone in Northamptonshire is considered by Torrens (1968), on the basis of ammonite evidence, to be younger than the base of the laterally equivalent White Limestone Formation in the Oxfordshire/Gloucestershire region. Similar reasoning indicates that the Upper Estuarine Formation is at least partly younger than the Hampen Marly Formation. The section at Croughton (text-fig. 3) supplies supporting evidence. Here the bottom beds of the White Limestone (the Shipton Member; see below) contain considerably more clay than the corresponding beds in Oxfordshire and Gloucestershire; they also contain rootlets, which are a feature typical of Upper Estuarine and Hampen Marly Formation conditions of deposition, rather than those of the White Limestone. Thus these lower beds at Croughton may represent the lateral transition from beds of White Limestone to the south-west, into beds of the Upper Estuarine Formation to the north and east.

At the base of the formation in the region around the type locality there are sometimes alternations of marls and cross-bedded calcarenites of typical Taynton Limestone facies, and it is not easy to decide on the precise junction between the two lithostratigraphic units (Richardson 1933). Similarly, the junction between the Hampen Marly Formation and the overlying White Limestone is seldom clear-cut, and the one formation passes into the other through an alternating sequence of marls and marly limestones. The nature of Hampen Marly Formation sediments is further affected by local variations between different depositional regimes within the formation; thus clays with freshwater fossils may pass vertically and laterally into limestones with marine fossils, and then into marls with rootlets (as at Wood Eaton), suggesting small-scale variations in relative sea-level of purely local distribution; perhaps associated with local changes in the conformation of emergent and submerged areas.

However, in spite of these complications, there are noticeable general trends within the formation. Field studies and previous accounts of the Hampen Marly Formation indicate that there is a marked change in their dominant lithology as one passes from north-east to south-west in the area over which they outcrop. To the north and east the formation is dominated by clays (sometimes sandy) and thin sands. Towards the south-east the proportion of marly clay and marl increases; further in this direction the marls start to become associated with small calcium carbonate peloids (usually referred to as ooliths by earlier authors) and beds of marly limestone. Eventually limestones completely replace the marls and the formation passes laterally into the base of the White Limestone Formation in the region around Cirencester.

These changes are shown on text-fig. 2. All available sectional details (see Table 1 for references) have been analysed, and the thicknesses of seven different lithologies (sand; sandy clay; clay; clayey marl and marly clay; marl; marly limestone; limestone) have been expressed graphically as a percentage of the total thickness of the Hampen Marley Formation seen at that particular locality. The variety of lithologies present in the Hampen Marly Formation at any one exposure is immediately obvious; in addition the three broad zones characterized by different sediment types can be distinguished. (i) The north-eastern and eastern area where clay and sand predominate. (ii) The central region where marls, marly clays, and marly limestones predominate. (iii) The south-western region where marly limestones and limestones predominate.

An exercise like this is not necessarily reduced in value by uncertainties in correla-



TEXT-FIG. 2. Relative proportions of different sediment types in exposures of the Hampen Marly Formation; see Table 1 for sources of information and map references of localities. The inset shows a putative environmental reconstruction.

tion. In the eastern part of the study area the Taynton Limestone Formation is absent beneath the Hampen Marly Formation, and beds of similar clayey facies extend to within a few metres of the Lias (see Davies and Pringle 1913 on the Calvert Borehole section). Possibly some of this thickening represents beds which are the lateral equivalent of the Taynton Limestone Formation, and perhaps part of the lower Great Oolite as well, although Sellwood and McKerrow (1974) suggest that this is absent east of Ardley. Similarly, it is likely that the bottom member of the White Limestone Formation (the Shipton Member) passes into a nearshore clayey and sandy facies in the region around Brackley and Buckingham. However, these considerations enhance the opinion that the sediments of both the Hampen Marly Formation and other formations of the Great Oolite Group, show greater terrigenous clastic influence to the north-east and east. Although the stratigraphic limits of the Hampen Marly Formation may become less distinct in this direction, the sediments are still predominantly clastic, as opposed to autochthonous.

### *Fauna and flora*

At Wood Eaton the base of Hampen Marly Formation bed 5 (the Monster Bed of Palmer 1973) contains a particularly well-preserved fauna and flora. I am very grateful to Professor T. M. Harris and Dr. R. H. Bate for their comments on the macroflora and the ostracods respectively. Both these categories are richly represented and would fully repay closer study.

*Flora*. Professor Harris has kindly pointed out several features of the flora: *Equisetites* is represented by *in situ* rootlets; otherwise this genus is unrepresented, being totally absent in the well-preserved fragmentary plant material. *Equisetites* was common in low-lying, marshy deposits of the Jurassic, while it is likely that the fragmentary flora comes from some way inland, being deposited by a river in the lowland area fringing the sea. The upland flora found in the Middle Jurassic Deltaic Series of Yorkshire consists largely of conifers, as does the fragmentary Wood Eaton plant material. However, here the resemblance stops, and Harris (pers. comm.) states: 'I was slightly astonished that none of the cuticles was of a species I knew from the Yorkshire Bajocian and Bathonian.' Clearly, a considerable separation between the Mid North Sea High and the London Landmass is indicated.

The cuticles of the Wood Eaton species are stated by Harris to be 'neither specially thick, nor specially thin in relation to other members of their classes, and do not suggest an arid climate'. This supports the idea of river drainage having been the transporting and depositional agent. The abundance of charophytes also suggests the influence of fresh water. Only the robust female receptacles (oogonia) are found, and fragments of other parts of the thallus are absent. This implies that they were derived from a source some way removed from the deposits where they are found, probably in lakes upstream.

*Microfauna*. Of the nine species of ostracod found in the bed, only two are marine, and these are both rare. The ostracod fauna has much in common with that of the Upper Estuarine Series (Aslin 1965), the following forms being common to both: *Lophocythere scabra*, *Micropneumatocythere postrotunda*, *Bisulcocypris sp.*, *Faba-*

*nella bathonica*, *Macrodentina* (*Mediodentina*) *bathonica*, and *Kliena levis*. In terms of both species represented, and total numbers of specimens, the ostracod fauna is predominantly brackish (R. H. Bate, pers. comm.). There are no wholly freshwater forms, and it seems likely that the ostracods lived in brackish lagoons fringing the shore, rather than being derived from up-river.

*Macrofauna*. The presence of several bones of *Cetiosaurus* suggests shallow swampy conditions with plenty of vegetation. Otherwise, the fauna of this bed is entirely molluscan (Table 2). The presence of *Viviparus* and *Valvata* indicates freshwater conditions. Usually when these forms occur in the Great Oolite they do so in great abundance, frequently to the exclusion of nearly everything else (Hudleston 1896; Palmer 1973). In this case, their rarity suggests that they have been derived from elsewhere, possibly the same freshwater source as the charophytes.

Several further species in the bed have been implicated as brackish or euryhaline forms, and there is a strong similarity between this fauna and the Bathonian faunas of the Hebrides (Hudson 1963*a*, *b*). *Cuspidaria ibbetsoni* and *Placunopsis socialis* are both suggested as being tolerant of slightly reduced salinities 25–30‰ (Hudson 1963*a*), and *Neomiodon* is thought by Hudson to be the dominant form at brackish water salinities of about 9‰, though ranging up into brackish marine and down into brackish/freshwater salinities. *Tancredia* and *Protocardia* have not before been implicated as brackish water forms, and probably had a fairly wide salinity tolerance.

It is well known that brackish-water faunas show a reduction in the number of species with large numbers of individuals, when compared with fully marine faunas (e.g. Hedgpeth 1957), and that at a higher taxonomic level certain groups (e.g. echinoderms, sponges, ectoprocts, and articulate brachiopods) are generally intolerant of salinities much below 35‰. This reduction in faunal diversity is true for the whole of the Hampen Marly Formation at Wood Eaton (Palmer 1973). Bed 2 of Palmer (1973), for example, also contains (except for a single echinoid spine) only molluscs, with *Eomiodon* and two species of *Corbula* accounting for 50% of the fauna (Table 2). On the other hand, the invertebrate macrofauna from these two beds still each contain fifteen different species (Table 1)—which is very different from the monotypic shell-beds typical of the Great Estuarine Series and other brackish-water deposits. There are two possible explanations for this apparent high diversity. First the species minimum is found not at salinities midway between fully marine (35‰) and freshwater (0–0·5‰), but shifted towards the freshwater end of the spectrum, at about 9‰ (Remane 1934). To the marine side of this value the fauna is of a restricted marine character, but not at a diversity minimum. Such a situation could explain the fauna in question if all the molluscs were euryhaline. The second, and more likely, explanation for their occurrence together is that some degree of mixing has occurred. This may have been brought about by current activity, but the relatively uniform nature of the sediment suggests that this has played only a minor part. What is more likely is that environmental conditions in the region of deposition fluctuated quite rapidly, as features such as rainfall, run-off, and conformation of the land varied, and the salinity of the water frequently changed. Under these changing conditions the nature of the benthos would fluctuate also, and the resulting death assemblage would be a mixture of species which lived in different environments. These fluctuations are

TABLE 2. Quantitative details of the fauna of selected beds from the Hampen Marly and White Limestone Formations of the study area.

**TABLE 2**

**KEY TO BIVALVE LIFE HABITS**
**(All are suspension feeders)**

- ◣ ADPRESSED BYSSATE
- ◮ FREE-SWINGING BYSSATE
- △ RECLINING
- ▲ CEMENTED
- ○ SEMI-INFAUNAL BYSSATE
- ▼ SLUGGISH, SHALLOW BURROWING
- ◗ ACTIVE, SHALLOW BURROWING
- ● DEEP BURROWING
- ▾ BORING

