British Tertiary Stratigraphy

Brian Daley

School of Earth, Environmental and Physical Sciences
University of Portsmouth
Portsmouth, UK

and

Peter Balson

British Geological Survey,
Keyworth, Nottingham, UK

GCR Editor: **L.P. Thomas**

JOINT NATURE CONSERVATION COMMITTEE

Chapter 5

Hampshire Basin: Isle of Wight localities

B. Daley

INTRODUCTION

There can be little doubt that the Palaeogene localities of the Isle of Wight (Figure 5.1) are the most spectacular and, from a variety of standpoints, the most scientifically revealing of present-day Palaeogene sites in Britain. Their stratigraphical range is greater than those on the mainland and represent strata from Palaeocene to Oligocene age. Indeed, it is only on the Isle of Wight that marine Oligocene strata are preserved in Britain.

Of the sites recognized, Whitecliff Bay and Alum Bay, with its extension in Headon Hill, are the most impressive. They represent the two most stratigraphically extensive 'continuous' sections in north-western Europe. Together, the sites have a varied and extensive fossil fauna and flora and sedimentary facies, and their contribution to biostratigraphy, lithostratigraphy and, in some cases, magnetostratigraphy is considerable. Furthermore, their study has contributed significantly to our understanding of Palaeogene environments, and in the case of the younger strata, have provided the only evidence we have for conditions in the southern British area during the latest part of the Eocene and the early Oligocene.

The lithostratigraphical terminology used is essentially that of Edwards and Freshney (1987b) for the lower part of the succession and that of Insole and Daley (1985) for the upper part. Because of the difficulty locally of formally applying and justifying the lithostratigraphical terminology recently introduced by Ellison *et al.* (1994) for early Palaeogene strata in the London Basin and East Anglia, this has only been adopted for the Palaeogene of the Isle of Wight and other parts of the Hampshire Basin at 'group' level.

Seven Palaeogene sites are recognized to be of stratigraphical importance on the Isle of Wight (see Figure 5.1) and it is significant that their scientific value is reiterated by their inclusion in other GCR volumes on fossil plants (*Mesozoic to Tertiary Palaeobotany* (Cleal and Thomas, in prep.)) and/or those on different vertebrate fossils (Benton and Spencer, 1995; Benton *et al.*, in prep.; Dineley and Metcalf, 1999).

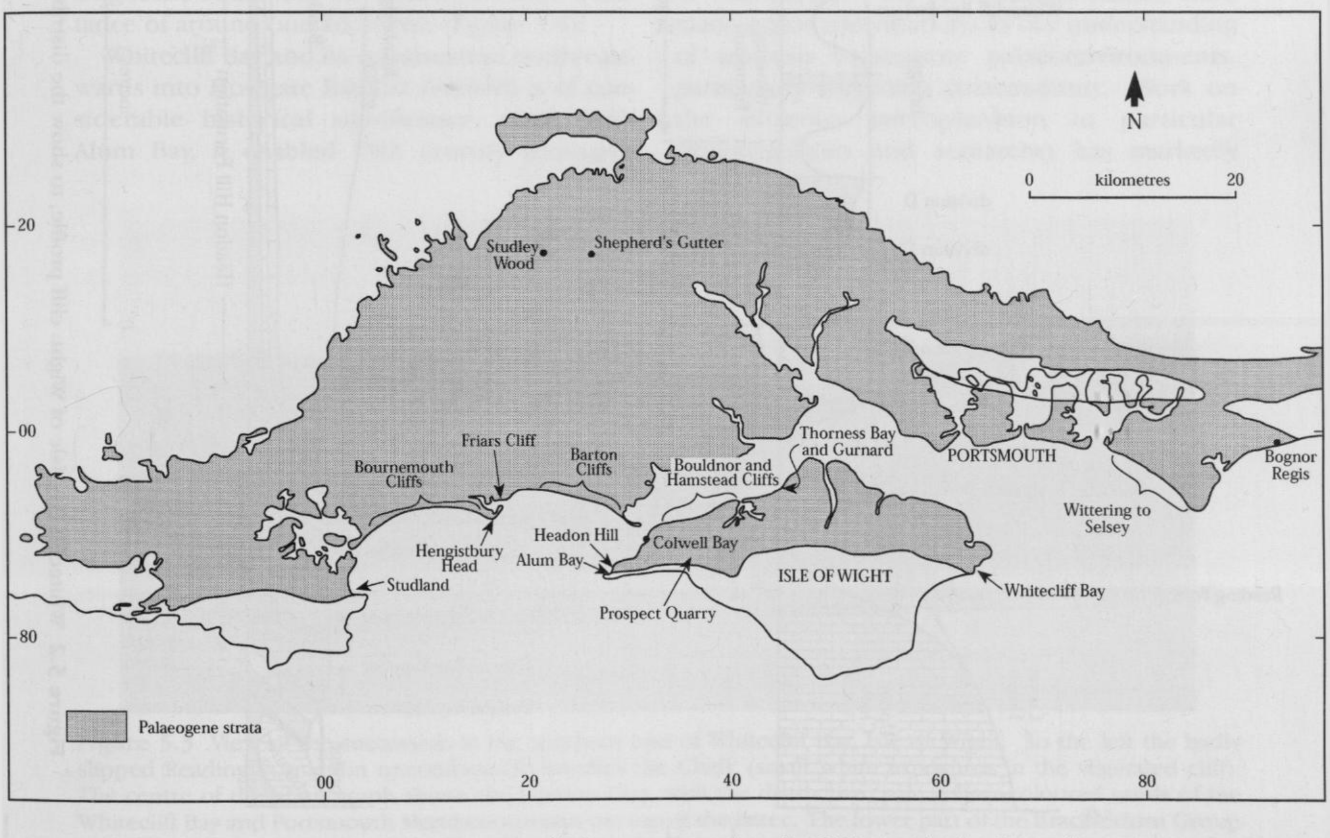

Figure 5.1 Map to show the location of Palaeogene stratigraphy GCR sites in the Hampshire Basin.

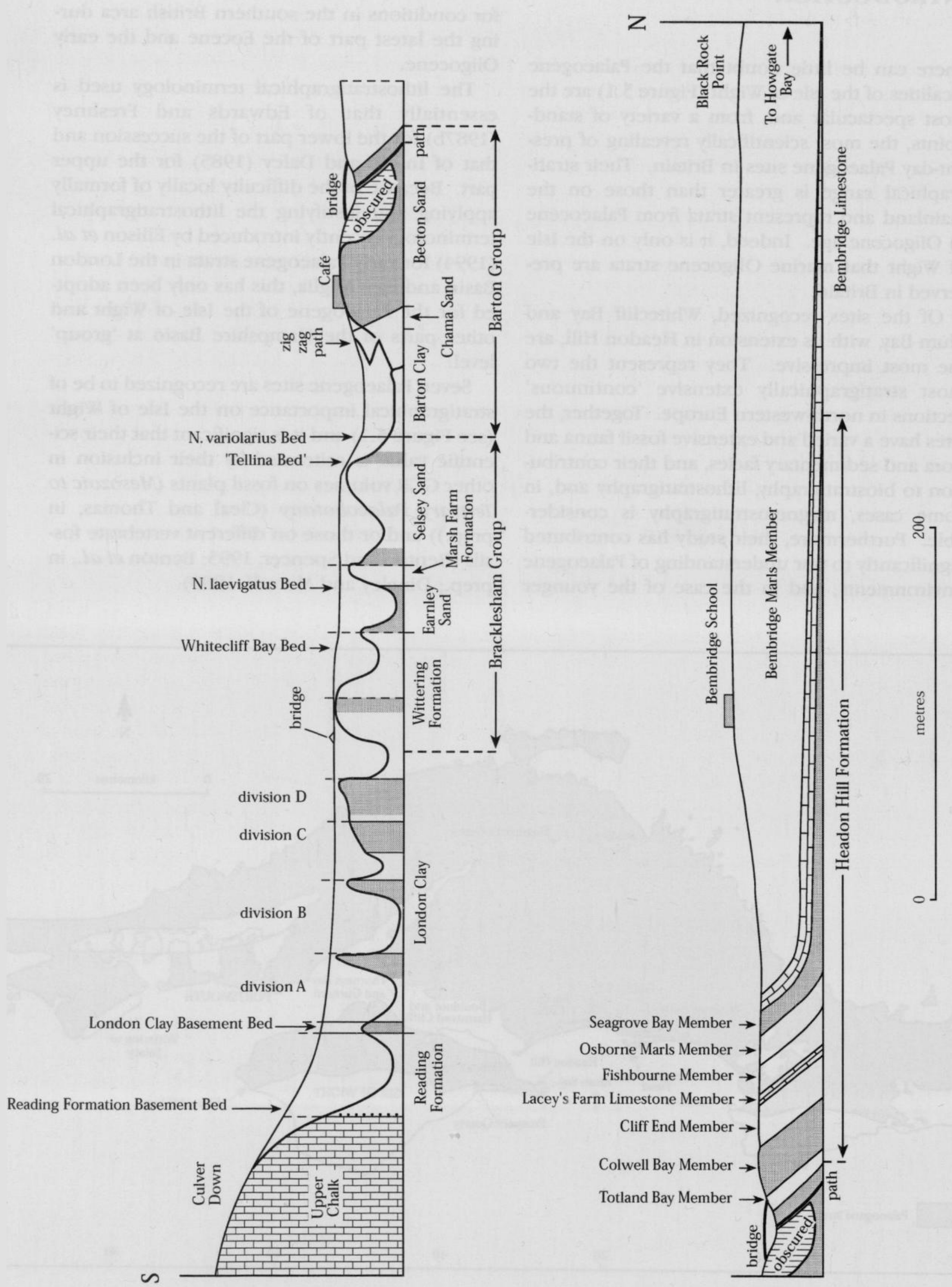

Figure 5.2 Whitecliff Bay, Isle of Wight: cliff profile, to show the distribution of the Palaeogene strata (adapted from Daley and Insole, 1984).

WHITECLIFF BAY, ISLE OF WIGHT (SZ 638857–SZ 645865)

Highlights

Whitecliff Bay contains the most stratigraphically extensive and important Palaeogene section in Western Europe. It is the type section for over 15 stratigraphical units and demonstrates, more than any other site, the characteristically cyclic nature of the British Palaeogene succession. A wide variety of marine and non-marine environments are represented by the section which has also proved of particular importance in micropalaeontological and magnetostratigraphical zonation and correlation.

Introduction

The section of Palaeogene strata in Whitecliff Bay (Figures 5.2 and 5.3) and its continuation north-eastwards provides one of the stratigraphically most continuous exposures of sediments of this age in Western Europe. Northwards from the junction with the Chalk in Whitecliff Bay, just over 550 m of Palaeocene to late Eocene–early Oligocene strata may be examined within a distance of around one kilometre (Figure 5.4).

Whitecliff Bay and its continuation north-eastwards into Howgate Bay (SZ 648868) is of considerable historical significance, since, with Alum Bay, it enabled 19th century geologists such as Edward Forbes to begin to understand the stratigraphy of the local Tertiary rocks. For some 150 years, the site has been extensively studied and reported in numerous publications. Amongst early descriptions are those in Memoirs of the Geological Survey (Forbes, 1856; Bristow, 1862; Bristow *et al.*, 1889; White, 1921). Other 19th century work includes that of Prestwich (1846) and the classic paper of Fisher (1862), whose subdivision of the Bracklesham Group is still widely used today. Further references are listed in Curry (1965a) and, for the Solent Group, in Edwards (1971b).

The latter part of the 20th century has seen an upsurge of interest in the section and its potential as a key to palaeoenvironmental and palaeogeographical interpretation of the Palaeogene in southern Britain. Following early studies of the large foraminifer *Nummulites* (Curry, 1937; Wrigley and Davies, 1937), research has been undertaken on the microfauna and microflora: Bhatia (1955, 1957) and Murray and Wright (1974) on the foraminifera, Haskins (1968a,b,c, 1969, 1970, 1971a,b) and Keen (1977) on the ostracods, and a number of workers on the microplankton (see Bujak *et al.* (1980) for a list of references). The microfaunal studies have made major contributions to our understanding of aqueous Palaeogene palaeoenvironments, particularly regarding palaeosalinity. Work on the siliceous microplankton in particular (dinoflagellates and acritarchs) has markedly

Figure 5.3 View of the succession at the southern end of Whitecliff Bay, Isle of Wight. To the left the badly slipped Reading Formation unconformably overlies the Chalk (small white exposures in the vegetated cliff). The centre of the photograph shows the London Clay, with the distinctive, pale yellow-coloured sands of the Whitecliff Bay and Portsmouth Members towards the top of the latter. The lower part of the Bracklesham Group succession is represented to the right. (Photograph: B. Daley.)

improved the correlation of clastic Palaeogene sequences such as that in Whitecliff Bay (Costa and Downie, 1976; Bujak *et al.*, 1980) whilst at some horizons, calcareous nannoplankton are biostratigraphically important (Aubry, 1986; Aubry *et al.*, 1986). Other microfloral work on the section includes that of Gruas-Cavagnetto (1976) on the palynology and Feist-Castel (1977) on the charophytes.

Broader stratigraphical/palaeontological studies, including work by Edwards (1967), Daley (1969, 1973a), Insole (1972) and King (1981), have considerably improved our understanding of the wide variety of shallow marine to freshwater environments represented by the Whitecliff Bay site. Plint's (1983a, 1988a) sedimentological work on the Bracklesham Group suggests that sea-level fluctuations contributed to the cyclicity characteristic of the lower part of the sequence.