| | **Strat. Unit** | | HAMPEN MARLY FORMATION | | WHITE LIMESTONE FORMATION | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | SHIPTON MEMBER | | | | ARDLEY MEMBER | | | BLADON MEMBER | | |
| | **Facies** | | lagoonal clays | | coral bed | non coraliferous facies | | | lime sand | shelly micrite | | lime sand | coral bed | fimb - walt clay |
| | **Bed** | | Woodeaton HMF 2 | Woodeaton HMF 5 | Ardley WL 18 | Croughton WL 16 | Croughton WL 19 | Ardley WL 19 | Ardley WL 15 | Woodeaton WL 4 | Northbrook Fm WL 4 | Shilton WL 1 | Shipton WL 1 | Shipton WL 2 |
| | **Taxon** | **Life Habit** | | | | | | | | | | | | |
| **BIVALVIA** | Parallelodon hirsonensis (d'Archaic) | ◣ | | | | | | | 0.3 | | | | | |
| | Parallelodon bynei Cox & Arkell | ◣ | | | | | | | 0.3 | | | | | |
| | Cucullaea sp | ◣ | | | | | | | | | | | | 0.9 |
| | Eonavicula minuta (J. de C. Sowerby) | ◣ | 0.5 | | 11.9 | 0.5 | | | | 3.0 | 0.8 | | 2.1 | |
| | Barbatia pratti (Morris & Lycett) | ◣ | | | | | 4.6 | | | | | | | |
| | Modiolus imbricatus J. Sowerby | ○ | 6.6 | | 4.5 | 2.2 | 3.8 | | 0.8 | 5.7 | 13.4 | 1.2 | 2.4 | |
| | Modiolus (Inoperna) plicatus J. Sowerby | ○ | | | | 1.1 | 0.8 | | | 0.4 | | | | |
| | Lithophaga fabella (J.A. Eudes-Deslongchamps) | ▾ | | | | | 1.5 | | | | | | | |
| | Myoconcha acteon Morris & Lycett ex d'Orbigny | ◣ | | | | | | | | | | | 0.2 | |
| | Pteroperna costatula (J.A. Eudes-Deslongchamps) | ▲ | 4.9 | | | | | | 0.5 | | | | | |
| | Bakevellia waltoni (Lycett) | ◮ | | | 0.7 | 0.5 | | | | | | 4.9 | | 7.3 |
| | Costigervillia crassicosta (Morris & Lycett) | ◮ | | | | 0.5 | | | | 2.3 | 3.1 | | | |
| | Gervillella ovata (J. de C. Sowerby) | ◣ | | | | 2.2 | 5.3 | | | | 5.5 | | | |
| | Isognomon isognomonoides (Stahl) | ◣ | | | 0.7 | 1.1 | 9.9 | | | | | | | |
| | Isognomon (Mytiloperna) bathonicus (Morris & Lycett) | ◣ | 3.8 | | | | | | | | | | | |
| | Isognomon (Mytiloperna) murchisonii (Forbes) | ◣ | | 9.6 | | | | | | | | | | |
| | Pinna odlingi Arkell | ○ | | | | | | | | | | | | 0.9 |
| | Chlamys (Radulopecten) vagans (J. de C. Sowerby) | ◣ | | | | | | | | 0.4 | | | | |
| | Camptonectes annulatus (J. de C. Sowerby) | ◣ | | | 1.0 | | 2.3 | | | 3.8 | | | 0.2 | |
| | Camptonectes rigidus (J. Sowerby) | ◣ | | | | | 0.8 | | | | 0.8 | 0.6 | 0.7 | |
| | Hypotrema sp | ◣ | | | | | | | | 1.1 | 5.5 | | 1.6 | |
| | Placunopsis fibrosa Laube | ▲ | | | | | | | 0.5 | 1.1 | | | | |
| | Placunopsis socialis Morris & Lycett | ▲ | 9.3 | 5.8 | | | | | | | | | | 1.8 |
| | Lima (Plagiostoma) subcardiiformis Greppin | ◣ | | | 0.7 | | 0.8 | | | | | | 2.6 | |
| | Lima (Plagiostoma) bynei Cox & Arkell | ◣ | | | | | | | 0.3 | | | | | |
| | Lima (Plagiostoma) sp | ◣ | | | 0.5 | 0.5 | | | | | | | | |
| | Pseudolimea duplicata (J. de C. Sowerby) | ◣ | | | | | | | | 4.6 | | | | |
| | Limatula gibbosa (J. Sowerby) | ◣ | | | | | | 1.2 | | | | | | |
| | Ctenostreon rugosum (W. Smith) | △ | | | | | | | | 0.4 | | | | |
| | Praeexogyra hebridica (Forbes) | ▲ | 1.6 | | 8.2 | 1.1 | 6.1 | | | 15.1 | | 0.6 | 1.4 | |
| | Lopha costata (J. de C. Sowerby) | ▲ | | | | | 1.5 | | | | | | | |
| | Trigonia pullus J. de C.Sowerby | ▼ | | | 0.2 | 6.1 | 0.8 | | 0.5 | | | | | |
| | Trigonia (Vaugonia) moretoni Morris & Lycett | ▼ | | | | | | | 1.0 | | | 3.7 | | |
| | Neomiodon brycei (Tate) | ◗ | | 30.8 | | | | | | | | | | 14.5 |
| | Eomiodon fimbriata (Lycett) | ▼ | 13.2 | 1.9 | | | | | | | | | | 1.8 |
| | Anisocardia loweana (Morris & Lycett) | ◗ | | | | 51.9 | 9.2 | 16.2 | | | 5.5 | 41.7 | | |
| | Anisocardia islipensis (Lycett) | ◗ | | | | | | | | 0.8 | 22.8 | | | |
| | Anisocardia minima (J. Sowerby) | ◗ | | | | | | | | | | | 0.2 | 0.9 |
| | Pseudotrapezium cordiforme (Deshayes) | ◗ | | | | 3.3 | 2.3 | 5.0 | 3.6 | 0.4 | | 4.3 | | |
| | Eocallista antiopa (Thevenin ex d'Orbigny) | ◐ | | | | | | | 18.4 | | | | | |
| | Lucina bellona d'Orbigny | ● | | | | | | | | | | 3.1 | | |
| | Corbis lajoyi (d'Archaic) | ▼ | | | | | | | 0.5 | | | | | |
| | Sphaeriola oolithica (Rollier) | ▼ | | | | 2.2 | 0.8 | | | 18.1 | 0.8 | | | |
| | Tancredia truncata Morris & lycett | ◗ | | 0.6 | | | | | | | | | | |
| | Tancredia extensa Lycett | ◗ | | 1.3 | | | | | | | | | | |
| | Tancredia planata Morris & Lycett | ◗ | | 0.6 | | | | | | | | | | |
| | Quenstedtia bathonica (Morris & lycett) | ◗ | | | | 1.1 | | | 1.3 | | | | | |
| | Quenstedtia morrisi Cossmann | ◗ | | | | | | 1.2 | | | | 4.9 | | |
| | Protocardia lycetti (Rollier) | ◗ | | | 2.7 | 7.2 | 3.8 | | | 1.1 | 1.6 | 20.2 | | |
| | Protocardia buckmani (Morris & Lycett) | ▼ | | 3.8 | | | 0.8 | | | | | | | |
| | Protocardia stricklandi (Morris & Lycett) | ▼ | | | | | 3.8 | 2.5 | 2.1 | | 1.6 | 1.2 | | |
| | Protocardia sp | ▼ | 7.7 | 1.9 | | 0.5 | | | | | | | | 1.8 |
| | Pleuromya uniformis (J. Sowerby) | ● | | | | 1.1 | | | 4.1 | | | 1.2 | | |
| | Gresslya sp | ● | | | | 0.5 | 1.5 | | | | | | | |
| | Corbula hulliana Morris | ▼ | 24.7 | 17.3 | | | | | | 0.4 | 2.4 | | | 28.2 |
| | Corbula sp | ▼ | 12.1 | 23.1 | | | | | | | | | | |
| | Myopholas acuticosta (J. de C. Sowerby) | ● | 1.1 | | | | | | | | | | | |
| | Pholadomya deltoidea( J. Sowerby) | ● | | | 0.7 | 4.4 | 10.7 | 2.5 | | | | 0.6 | | |
| | Homomya gibbosa (J. Sowerby) | ● | | | | | | 17.5 | | | | | | |
| | Arcomya sp | ● | | | | | | 3.7 | | | | | | |
| | Cercomya undulata (J. de C. Sowerby) | ● | | | | 0.5 | 0.8 | | | | | | | |
| | Gastrochaenopsis sp | ▾ | | | 9.4 | | | | | | | | 10.4 | |
| | Cuspidaria ibbetsoni (Morris) | ▼ | 3.3 | 1.3 | 0.4 | | | 1.2 | 0.5 | | 3.1 | 1.8 | | 0.9 |

**TABLE 2 (cont.)**

**KEY TO MAIN GROUPS**

I = SPONGES
II = CORALS
III = WORMS
IV = CRUSTACEAN
V = GASTROPODS
VI = BRYOZOANS
VII = BRACHIOPODS
VIII = ECHINOIDS

| | **Strat. Unit** | | HAMPEN MARLY FORMATION | | WHITE LIMESTONE FORMATION | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | SHIPTON MEMBER | | | | ARDLEY MEMBER | | | BLADON MEMBER | | |
| | **Facies** | | lagoonal clays | | coral bed | non coraliferous facies | | | lime sand | shelly micrite | | lime sand | coral bed | fimb - wait clay |
| | **Bed** | | Woodeaton HMF 2 | Woodeaton HMF 5 | Ardley WL 18 | Croughton WL 16 | Croughton WL 19 | Ardley WL 19 | Ardley WL 15 | Woodeaton WL 4 | Northbrook Fm WL 4 | Shilton WL 1 | Shipton WL 1 | Shipton WL 2 |
| | **Taxon** | **Life Habit** | | | | | | | | | | | | |
| **I** | Limnoria sp | CD | | | 1.7 | | | | | | | | | |
| | Enaulofungia sp | CD | | | | | | | | | | | 0.5 | |
| **II** | Isastrea / Thamnasteria | FB | | | 1.5 | | | | | | | | 1.9 | |
| | Cyathophora pratti Edwards & Haime | FB | | | 0.2 | | | | | | | | | |
| | Chomatoseris sp | AR | | | | 0.5 | | | | | | | | |
| **III** | Serpula (Dorsoserpula) sp | ES | | | 0.5 | | | 3.7 | | 15.8 | | | 0.2 | |
| | Serpula (Cycloserpula) sp | CD | | | 1.5 | | | | | | | | 0.7 | |
| | Serpula (Tetraserpula) sp | ES | | | | | | | | | | | 0.2 | |
| | terebelloid | TS | | | | 0.5 | | | | 4.5 | 7.9 | | | |
| | Helminthopsis sp | VD | | | | | 0.8 | | | | | | | |
| **IV** | ? decapod | ?BD | | | | | 0.8 | 1.2 | | | | | | |
| **V** | Pleurotomaria sp | ?VS | | | 1.2 | | | | | | | | | |
| | Trochotoma obtusa (Morris & Lycett) | ?VG | | | | | | | | | | | 0.5 | |
| | Scurria bathiensis (Rollier) | VG | 4.4 | | | | | | | | | | | |
| | Chartrionella bunburii (Morris & Lycett) | VG | | | | | | | 1.8 | | | | | |
| | Amberleya bathonica Cox & Arkell | ?VG | | | | | | | | | | | | 1.8 |
| | Notodelphinula depauperata (Morris & Lycett) | VG | | | 0.2 | | 3.0 | | | | | | | |
| | Proconulus sp | VG | | | | | | | 0.3 | | | | | |
| | Pseudomelania sp | ?VG | | | 1.0 | 2.2 | 4.6 | | | | | | | |
| | Neridomus cooksoni (Deslongchamps) | VG | | | | | 3.0 | 3.7 | 1.3 | | 0.8 | 0.6 | | |
| | Brachytrema sp | VG | 6.0 | | | | | | | | | | | |
| | procerithiid | VG | | 1.3 | | | | | | | | | | |
| | Ceritella sp | ?VG | | | | | | 5.0 | | | | 3.7 | | |
| | Fibula phasianoides (Morris & Lycett) | ? IS | | | | | | | 0.5 | 0.4 | 1.6 | | | |
| | Cossmannea bathonica (Rigaux & Sauvage) | IS | | | | | | 1.2 | | | | | | |
| | Nerinella scalaris (d'Orbigny) | IS | | | | | | | 48.8 | | | | | |
| | Endiaplocus roissyi (d'Archaic) | ? IS | | | | | | | 1.5 | | | | | |
| | Dicroloma sp | ?VG | | | 0.5 | | | | 0.3 | | | 4.3 | | |
| | Globularia sp | IC | | | 2.5 | 6.1 | 3.8 | 2.5 | 0.3 | | | 2.4 | | |
| | Palaeohydatina sp | ?VC | | | | | | | 0.3 | | | | | |
| | Cylindrites sp | ?VC | | | | | | 1.2 | | | | | | |
| | Viviparus sp | VS | | 1.3 | | | | | | | | | | 40.0 |
| | Valvata sp | VS | | 1.3 | | | | | | | | | | |
| **VI** | 'Berenicea' sp | ES | | | 3.2 | | 3.0 | | | 11.0 | 12.6 | | 49.6 | |
| | Stomatopora dichotoma (Lamouroux) | CD | | | | | | | | 6.8 | | | | |
| | ? ctenostome | ES | | | | | | | | | | | 2.1 | |
| **VII** | Epithyris oxonica Arkell | ES | | | | | | | | 12.1 | 9.4 | | 22.2 | |
| | Epithyris sp | ES | | | 35.8 | | 5.3 | 3.7 | 0.3 | | | | | |
| | Digonella digonoides (S.S. Buckman) | ES | | | | | | | | 1.5 | 0.8 | | | |
| | Kallirhynchia concinna (J. Sowerby) | ES | | | 5.0 | | | | | | | | | |
| | Moorellina sp | CD | | | 2.5 | | | | | | | | 0.7 | |
| **VIII** | Acrosalenia hemicidaroides Wright | VG | 0.5 | | 0.5 | 1.1 | 1.5 | | | | | | | |
| | Pseudodiadema sp | VG | | | | | | | | 0.4 | | | | |
| | Clypeus muelleri Wright | DP | | | | | | 27.5 | | | | | | |

Figures indicate percentages of a bulk-sampled collection of the bed in question. Key to life habits is as follows: CD—cavity dwelling encruster (suspension feeder); FB—frame builder (suspension feeder/carnivore); AR—active recliner (suspension feeder); ES—exposed surface suspension feeder; TS—tube dwelling suspension feeder; VD—vagile deposit feeder; BD—burrowing deposit feeder; VG—vagile grazer; VS—vagile scavenger; VC—vagile carnivore; IS—infaunal suspension feeder; IC—infaunal carnivore; DP—deposit feeding plougher.

characteristic of lagoonal environments today (Shepard and Moore 1960), and are of sufficiently short period for the different shell assemblages not to be separated into different sedimentary strata.

That the restricted nature of the fauna is a response only to the adverse substrate is unlikely. Approximately contemporaneous clays, usually considered to have a fully marine origin, contain a very different bivalve fauna, e.g. *Nucula*, *Grammatodon*, *Oxytoma*, *Trigonia*, *Lucina*, and *Goniomeris* in the Fuller's Earth Clays of Dorset (Arkell 1933*a*, p. 253).

There is evidence in previously published literature that the sands and clays of the Hampen Marly Formation in the eastern part of the study area (see text-fig. 2) may also have been laid down under conditions of reduced salinity. In the Oxford City Brewery borehole (Pocock 1908), 8·60 m of 'Upper Estuarine Series', which may be referred to the Hampen Marly Formation, are recorded immediately beneath the White Limestone. Predominantly, they consist of sandy clays and black shales with abundant plant debris, some of it well-preserved. In two of these beds, is the only recorded species '*Cyrena*', a name often applied by early workers. In the sands and clays of the Ardley/Fritwell railway cutting (see Arkell *et al.* 1933), Odling (1913) records '*Cardium*' *stricklandi* (= *Protocardia stricklandi*), '*Cardium*' *incertum* (= ?*Protocardia morrisi*; see Cox and Arkell 1948) and '*Astarte*' *angulata* (= *Eomiodon angulata*). Both these genera include species found at Wood Eaton in the Hampen Marly Formation which may have been euryhaline. In their bed 17 at Ardley, Arkell *et al.* (1933) recorded rootlets of *Equisetum* and abundant ostracods 'of the *Darwinula* style'. *Darwinula* is a freshwater form (Van Morkhoven 1962–1963).

It would seem, then, that reduced salinities were of more than local influence in the control of facies and faunas over the eastern region.

Associated with the changing lithofacies across the region of Hampen Marly Formation outcrop are faunal changes. The brackish- and fresh-water indicators disappear; at Milton (text-fig. 2), for example, Aslin (1965) identified ten ostracod species, of which nine are considered marine and one brackish-marine, and there is a similar loss of beds with rootlets. Marls with abundant *Praeexogyra hebridica* become common, some reaching over 2 m in thickness (Richardson 1933). *Kallirhynchia concinna* is recorded occurring in some of these oyster beds, and, with the exception of occasional encrusters on the oysters, other species are not common. Where they are recorded, they are usually confined to limestones. This is probably due to preservational effects, the marls are soft and have undergone compaction. As a result of this all the originally aragonitic fossils are preserved as rather indeterminate composite moulds. These are difficult to identify even when sections are fresh, but as the beds weather the fossils are destroyed completely. Poorly preserved and unidentifiable bivalves can be found by digging back into the marls at old exposures, such as Milton Quarry. In contrast to this, forms which were originally calcite (e.g. *K. concinna* and *P. hebridica*), have not dissolved away during diagenesis, and weather out of the marls in good preservation. This gives the false impression that these forms dominated the assemblages when the rocks were laid down.