Mineralogical studies have included work on the heavy minerals by Walder (1964), Blondeau and Pomerol (1968) and Morton (1982b), and on the clay mineralogy by Gilkes (1968, 1978).

Not surprisingly, the thick succession of Whitecliff Bay has interested those concerned with regional and international correlation. Glauconites from the section were used by Odin *et al.* (1969, 1978) in radiometric dating of the Palaeogene strata, whilst the importance of the site to magnetostratigraphy was demonstrated by Townsend and Hailwood (1985). In conjunction with the Bouldnor Cliff section, Whitecliff Bay was selected to typify the English succession spanning the Eocene–Oligocene boundary (Curry and Hailwood, 1986). How the succession in Whitecliff Bay relates to that of northwestern Europe is referred to in the recent comprehensive paper on the sequence stratigraphy of this region by Neal (1996).

Various aspects of the site have been described in reports of field meetings such as those arranged by the Geologists' Association (Stinton, 1971a; Daley and Edwards, 1974) and for international conference excursions (Curry, 1968). A brief guide to the section is given in the Geologists' Association Guide to the Isle of Wight (Daley and Insole, 1984), recently revised and updated by Insole, Daley and Gale (1998). An account of the succession of the Thames, Bracklesham and Barton Groups obtained from foreshore exposures has recently been published by Huggett and Gale (1997). More recently, Daley (1999, pp. 7–29) has written a comprehensive re-evaluation of the section.

This site was also independently selected for its fossil plant and mammal content, more detailed accounts of which can be found elsewhere in the GCR series (*Mesozoic to Tertiary Palaeobotany of Great Britain* (Cleal and Thomas, in prep.); *Fossil Mammal and Birds of Great Britain* (Benton *et al.*, in prep.)).

Description

The stratigraphical succession of the Palaeogene strata in Whitecliff Bay is summarized in Figure 5.4 and, for its various component parts, illustrated in more detail in Figures 5.3 and 5.5 to 5.16. At the southernmost end of the bay (SZ 637857), the Palaeogene rests unconformably on the *Belemnitella mucronata* Zone of the Upper Chalk. No angular discordance is apparent, but the top of the Chalk is pot-holed and irregular. A thin conglomerate and pebbly sand rests on this surface, the pebbles being both angular and well-rounded flints, including occasional silicified echinoids. The unconformity is significant because it represents a time gap of some 15 Ma (the Maastrichtian, Danian and part of the Thanetian Stages).

In the southern part of Whitecliff Bay, the Palaeogene strata are vertical, striking E–W, reflecting the steep, northern monoclinal limb of the Sandown Anticline. Northwards, the dip changes within a short distance such that by Black Rock Point (SZ 645865), a northerly dip of about 5° is apparent. Further northwards, almost horizontal, hard lithified beds within the Bembridge Limestone form the Bembridge Ledges, which are exposed at low tide.

Lithological succession

Five lithostratigraphical groups are represented in the Whitecliff Bay succession: the Lambeth Group, the Thames Group (Figure 5.5), the Bracklesham Group (Figure 5.6), the Barton Group (Figure 5.7) and the Solent Group (Figures 5.10 and 5.11). The succession is predominantly clastic. Much of the sequence comprises muds (various admixtures of silt and/or clay, sometimes sandy). Many are grey or greenish-grey (where glauconitic) when fresh but at some horizons (e.g. the Reading Formation and the Osborne Marls Member of the Headon Hill Formation), are varicoloured and mottled, especially in red and green. Gullies in the cliff pro-

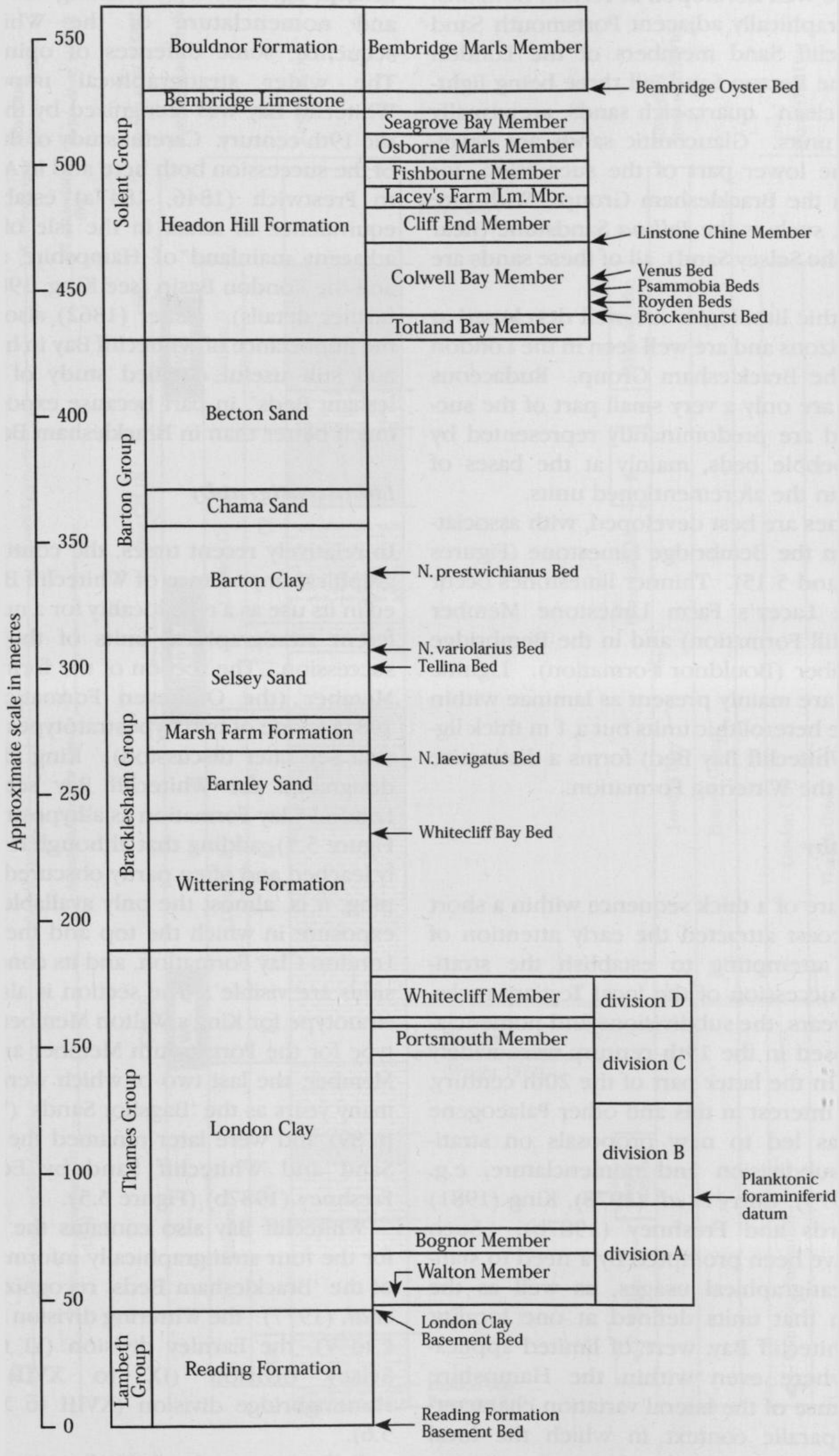

Figure 5.4 Lithostratigraphical succession in Whitecliff Bay, Isle of Wight.

file reflect the unstable nature and mobility of some of the mud units (see Figure 5.2).

Sands are well developed at certain horizons. The stratigraphically adjacent Portsmouth Sand and Whitecliff Sand members of the London Clay and the Becton Sand, all three being light-coloured, 'clean', quartz-rich sands, are visually distinctive units. Glauconitic sands are developed in the lower part of the succession, for example in the Bracklesham Group. With rare exceptions, such as the *Tellina* Sandstone (near the top of the Selsey Sand), all of these sands are unlithified.

Heterolithic lithologies are well developed at certain horizons and are well seen in the London Clay and the Bracklesham Group. Rudaceous lithologies are only a very small part of the succession and are predominantly represented by thin flint-pebble beds, mainly at the bases of cycles within the aforementioned units.

Limestones are best developed, with associated marls, in the Bembridge Limestone (Figures 5.11, 5.14 and 5.15). Thinner limestones occur within the Lacey's Farm Limestone Member (Headon Hill Formation) and in the Bembridge Marls Member (Bouldnor Formation). Lignitic lithologies are mainly present as laminae within some of the heterolithic units but a 1 m thick lignite (the Whitecliff Bay Bed) forms a distinctive horizon in the Wittering Formation.

Stratigraphy

The exposure of a thick sequence within a short extent of coast attracted the early attention of geologists attempting to establish the stratigraphical succession of the local Tertiary rocks. For many years, the subdivisions and nomenclature proposed in the 19th century were widely accepted. In the latter part of the 20th century, a renewed interest in this and other Palaeogene sections has led to new proposals on stratigraphical subdivision and nomenclature, e.g. Stinton (1975), Curry *et al.* (1978), King (1981) and Edwards and Freshney (1987b). Such changes have been prompted by a need to standardize stratigraphical usages, as well as the recognition that units defined at one locality, such as Whitecliff Bay, were of limited application elsewhere even within the Hampshire Basin, because of the lateral variation characterizing the paralic context in which the local Palaeogene strata accumulated.

Some of the proposals stimulated discussion on the validity of certain stratigraphical units (see Daley *et al.*, 1979) and, whilst there is now general agreement concerning the subdivision and nomenclature of the Whitecliff Bay sequence, some diffences of opinion persist. The wider stratigraphical importance of Whitecliff Bay was recognized by the middle of the 19th century. Careful study of the older part of the succession both here and in Alum Bay led to Prestwich (1846, 1847a) establishing the equivalence of strata in the Isle of Wight, the adjacent mainland of Hampshire and Sussex, and the London Basin (see King, 1981, p. 10 for further details). Fisher (1862) also recognized the importance of Whitecliff Bay in his important and still useful detailed study of the 'Bracklesham Beds', in part because exposures are so much better than in Bracklesham Bay.

Lithostratigraphy

In relatively recent times, the continuing stratigraphical importance of Whitecliff Bay is reflected in its use as a type locality for a number of different stratigraphical units of the Palaeogene succession. The section of the former Tilehurst Member (the Oldhaven Formation of King, 1981) is one of two hypostratotypes for this unit (but see later discussion). King (1981, p. 21) designated the Whitecliff Bay section of the London Clay Formation as a hypostratotype (see Figure 5.5), adding that although it is extensively leached and often partly obscured by landslipping, it is 'almost the only available permanent exposure in which the top and the base of the London Clay Formation, and its constituent divisions are visible'. The section is also the hypostratotype for King's Walton Member, and stratotype for the Portsmouth Member and Whitecliff Member, the last two of which were known for many years as the 'Bagshot Sands' (White, 1921, p. 89) and were later renamed the Portsmouth Sand and Whitecliff Sand by Edwards and Freshney (1987b) (Figure 5.5).

Whitecliff Bay also contains the 'stratotypes' for the four stratigraphically informal 'divisions' of the 'Bracklesham Beds' recognized by Curry *et al.* (1977): the Wittering division (Fisher Beds I to V), the Earnley division (VI to VIII), the Selsey division (IX to XVII) and the Huntingbridge division (XVIII to XIX) (Figure 5.6).

Following modern 'Hedbergian' principles, Edwards and Freshney (1987b) assigned strata

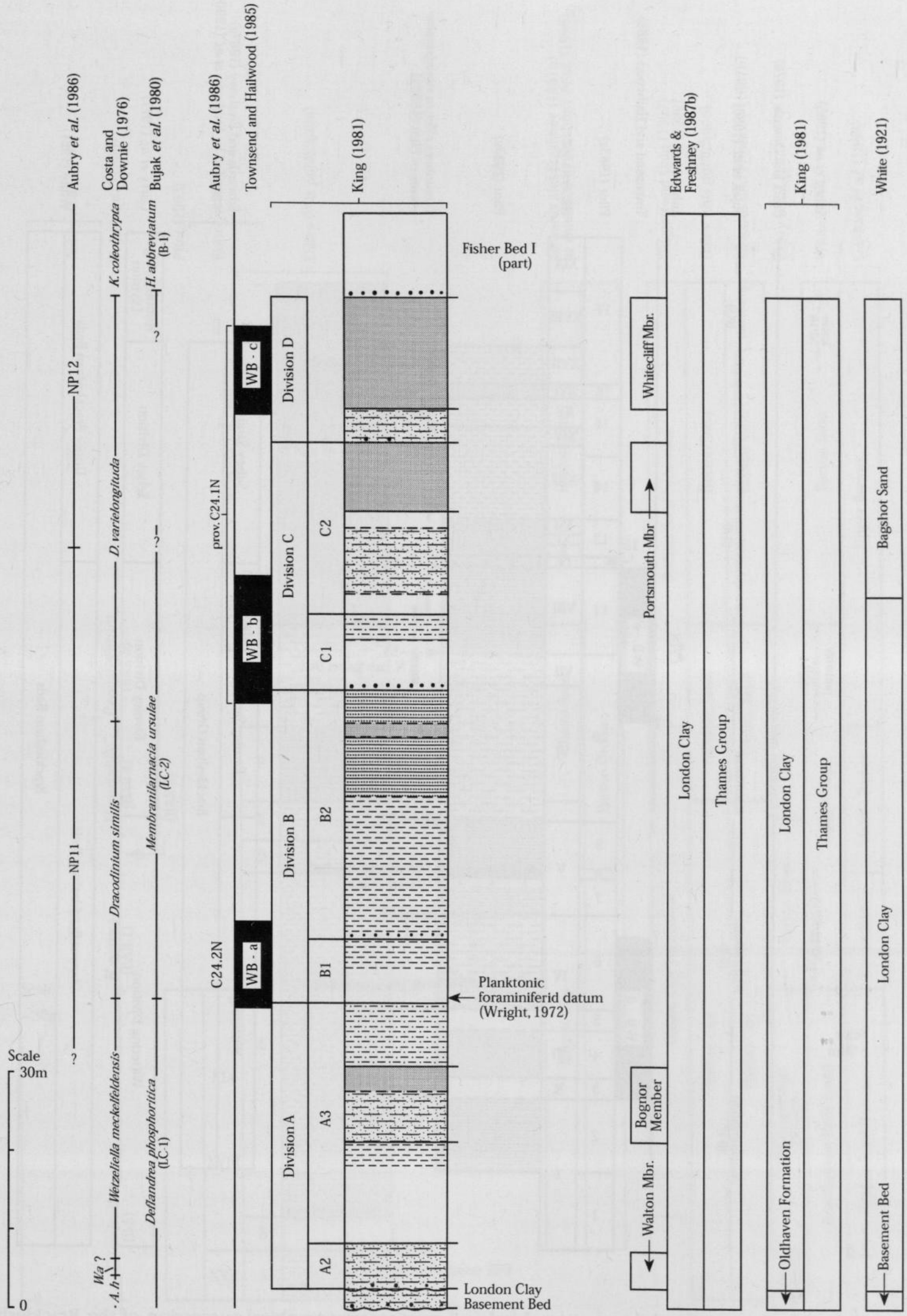

Figure 5.5 Lithostratigraphical, biostratigraphical and magnetostratigraphical succession of the London Clay, Whitecliff Bay, Isle of Wight (after King, 1981 and other authors).

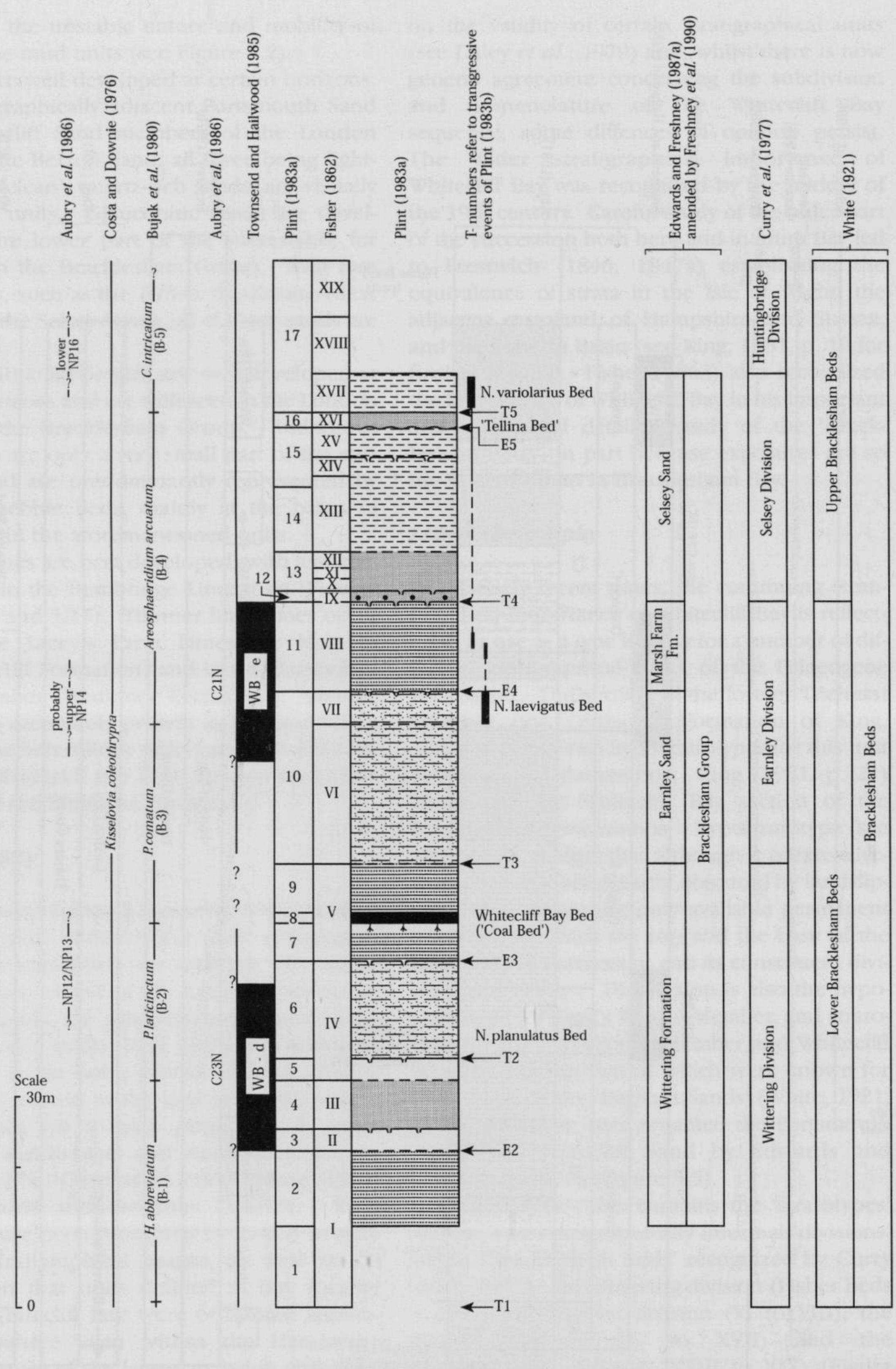

Figure 5.6 Lithostratigraphical, biostratigraphical and magnetostratigraphical succession of the Bracklesham Group, Whitecliff Bay, Isle of Wight (after Plint, 1983a; Edwards and Freshney, 1987b and other authors).

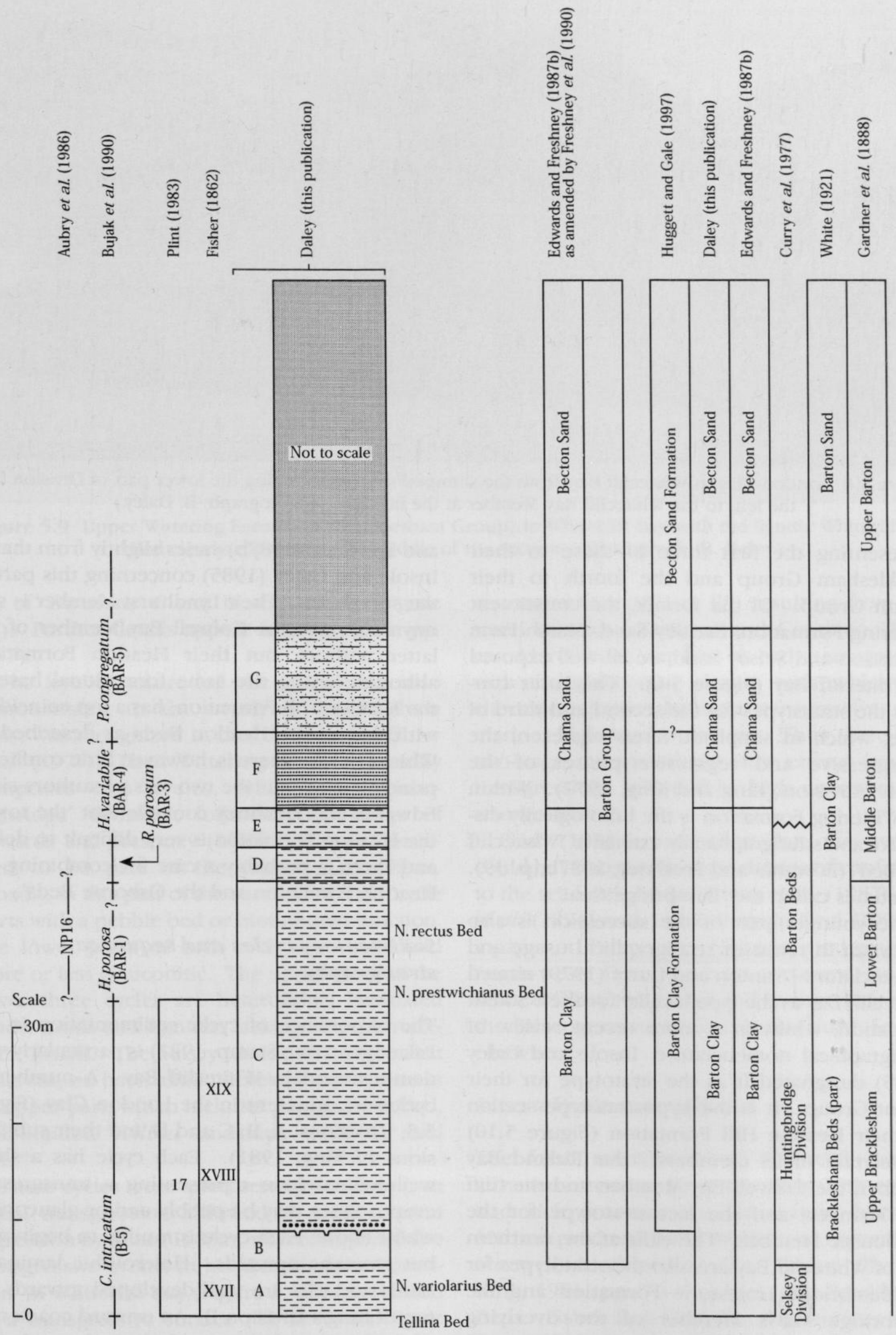

Figure 5.7 Lithostratigraphical and biostratigraphical succession of the Barton Group, Whitecliff Bay, Isle of Wight (after various authors).

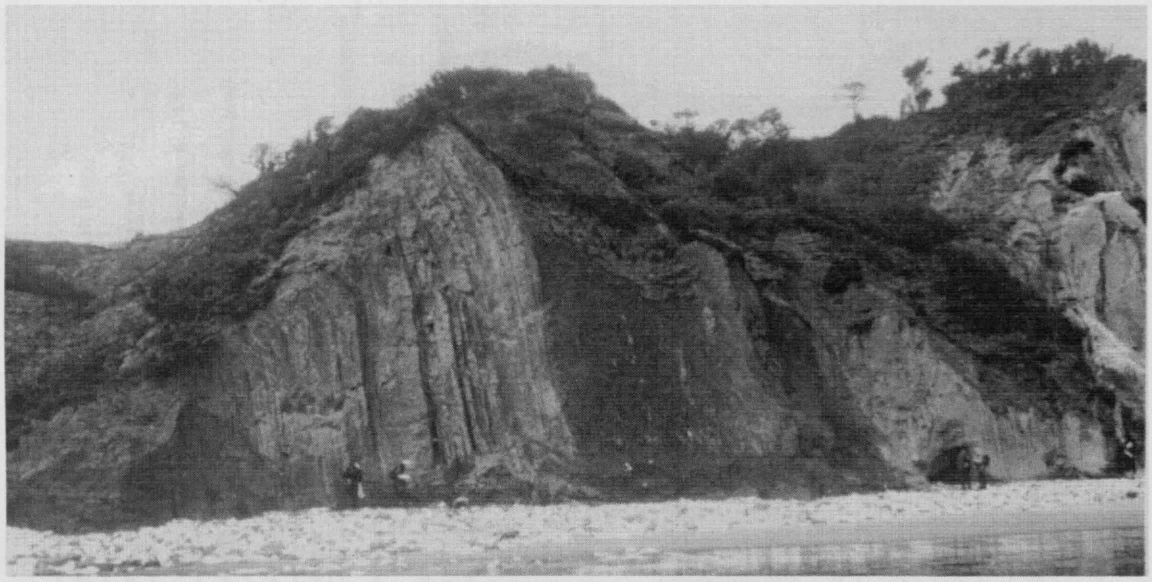

Figure 5.8 London Clay in Whitecliff Bay, from the slumped muds comprising the lower part of Division B at the left, to the Whitecliff Bay Member at the far right. (Photograph: B. Daley.)

representing the first three of these to their Bracklesham Group and the fourth to their Barton Group. Of the former, the constituent Wittering Formation, Earnley Sand, Marsh Farm Formation and Selsey Sand are all well exposed in Whitecliff Bay (Figure 5.6). The latter contains the stratotypes for the second and third of these, which in simplistic terms represent the transgressive and regressive phases of the Earnley division (King and King, 1977). Within the Wittering Formation is the lithologically distinctive and stratigraphically extensive 'Whitecliff Bay Bed' (Edwards and Freshney, 1987b, p. 39), sometimes called the 'Bembridge Coal'.

The younger part of the succession is also important in terms of stratigraphical usage and nomenclature. Stinton and Curry (1979) named Whitecliff Bay as the type locality for their Solent Formation, whilst in a more recent review of stratigraphical nomenclature, Insole and Daley (1985) designated it as the stratotype for their Solent Group. It is the hypostratotype section for their Headon Hill Formation (Figure 5.10) and certain of its members: the Totland Bay Member, the Colwell Bay Member, and the Cliff End Member; and the lectostratotype for the Fishbourne Member. The cliffs at the northern end of Whitecliff Bay are also the stratotypes for the Bembridge Limestone Formation and the Bembridge Marls Member of the overlying Bouldnor Formation (Figure 5.11).