Nevertheless, *K. concinna* and *P. hebridica* do occur in enormous numbers in the Hampen Marly Formation. Richardson (1929) records a bed at Lower Swell which was over 2 m thick, and composed entirely of valves of *P. hebridica*. Similar beds, up to 2 m thick, are met frequently, and are reminiscent of the reefs formed by other oyster species ranging from the Jurassic (e.g. *Liostrea distorta* in the Purbeck) to the present day (e.g. *Crassostrea virginica* in the lagoons of the Texas Gulf coast). Hudson (1963*b*) and Hudson and Palmer (1976) have argued the similarities of *Praeexogyra* to *Crassostrea*, and it seems reasonable to look at the Hampen Marly Formation oyster reefs in the light of our knowledge of the present-day ones.

Most oysters require a hard surface on which to settle (Stenzel 1971, p. N1012). In gregarious oysters, larvae prefer to settle close to conspecific adults, which is obviously important in the maintenance of reefs. Presumably the first generation founding a new reef requires a substrate such as a shelly or coarse-grained bottom, rather than a soupy mud. The only way of determining whether the Hampen Marly Formation oysters obey this rule was to survey the previous literature (see Palmer 1974 for details) for all mention of what appear to have been oyster reefs (either oyster beds over 15 cm thick, or beds in which oysters are stated to have been very abundant), and take note of the underlying bed. Of the twenty-one Hampen Marly Formation oyster reefs considered in this way, all nineteen for which details of the underlying bed are known are supported by limestones. Although there is no evidence that these limestones were cemented at the time of oyster settlement, they no doubt formed a substrate that was firm enough and contained enough hard particles for the oysters to get established.

Once an oyster reef has become established, it greatly influences the nature of sedimentation in the vicinity (Lund 1957). Inorganic material in suspension is caught up in the feeding currents, and compacted into either pseudofaeces or faeces. These compacted pellets then behave as coarse sediment particles and sink to the bottom in the neighbourhood of the reef. Oyster beds are thus effective sediment accumulators, taking fine material in suspension, and depositing it as coarse grains, so that the beds are centres of rapid sedimentation. The fine pelleted nature of such deposits in the fossil record is not immediately obvious. However, where the sediment has been protected from agitation and compaction (e.g. inside a shell), it may sometimes still be seen to have a pelleted form.

It seems likely that the development of the predominantly marly facies of the Hampen Marly Formation, between the muddy brackish lagoons adjacent to the London Landmass and the offshore marine region, was closely associated with the development of the oyster reefs. The environment in which these reefs flourished was quiet, and not greatly current influenced. Hence, unpelleted fine material may also have been able to settle out. This situation would have been enhanced by the baffling effect of the reefs themselves.

On this model it is possible to explain the lateral transition of Hampen Marly Formation into expanded White Limestone in the Cirencester region: conditions became fully marine in the offshore, south-westerly direction, such that the conditions for the oyster-reef growth became unsuitable. At the present day, *Crassostrea* reefs cease normal growth during the high salinities above 36‰, and are replaced by *Ostrea equestris* under permanent fully marine conditions (Stenzel 1971). However, the encrusting fauna, typically of ectoprocts and foraminiferans, which is sometimes associated with the Hampen Marly Formation *P. hebridica*, suggests tolerance of the fully marine salinities. Therefore depth and increasing substrate instability seem the most likely reasons for the sudden loss of oyster reefs and the associated marls. Similarly, recent oyster reefs thrive best in shallow water (1–10 m deep—see Stenzel 1971).

In the Texas Gulf coastal lagoons at the present day the reefs themselves and the inter-reef areas support different animal communities (Parker 1960). In the Hampen Marly Formation the main inhabitant of the reef other than *P. hebridica* itself seems to have been *K. concinna*. This is in contrast to the more clayey environments in the Upper Estuarine Series and the Great Estuarine Series, where the main assiciate of *Praeexogyra* is *Modiolus* (Hudson 1963*a*) and the Recent situation where *Crassostrea* is associated with *Brachidontes* (Parker 1960). In addition to this, the Hampen Marly reefs are often encrusted by ectoprocts ('*Berenicea*' and *Stomatopora*), serpulids (*Dorsoserpula* sp.) and foraminiferans (*Nubeculinella* sp.), and occasionally bored by worms and ?phoronids. These associations are not found in the Upper Estuarine Series, and seem to suggest a much higher degree of marine influence than in those formations. The inter-reef assemblage of the Hampen Marly Formation, if present, is likely to have consisted of aragonitic infaunal bivalves and new fresh sections are needed before any attempt can be made to elucidate it.

### *Summary*

The available evidence, therefore, is consistent with the following model for the environment of deposition of the Hampen Marly Formation. In the east and north-east the London Landmass supported a fully terrestrial flora, and was drained by rivers. These rivers discharged into a system of lagoons around the edge of the land, whose salinities showed fluctuations. Further south-westwards these brackish lagoons came under a more marine influence. Occasionally, fully marine deposits were laid down. These sediments subsequently provided stable substrates for reefs of *P. hebridica* and an associated fauna, which greatly influenced the nature of the sediments in their vicinity by the self-sedimentation process and baffle action. These sediments were predominantly marls. Still further offshore (further to the south-west) deeper open marine conditions were unsuitable for the maintenance of oyster reefs, and the formation passes laterally into White Limestone facies. The approximate limits of these three broad regions are shown in text-fig. 2.

## THE WHITE LIMESTONE FORMATION

The White Limestone Formation is the best exposed and most fossiliferous subdivision of the Great Oolite Group between Burford and Buckingham. It varies in thickness along the outcrop between about 20 m in the Cherwell valley, and about 6 m in the most north-easterly part of the region. It is predominantly composed of well-cemented limestones. Locally, clay horizons are developed, but these nowhere attain the thickness and lateral extent which would justify their being classed as separate members within the formation.

The limestones which compose the bulk of the formation vary between sparites, originally deposited as grain-supported lime sands, and micrites, originally deposited as fine-grained lime muds. The dominant particles which make up the lime sands, and which are usually also common in the lime muds, are peloids and shell fragments.

The term 'peloid' implies doubtful origin (McKee and Gutschick 1969) but the vast majority of peloids in the Great Oolite Group were probably produced as the pseudofaeces or faeces of suspension and deposit-feeding animals. In Recent carbonate environments, such pellets start as soft accretions of sediment, but are known sometimes to harden slowly by a poorly understood process of intra-cementation, to form resistant particles of micritized rock (Illing 1954; Bathurst 1971), which behave as sand-sized grains. This process is likely to be the single most important factor controlling deposition of sediment in the White Limestone Formation. Other peloids may represent micritized shell fragments, and ooliths which have lost their concentric structure during diagenesis according to the sort of process described by Shearman, Twyman, and Karimi (1970).

Of the shell fragments, those derived from species whose shells were composed of calcite (at least in part) are invariably preserved in their original mineralogy, whilst fragments that were originally aragonite have always been subsequently dissolved, and are usually replaced by void-filling sparry calcite. They frequently retain their original outline in the form of a micrite envelope (Bathurst 1966).

Ooliths are locally common and sometimes abundant. However, many of the beds described as oolitic by earlier authors who saw small spherical grains in them are likely to have been peloidal rather than oolitic; it is often difficult to recognize the true oolitic structure in a hand specimen, even with a lens. Even if fractured pellets are seen, they frequently appear to be concentrically banded, because a micrite envelope or a ferruginous pellicle penetrates to some distance beneath the surface, and can give a false impression of accretionary banding. Although this distinction was recognized as important in the Great Oolite Group by Woodward (1894), subsequent workers tended to over-generalize, and the distinction between 'ooliths' and 'pseudo-ooliths' never became in England the commonplace that it did, for example, in France. Locally, compound intraclasts and larger limestone pebbles are also found, indicating nearby cementation and erosion.

The limestones at the top of the White Limestone Formation are almost invariably micrites, with or without scattered peloids and shell fragments. This fact makes the formation easily distinguishable from the overlying Forest Marble Formation in which micrite is usually absent. The two formations are further distinguished by the abundance of bioturbation in the White Limestone, which is probably associated with a high micrite content giving the sediment stability. The Forest Marble, in contrast, was a loose grain-supported lime sand and contains very few burrows. Consequently the original bedding is usually preserved.

The origin of the micrite in the White Limestone Formation is not obvious. That it originated as lime mud, and is not a diagenetic fabric, is indicated by the frequency with which it forms a matrix within which other particles are embedded. Under the scanning electron microscope it appears as minute granular calcite crystals, which are presumably recrystallized aragonite. Therefore neither morphology nor isotope chemistry of the mud particles can be expected to show whether the original sediment had an inorganic or an organic origin. It is assumed that breakdown of skeletal material, particularly of calcareous algae, was the principal source of the lime mud as it is today.

### *Lithostratigraphy of the White Limestone*

The White Limestone Formation falls within the ammonite zones of *Tulites subcontractus* to *Prohecticoceras retrocostatum* (Torrens 1968). Schemes of further subdivision have been based on specific faunal marker horizons, some of which appear to extend over most of the region between Burford and Buckingham. Others, however (e.g. the Upper *Epithyris* Bed of the Cherwell valley), are of more limited geographic extent. In both cases these horizons mark constant lithofacies, supporting a characteristic fauna. They do not necessarily represent time lines.

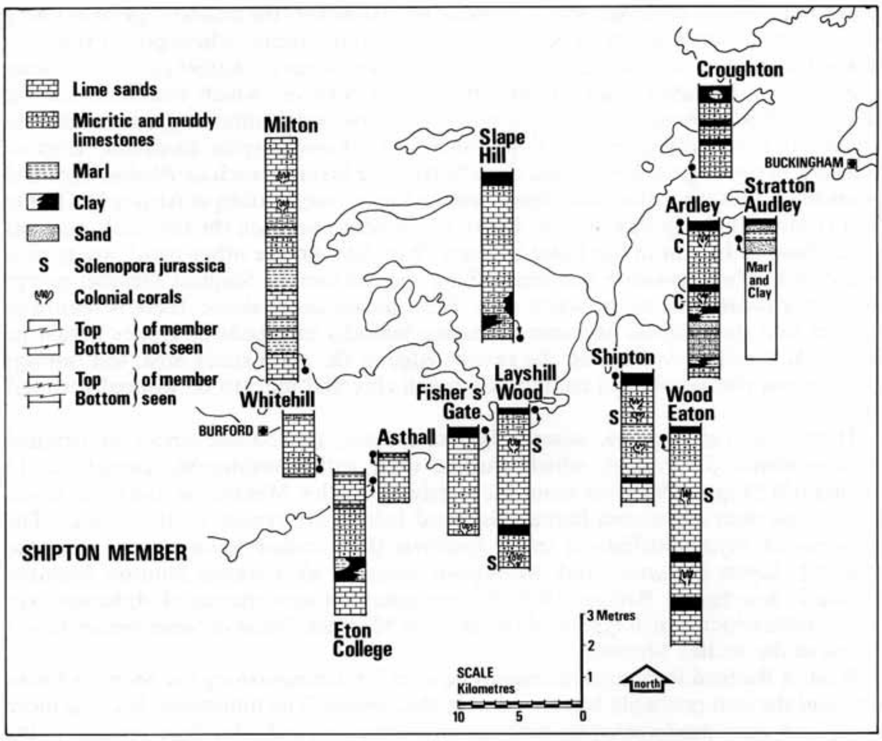
Arkell (1931) introduced a scheme of subdivision based on nerineid gastropods, distinguishing the upper third of the formation (*Aphanoptyxis bladonensis* Beds). Recently, Barker (1976) has extended this scheme by recognition of a third species of *Aphanoptyxis*, *A. excavata*, which occupies a zone approximately equivalent to the lower half of Arkell's *ardleyensis* Beds.

These high-spired gastropod horizons, which also include the *Nerinea eudesii* bed (actually a species of *Nerinella*) which Arkell (1931) first noted at a level about 4 m below the top of his *ardleyensis* zone, have considerable value in correlation over short distances and in field recognition of sections. Nevertheless, the control of all these species by lithofacies is strong, and their use as stratigraphic markers must be seen in the light of considerations of changing palaeogeography. The scheme of subdivision employed here is based on lithology, and it has proved possible to recognize three cycles of sedimentation within the White Limestone Formation. These cycles are interpreted as representing relatively rapid episodes of deepening, followed by a filling-in of the basins thus created. The resultant sequence of facies from deep to shallow is not everywhere identical, but correlation of slightly different sequences which can nevertheless both be interpreted as shallowing upwards, seems empirically more useful than correlation by facies dependent species in nearshore heterogeneous environments.

The three shallowing upwards cycles here recognized comprise, in ascending order, the Shipton Member, the Ardley Member, and the Bladon Member (text-fig. 1).

*The Shipton Member*. The type section of the lowest member of the White Limestone Formation is at Shipton quarry (see text-fig. 3). This member has previously been called the Croughton Member (Palmer 1974). However, these beds can no longer be seen at Croughton, whereas a new section throughout the whole of the member can now be seen at Shipton Cement Works.

The Shipton Member is characterized by both sparitic, micritic, and muddy limestones, alternating with thin clays and marls. In the south-eastern part of the study area (Wood Eaton and Shipton) there is a tendency for the proportion of fines to increase upwards. The over-all proportion of clastic material, both as individual beds and as disseminated fine sand grade quartz and clay in the limestones, is greater than in the overlying Ardley Member. The limestones are furthermore rather more poorly cemented than those in the Ardley Member. This is clearly seen in thin section, where the inter-granular pores are often filled with clay, unfilled, or collapsed, whereas a well-developed calcite cement is the rule in the Ardley Member. This poorer cementation is also obvious in the field: the limestones are softer, and allow the frost to penetrate their surfaces and cause a rough exfoliation of the superficial layers. Furthermore, after the solution of the original aragonite of the gastropods and many of the bivalves, the surrounding matrix was often not sufficiently cemented to hold open the resulting voids, so there is usually no calcite replacement. Thus fossils that were originally aragonite are frequently preserved in the Shipton Member as composite moulds.



TEXT-FIG. 3. Thickness and sediment types of the Shipton Member (White Limestone Formation) in the main study area.

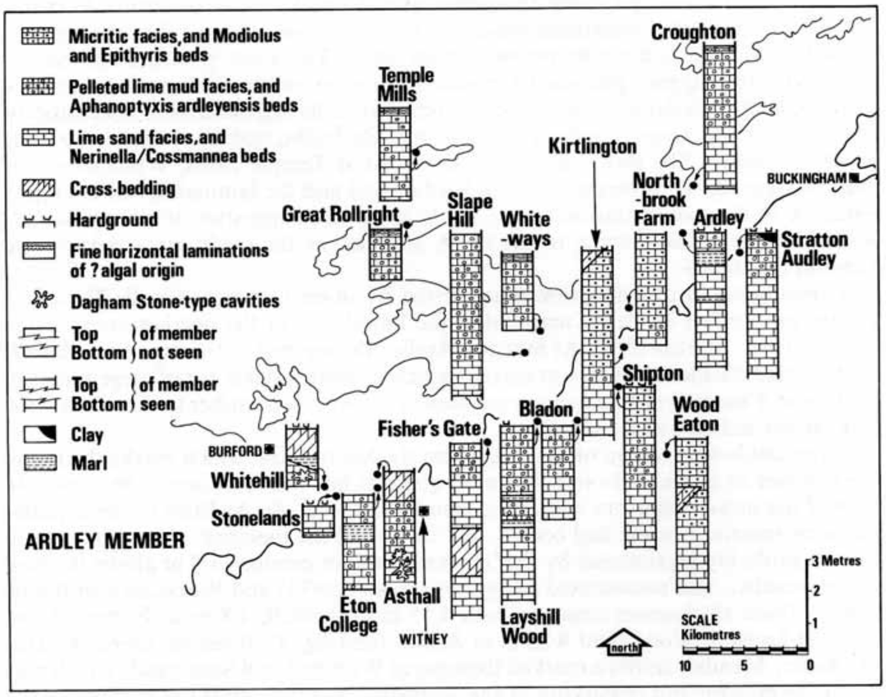
The junction between these two members is easy to recognize at all the localities shown in text-fig. 3. The bottom bed of the overlying Ardley Member throughout the study area is invariably a thick, massive, well-cemented biopelsparite, which may become dearagonitized at its base (e.g. the Roach Bed at Ardley). This bed contains a rich fauna of burrowing bivalves as well as large nerineid gastropods (Table 2), and the solitary coral *Chomatoseris*. Beneath this the top bed of the Shipton Member is a clay in the north-eastern region (Croughton, Ardley) and passes south-westwards into a sandy clay or marl which is often laminated. The soft nature of this bed allows it to weather back rapidly beneath the hard overlying basal bed of the Ardley Member, which then sticks out and forms a prominent overhang which is a characteristic of all weathered vertical faces in this part of the White Limestone Formation (e.g. Slape Hill; Fisher's Gate, North Leigh).

As discussed above, the junction between the Hampen Marly Formation and the base of the Shipton Member is gradational. At some localities (e.g. Shipton) the basal Shipton Member Limestones are sparites, in contrast to the marly limestones in the upper parts of the Hampen Marly Formation. However, the easiest way of defining the base of the latter seems to be on faunal and floral criteria; where good exposures of the beds either side of the contact are seen, the fauna of *Kallirhynchia concinna*, *Praeexogyra hebridica*, and shallow burrowing bivalves which characterizes the Hampen Marly Formation, is replaced upwards by beds containing a more diverse fauna often including corals, *Stiphrothyris*, *Epithyris*, *Lopha costatum*, *Clypeus muelleri*, nerineid gastropods, and deep burrowing bivalves such as *Pholadomya* and *Homomya*. This transition was clearly seen in the railway cutting at Ardley by Odling (1913) and Pringle (in Arkell *et al.* 1933); the junction between the two units here lies at the base of bed 20 in the latter account. Rootlets, on the other hand, are typical Hampen Marly Formation features and are absent from the Shipton Member except in the north-east part of the study area. Here, as discussed above, there is reason to suspect that the Shipton Member is passing laterally into beds of Upper Estuarine facies. At Stratton Audley, on the eastern edge of the main study area, test borings have shown the member to contain too much clay and marl to be worked for road metal.

There are, furthermore, several faunal criteria, the consequences of original environmental differences, which can be used with considerable confidence to distinguish Shipton Member from the overlying Ardley Member in the field. Coral shoals and their associated fauna (discussed below) are typical of the former. The presence of rhynchonellids, a small *Epithyris* (here called *Epithyris* sp.), *Clypeus muelleri*, *Lopha costatum*, and *Solenopora jurassica* all indicate Shipton Member (Table 2; text-fig. 3). Barker (1976) has recognized a new species of *Aphanoptyxis*, *A. excavata* which is also typical of the Shipton Member. None of these species have I found in the Ardley Member.

West of Burford these criteria cannot be used for distinguishing the Shipton Member, and the unit probably has no value in that region. The limestones become more pure, and were predominantly well-sorted oolitic and peloidal lime sands. At the same time the coral shoals and their associated faunas die out. Presumably the sea bottom was sufficiently agitated and unstable to be unsuitable for predominantly sedentary epifaunal faunas of this sort. As Worssam and Bisson (1960) point out, this region is also marked by a general thickening of the White Limestone as a whole, and represents the boundary between the London Platform and the Severn Basin.

*The Ardley Member*. The type section of the Ardley Member is taken at Ardley Fields Farm Quarry (text-fig. 4) on the north-eastern boundary of Oxfordshire. The member includes all the beds given in the account of Palmer (1973) between the hardground at the top of bed WL 5, and the base of bed WL 15. The top of the member coincides with the top of the Ardley Beds of Arkell (1947), as defined in the railway cutting adjacent to the quarry at Ardley. The lower part of the massive basal bed, which immediately overlies the top clay of the Shipton Member, contains a fauna exquisitely preserved as moulds. This is the Roach Bed of Arkell *et al.* (1933). The basal bed is a well-cemented biopelsparite with a characteristic molluscan fauna which is discussed more fully below. As stated above, it is easily distinguishable throughout the study area standing out above the softer Shipton Member. In the Burford region this bed has been burrowed, and takes on the appearance of Dagham Stone (text-fig. 4). This name is given to a particular texture of hard limestone with open crustacean burrow systems preserved (Fürsich and Palmer 1975).



TEXT-FIG. 4. Thickness and sediment types of the Ardley Member (White Limestone Formation) in the main study area.

The top of the member represents a considerable period of time during which no, or minimal, deposition of sediment took place. This depositional break is frequently marked by a hardground (text-fig. 4), which is bored and encrusted, and often has a knobby ferruginous surface suggestive of burrowing activity before cementation occurred. Locally, the borers and encrusters are absent, but the same knobby ferruginous surface is recognizable.

In the north and eastern part of the study area, the depositional break is marked by a different fabric. This is a thin bed (up to 10 cm) of finely laminated limestone. In thin section the laminae are seen to be composed of thin fining-upwards units (1-4 mm) entirely made up of small peloids and occasional quartz grains. The top surfaces of the laminae sometimes support a very thin ferruginous layer, which may be an indication of a former algal coating. The bed contains crustacean burrows filled with faecal pellets, vertical sparry calcite filled worm burrows, and the gastropod *Valvata*. This represents a similar fauna to that locally seen in the bed which caps the Bladon Member in the north-east region, and which is supratidal in origin (Palmer and Jenkyns 1975). However, the laminated bed at the top of the Ardley Member is less micritic and does not show desiccation shrinkage. The similar vertical burrows, and the presence of laminations which are possibly algal, suggest that it may have formed in a zone subject to periodic emergence. The local presence of *Valvata* towards the top suggests periodic freshwater saturation which may have been supplied by rainfall. This laminated bed is itself capped by a hardground, and encrusted by large flat oysters (*Liostrea wiltonensis*) at Great Rollright, and by small *Nanogyra* at Stratton Audley. The bed is also well developed at Temple Mills, Whiteways, and Shipton (text-fig. 4). Whereas both the hardground and the laminated bed are representative of the sedimentation break, the latter is also suggestive of emergence and is evidence for a shallowing, in the north and east of the study area, towards the London Landmass.

A shallowing in this direction is suggested by other features as well. There is a greater proportion of clastic material in the limestones of the north-eastern region (Odling 1913; Martin 1958). At Stratton Audley the top bed of the member is locally cut by small channels, up to 4 m across, which contain a basal lag of large pieces of driftwood. Channels of this sort are not seen in the Ardley Member to the south-west, and further indicate nearby land.

In the south-west region of the study area the hardground which marks the top of the member at Stonelands and Whitehill quarries lies only just over 2 m above the base of the massive bottom bed of the member (text-fig. 4). At Eton College quarry the same massive bottom bed occurs, and the top of the member, although not now seen, is probably represented by the 'marked plane of erosion' 3·2 m above the base of the member, and commented on by both Arkell (1931) and Worssam and Bisson (1961). These thicknesses compare with 4·55 m at Asthall, 4·8 m at Fisher's Gate, 5·8 m at Layshill Wood, and 4·55 m at Ardley (text-fig. 4). It seems, therefore, that the Ardley Member shows a marked thinning at Whitehill and Stonelands which may be due to erosion and reworking of the sediment. At Stonelands the hardground at the top of the member truncates the fossils embedded in the matrix, clearly indicating some compaction or early cementation followed by an erosive period. Similarly, there is clear evidence of reworking at Whitehill, where the cross-bedded biopelsparite immediately below the hardground contains large angular clasts of compacted marly limestone which were presumably torn up from nearby during some disturbances such as a storm. Probably these trends are again associated with the passage westwards from the London Platform into deeper water.

Over the study area as a whole, examination of the rocks both in the field and in thin section allows three principal lithofacies to be recognized.

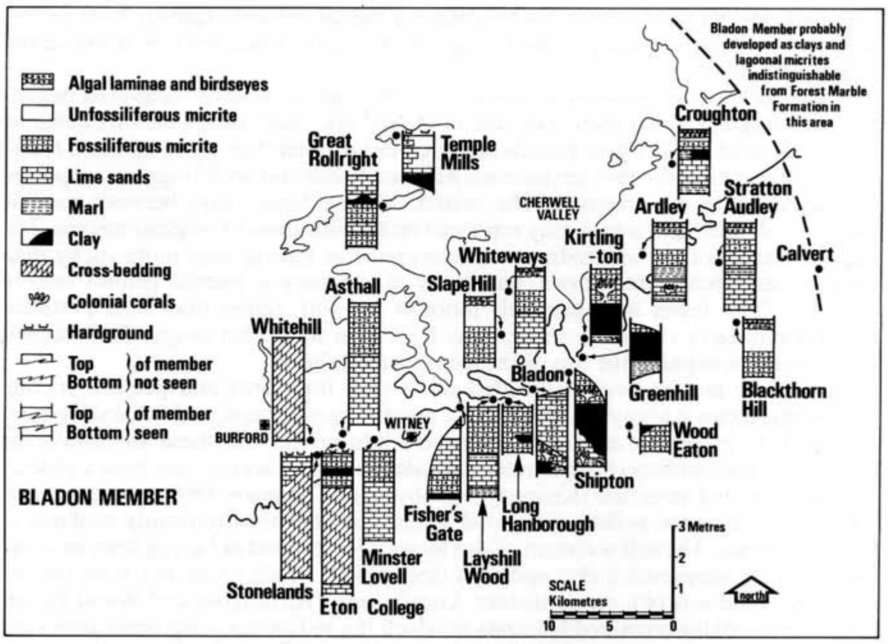
1. A well-sorted pelletal and skeletal lime sand, locally with ooliths, and containing virtually no lime mud. Except in the case of roach beds, this facies is invariably cemented into hard massive units by a coarse sparry calcite cement which also replaces the predominantly aragonitic fauna. The peloids and shell fragments often show a well-developed micrite envelope or a ferruginous pellicle which suggests that they were rigid discrete units, rather than soft compacted ones, and the original soft sediment is interpreted as being loose. This facies predominates in the south-west of the region, where the member shows marked thinning; in this region, cross-bedding is common. Over the rest of the study area this facies is characteristic of the lower beds of the Ardley Member, and cross-bedding is generally absent. Locally beds of this facies are made up of thin (5-mm) fining-upwards units which may be storm settle-outs (Klein 1965).