A revision of the lithostratigraphical scheme for the Hampshire Basin Palaeogene by Edwards and Freshney (1987b) varies slightly from that of Insole and Daley (1985) concerning this part of the succession. Their Lyndhurst Member is synonymous with the Colwell Bay Member of the latter authors, but their Headon Formation, although having the same formational base as the Headon Hill Formation, has a top coinciding with that of the Headon Beds as described by White (1921). There is, however, little conflict of principle between the two sets of authors since Edwards and Freshney concede that 'the top of the Headon Formation is very difficult to define and there is probably a case for combining the Headon Formation and the Osborne Beds'.

Sedimentary cycles and sequence stratigraphy

The importance of cyclic sedimentation in the Palaeogene (see Stamp, 1921) is particularly well demonstrated in Whitecliff Bay. A number of cycles are apparent in the London Clay (Figure 5.5; 'Divisions' A, B, C and D and their sub-divisions of King, 1981). Each cycle has a sharp well-defined base representing a transgressive event. Bases may be pebbly and/or glauconitic, whilst above, each cycle is muddy to begin with but coarsens upwards. Heterolithic laminated sands and silts are well developed towards the top of King's Division B. An upward coarsening of the London Clay as a whole is shown by the development of the cross-stratified, clean sands of the Portsmouth and Whitecliff Members at the

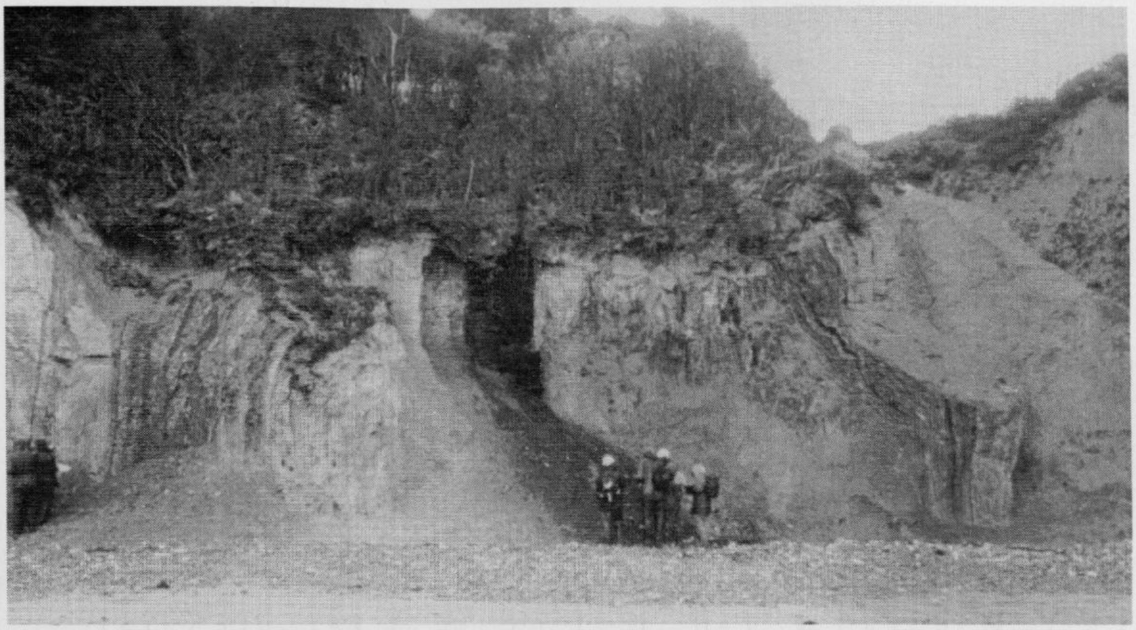

Figure 5.9 Upper Wittering Formation (Bracklesham Group) in Whitecliff Bay, with the lignitic Whitecliff Bay Bed clearly apparent in the middle of the section. (Photograph: B. Daley.)

top of 'Divisions' C and D respectively (Figure 5.5). Further details appear in King (1981, pp. 75–7).

The cyclic nature of the sequence, also demonstrated in the overlying Bracklesham Beds, was recognized in the 'divisions' of Curry *et al.* (1977). Their Wittering 'division' actually comprises two cycles, whilst their Huntingbridge 'division', following the usage of Edwards and Freshney (1987b), is now considered to be part of the Barton Clay above. Broadly, in this part of the succession, each cycle starts with a pebble bed or bioturbated junction. The lower parts of each cycle are shelly, and more or less glauconitic. The upper parts of the lower three cycles are heterolithic, laminated sands, muds and lignites, lacking macroinvertebrate fossils. The Selsey 'division' is somewhat different; no heterolithic development occurs in its upper part, which includes the cross-bedded, well-lithified '*Tellina* sandstone' of Fisher Bed XVI.

These cycles were interpreted as reflecting an initial transgression followed by a subsequent regression by Plint (1983a), who recognized five transgressive events in his 'Bracklesham Formation' in Whitecliff Bay (Figure 5.6), each defined by a transgressive surface (T1 to T5 in Figure 5.13). Later, Plint (1988a) suggested that the whole of the lagoonal and estuarine deposits represent the early stages of sea level rise and rest on surfaces (E1 to E5) resulting from low-stand erosion. Amorosi and Centineo (1997) considered such deposits as early transgressive, with the glauconitic clastics with which they alternate representing later transgressive, open marine, highstand situations. Thus there were two-stage transgressions: low energy brackish transgressions followed by high energy marine transgressions.

Plint (1988a) concluded that the cyclicity could be related with some degree of confidence to the sea-level curves of Haq *et al.* (1987). Neal *et al.* (1994) and, more recently, Neal (1996), in a paper on Palaeogene sequence stratigraphy in north-west Europe, have referred to the Whitecliff Bay succession and its correlation with the Palaeogene succession in the North Sea and elsewhere.

Invertebrate macrofauna

The fossil macrofauna of Whitecliff Bay has attracted attention since the early 19th century and rich faunas occur at certain horizons. Marine, predominantly molluscan, macrofaunas are well developed in the London Clay (see King, 1981, pp. 76–7) and in the Bracklesham Beds. Fisher Bed XVII (the *Nummulites variolarius* Bed) is particularly interesting since it contains, in addition to its molluscan fauna, the small coral *Turbinolia*.

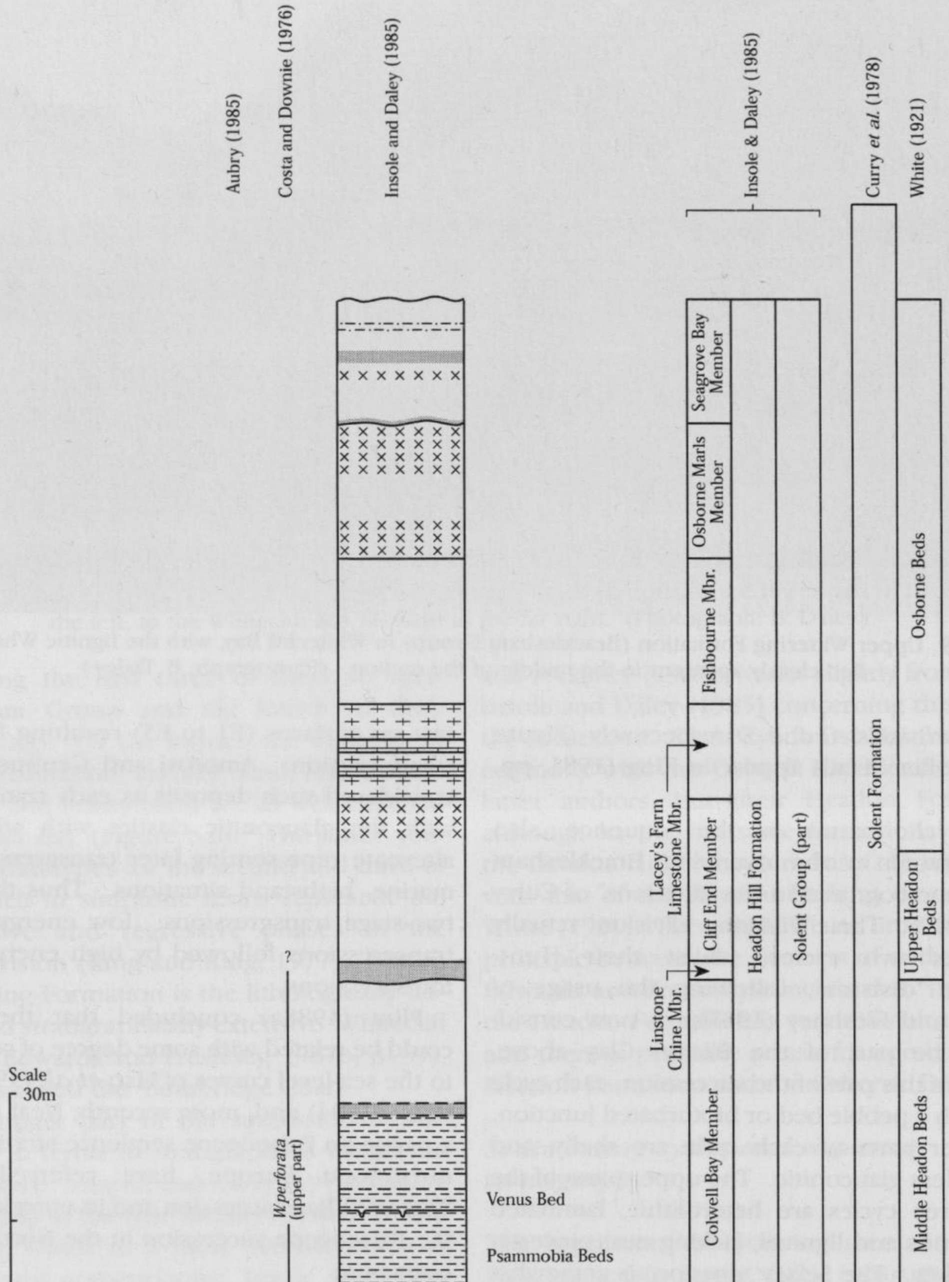

Figure 5.10 Lithostratigraphical and biostratigraphical succession of the Headon Hill Formation, Whitecliff Bay, Isle of Wight (after Insole and Daley, 1985 and other authors).

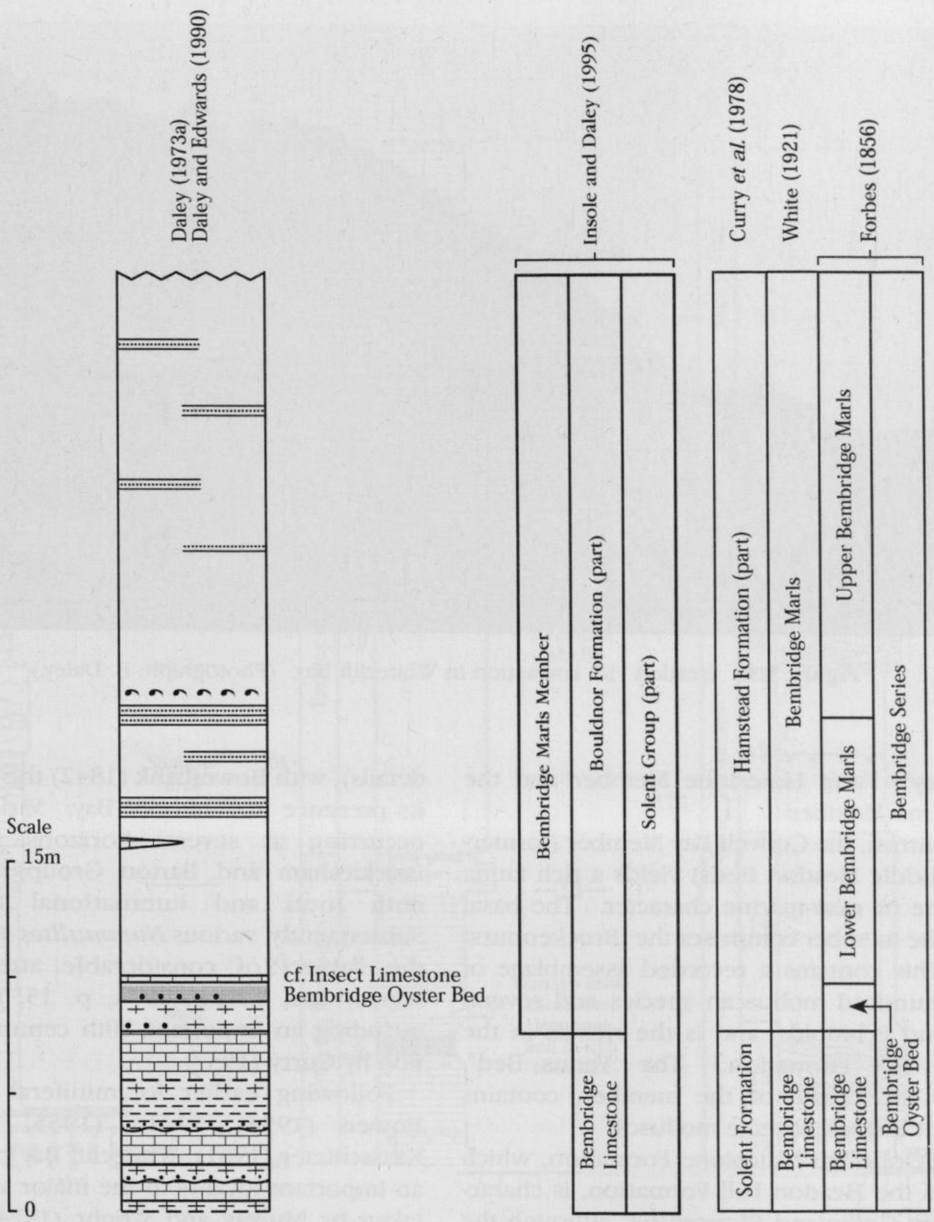

Figure 5.11 Lithostratigraphical succession of the Bembridge Limestone and Bembridge Marls Member (Bouldnor Formation), Whitecliff Bay, Isle of Wight (after Daley, 1973a; Daley and Edwards, 1990 and other authors).

The Barton Clay is poorly exposed, although the so-called 'Chama Bed' at its top contains a shallow-water fauna including *Chama squamosa*. Above the barren (decalcified) 'Barton Sand' (the Becton Sand of Edwards and Freshney, 1986), the Headon Hill Formation (Figure 5.10) is highly fossiliferous, but illustrates the increasing importance of low-diversity, low-salinity faunas in the younger part of the local Palaeogene succession. The Totland Bay Member, for example, contains a freshwater fauna comprising *Viviparus*, *Galba* and *Planorbina*, whilst in a green marl towards the top of the member, brackish water conditions are represented by an assemblage including *Potamomya*, *Melanopsis*, *Potamides*, *Tarebia* and *Theodoxus*. Other low-salinity faunas occur higher in the formation in the Cliff End Member,

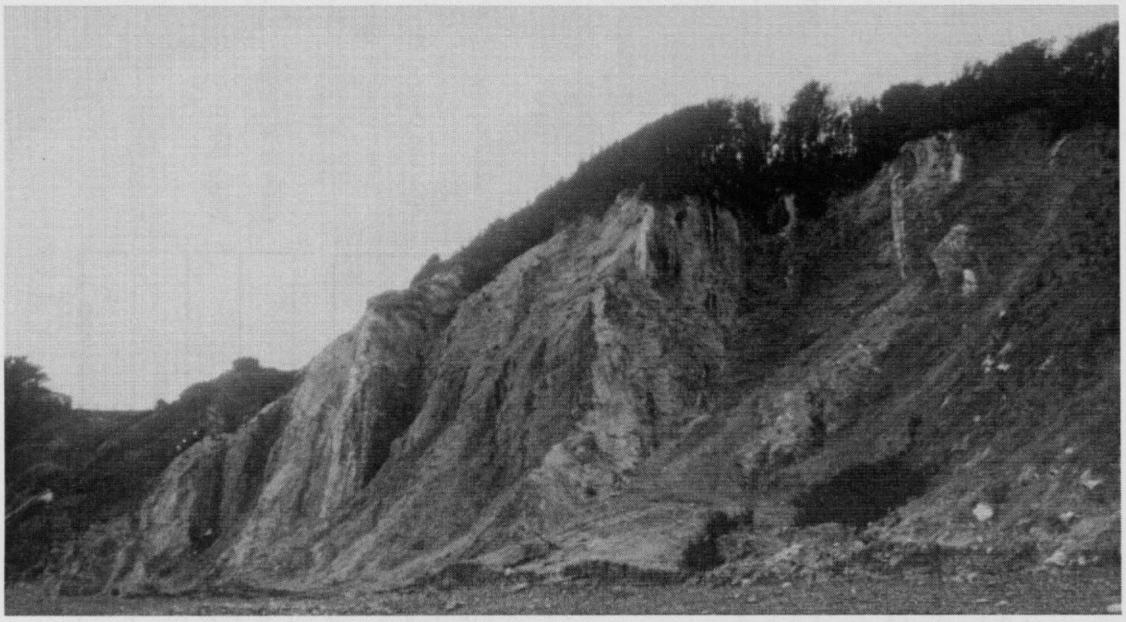

Figure 5.12 Headon Hill Formation in Whitecliff Bay. (Photograph: B. Daley.)

the Lacey's Farm Limestone Member and the Fishbourne Member.

By contrast, the Colwell Bay Member (formerly the Middle Headon Beds) yields a rich fauna of marine or near-marine character. The basal part of the member comprises the 'Brockenhurst Bed'. This contains a recorded assemblage of over a hundred molluscan species and several corals and echinoids, and is the richest in the Headon Hill Formation. The 'Venus Bed', towards the centre of the member, contains abundant but less diverse molluscs.

The Bembridge Limestone Formation, which succeeds the Headon Hill Formation, is characterized by *Galba* and *Planorbina*, although the land gastropods *Dissostoma mumia*, *Abida oryza* and *Palaeoxestina occlusa*, identified by Pain and Preece (1968), are a significant addition to the fauna. The brackish to freshwater faunas of the overlying Bembridge Marls Member of the Bouldnor Formation have been described by Daley (1972b).

Microfauna

The microfaunas of Whitecliff Bay have been the subject of considerable research. The importance of the foraminifer genus *Nummulites* in Palaeogene correlation was recognized in the 19th century (see Curry *et al.*, 1978, p. 13, for details), with Bowerbank (1842) the first to note its presence in Whitecliff Bay. Various species occurring at several horizons within the Bracklesham and Barton Groups have aided both local and international correlation. Subsequently, various *Nummulites* species were the subject of considerable attention (see Murray and Wright, 1974, p. 15, for details), including an important 20th century contribution by Curry (1937).

Following earlier foraminiferal studies by Bowen (1954), Bhatia (1955, 1957) and Kaasschieter (1961), Whitecliff Bay proved to be an important locality in the major study undertaken by Murray and Wright (1974). Benthic forms predominate, but in the London Clay, planktonic foraminiferids are well represented and are reported to be more abundant in this formation in Whitecliff Bay than at any other horizon or locality in the Hampshire Basin. Wright (1972) recognized the first appearance of planktonic foraminifera in the succession around 40 m above the top of the Reading Formation as an important marker horizon for correlation throughout the Hampshire Basin.

Most of the foraminiferid faunules recognized by Murray and Wright (1974) comprise low-diversity assemblages, interpreted as indicating mainly hyposaline conditions. Fully marine conditions are, however, represented by some

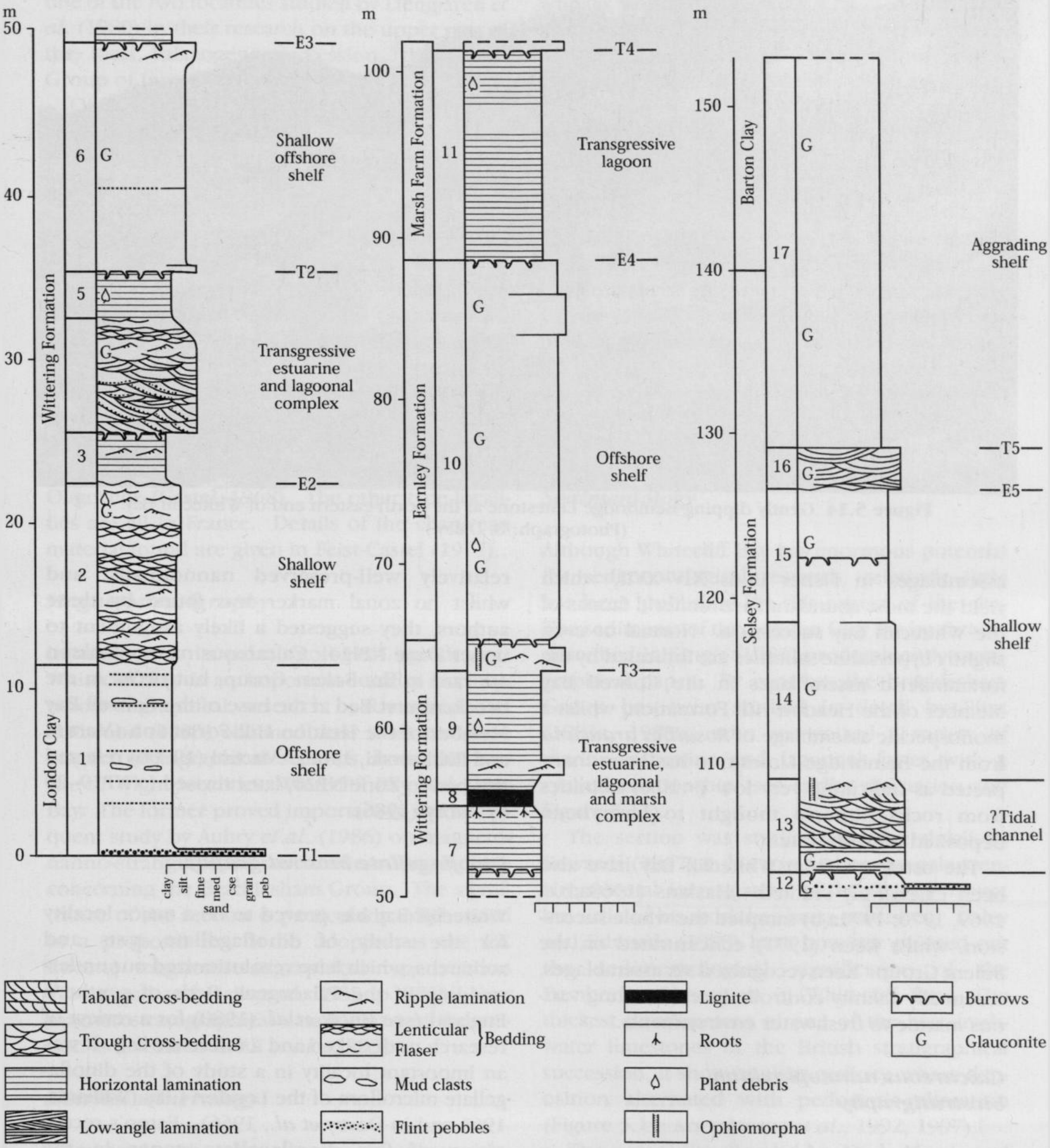

Figure 5.13 Bracklesham Group succession in Whitecliff bay, Isle of Wight (after Plint, 1983a, 1988a). Plint's (1983b) bed numbering scheme is used. 'T' numbers denote surfaces produced by marine transgressions whilst 'E' numbers denote surfaces of lowstand erosion and channel incision. Interpretations are those of Plint (1988a) modified by King and Hooker (1995).

Figure 5.14 Gently dipping Bembridge Limestone at the north-eastern end of Whitecliff Bay. (Photograph: B. Daley.)

assemblages in Fisher Beds XIV–XVII, which yield the most abundant foraminiferid faunas of the Whitecliff Bay succession. Normal or even slightly hypersaline salinities are indicated by the foraminiferid assemblages in the Colwell Bay Member of the Headon Hill Formation, whilst a monospecific assemblage of *Rosalina araucana* from the Bembridge Limestone has been interpreted as indicating very low (<10%) salinities from rocks hitherto thought to have been deposited in fresh water.

The ostracods from Whitecliff Bay have also been extensively studied. Haskins (1968a,b,c, 1969, 1970, 1971a,b) sampled the whole succession, whilst Keen (1977) concentrated on the Solent Group. Keen recognized six assemblages, essentially salinity controlled, representing various marine to freshwater environments.

Calcareous nannoplankton biostratigraphy

Calcareous nannoplankton are not common in Whitecliff Bay, but what does occur is significant for correlation (see Martini, 1970a). Aubry *et al.* (1986) were unable to identify any calcareous nannofossil (NP) biozones in the London Clay or 'Bagshot Beds'. The lowest datable level, Fisher Bed IV, indicates upper Zone NP12/lower Zone NP13. Fisher Bed VII also contains common and relatively well-preserved nannofossils, and whilst no zonal marker was found by these authors, they suggested a likely assignment to upper Zone NP 14. Calcareous nannoplankton are rare in the Solent Group, but occur in the Brockenhurst Bed at the base of the Colwell Bay Member of the Headon Hill Formation (Martini and Ritzkowski, 1968). Martini (1970b) referred this bed to Zone NP20, later revised to NP19–20 by Aubry (1986).

Dinoflagellate biostratigraphy

Whitecliff Bay has proved to be a major locality for the study of dinoflagellate cysts and acritarchs, which have revolutionized our understanding of the Palaeogene Beds of southern England (see Bujak *et al.* (1980) for a review of research undertaken and a reference list). It was an important locality in a study of the dinoflagellate microflora of the London Clay (Williams, 1964 and in Davey *et al.*, 1966). Eaton's recognition of five dinoflagellate zones in the Bracklesham Beds (Eaton, 1971a, 1971b, 1976) was likewise based on a study of the rich microflora from Whitecliff Bay, together with that from Alum Bay. Whitecliff Bay was also an important locality for dinoflagellate research on the Barton Beds by Bujak (1976, 1979). Other dinoflagellate work on the section includes that of Costa and Downie (1976) on the valuable dinoflagellate zone fossil *Wetzeliella*, and it was one of the two localities studied by Liengjaren *et al.* (1980) in their research on the upper part of the local Palaeogene succession (the Solent Group of Insole and Daley, 1985).

Of the 13 dinoflagellate cyst assemblage zones erected by Bujak *et al.* (1980) and based on this earlier work, eight have Whitecliff Bay as a type locality.

Charophytes

Charophyte gyrogonites occur in mainly freshwater sediments towards the top of the succession (Groves, 1926) and are most obvious at certain horizons in the Bembridge Limestone. Their occurrence is important stratigraphically (Grambast, 1962), with Whitecliff Bay the type section for the charophyte Bembridge Zone, the lowest of five charophyte zones assigned to the Oligocene (Castel, 1968). The other type localities are all in France. Details of the characean material found are given in Feist-Castel (1977).