2. A poorly sorted pelleted lime mud, which locally consists of scattered peloids and shell fragments in a matrix of lime mud, and elsewhere shows distinct pelleting of the lime mud itself. These peloids are often less distinct than those in facies 1, and do not always have the thin ferruginous pellicles. Shells and shell fragments replaced by sparry calcite are common. The matrix of these beds varies between micrite, sparite, and microspar which may represent recrystallization of original micrite. The original texture of the soft sediment is interpreted as having been more sticky than the lime sand considered above, and many of the discrete micrite peloids seen in sections of this facies were probably more or less soft, rather than rigid particles. The top surface of the soft sediment may have been somewhat soupy. This facies is more common towards the top of the member (text-fig. 4).

3. A shelly micrite, with associated small shell fragments and peloids. In thin section this facies is always composed of a micritic groundmass, and is locally poorly cemented. In places the micrite is compacted into pellets, but these are always the discrete microcoprolites (*Favreina decemlunulatus*) of crustaceans, and have a characteristic shape and structure (Kennedy, Jakobson, and Johnson 1969) not seen in the micrite peloids of the pelleted lime mud facies. They are also frequently confined to burrow systems. The soft sediment of this facies is interpreted as having been firm and fairly stiff. It supported a rich epifauna (see below), which could not have thrived if the lime mud was of a soupy texture. Locally, as at Kirtlington and Wood Eaton, this facies contains cross-bedded units in which the millimetre scale laminations are picked out as alternations of shelly debris and fine lime mud. The shelly micrite facies is only seen at Wood Eaton, in the Cherwell valley (Shipton and Kirtlington), and at Northbrook Farm. It occurs at the top of the member, forming what is probably a continuous unit over this region (text-fig. 4). It sometimes occurs above beds of the pelleted lime mud facies (as at Kirtlington), and sometimes replaces them (as at Wood Eaton).

*The Bladon Member*. The Bladon Member is the topmost subdivision of the White Limestone Formation. Arkell (1931) did not appreciate the autonomy of this unit, and ascribed the beds here included in it to the sublithographic facies of the Kemble Beds, the *fimbriata-waltoni* Beds (in the region of the Cherwell valley), and the Middle *Epithyris* Bed. Later, Arkell (1947) revised the classification and regarded the latter two units as within his Bladon Beds (subzone of *Aphanoptyxis bladonensis*), which also included locally beds here taken as the top of the Ardley Member (e.g. Arkell 1947, p. 57).

It is because of Arkell's use of the term Bladon Beds, that the name is retained and given member status here. The type section is therefore taken to be at Old White House Quarry, Bladon, and includes beds 2 to 7 inclusive of Arkell (1933*b*). In the Cherwell Valley (e.g. McKerrow, Johnson, and Jakobson 1969) this includes the beds between the top of the Upper *Epithyris* Bed and the base of the Middle *Epithyris* Bed. Principal variations in facies and thicknesses are shown in text-fig. 5.



TEXT-FIG. 5. Thickness and sediment types of the Bladon Member (White Limestone Formation) in the main study area.

The stratigraphic limits of the Bladon Member are easily recognizable. At the bottom it is nearly always seen resting on top of the hardground or non-deposition surface which caps the underlying Ardley Member. At the top the sediments of the overlying Forest Marble Formation usually consist of thick pure clays or cross-bedded shelly oolitic limestones with thin clay partings, which stand out in contrast to the underlying micrites of the Bladon Member. Furthermore, in the north-east part of the study area the top bed of the Member is developed as an algally laminated micrite with birdseyes and desiccation cracks (Palmer and Jenkyns 1975) which is quite unmistakable and totally unlike any other bed in the Great Oolite. In the Burford region, where the Bladon Member becomes cross-bedded and oolitic, the top is usually marked by a hardground. Above this the oobiosparites of the Forest Marble contain more oyster debris than the underlying beds. Abundance of oysters, however, cannot be used to distinguish Forest Marble from Bladon Member over the whole of the study area.

The lithologies represented in the Bladon Member are more varied than those seen in the lower members of the White Limestone; nevertheless their geographic distribution fits in to form a concise and simple pattern of marginal marine sedimentation and palaeogeography. The laminated birdseye bed mentioned above indicates supratidal deposition. The genesis, distribution, and palaeogeographic implications of this bed (called 'unfossiliferous Cream Cheese Beds' by earlier workers) have been fully discussed by Palmer and Jenkyns (1975) and do not need stating again. The distribution of this formerly emergent island barrier, however, is the key to the processes controlling sedimentation at the top of the White Limestone and throughout the Forest Marble Formation.

Wherever the laminated micrites of the emersion horizon are seen, the laminations diminish downwards, and the bed becomes fossiliferous. At the same time, the sediment contains more shell fragments, and may locally become pelleted so that it resembles the pelleted lime mud facies of the Ardley Member. It is in this facies, immediately underlying an horizon which was clearly deposited in supratidal conditions, that one would expect to find indications of intertidal conditions if such existed. I have found none in spite of careful searching. The fossiliferous micrites at this level do show bioturbation mottling, but the absence anywhere of signs of tidal activity or intertidal exposure are taken as strong evidence against the Great Oolite sea having exhibited significant diurnal tidality. This is discussed more fully below.

The unlaminated fossiliferous micrite was probably deposited as a somewhat soupy lime mud in less than a metre of water. Locally (as at Bladon, Long Hanborough Station, Temple Mills), this facies forms the top of the Bladon Member, and the emersion horizon is absent (text-fig. 5).

In addition to the tendency for coarser-grained sediments to predominate in the lower part of the Bladon Member, there is also a tendency for the sediments to become coarser passing south-westwards. Massive biopelsparites with subsidiary ooliths occur in the lower Bladon Member at Layshill Wood, Fisher's Gate, and Minster Lovell. Further towards Burford the proportion of ooliths increases, and cross-bedded calcarenites of varying composition make up most of the member. These cross-bedded calcarenites are well developed at Whitehill and Stonelands quarries where they have been called Kemble Beds (e.g. Martin 1958). In thin section, well-developed oolitic structures are not usually seen clearly. On close scrutiny, however, some of the grains show a poorly developed system of concentric bands, sometimes round a nucleus. They are interpreted as ooliths which have undergone diagenetic micritization, with almost total loss of their original concentric laminations, in a process similar to that described by Shearman *et al.* (1970). They appear to have been deposited on submarine shoals deposited by the agency of periodic currents sweeping from the north-west (Palmer and Jenkyns 1974). Locally these shoals emerged, and subaerial cementation with early dissolution of the aragonite fauna occurred. Such a hardground is seen capping the Bladon Member at Stonelands quarry.

Beds containing abundant branching corals occur in the central part of the study area (see text-fig. 5). One of these beds, the Upper *Epithyris* Bed of Arkell (1931), forms a constant horizon at the top of the Bladon Member, in the region of the Cherwell Valley. This is the same region as that to which the *fimbriata-waltoni* Beds are confined (see below). This coral bed is the lateral equivalent of the emersion horizon.

The corals appear to have colonized firm substrates containing shell material, and then to have grown up in arborescent growths above the surface of the substrate. As in the coral beds of the Shipton Member, regions of still water persisted down amongst the stems of the corals, and dead shells and micrite accumulated there.

McKerrow *et al.* (1969) assumed that beds of this facies at Kirtlington represented a transported assemblage. This, as Allen and Kaye (1973) point out, is contrary to the evidence of (i) abundant micrite; (ii) the geopetal fills in most of the articulated brachiopods; (iii) the concave-up position of most of the single *Epithyris* valves. Allen and Kaye's analogue of Florida back-reef corals is equally mistaken: the quiet conditions amongst the fronds are much more analogous to conditions in Florida *Porites* shoals where mud and shells similarly accumulate due to baffle action.

Well developed in the quarries of the Cherwell valley, and best seen at Shipton quarry, is a thin sequence of fine-grained clastics and associated marls called the *fimbriata-waltoni* Beds by Arkell (1931), and the *fimbriatus-waltoni* clays by McKerrow *et al.* (1969).

At Shipton, this horizon can be followed along the whole of the south-west face, and can be seen to vary between thicknesses of 0·8 and 1·9 m. McKerrow *et al.* (1969) noted that it appeared similarly continuous at Kirtlington. On close inspection, however, this horizon at Shipton is seen to be made up of complex interdigitation of laterally impersistent clay beds, some of which are lens-shaped when seen on a vertical face. Disturbed contacts between these beds occur locally and suggest that deposition of some of the clays was also local and catastrophic. The coarser silty beds are confined to channels within the clays, and are frequently lined by a driftwood lag. Some of the clays contain evidence of erosion in the form of stringers of carbonate pellets or larger pebbles of micritic limestone of a similar lithology to the 'Cream-Cheese' limestone mentioned above. Klein (1965) considered these to have been caliche nodules formed by *in situ* growth of calcium carbonate, forming irregular masses. Many of these nodules, however, contain shells and microfossils, and are locally clearly peloidal in texture rather than uniformly crystalline or banded as is real caliche (Bernard, Le Blanc, and Major 1962). The rounded, knobbly shape of the pebbles is atypical of eroded clasts, and this has probably contributed to their not being recognized in the past. This shape may be due to partial nodular cementation within the bed from which they were originally derived, so that only the nodules withstood reworking.

The *fimbriata-waltoni* clays are interpreted as having been deposited under predominantly quiet-water lagoonal conditions, subject to periodic current activity and influx of new sediment, perhaps during storms. The impersistent nature of the clays, and the local development of shelly marls suggests that the environment was heterogenous, probably a complex system of marsh and creeks, with local carbonate mud mounds, the precise conformation of which was always changing. This picture is supported by faunal evidence of brackish water (see below) and driftwood. Orientation of this driftwood indicates origin of the clays from the north-east (Allen and

Kaye 1973); the direction of the London Landmass, from which one would expect freshwater influence to come.

### *Fauna of the White Limestone Formation*

The nature of the fauna in the White Limestone was naturally strongly influenced by the nature of the soft substrate. This is true both for those assemblages dominated by infaunal species, of which the vast majority are bivalves and gastropods, and also for the sessile epifaunal forms. The latter are predominantly found in those micrites or muddy limestones which are interpreted as having been coherent, pasty, and firm prior to lithification. Loose, unstable lime sands (now forming sparites), and certain clays and lime muds which were probably soupy when forming the sea floor, contain few sessile epifaunal species. Their faunas are dominated by burrowers, the morphologies of many of which can be interpreted as being directly adapted to coping with the exigencies of the particular enclosing sediment.

The following account of the principal faunal communities recognizable in the White Limestone is based on field observation over several years of hundreds of beds of the principal lithological types discussed in the previous section (see Palmer 1974). Where they have been readily available, bulk samples of the faunas typical of the various lithologies have been made. These were prepared in the laboratory and analysed quantitatively. The details of some of these bulk collections are shown in Table 2, and serve as examples, rather than as rigid descriptions, of the communities herein recognized.

*Coral Beds*. The most conspicuous of the White Limestone communities is provided by the beds with abundant colonial corals seen in the Shipton and Bladon Members (see text-figs. 3 and 5). This community is absent from the Ardley Member in the study area. These coral beds are soft or well-cemented limestones, and the corals themselves are invariably replaced by sparry calcite, so that only their superficial features are observed. In previous accounts they have usually been referred to species in either of the two genera *Thamnasteria* and *Isastrea*, according to whether they have, respectively, confluent septa with beaded margins, or distinct corallite walls and entire septa. McKerrow *et al*. (1969) recognized that intermediate forms occurred in the White Limestone, and that corallites of apparently different genera sometimes appear on the same specimen. Since the fine details of septal structure on which these two genera can best be distinguished (Wells 1956) are never preserved, it is best to consider the distinction between them as not proven. I have therefore not separated them in this account.

The total fauna of the coral beds may be subdivided into five different ecological groups:

1. Frame builders: *Thamnasteria* and/or *Isastrea* predominate in this role. Other corals occasionally occur, belonging to two genera: *Cyathophora*, a massive form with a well-developed coenosteum, is found in the Shipton Member at Ardley, Wood Eaton, and Shipton, and the solitary *Montlivaltia* is found in the Shipton Member only, at Milton and Shipton.

The colonial corals usually show a branching, dendritic growth form suggestive of quiet-water conditions, but massive knobbly heads also occur. The corals in the base of the Bladon Member at Shipton, however, grow as thin platy laminae over the surface of shell debris. This form is suggestive of the platy growth form of Recent *Montastrea annularis*, in which it is a light gathering response restricted to darker environments (Graus and McIntyre 1976). It is not clear whether a similar control in the base of the Bladon Member might have been a response to greater depth or greater turbidity than higher up in the unit.

2. An organohesive fauna: this term is coined to cover sessile animals which are attached to the substrate by organic tissue, which decays on death, so that the shell may not finally be buried in life position. The main groups falling into this category are pedically attached brachiopods, such as a small *Epithyris* sp. which occurs in all the Shipton Member coral beds, and byssally attached nestling bivalves, of which *Eonavicula minuta* and *Plagiostoma subcardiiformis* are the most common. In the Bladon Member, *Epithyris* sp. is absent, and the same niche is filled by the larger, more plicate *E. oxonica*. It occurs in vast numbers in all growth stages. Individuals often show interference in their growth caused by crowding, and large specimens may have up to thirty sites of attachment of younger individuals (*Podichnus*) on their surfaces. They presumably lived in clusters amongst the coral fronds. Rhynchonellids also occur, but are much more common in the Shipton than the Bladon Member.

3. A boring and encrusting fauna: predominantly of small and inconspicuous species which are obligate hard substrate dwellers, relying on pieces of coral rubble and shell material for attachment; the main encrusting species are the thecideacean brachiopod *Moorellina*, the ectoprocts '*Berenicea*' and *Stomatopora dichotoma*, *Serpula* (*Cycloserpula*) *sp.* and small calcisponges. These forms probably lived well down in sheltered microenvironments amongst the coral rubble (see Palmer and Fürsich 1974). *Praeexogyra hebridica* is also common.