Magnetostratigraphy

In addition to its palaeontological significance, Whitecliff Bay is an important locality for magnetostratigraphical research. Townsend and Hailwood (1985) obtained their most complete magnetostratigraphical sections from the two Isle of Wight localities, Whitecliff Bay and Alum Bay. The former proved important in the subsequent study by Aubry *et al.* (1986) on magneto-nanno-stratigraphical correlation, particularly concerning the Bracklesham Group. The significance of the section is particularly emphasized in a proposal that it be adopted as the UK Eocene magnetostratigraphical type section (Townsend and Hailwood, 1985, p. 981). New magnetostratographical data for part of the section is discussed in Ali *et al.* (1993).

Detrital mineralogy

Compared with other aspects of geology, relatively little mineralogy work has been undertaken in Whitecliff Bay. It was the main section sampled by Walder (1964) in her study of Eocene heavy minerals and was also investigated by Blondeau and Pomerol (1962). Later, Morton (1982b) used material from the section in a study attempting to restate the value of heavy minerals in correlation. He recognized three suites from 'Scotland', Armorica and Cornubia whose influences vary up the succession. Amongst his conclusions was that the first definite occurrence of the Cornubian suite represents a major palaeogeographical change 'with the first uplift and exposure of the Cornubian landmass in Tertiary times'. It coincides with the dramatic influx of tourmaline noted by Blondeau and Pomerol (1968) in the Whitecliff Bay succession in Fisher Beds IV, V and VI. Morton considers that this part of the succession is the most regressive of the entire sequence.

Clay mineral studies have been undertaken by Gilkes (1968, 1978), whilst glauconites, common at several horizons, were used by Odin *et al.* (1969) in their work on the radiometric dating of the local Palaeogene strata. Recent work on glaucony includes that by Amorosi and Centineo (1997) and Huggett and Gale (1997).

Sedimentology

Although Whitecliff Bay has enormous potential for sedimentological research, relatively little has been published on this aspect of the site. The sediments of the London Clay are but briefly described in King's (1981) predominantly stratigraphical paper. By contrast, the Bracklesham Group has been studied in detail by Plint (1983a, 1988a), who recognized a variety of marine, estuarine and lagoonal facies with a cyclical relationship (see earlier discussion and Figure 5.13).

The section was studied in some detail by Edwards (1967) in his comprehensive palaeoenvironmental investigation of the Solent Group, but little of his work has been published. Daley and Edwards (1990) have however pointed out the sedimentological significance of the Bembridge Limestone in Whitecliff Bay. The thickest development of one of the best freshwater limestones in the British stratigraphical succession, it shows a clear cyclicity, where deposition alternated with pedogenic alteration (Figure 5.15; Armenteros *et al.*, 1992, 1997).

The succeeding Bembridge Marls Member of the Bouldnor Formation (Figure 5.16) contains a variety of important sedimentological features. Just above the 'Bembridge Oyster Bed', the lateral equivalent of the 'Insect Limestone' at Gurnard (but virtually bereft of insects) contains a variety of beautifully preserved, small-scale water-escape structures (Daley, 1971). A little

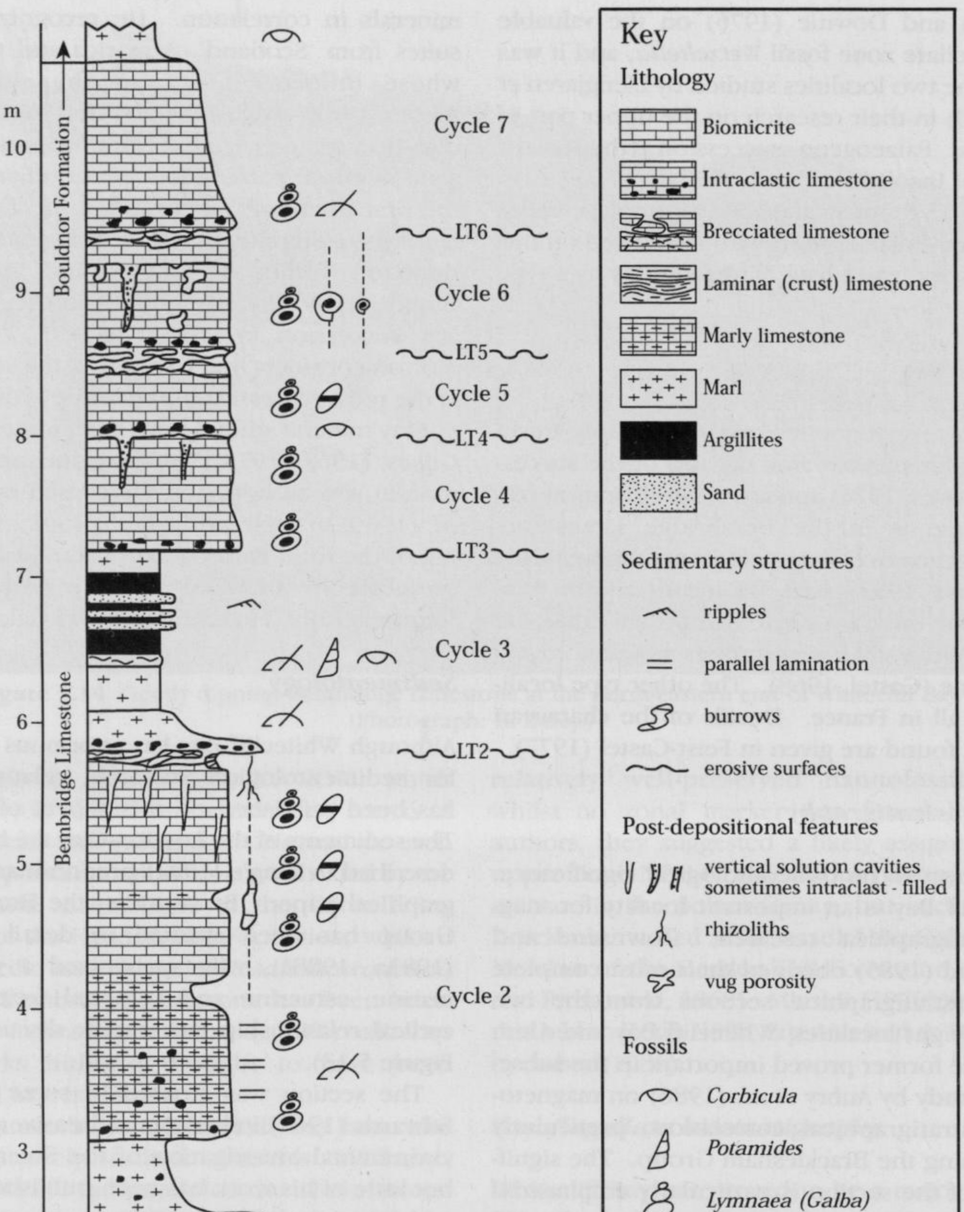

Figure 5.15 Bembridge Limestone succession in Whitecliff Bay, Isle of Wight (after Armenteros *et al.*, 1997), to illustrate how lithology is related to cyclicity. LT1 to LT6 refer to transgressive surfaces at the bases of the lacustrine cycles.

above, Daley (1974) found fossil blue-green algae (the first described from the Hampshire Basin) encrusting the surfaces of bivalves. In the upper part of the member, fining-upwards cycles have been described (Daley, 1973b). At the base of one of these an unusual and well-preserved suite of sedimentary structures includes clastic pseudomorphs after gypsum (Daley, 1967), gutter casts and palaeoslope-influenced parallel crack fills (Daley, 1968).

Less than 0.5 km north-eastwards from Black Rock Point, the Palaeogene cliff section ends. The remainder of the section comprises almost horizontal hard units within the Bembridge Limestone, together with the 'Insect Limestone', which are exposed on the foreshore at low tide. In this part of the section, Daley and Edwards (1971) recognized that the Bembridge Marls Member rests with angular unconformity on the Bembridge Limestone, thereby recording a phase of previously unrecognized intra-Palaeogene warping.

Interpretation and evaluation

Within a distance of just over 1 km, the just over 550 m of strata exposed in Whitecliff Bay represent some 15 million years. Not surprisingly, the site as a whole has provided a vital source of data from which much has been ascertained about the local Palaeogene palaeogeography and palaeoenvironments. Stratigraphically, it is more extensive than any other single Palaeogene site in Britain, even if Alum Bay and Headon Hill are considered as a single locality. It is, therefore, of considerable national and indeed international importance.

Since the 19th century, perhaps more than any other site, Whitecliff Bay has provided a basis for establishing the Hampshire Basin Tertiary succession. It cannot, of course, be regarded as either a representative or typical succession, since due to the paralic nature of the local Palaeogene palaeogeography, considerable lateral environmental and therefore stratigraphical variations occurred. However, it broadly represents a more marine influenced succession than localities such as Alum Bay and the Dorset sites further west.

Comparison with other localities

Whitecliff Bay differs from other Palaeogene sites in various respects, at some horizons more so than others. At the bottom of the succession, the Reading Formation is twice as thick as that at Alum Bay. The London Clay is thicker too (142.3 m compared with some 71 m at Alum Bay), but comparisons depend, in part, on the definition of units and their stratigraphical limits (see discussions of what comprises the London Clay at Alum Bay, below).

Comparison and lithological correlation of the Palaeogene of the Hampshire Basin is made difficult by marked lateral facies changes, but in recent years relationships from one locality to another have become more readily understood by what has come to be called 'event stratigraphy'. This has emphasized the importance of cyclicity in the Palaeogene sediments of the Hampshire Basin (see Curry *et al.*, 1977), by showing that packages of strata are separated by transgressive surfaces. The well-exposed and continuous Whitecliff Bay succession has provided a sound basis for this approach. As many as seven transgressive events have been recognized here from the London Clay (King, 1981), whilst five were recorded from the 'Bracklesham Formation' by Plint (1983a).

Higher up the succession in Whitecliff Bay, the Headon Hill Formation is broadly comparable with this unit at the west end of the Island, in that the Colwell Bay Member represents a transgressive, more marine interval in a sequence otherwise characterized by low-salinity to freshwater conditions. In detail, however, it is somewhat different. The Linstone Chine Member is questionably present. The Hatherwood Limestone is absent, as are the other thinner freshwater *Galba*-bearing limestones of the west Wight localities. The Lacy's Farm Limestone Member is present but lacks the thick limestone development of Headon Hill. Some members have quite different thicknesses in Whitecliff Bay compared with other localities. The 8.3 m Totland Bay Member is much thinner than at Totland itself (32.2 m) whilst, by contrast, the Colwell Bay Member is three times as thick here compared with its development at Headon Hill. The uppermost Seagrove Bay Member present here is not found at the western localities, but is better developed on the north-eastern coast of the Island to the south of Seaview, where limestone and conglomerates occur at this level. Above, the Bembridge Limestone (one of the best examples of a freshwater limestone in the British stratigraphical column) is both at its thickest and best in Whitecliff Bay, whilst the

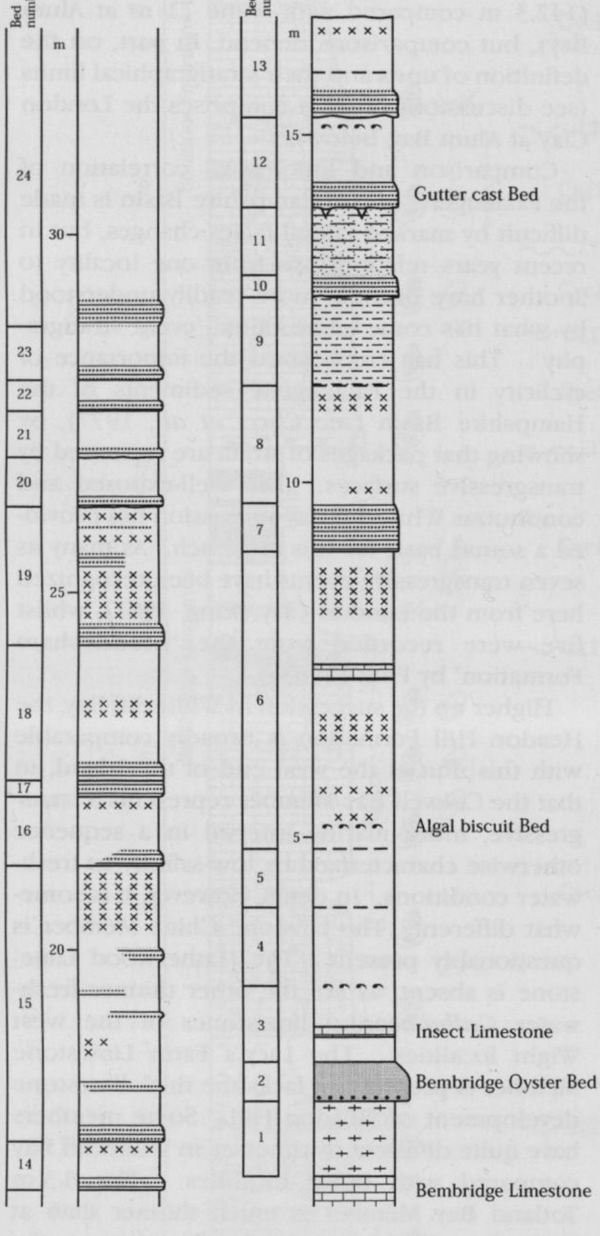

Figure 5.16 Bembridge Marls Member (Bouldnor Formation) succession in Whitecliff Bay, Isle of Wight (after Daley, 1973).

succeeding Bembridge Marls Member of the Bouldnor Formation, although thicker here than elsewhere, is intermittently exposed. The Bembridge Oyster Bed is better developed here than at all other localities, whilst just above, the equivalent of the Insect Limestone in Thorness Bay contains only very rare insects and few plants.

Stratigraphy

The importance of the site in terms of formal stratigraphy is considerable and more so than any of the other onshore Palaeogene localities in Britain. In the 19th century, Fisher (1862) considered that Whitecliff Bay provided a better section of the Bracklesham Beds than Bracklesham Bay, whilst, as mentioned earlier, it has the only complete section of the London Clay and its constituent divisions (King, 1981). Altogether, it provides type sections (stratotype, hypostratotype, lectostratotype) for one group, four formations and eleven members, of which most, although not all, are accepted as valid stratigraphical units. Whitecliff Bay was also the type section for the four informal 'divisions' of Curry *et al.* (1977) (see earlier discussion of 'event stratigraphy').

Amongst the 'disputed' units of Whitecliff Bay is that named the Oldhaven Formation by King (1981). The author concurs with the view of Edwards and Freshney (1987b) that, at least in the Hampshire Basin, this is not sufficiently distinct lithologically to be considered as a separate 'mappable' formation. The Tilehurst Member of King (1981) in Whitecliff Bay therefore might revert to Prestwich's (1850) original term, the London Clay Basement Bed. Alternatively, member status could be retained but within the London Clay rather than the Harwich Member of Ellison *et al.* (1994), since it is uncertain whether the latter has validity as a formation in the Hampshire Basin.

A number of named units in Whitecliff Bay have titles of some antiquity. Over recent years, and particularly under the influence of Hedberg (1976), some of these have already disappeared or will disappear from the local stratigraphical terminology, whilst the limits of others have been redefined. An example is the term 'Bagshot Sands', now omitted from the formal terminology and almost certainly least to be mourned, since although widely used historically in both the Hampshire and London Basins, both definition and recognition have been difficult. Inevitably, there is as yet no universal agreement as to what names should be used but a general concensus exists, based on Edwards and Freshney (1987b) and Daley and Insole (1985).

The London Clay Formation now includes the 'Bagshot Sands' (see earlier description). Furthermore, it is compatible with Hedbergian principles to follow Edwards and Freshney (1987b, p. 49) in also including 11 m of the overlying Fisher Bed I (Bracklesham Beds, Wittering 'division' of Curry *et al.*, 1977, p. 245) in the London Clay on the grounds of lithological continuity. Hence, in Whitecliff Bay, the onset of the Wittering transgressive 'event' represented by a pebble bed at the bottom of Fisher Bed I, does not coincide with the base of the lithostratigraphical unit, the Wittering Formation of Edwards and Freshney (1987b, p. 57).

The problems of defining boundaries between different stratigraphical units is also exemplified by the Bracklesham/Barton junction in Whitecliff Bay. Traditionally (see, for example, White, 1921), Fisher Beds I to XIX were included in the Bracklesham Beds, with the base of the Barton Beds defined by the appearance of *N. prestwichianus* (*elegans*). Curry *et al.* (1977) followed this tradition by including all the Fisher Beds from I to XIX in their Bracklesham Group, despite the fact that many years earlier, long before the introduction of formal rules of lithostratigraphy, White (1921, p. 100) had noted that 'there is nothing in the general appearance of the Lower Barton clays to distinguish them from the Upper Bracklesham clays, into which they pass.'

Following Hedberg (1976), it has become clear that the muddy units originally included in the highest Bracklesham Beds, both in Whitecliff Bay and elsewhere, are better reassigned to the Barton Clay. Edwards and Freshney (1987b) transferred the Huntingbridge 'division' of Curry *et al.* (1977) to the Barton Clay, as was earlier done though not overtly stated in Daley and Insole's (1984) account of the Whitecliff Bay succession. Edwards and Freshney (1987b) also placed the *N. variolarius* Bed of Whitecliff Bay (Fisher Bed XVII) in the Barton Clay, arguing that differentiating the latter from the underlying formation was essentially one of sand content. However, as a result of grain size analysis by Freshney *et al.* (1990) which showed it to predominantly comprise sand and silt, this unit has been reassigned to the Selsey Sand. Hence, the lithified and easily identifiable '*Tellina* Bed' (Fisher Bed XVI) occurs a little below rather than at the top of this formation.

Chronostratigraphy and biostratigraphy

Our now considerably improved understanding of the lithostratigraphy of Whitecliff Bay and its relationship to other localities has been paralleled by chronostratigraphical and biostratigraphical work aiming to achieve a sound understanding of time equivalence both locally, nationally and internationally. To this end, research in Whitecliff Bay has made a major contribution. The latter reflects two advantages which this section has over all others of the British on-land Tertiary succession. Firstly, there is its stratigraphical extent and continuity. Secondly, its greater proportion of marine strata has facilitated the use of marine zone fossils which are absent or poorly represented at some other localities.

Foraminifera

Early work on the section demonstrated that the different species of *Nummulites* characterizing a number of horizons in the Bracklesham Group and Barton Clay could be used for correlation. This did not solve the problem of matching marine and non-marine sediments, but facilitated both local and international correlation of marine units. Fisher Bed VII, for example, which is rich in *N. laevigatus*, can be correlated locally with Fisher Bed VI at Bracklesham, and internationally with the lower parts of the Calcaire Grossier of the Paris Basin and the Brussels Sands (Curry *et al.*, 1978, p. 42). This paper, together with Curry (1966), presented national and international correlation schemes. The locally important 'planktonic foraminiferid datum' of Wright (1972) was based on work mainly undertaken in Whitecliff Bay.

Calcareous nannoplankton

Both the zonal scheme for planktonic foraminifera and that for calcareous nannoplankton have proved of limited value as far as British sites are concerned. However, some nannoplankton dates have been obtained from Whitecliff Bay and have contributed to a better understanding of how the local succession fits into a wider European regional context (Neal *et al.*, 1994; Neal, 1996).

Martini (1970b), in dating the Brockenhurst Bed (base of Colwell Bay Member) in Whitecliff Bay as being NP20 in age, refuted an older view that it was equivalent to the type Lattorfian (lower Oligocene) and established that this part of the succession was of Eocene age. Aubry's (1986) more recent view is that the Brockenhurst Bed cannot be dated quite so specifically and she prefers an NP19–20 age.

Dinoflagellates

Research on Whitecliff Bay has contributed to the development of a variety of zonal schemes based on dinoflagellates. Here, Eaton (1971a, 1971b) recognized five microplankton zones which have facilitated the correlation of the perplexingly different lithological sequences at Whitecliff and Alum Bays. The importance of the section is further emphasized by the fact that of the 13 dinoflagellate zones established by Bujak *et al.* (1980), eight have Whitecliff Bay as the type section.

Studies of the dinoflagellate genus *Wetzeliella* (*sensu lato*) from the site have contributed to the development of a correlation scheme based on species of this fossil (Costa and Downie, 1976).

Interestingly, *Wetzeliella* dates for the top of the London Clay here are older than at Sheppey but younger than for sites further west in the Hampshire Basin. The *D. varielongituda* zone is the highest zone present in the London Clay (*sensu* King) of Whitecliff Bay, whilst to the west at Studland, the top of the formation is in the *W. meckelfeldensis* zone. The top of the London Clay is therefore strongly diachronous.

Depositional environments

In terms of palaeogeographical reconstruction, Whitecliff Bay, more than any other locality, demonstrates the cyclic nature of the Palaeogene succession of south-eastern England, with the recognition of approaching 20 transgressive events. However, despite the common occurrence of marine macrofossils at many horizons, research has indicated that the development of open sea conditions was the exception rather than the rule. Murray and Wright (1974) have suggested that much of the succession from the London Clay to the Barton Clay represents river-influenced shallow shelf conditions with hyposaline waters. Only on relatively few occasions, such as the period represented by Fisher Beds XIV–XVII in the Bracklesham Group, were fully marine conditions established. There is evidence that such conditions are also represented by parts of the Colwell Bay Member, but, in general, the restricted faunas of the higher parts of the succession indicate still lower salinities. With the rare development of fully marine conditions, the domination of the Whitecliff Bay macrofauna by molluscs and the general absence of corals, echinoids, etc., is hardly surprising.

The heterolithic, sometimes lignitic, lithologies of the London Clay and Bracklesham Group are probably peripherally marine and intertidal, whilst the 'Bagshot Sands', at one time thought of as fluvial, are, with the Becton Sand Formation, now considered to be shallow marine tidal to littoral sands.

Whilst aspects of the sequence once considered to be regressive may possibly represent brackish transgressions (see p. 97), there are three stratigraphical levels for which a regressive interpretation remains valid.

An early substantial regression is represented by the Reading Formation which has been considered to be of fluvial origin, with its distinct mottled colouration interpreted as a reflection of subaerial weathering (Buurman, 1975). Ellison (1983) suggested a brackish lagoonal origin for similar facies of this age in the London Basin, emphasizing that pedogenic modification inhibits environmental interpretation, but according to Neal (1996), deposition at this stratigraphical level coincides with the peak regression of the upper Palaeocene cycle in the central North Sea.

A second major regressive event is represented within the Wittering Formation. Plint (1983a) suggested that in the Bracklesham Group there is little evidence for major regression, but a variety of evidence, including the reported absence of any record of Chron C22N (Aubry *et al.*, 1986), led to the conclusion that a major regression occurred over a wide area of the Hampshire Basin at the level of the 'Whitecliff Bay Bed' (within Bed V of Fisher, 1862; Bed 8 of Plint, 1983a) (Morton, 1982b; Edwards and Freshney, 1987b). Ali *et al.* (1993, p. 103) queried the placing of the hiatus at the level of the 'Whitecliff Bay Bed' and suggested alternative possibilities both below and above this horizon. The nature of this problem was further discussed by Neal *et al.* (1994) whilst Neal (1996, pp. 30–1) concluded that Fisher Beds IV and V could be interpreted to fall within the 'Intra-Frigg' hiatus of the North Sea succession.

A third major regression, well demonstrated by the Whitecliff Bay succession, commenced with the shallowing initiated by the deposition of the Becton Sand and led to the long period of essentially non-marine to marginal-marine conditions represented by the Solent Group, interrupted only by the relatively short-lived marine incursions of Colwell Bay Member and 'Bembridge Oyster Bed' times.

Although Whitecliff Bay has been the subject of greater study than any other single Palaeogene site, with the possible exception of Sheppey, the research potential of the section remains considerable. Palaeoenvironmental reconstructions based on sedimentological studies are, with some notable exceptions, for the most part incomplete and/or unpublished. Modern studies of the invertebrate macrofaunas, e.g. those of the Headon Hill Formation, have yet to be undertaken.

Conclusions

For a variety of reasons, Whitecliff Bay is one of the most important Palaeogene sites, not only in Britain, but internationally. With more than 550 m of strata ranging from Palaeocene to late Eocene/early Oligocene age, it is probably *the* most continuous exposure of sediments of this age in western Europe.

Whitecliff Bay in particular has been studied since the 19th century and is the subject of numerous publications. The importance of its contribution to our understanding of the Palaeogene is therefore considerable. Historically, it was of major importance to those early geologists attempting to establish the local Palaeogene succession, whilst very recently it has been proposed as the UK magnetostratigraphical type section.

The site has achieved recognition from many different standpoints. It is the type section for over 15 lithostratigraphical units. From another stratigraphical standpoint, it demonstrates Palaeogene cyclicity more clearly than any other British site. A series of 'events', in particular transgressions of various magnitudes and regressions, are represented, and consequently the site includes strata recording a wide variety of environments from shallow marine to freshwater. A feature of the succession is the predominance of marine environments early on and the increasing importance of brackish and freshwater strata in the upper part of the sequence.

The palaeontological aspects of the site have made significant contributions both to our understanding of the local Palaeogene palaeoenvironments and palaeogeography and in terms of zonation and correlation.

Foraminiferal studies in Whitecliff Bay have indicated that, even for the parts of the succession traditionally considered to be marine, the sea was for the most part hyposaline. Rich molluscan faunas occur at some horizons, but corals, echinoids and other forms more associated with wholly marine salinities are rare. Higher up the succession, faunas with low species diversity are associated with brackish to freshwater environments.

From the point of view of correlation, the early recognition of different species of *Nummulites* in Whitecliff Bay provided a basis for correlation. Later studies of planktonic foraminifera and phytoplankton revolutionized Palaeogene zonation and correlation. Whitecliff Bay has made a major contribution, in particular, to the development of dinoflagellate zonation. Of the 13 dinoflagellate zones established for the London Clay to Barton Clay succession, eight have Whitecliff Bay as the type locality. More recently, integrated bio/magnetostratigraphical research has enhanced our understanding of the Whitecliff Bay sequence and its correlation with other Palaeogene sequences in the north-west European area, including those of the North Sea.

ALUM BAY, ISLE OF WIGHT (SZ 305855)

Highlights

One of the most stratigraphically extensive sections in Western Europe, Alum Bay is the site that best demonstrates the relationship between the more marine succession to the east and the more continental succession to the west. Although less fossiliferous than Whitecliff Bay, it has been an important source of macrofloral remains and for macroinvertebrates at certain levels, such as the Barton Clay. The succession has also proved of importance in microfloral zonation and correlation whilst, from a palaeoenvironmental point of view, a wide variety of depositional conditions are well demonstrated by the succession.

Introduction

For the purposes of this volume, the Totland Bay–Alum Bay site (extending between SZ 305852 and SZ 320866) is subdivided into two, both geographically and geologically. The geographical 'boundary' is a short distance to the north of Alum Bay Chine. To the south, a predominantly vertical Palaeogene succession extends from the contact with the Chalk up to and including the Barton Clay (Figure 5.17). This sequence comprises 'Alum Bay' in the sense used here. Further northwards, predominantly near-horizontal strata extend to Totland Bay. Apart from the Becton Sand at the base, the sequence here comprises the Solent Group up to the Bembridge Limestone Formation. This more northerly part of the site is considered later under the title 'Headon Hill'.