Coral rubble, when found in the White Limestone Formation, is often heavily bored by bivalves, whose mud- and limestone-filled crypts can easily be collected complete from the surrounding mass of sparry calcite which replaces the coral. The principal borer of coral debris in the Shipton Member is not *Lithophaga*, as generally supposed, but a hitherto unrecognized species of the gastrochaenacean *Gastrochaenopsis*. Members of this superfamily of the Myoida have not been widely recorded below the Upper Jurassic, although they also occur in the Sharp's Hill Formation (Lower Bathonian), and the Lincolnshire Limestone of Bajocian age.

4. A vagile epifauna: this consists mainly of *Acrosalenia* and '*Pleurotomaria*' (usually too poorly preserved for a closer identification), together with other gastropods. These were the grazing and predatory species, which had to search for their food, rather than let it come to them as did the predominantly filter-feeding groups (2 and 3). Other likely predators and scavengers are fish and decapod crustaceans, of which small unidentifiable fragments are often found.

5. A burrowing and ploughing fauna, which occupied patches of soft sediment beneath and between the patches of coral and coral rubble, but to which the corals and other members of the coral community were not a life requirement. This group includes *Pholadomya*, *Cuspidaria*, *Protocardia*, *Clypeus*, *Globularia*, and the occa-

sional nerineid gastropod; all of them are also frequently encountered in non-coralliferous beds of the Shipton Member.

A complete faunal analysis of representative Shipton and Bladon Member coral beds is given in Table 2. In addition to the *Epithyris* mentioned above, the main differences between the communities in the two members lie in the presence of *Isognomon isognomonoides* and *Lopha costata*, both of which are common in the Shipton Member (also in non-coralliferous beds) but absent at the higher level. On the other hand, the *Epithyris* in the Bladon Member often provided attachment sites for the *Anomia*-like pulvinitid bivalve *Hypotrema* which does not occur in the Shipton Member and which has never before been recognized in the Great Oolite.

The coral beds of the White Limestone Formation are not reefs in the modern sense of the word: they do not have the relief of either the fringing reefs or the patch reefs of modern tropical seas. Their closest equivalent is the inshore coral shoals which are common in water less than 3 m deep along the seaward edge of the Florida Keys (Ginsburg 1964). The principal corals of these shoals are *Porites divaricata* and the rose coral *Manicina areolata* on sandy bottoms, and *Siderastrea radians* and *Solenastrea hyades* on rocky bottoms (Ginsburg 1964). *Solenastrea* is remarkably similar in appearance to the Bathonian *Cyathophora*, both having raised corallites separated by a vesicular coenosteum (Wells 1956). Similarly, *Porites* and *Manicina* of the Recent, bear a superficial resemblance to *Thamnasteria/Isastrea* and *Montlivaltia* respectively. *Porites* is either massive or branching, with small, closely united corallites characterized by more or less weakly defined synapticular rings (Wells 1956), all of which features it has in common with *Thamnasteria*; *Montlivaltia* resembles *Manicina* in that both are large solitary corals of the superfamily Faviicae. It may be, therefore, that members of this particular lineage have occupied similar niches since at least the Bathonian. *Manicina* can clear loose sediment off its surface (Ginsburg 1964), which is an obvious adaptation to life on a sandy substrate in shallow turbulent seas. Such an adaptation would also have benefited *Montlivaltia*, which was likely to have been subjected to the same problem.

Neither the colonial corals (*Isastrea/Thamnasteria*) nor the solitary *Montlivaltia* seem to have needed an extensive hard substrate for initial attachment, and they are found in the White Limestone Formation entirely surrounded by sediment in which the most extensive hard surfaces are shells and shell fragments. Probably initial larval settlement took place on a shell fragment. The shell fragment became superfluous as the coral grew and became stable due to its own weight, or to support from adjacent colonies and rubble. Cores through Recent but smothered *Porites* shoals from Florida, show a very similar array of coral rubble and associated fauna (see below) entirely surrounded by lime sand, lime mud, and shell fragments (pers. obs.).

Observations on the accessory faunas associated with *Porites* shoals show that these faunas are very similar in life habits to those found in White Limestone coral beds. *Barbatia cancellaria* (Lamarck) is often abundant amongst the terminal branches of *Porites* colonies, attached by a weak byssus which may be released if disturbed: *B. domingensis* (Lamarck) is gregarious, but prefers the lower region of the *Porites* colonies, amongst the dead branches; *Isognomon radiata* (Anton) also prefers the region of dead branches; *Pinctada radiata* (Leach) occurs rarely between branches; and *Lima scabra* (Born) is loosely attached either within or on top of

*Porites* colonies, and may detach itself and swim away if disturbed (Stanley 1970). The Bathonian equivalents to these species, based on morphology and inferred life habits are *Eonavicula minuta* (≡*Barbatia*), *I. isognomonoides* (≡*I. radiata*), *I. ooliticus* (≡*P. radiata*), and *Plagiostoma subcardiiformis* (≡*L. scabra*). In addition to Stanley's information, Coogan (1971) records Recent *Lithophaga* boring in dead coral (≡*Lithophaga* and *Gastrochaenopsis* in the White Limestone). It is locally abundant amongst the dead rubble of *Porites* shoals, together with at least three species of serpulid, several ectoprocts, *Homotrema*, hydrozoans, *Clypeaster rosaceus*, and shells of several burrowing bivalves (pers. obs.).

These Recent *Porites* shoals and their associated fauna occur in water down to about 3 m deep in Florida (Ginsburg 1964). To the south of Rodriguez Bank where they are particularly well developed, the lower limit of the most abundant growth is about 1·3 m in depth. The upward limit of growth is low-water spring-tide level (Turmel and Swanson 1964). A similar depth range is envisaged for the Bathonian coral shoals.

The one great difference between Recent and Bathonian shoals is the apparent lack of algae in the latter. Today, *Porites* shoals are often accompanied by abundant green and red algae, such as *Halimeda opuntia* and *Goniolithon*, which incidentally are both major producers of medium and coarse sediment in the shoals. In none of the thin sections made for this study is there any obvious trace of any codiacean or dasycladacean, even though both groups go back to the Cambrian (Wray 1971) and they have a characteristic texture in thin section, even after replacement of the original aragonite by calcite (Stanley 1966). The only alga found in the White Limestone is *Solenopora jurassica*, the long-ranging rhodophyte, thought to have been the ancestor of some of the Recent corallines. In the study area, it is confined to the Shipton Member (text-fig. 3). Red algae can utilize the blue end of the light spectrum whereas green algae need the red end, which penetrates less far into sea water; therefore the red algae can tolerate deeper and more turbid water. Since we are postulating a depth of only a few metres for the coral shoals of the Shipton Member, however, depth alone is unlikely to have been the controlling factor. It may be that a high proportion of fine clastic material derived from the land to the north-east tended to make the shallow water murky.

*Muddy lime sands*. Where corals are absent from the muddy limestones of the Shipton Member, there is a reduction or absence of several of the encrusting, boring, and nestling forms (e.g. calcisponges, *Cycloserpula*, *Moorellina*, *Kallirhynchia concinna*, *E. minuta*, *Epithyris* sp., *Gastrochaenopsis*). Nevertheless, the sedentary epifauna is still quite varied and again indicates a stable sea bottom, probably littered with dead shells and soft-bodied organisms which provided attachment sites for a few cementers and a range of byssally attached Pteriomorphia. The principal species found are *Praeexogyra hebridica* (cemented, but never forming reefs as in the Hampen Marly Formation), and *I. isognomonoides* (byssally attached). *Lopha costatum* (cemented), *Girvillella ovata*, *Camptonectes annulatus*, *C. rigidus* (all byssally attached) and *Epithyris* sp. are also common. Streamlined, alate forms, such as *Pteroperna costatula* occur only occasionally. From analogy with the Recent *Pteria*, whose shape is very similar, it might be concluded that this form lived in exposed water perhaps amongst the fronds of soft-bodied animals and plants which are not preserved. The rarity of *P. costatula* may reflect rarity of this habitat. The inequivalve condition of *G. ovata* and *Costigervillia crassicosta* (which occurs only rarely in the Shipton Member), and the unstreamlined shape of the other byssate forms mentioned above, suggests that most of the community lived close to the substrate, or in cracks and fissures (cf. Kauffman in Moore (ed.) 1969; Stanley 1970).

The other main faunal component of the non-coralliferous Shipton Member muddy limestones consists of semi-infaunal and infaunal species. Some of these species also burrowed amongst the rubble in the coral beds, but always in much fewer numbers.

The semi-infauna is principally represented by *Modiolus imbricatus* and *M*. (*Inoperna*) *plicatus* (as judged on the criteria discussed by Stanley 1970). The main infaunal species is the cyprinid *Anisocardia loweana*, a smooth, streamlined form which was probably shallow burrowing and active. Other common shallow burrowers include *Trigonia pullus*, *Pseudotrapesium cordiforme*, *Quenstedtia* sp., *Protocardia stricklandi*, and *P. lycetti*. The relative abundances of these species vary considerably, not only from bed to bed, but also in different parts of the same bed, in what appears to be a uniform sediment. This means either that control of distribution was to some extent fortuitous (spatfall just happened to take place in a particular region at a particular time), or that it was controlled by micro-environmental variations of the sort that are difficult to observe in living systems, and quite impossible in ancient situations; for example, minor differences in chemical composition of the seawater (see Wilson 1951; Cooper 1951). It may be for these local reasons that relative abundances of species in these Bathonian shallow marine communities appear so variable: nevertheless, certain species can be recognized as characterizing certain habitats and substrates.

Deep-burrowing Pholadomyoida also occur abundantly in the Shipton Member, whereas they are rare except at certain restricted horizons in the higher members. They include *Pholadomya*, *Goniomya*, *Homomya*, *Gresslya*, and *Pleuromya*, all of which have large pallial sinuses, and are almost invariably found in life positions. The first three of the above-mentioned genera are similar in form to Recent *Mya arenaria*, which shows a preference for muddy sand substrates, and is intolerant of strong currents and waves (Stanley 1970; Swan 1952); such an environment would seem from the sediments to fit much of the Croughton Member. *M. arenaria* is a slow burrower, and is subject to mass-mortality during storms, since the adult form can neither reburrow easily if exposed nor clear material which plugs its siphons (Weymouth 1920). It is likely that plugging of siphons was a major cause of mortality of those forms found in life position in White Limestone sediments. *Pleuromya* and *Gresslya*, being smaller and more streamlined, are more likely to have been able to excavate themselves if smothered in adulthood.

The non-bivalve fauna is represented by high-spired gastropods, *Clypeus muelleri*, and open crustacean dwelling-burrows of the *Spongeliomorpha*-type which frequently contain the faecal pellets of the species which lived in them. Such open burrows in the White Limestone are again limited to beds with a high enough proportion of fines to have rendered the substrate pasty and not liable to collapse. *Clypeus* also appears to have demanded such substrates. It is usually found within or on top of beds of muddy lime sand, and which probably ploughed through the soft sediment, either just below or at the sediment-water interface, detritus feeding in the way *Clypeaster rosaceus* does today. It is absent from sediments which are not muddy, and is consequently highly characteristic of the Shipton Member in the study area.

*Clean washed lime sands.* The well-developed Roach Bed at Ardley yields an abundant fauna which is typical of the well-sorted biopelsparites which are particularly characteristic of the lower part of the Ardley Member, and which also occur in the Shipton Member. This is shown in Table 2. The only typical form absent from the Roach Bed, but common in most other beds of this facies, is the button-coral *Chomatoseris*. Apart from this coral, the fauna of this facies is dominated by molluscs. The most abundant single species is the high-spired *Nerinella scalaris* (d'Orbigny), but other high-spired nerineids also occur. These are interpreted as having been sedentary burrowing filter feeders, similar to Recent *Turritella*. The most extreme of these forms is *Bactroptyxis bacillus* which starts to occur in the lime sand facies of the Ardley Member in the region west of Witney and becomes common in the White Limestone around Cirencester. *B. bacillus* is the ultimate in slender high-spired gastropods, with a spiral angle of only 4–5°, and a length of up to 15 cm. As in other nerineids, the shape is extremely cumbersome for a mobile form and it seems most likely that the shell acted as an anchor. That this extreme form becomes more common away from the Oxfordshire shallows, into the more open-sea current-affected lime sands of the Cotswolds, supports this hypothesis. The longer shell was a more efficient anchoring system, more appropriate to these energy conditions than the somewhat shorter and fatter shells of the nerineids more common in Oxfordshire. These forms, in contrast, become rarer south-westwards as *B. bacillus* becomes more common.

The forms associated with the nerineids are primarily bivalves. The principal species are *Eocallista antiopa* and *Protocardia stricklandi*. Also common are *Vaugonia moretoni*, *Corbis lajoyi*, *Lucina bellona*, *Pseudotrapesium cordiforme*, *Protocardium buckmani*, and *Pleuromya uniformis*. Less common, but also occurring are *Trigonia pullus*, *Quenstedtia bathonica*, *Parallelodon hirsonensis*, and *Modiolus imbricatus*.

The most striking feature of this fauna is the rarity of epifaunal forms; the pectinaceans which are relatively common in the Shipton Member and Bladon Member, and also in the micritic facies at the top of the Ardley Member, are very rare. If *M. imbricatus* was semi-infaunal as discussed above, then the only epifaunal species which characterizes this facies is the occasional large *P. hirsonensis*. This, again, is probably a reflection of the loose nature of the substrate, which was susceptible to current scour.

The burrowing bivalves considered above exhibit a variety of morphologies from smooth streamlined species like the very common *E. antiopa*, to inflated forms like *C. lajoyi* and heavily ornamented ones like *V. moretoni*. The more streamlined species were probably rapid burrowers, perhaps moving actively within the sediment, whereas the more inflated or ornamented forms were probably slow, inactive burrowers. Today, slow burrowers are not found in lime sands which are readily affected by currents, and only fast burrowers which can reburrow quickly if exhumed by current scour, can thrive (e.g. the *Tivela* biofacies of Newell, Imbrie, Purdy, and Thurber 1959). This suggests that the lime sand facies of the Ardley Member was not subject to frequent high current activity. On the other hand, there is no stabilizing micrite or fine mud in the sediment, and the deep-burrowing anomalodesmatans and burrow-dwelling crustaceans appear to have found conditions unsuitable. Possibly gentle winnowing and occasional more severe storm currents prevented accumulation of fines and kept the sediment loose.

It was beds of this facies at the base of the Ardley Member which Arkell (1931) recognized as his *Nerinea eudesii* beds. They are by no means confined to this level, however, and also occur widely in the Shipton Member of the study region.

*Cross-bedded lime sands.* In the west of the study region (around Burford) some units within the Ardley Member, and most of the Bladon Member, become cross-bedded. This is seen as being the result of a slight deepening and increase of current activity towards the edge of the Oxfordshire shallows. Further into the shallows the development of banks and shoals dampened current activity. The cross-bedded units are often oolitic, and massive oolites also occur in the lower part of the Bladon Member at Bladon.

Today, oolites and other cross-bedded lime sands contain a conspicuously reduced fauna because so few species can cope with the exigencies of a constantly shifting substrate. This appears also to have been so in the White Limestone. The cross-bedded units locally contain lag deposits of bivalves and high-spired gastropods which are obviously not *in situ*, but which probably constituted the more stable lime sand community discussed above during occasional periods when current activity was reduced. The indigenous fauna consists of occasional large *Purpuroidea* and a species of pectinid with an umbonal angle of 110° and symmetrical auricles. This reduced fauna is reminiscent of that of shifting oolite dunes in the Bahama region today where the large herbivorous gastropod *Strombus samba* (morphologically similar to *Purpuroidea*) is the principal species (Newell *et al.* 1959). The pectinid is clearly a swimming form (Stanley 1970, fig. 11), and could presumably have moved away from encroaching sediment.

Where the tops of the cross-bedded units remained undisturbed for a period, an infauna became established, and a stabilizing fine-grained component was introduced into the otherwise loose lime sand. An example of this, with a rich and well-preserved fauna, is seen at the top of the Bladon Member at Stonelands Quarry (Table 2). The lithology of this bed resembles the micritic and slightly clayey lime sands of the Shipton Member at Croughton and Ardley and it contains some of the same burrowing fauna and semi-infauna as these beds (*M. imbricatus*, *Protocardia lycetti*, *Anisocardia loweana*, *Pseudotrapesium cordiforme*, *Pleuromya* sp., *Pholadomya* sp. and crustacean burrows). Also present are some of the species found in the looser lime sands of the Ardley Member, including *V. moretoni* and *L. bellona.*

*Pelleted lime mud.* The pelleted lime mud lithofacies is regularly developed in the Ardley Member above the lime sands at the base, and also in the fossiliferous micrites in the upper parts of the Bladon Member. The pellets (or peloids) are clearly seen where protected from compaction within shells, but are usually squashed together in the matrix of the rock to give a more or less uniform micritic appearance. As a soft sediment, its mechanical properties are interpreted as having been intermediate between those of the loose, clean washed lime sand, and the stable pasty sands with abundant fines which are common in the Shipton Member.

The fauna of this lithofacies is dominated by high-spired gastropods of the genus *Aphanoptyxis. A. ardleyensis* is the dominant species in the Ardley Member, but this is replaced by the slightly blunter *A. bladonensis* in the Bladon Member. These are again thought to have been sedentary infaunal filter feeders.

Unfortunately, there is no single locality within the Ardley Member at which good preservation allows a close analysis of all those species which occur with *A. ardleyensis*. However, a picture of the main components of the community can be built up from observations over the whole study area.

The associated fauna includes some of the species present in the lime sand facies. *Trigonia pullus* and *L. bellona* are occasionally found. More common, but never occurring in the vast abundance of *A. ardleyensis*, is a species of *Cossmannea* or *Nerinella*, easily recognizable in cross-section from its internal ribs. In addition, however, there is a fauna which is absent from the lower beds: this consists of *Corbula hulliana, Eomiodon fimbriata, Bakevellia waltoni*, and small vertical worm burrows. Species from the lime sands which do not persist into these higher beds are *Parallelodon hirsonensis, Corbis lajoyi, Protocardia stricklandi, V. moretoni*, and *Chomatoseris* sp.

In the pelleted lime mud facies it is the infauna which again predominates; *B. waltoni* is the only common epifaunal form. The burrowing bivalves are principally ornamented forms, and were probably shallow burrowing and rather inactive. The two principal incomers *Corbula hulliana* and *E. fimbriata*, both become abundant in the micrites and clays of the overlying Bladon Member, and seem to show a marked preference for fine-grained sediments. The asymmetry of the valves in Recent *Corbula* has been interpreted by Yonge (1946) as an adaptation to this sort of environment. When the valves close, it results in complete collapse of the inhalent chamber, and hence complete voiding of pseudofaeces. Such behaviour may be contributory to the pelleted nature of the facies under discussion.

Deep-burrowing bivalves are again rare in the micritic facies, although they may occur abundantly in interbedded thin sandy or marly beds. Bed WL7 at Ardley Fields Farm quarry (see Palmer 1973) is a good example of this: it contains a large number of small *Pholadomya ? lirata* in life position, and occasional *Globularia* which probably preyed on them.

This facies of the White Limestone Formation contains few body fossils other than molluscs, and some of the mollusc species may also be implicated as euryhaline in other Great Oolite deposits (e.g. *C. hulliana* in the Hampen Marly and Forest Marble Formations). This may suggest slight brackish water influence in the pelleted lime mud facies, but it is equally likely that the apparent low diversity was the result of unfavourable substrate, rather than unfavourable salinity. The loose and sometimes soupy texture of the sediment would have been best suited to infauna rather than epifauna, and the apparent dominance of molluscs reflects the success of this group in infaunal niches.

The fauna of the Bladon Member pelleted lime muds does not include any of the common lime sand species (*T. pullus, L. bellona, Cossmannea/Nerinella*). On the other hand, the newcomers in the Ardley Member pelleted lime muds (*Bakevellia waltoni, Corbula hulliana, E. fimbriata*) become more common. This implies a continuum of decreasing sediment looseness, perhaps with increasing soupiness which was also unfavourable to epifauna, passing from lime sand to Ardley Member pelleted lime muds to Bladon Member pelleted lime muds. *Cuspidaria ibbetsoni* (in fact probably a corbulid) and *Amberleya nodosa* also occur in the Bladon Member.

*Shelly micrite*. The most conspicuous fossil beds in the White Limestone occur in this facies which is confined to the upper part of the Ardley Member (text-fig. 4). The dense white lime mud contains abundant shells in all stages of breakdown, and is frequently pelleted into the large microcoprolite *Favreina decemlunulatus* (see Kennedy *et al.* 1969). *Favreina* is often packed into large burrow systems of the *Spongeliomorpha suevica*-type. The abundance of such dwelling burrow systems and the many common epifaunal species in this facies again indicates a firm stable bottom, similar to those in the Shipton Member discussed above.

The epifauna is dominated by the brachiopod *Epithyris oxonica*; bivalves such as *Gervillella ovata*, *Pseudolimea duplicata*, *Costigervillia crassicosta*, *Hypotrema* sp. and *Praeexogyra hebridica* are also common. Semi-infaunal species are represented by *Modiolus imbricatus* and *M.* (*Inoperna*) *plicatus*, and infauna particularly by *Anisocardia islipensis* and *Sphaeriola oolithica*. The fauna other than bivalves includes many ectoprocts and serpulids encrusting shell material (see Table 2). There are also abundant terebelloid worms (McKerrow *et al.* 1969), represented by tubes composed of peloids and shell fragments originally embedded in an organic matrix. These tubes represent a large constituent of the sediment, and were presumably of major importance in removing sand-sized particles from circulation as sediment grains.

McKerrow *et al.* (1969) studied size/frequency distribution of *Epithyris* and *Modiolus* from beds of the micritic facies at Kirtlington (their beds 1e, 2j, 2k, and 3k). They concluded that articulated specimens represented an *in situ* fauna, but that single valves had been transported. However, the large amounts of micrite, the general rarity of disarticulated brachiopods, and the undamaged condition of many of the fossils in general, suggests little transportation in beds of this facies, and for small distances when it did occur.

In all the beds of this facies studied, the epifauna and semi-infauna forms the dominant part of the total community, both in numbers of species and numbers of individuals (Table 2). Some of these species (e.g. *M. imbricatus*) are forms which occur throughout the Great Oolite, wherever loose shell debris lay on or within a firm substrate; whereas others (e.g. *Hypotrema*, *C. crassicosta*, *Digonella digonoides*, terebelloid worms) seem to be either restricted to, or else show a marked preference for, this particular micritic facies. A third group (e.g. *G. ovata*, *E. oxonica*, *Camptonectes annulatus*, *M.* (*Inoperna*) *plicatus*) occurs in the White Limestone micrites and more clayey beds, but is absent from the lime sands and the pelleted lime muds of the lower part of the Ardley Member.

It is impossible to envisage all the different niches which were occupied by this variety of epifaunal filter-feeding species. The more inequivalve bivalves are likely to have lived close to the substrate with a horizontal plane of commissure, but it is tempting to think that the more equivalve and streamlined forms (e.g. *G. ovata*, *Pseudolimea duplicata*) may have been attached to the fronds of sponges, sea-whips, and other octocorals, which leave no trace in the fossil record, in the same way that

Recent *Pteria colymbus* (Roding) in Florida shows a marked preference for the upper portions of alcyonarians (Stanley 1970).

The bivalve infauna is dominated by shallow burrowers. *A. loweana*, common throughout the White Limestone is a streamlined form which was probably a fairly active burrower. *A. islipensis* and *S. oolithica* are inflated forms with thick shells, and were probably more sluggish.

The crustacean infauna, although packing its burrows with faecal pellets, does not appear to have covered the walls of these burrows with a supporting pelleted lining. This implies that the original micrite substrate was firm enough to support open burrow systems, rather than of a soupy fluid consistency. This observation is supported by the greater variety of molluscan epifauna, which would easily have become choked on a soupy substrate. Epifauna today are absent on soupy mud-mounds in Florida Bay, except where they grow on sea-grass, above the surface of the sediment (pers. obs.).

In the micrite facies, some of the species reach a size larger than that reached by the same species in any other facies of the Great Oolite. *M. imbricatus*, for example, reaches a length of over 70 mm, whereas 50 mm is large for other beds. Similarly, *E. oxonica* grows to a length of over 50 mm, longer even than the large individuals which occur in the coral beds of the Bladon Member. The environment, therefore, seems to have been very equable. The geographical distribution of the micritic facies (see text-fig. 4) the inferred nature of the substrate, and the apparent equability of the environment support the model of a quiet, shallow, lagoonal environment, protected from open marine currents, but not so near the shore that there was any apparent reduction of salinity. Presumably this setting was highly productive in energetic terms, providing the algae on which the apparently large and abundant fauna fed. This high productivity may also have resulted in high algal production of the micrite.

At certain localities in the south-east of the study area (e.g. Kirtlington; Wood Eaton; Whitehill Quarry, Gibralter), this facies passes laterally into cross-bedded limestones with much broken shell debris which appears on close examination to be derived from the shelly micrite community. The shelly micrite is envisaged as having formed extensive stable muddy mounds on the sea floor, perhaps less than a metre in depth. The cross-bedded units are interpreted as having filled in extensive deeper areas (perhaps up to 5 m deep) in between the mounds. These deeper areas were wider and more irregularly distributed than channels, but they were probably maintained by storm- and wind-generated currents which periodically eroded material from the sides of the mounds, and deposited it as current-bedded units in the deeper water.

*Nearshore lagoonal clays.* The *fimbriata-waltoni* beds of the Bladon Member in the Cherwell Valley (text-fig. 5) contain a fauna which has much in common with that of the pelleted micrites beneath the laminated emersion horizon. As Arkell (1931) first pointed out, the most abundant species are *Bakevellia waltoni*, *Eomiodon fimbriata* and *Cuspidaria ibbetsoni*, with occasional *Protocardia lycetti*. The fauna from a locally developed bed within the *fimbriata-waltoni* clay at Shipton is detailed in Table 2. However, these clays contain an additional fauna and flora which is absent from the limestones. This difference lies foremost in the enormous volume of coalified wood which is found in the clays. Most is derived from conifers which must have grown on land. These pieces of wood reach a length of 4 m, and may be up to 12 cm in diameter; locally they are concentrated into layers up to 4 cm thick which constitute impure coals. Also occurring commonly in these clays is the freshwater gastropod *Valvata*.

The bivalve fauna of the *fimbriata-waltoni* clays does not specifically suggest freshwater of fresh/brackish conditions, although some species (e.g. *Corbula hulliana*, *Eomiodon fimbriata*) have already, been implicated as euryhaline in the Hampen Marly Formation. The association of wood and *Valvata*, however, strongly suggests a freshwater influence not far away. This conclusion was also reached by Bate (1965) who recorded the freshwater ostracods *Bisulcocypris sp.* A, *Theriosynoecum kirtlingtonense* Bate, and *Timiriasevia mackerrowi* Bate from the *fimbriata-waltoni* clay at Kirtlington, in association with charophytes.

The bivalves preserved in the clays consist largely of disarticulated and broken specimens arranged on bedding planes. In contrast, material collected from the marly limestones seen interdigitating with the clays at Kirtlington by Arkell, and now in the Oxford University Museum, contains many articulated specimens. The similar fauna of the fossiliferous micrite facies also includes articulated specimens, and it seems likely that some at least of the common bivalves recorded from the clay actually represent the fauna which lived associated with the more calcareous sediments. These marly sediments probably formed the banks and the surrounding areas of the extensive system of creeks through which water from the land to the north-east drained towards the sea. A north-easterly derivation is supported by the orientation of the driftwood in the clays (Allen and Kaye 1973), and the system probably drained through a series of slow-moving freshwater lakes and gullies in which the freshwater fauna flourished. The general sedimentary picture of horizons of derived shells, pellets, and micrite pebbles against a background of clay suggests some variation in the strength of the discharge; perhaps again associated with storms, or a wet season. Locally, silts occur in lensoid beds within the clays; the molluscan fauna of these beds is confined to broken and disarticulated specimens of *Praeexogyra hebridica*, and suggests origin from a slightly different source.

At Shipton, horizons of rootlets have been seen in the *fimbriata-waltoni* clays. At Enslow Bridge (Phillips 1871) and Kirtlington (Arkell 1931), *Cetiosaurus oxoniensis* has also been found. The similarity between this fauna and flora and that of both the Hampen Marly Formation at Wood Eaton, and the Forest Marble Formation around Stratton Audley is very striking, and further indicates a very shallow, swampy region, channelled by creeks. The environment was probably somewhat similar to the Everglades of Florida today.

*Hardgrounds*. Hardgrounds occur at the top of the Ardley and Bladon Members at the localities shown in text-figs. 4 and 5 respectively. The faunas associated with them are *Exogyra crassa*, *Liostrea wiltonensis*, rare *Serpula* (*Cycloserpula*) sp., and the crypts of boring worms and bivalves. The species diversity on these surfaces is thus much lower than that on contemporaneous hardgrounds in the region to the south-west, e.g. that at the base of the Bradford Clay (Palmer and Fürsich 1974) which supports seventeen different species of borers and encrusters. This is a reflection of a general trend within the Bathonian; a marked diversity increase towards the more stable open marine conditions to the south-west, with the incoming of stenotopic organisms that found the exigencies of the nearshore Oxfordshire shallows unsuitable.

## DISCUSSION

The interplay of two trends is responsible for the lateral and stratigraphic variation which characterizes the White Limestone of the study area. The first is the shallowing in the direction of the shore line of the London Landmass in the north-east part of the region. The second is the cyclicity which gives rise to the three members.

We have already seen how the deposits and fauna of the Hampen Marly Formation became influenced by river discharge at Wood Eaton and Ardley. Similarly, at the south-western edge of the Oxfordshire shallows, they pass into a deeper water, more fully marine, facies. The same is true for the whole of the White Limestone Formation. Evidence for shallowing towards the London Landmass north-eastwards includes the following observations (member and locality in brackets where appropriate). There is an increase in the insoluble component of the limestones and in the amount of clastic material generally (particularly clear in the Shipton Member at Stratton Audley). In the Bladon Member the *fimbriata-waltoni* clays have been interpreted as representing a south-westwards extension of the clastic trap contained between the land and the emergent lime mud barrier formed by the laminated micrite (Palmer and Jenkyns 1974). There is also an increase in the number of channels at the top of the Ardley and Bladon Members (Stratton Audley), which are clay filled and contain a basal driftwood lag. Rootlets also occur in the north-eastern region only (Shipton Member, Croughton). The trends of more clastics, more wood, more channelling, more rootlets, and increasing numbers of brackish and freshwater fossils is also seen very clearly in the overlying Forest Marble Formation as one passes north-eastwards across the region where the top of the underlying Bladon Member is developed as the emergent horizon (Palmer and Jenkyns 1974). These trends continue as far as the most easterly locality for which published information exists, the Calvert Borehole (Davies and Pringle 1913). Here, the White Limestone is reduced to less than 4 m of impure, marly limestones. Conversely, the Hampen Marly Formation is 13 m thick, and the Forest Marble (here developed as lagoonal clays with rootlets) 12 m. This expansion of the non-marine units above and below the White Limestone almost certainly involves the development of both the Bladon and the Shipton Members in a non-marine facies. The Great Oolite feathers out completely about 20 km east of Calvert.

The evidence for deepening and the attainment of more open marine conditions at the south-western edge of the Oxfordshire shallows in the Burford region has been mentioned several times in the text above. Primarily, this lies in the changing nature of the lithologies of all three members in this region. Micrites, marls, muddy limestones, and subordinate clays are common on the shallows. They represent very shallow water (perhaps in the order of 1·5 m), where sediment banks and shoals developed. Wave fetch was necessarily low, and currents were dampened by the shallowness of the water and the baffle action of the sediment shoals. South-westwards, at and off the edge of the shelf, larger wind-generated waves and currents could develop in somewhat deeper water (perhaps about 5–15 m), causing winnowing of the substrate and forming loose lime sands. Locally, these became oolitic, and periodically they were swept by storm currents and became cross-bedded. The faunal changes discussed above are directly or indirectly (via the changing nature of the sediment) the result of more fully marine conditions and better circulation of sea-water south-west of the Burford region, than in the Oxfordshire shallows.

Superimposed on this palaeogeographic trend are the three shallowing upward cycles of the three members. Much of the evidence for shallowing north-eastwards discussed above comes from observations made in the top beds of the members. There are rootlets at the top of the Shipton Member at Croughton (Palmer 1974), and there is a putative dinosaur trackway at the same level at Ardley. There is the laminated bed with *Valvata* and the wood-lined channels at the top of the Ardley Member (text-fig. 4). There is the emergent birdseye limestone at the top of the Bladon Member over much of the north-east of the region. Similarly, it is the lowest beds of the members which appear to be best sorted by current winnowing; and the proportion of fine-grained material increases upwards until some sort of stand-still is represented at the top. This is most clearly seen in the Ardley Member which passes from lime sand to pelleted lime mud to shelly micrite, representing a drop in current activity as the region of deposition becomes silted up.

The increase in micrite upwards is seen partly as a reduction in current winnowing, and partly as an increase in the abundance of aragonite needle-producing green algae as conditions became more protected and lagoonal.

The shallowing of each member is thus seen as being primarily dependent on sedimentation. The deepening which heralded the onset of each member, however, is seen as a relatively rapid event probably under tectonic control. The recent discoveries of Bathonian vulcanicity in the northern North Sea place Britain firmly in a tectonic province at this time, and indeed contemporaneous faulting of the Jurassic strata or within the underlying basement has recently been postulated as the dominant mechanism affecting the facies distribution of Jurassic sediments over the whole of southern Britain (e.g. Sellwood and Jenkyns 1975; Jenkyns and Senior 1977). On the stable platform of the Oxfordshire shallows vertical displacement at any one time probably never exceeded a few metres, but in such shallow water this greatly affected the nature of sedimentation before and after deepening. It is no coincidence that the change of facies along the edge of the Oxfordshire shallows runs along the line of the Moreton Axis which greatly affected sediment distribution and facies in the Lower Jurassic and Inferior Oolite. Recently, Sellwood and McKerrow (1974) have discussed facies change in the lower Great Oolite over this area and suggested a fault zone in the underlying Palaeozoics. It is quite likely that the relatively sudden thickening and change of facies over the same area in the upper Great Oolite was under the same control.

Previous interpretations of the environmental picture in the White Limestone (Klein 1965; McKerrow *et al.* 1969) have concluded deposition in intertidal conditions. Klein (1965) extended this interpretation into Gloucestershire, and based his conclusions on the evidence of thick laterally persistent, graded beds, becoming finer upwards, which he states could have been formed by regression of high tidal flat sediments (finer grained) over low tidal flat sediments (coarser grained).

It has been shown how the members as a whole fine upwards, and this has indeed been interpreted as a shallowing. The graded units recognized by Klein, however, are in the order of $\frac{1}{2}$–$1\frac{3}{4}$ m, and are burrowed at the top and capped by hardgrounds (Klein 1965, p. 187). It seems that a simpler explanation of the grading is that after deposition of the coarse lime sands, there was a period of non-deposition and reduced current activity. During this period the burrowing fauna colonized the bed from the top surface, and the upper part of the sediment was bioturbated. During this period fine sediment was produced, principally by the breakdown of animal skeletons, but perhaps also by Codiacea similar to *Penicillus* which were able to establish themselves on the relatively stable bottom sediment. The fine lime mud so produced, together with fines removed from suspension and pelleted by filter-feeders, became incorporated into the sediment and mixed up by the bioturbation in the upper part of the bed, giving the whole thickness a fining-upward appearance. Support for this hypothesis comes from one of the fining-upward sequences at Foss Cross Quarry (see Table 1) where the top of the bed contains a rich molluscan infauna, and a high proportion of fines are seen in thin section. The same bed seen at Dagham Downs Quarry (bed 6 of Torrens 1967) contains no molluscan infauna, and does not show an upward increase in the proportion of fines.

Even without bioturbation, beds which are capped by hardgrounds may also show a greater proportion of fines at their tops. Hardground formation may have started by the growth of thin veneer of cement around each constituent particle, which holds adjacent particles rigidly together; the inter-granular spaces may then have acted as sediment traps for suspended fines, or mud-size particles produced by boring organisms. I have noted this phenomenon frequently in Bathonian hardgrounds in Normandy.

There are other, more empirical, objections to Klein's intertidal hypothesis. First, it may be surmised that such a variety of lithofacies and faunas over such a wide area cannot all represent the same depositional environment. Second, there is a complete absence of depositional structures indicating tidal activity. These including herring-bone cross-bedding, flaser bedding, and tidal bedding which he later (Klein 1972) considered to be so important in the recognition of tidalites. Third, none of the fabrics and desiccation structures which have been found associated with Recent intertidal carbonate sequences have been seen in Klein's study area. These include algal stromatolites; wide, shallow mud cracks; deep prism mud cracks (Ginsburg, Bricker, Wanless, and Garrett 1970); and birdseye structures (Shinn 1968). Although Klein (1965, p. 178) states that mud cracks are common to many limestones in the Great Oolite, in the present study they have only been noted in one bed within the Bladon Member, in a facies not seen by Klein (pers. comm. 1972). It seems more likely that Klein mistook burrows for mud cracks.

In the total absence of any evidence for intertidal conditions, other than that graded bedding is known to have been produced by prograding of high tidal flats over low tidal flat (e.g. Evans 1965), and in the light of a reasonable alternative explanation for the same phenomenon in the subtidal zone, it seems most unlikely that Klein's hypothesis is correct. Where indications of emergence are seen at the top of the White Limestone to the north-east of Klein's study area (around Ardley and Stratton Audley), the fabrics are quite distinctive. Millimetre laminations, curled algal mats, mud flake conglomerates, and birdseyes, associated with shrinkage cracks, give a rock of totally different appearance to Klein's White Limestone. It seems likely that this was a very limited area of emergence and that most of the White Limestone was deposited in shallow, subtidal conditions.

The presence of both supratidal and subtidal deposits, and the absence of unequivocal intertidal structures strongly suggests very reduced diurnal tidality in this part of the Bathonian sea. Such a situation is to be expected over wide shallow shelves, where tidal currents coming in from the open sea are dampened by friction and the baffling effect of sediment shoals. In Florida Bay today the tidal range is reduced to 13 cm in the eastern part, and there is no exchange of water with the open sea. Similarly, tidal range across the Great Bahama Bank falls from 0·78 m at the edge to virtually nothing in the middle (Bathurst 1971). The situation is likely to have been the same crossing on to the Oxfordshire shallows, and to have become accentuated in the shallowest upper parts of the members. Only during storms was current activity increased, forming and maintaining channels, causing deposition of lime mud layers on the algally covered supratidal flats, and causing fluctuations in salinity. Under these periodically harsh and variable conditions, only the most tolerant of eurytopic organisms were able to exist. Some open marine groups, such as cephalopods, were absent. Other predominantly stenotopic groups are represented only by one or two species which were particularly tolerant of the adverse conditions. These include sponges, corals, foraminifera, brachiopods, bryozoans, and echinoderms. The group that thrived best was the bivalves, perhaps partially because of their ability to seal themselves from the outside environment and thus at least ameliorate the adverse effects of short-term fluctuations in the physical environment.

South-west of the Oxfordshire shallows, on the deeper more open marine carbonate shelf of Bath and the Cotswolds, water circulation was much better, and fluctuations in the physical environment were dampened. The same is true in the contemporaneous shallow-water carbonates around the Armorican Massif in Normandy. As a result, a much more diverse stenotopic fauna became established, with groups such as sponges, corals, foraminifera, brachiopods, bryozoans, and echinoderms much more fully represented. Over-all diversity of invertebrate species was about four times as high as in Oxfordshire. The marine fauna of the Great Oolite discussed above, therefore, consists principally of those forms which, by physiology or ecological strategy, could withstand the exigencies of an environment in which considerable fluctuations in various physical parameters were to be expected. The more diverse stenotopic counterpart to this fauna is more rarely seen in southern England. Consequently, where it does occur, at least some of its elements have been given their own name (Bradfordian fauna) and invested with a stratigraphic significance that they do not have. This problem will be dealt with separately.

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T. J. PALMER
Department of Geology and Mineralogy
Parks Road
Oxford OX1 3PR

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