Although mainly known to the general public for its famous coloured sands, the Alum Bay section has been the subject of serious scientific study since the early 19th century. With its continuation in 'Headon Hill', it is one of the most stratigraphically extensive successions in Western Europe, though less so than that of Whitecliff Bay.

From the unconformable contact with the Upper Cretaceous Chalk to the south, a nearly 420 m unbroken succession of near-vertical strata extends northwards to Alum Bay Chine. Predominantly muddy sediments occur near the bottom and top of the succession, whilst the middle part (the Alum Bay Sands of Daley and Insole, 1984) comprises some 230 m of white, yellow, brown and red sands interbedded with brown and grey muds and subordinate lignites.

The first account of the section was provided by Webster (1814), although it was Prestwich (1846) who published the earliest detailed description and whose bed numbers are often still used today (see Figures 5.21, 5.22 and 5.23). Other early general accounts occur in Bristow *et al.* (1889) and White (1921), whilst Fisher (1862) and Gardner *et al.* (1888) undertook more specialist stratigraphical studies.

Over the last thirty years or so, there has been a considerable renewal of interest in the section. Relatively brief descriptions are given in Curry (1968), Curry *et al.* (1972) and Daley and Insole (1984). Recently, a comprehensive account of the whole succession has been published by Daley (1999, pp. 29–39). Parts of it have been studied in some detail by other authors. The presence of fossil soils in the Reading Formation was recognized by Buurman (1975, 1980), whilst King (1981) described the London Clay in his broader study of this formation in south-eastern England. Plint (1983a, 1988a) has undertaken a detailed sedimentological study of the Bracklesham Group.

Both the London Clay and the Barton Clay have good molluscan macrofaunas, but these have not been investigated comprehensively in recent years. Crane (1977, 1978) has, however, published on the plant macrofossils, including those from the famous 'Alum Bay Leaf Bed'.

Micropalaeontological studies have included work on the phytoplankton (e.g. Eaton, 1971a,b, 1976) including species of the important dinoflagellate zone fossil *Wetzeliella* (Costa and Downie, 1976). Foraminiferal studies include work by Murray and Wright (1974). Magnetostratigraphical work on the section (Townsend and Hailwood, 1985) subsequently led to research into its relationship with the nannoplankton flora (Aubry *et al.*, 1986).

Description

At the southern end of Alum Bay, where the Chalk cliff extends westwards to terminate in the stacks known as the 'Needles', the Palaeogene sediments lie unconformably on the *Belemnitella mucronata* Zone of the Upper Chalk. As at Whitecliff Bay, there is no angular discordance, although the surface is pot-holed and irregular. Northwards, the near-vertical Palaeogene strata represent a section through the steep, northern limb of the Brighstone Anticline (Figure 5.18).

Lithological succession

The succession in Alum Bay is summarized in Figure 5.19. Four lithostratigraphical groups are represented: in ascending order, the Lambeth Group, the Thames Group (Figure 5.21), the Bracklesham Group (Figures 5.22 and 5.23) and the Barton Group (Figure 5.23). The succession is predominantly an alternation of sands and muds. The Reading Formation at the base comprises colour-mottled muds. Above, fining-upwards cycles of the London Clay comprise sometimes glauconitic clays to fine sand. In the 'Alum Bay Sands' of Daley and Insole (1984) (Bracklesham Group and overlying Boscombe

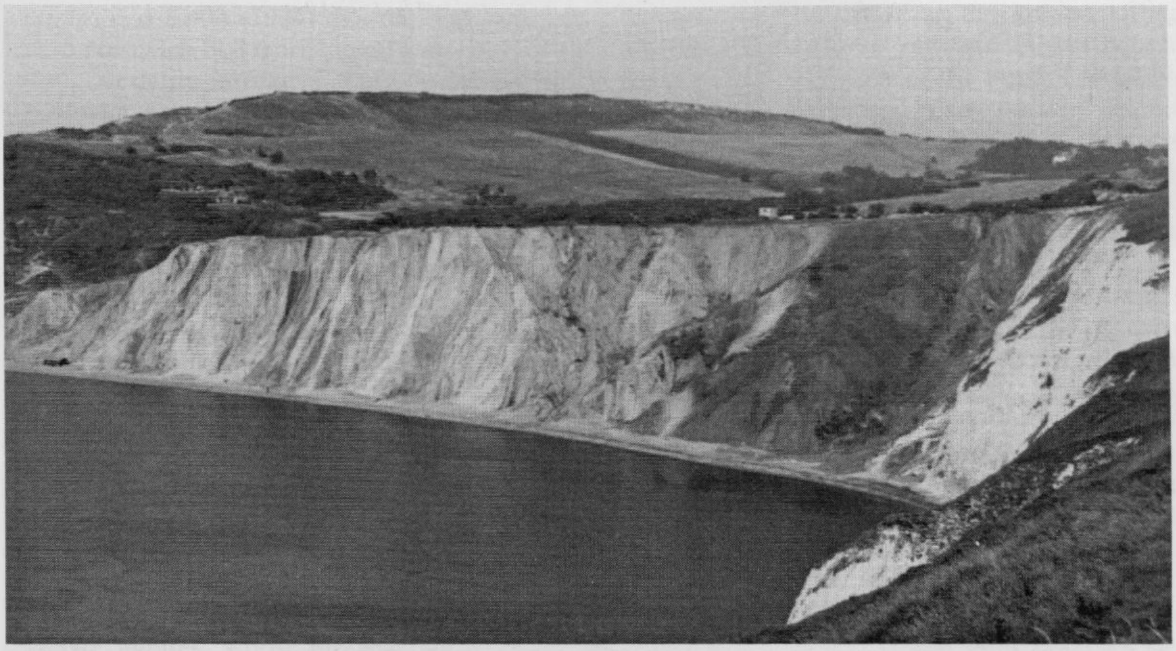

Figure 5.17 Alum Bay, Isle of Wight, viewed from West High Down. Steeply dipping, light-coloured Bracklesham Group Strata form the central part of the cliff section. To their right (south), the darker units are the London Clay and (forming a gully) the Reading Formation which rests unconformably on the Chalk. The lower cliff profile at the left (north) of the photograph comprises the Barton Clay. (Photograph: B. Daley.)

Sand), five sand bodies alternate with laminated strata comprising finely interbedded muds (clay/silt mixtures) and sands (Figure 5.20). Some horizons contain a good deal of lignitic matter. The Barton Group sediments comprise sometimes glauconitic muds and sandy muds below (Barton Clay) and pale quartz sands at the top (Becton Sand). Rudaceous rocks are confined to relatively few horizons. Flint pebbles occur at the contact with the Chalk and within the London Clay, whilst the band of large flint pebbles at the top of the Boscombe Sand is a distinctive marker horizon (Figure 5.23). Concretions occur within some of the muds and several ironstone bands are present in the Bracklesham Group strata but elsewhere the succession is unlithified.

Stratigraphy

The thick and well-exposed sequence attracted the early attention of geologists attempting to establish a local stratigraphical succession. The most significant early stratigraphical work on the section was that of Prestwich (1846, 1847) whose bed-numbering system continues to be of considerable practical value. However, although the section has been studied for many years, only recently has a consensus begun to emerge regarding lithostratigraphy and nomenclature. Differences of opinion have reflected the lateral variation in facies which characterizes the local Palaeogene and the difficulty in assigning the beds at Alum Bay to stratigraphical units named and defined elsewhere. Other differences in the definition of stratal units resulted from disagreement over stratigraphical principles (see Daley *et al.*, 1979).

Alum Bay provides a number of examples of the difficulty encountered in stratigraphical classification and nomenclature. The use of the term Reading Formation (Reading Beds, Reading Clay) follows Edwards and Freshney (1987b) who designated the section here as the Hampshire Basin hypostratotype. The more recent definition by Ellison *et al.* (1994) seems difficult to apply in the Hampshire Basin and has not been adopted for the Alum Bay succession.

There is considerable disagreement over the definition of the London Clay (Figure 5.21). According to White (1921) it is some 124 m thick and includes Prestwich Bed 13. Whilst a number of more recent accounts follow this usage, the present author agrees with Murray and Wright

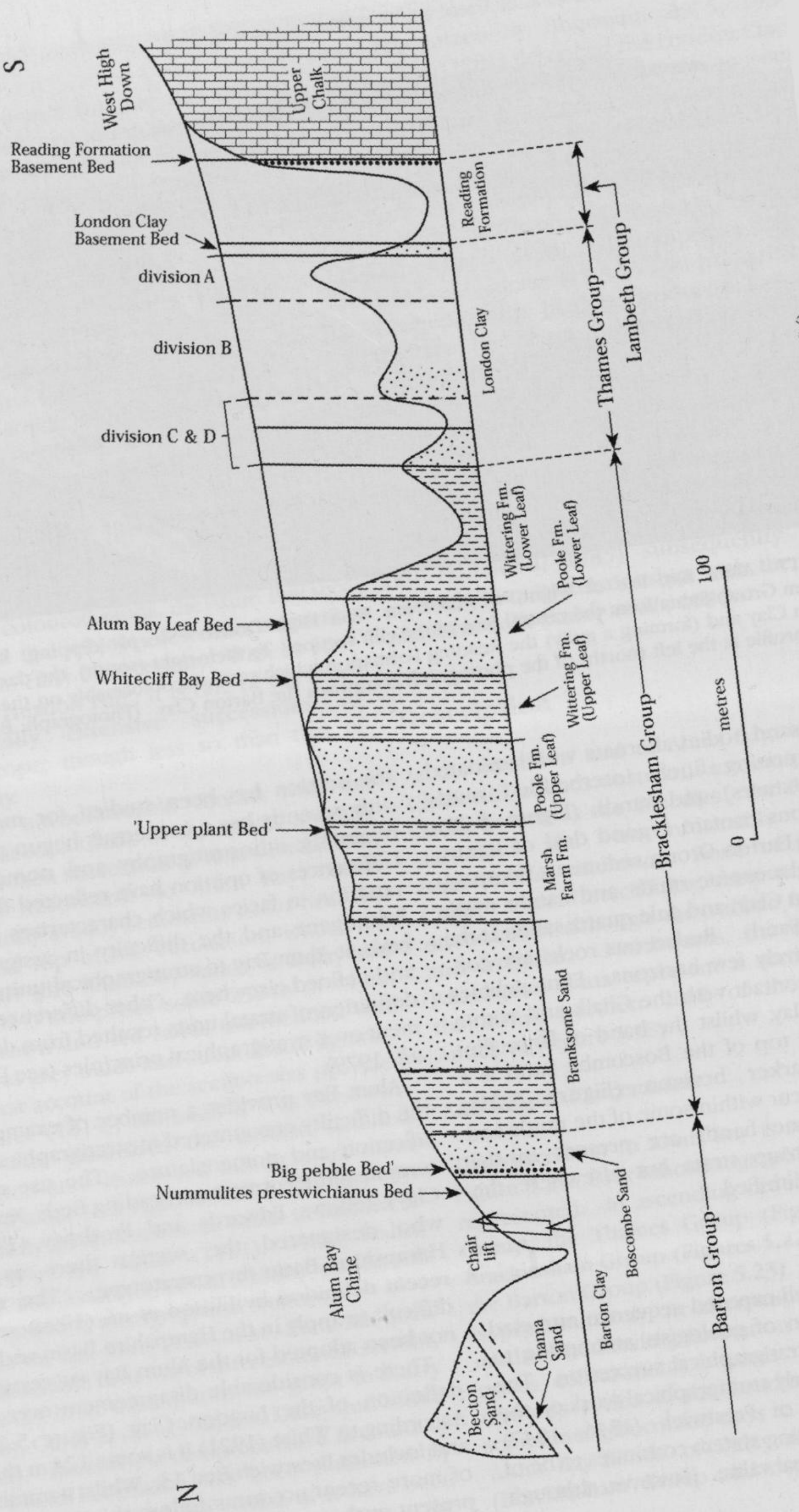

Figure 5.18 Alum Bay, Isle of Wight: cliff profile (adapted from Daley and Insole, 1984).

(1974) and Eaton (1976) that the beds younger than Prestwich Bed 6 are logically more allied to the overlying strata. This accords with Prestwich's own usage for the London Clay, but is at variance with the views of King (1981) who carried out the most comprehensive study of the London Clay in recent years and who prefers to include Prestwich Bed 7 in the formation. Furthermore, the lowest 4.3 m (the Basement Bed; see White 1921, p. 87) was assigned to the Oldhaven Formation by King (1981, p. 91), although this is not separately mappable locally and hence not a *bona fide* formation *sensu* Hedberg (1976) (see also Edwards and Freshney, 1987b, p. 49). Consequently, by definition, the Harwich Formation (within which the 'Oldhaven Beds' were placed by Ellison *et al.*, 1994) is not recognized in Alum Bay.

Above the London Clay is a thick sequence of variously coloured sands and muds with subordinate lignites, whose stratigraphical affinities and nomenclature have been under discussion since the 19th century (Figures 5.22 and 5.23). Parts of the sequence have at various times been assigned to the London Clay, the Bagshot Beds and the Bracklesham Beds of earlier authors. Daley and Insole (1984) used the informal name 'Alum Bay Sands', to include Prestwich Beds 7 to 28 inclusive, partly in order to emphasize the difference in lithological character between this section and others such as Whitecliff Bay. In the most detailed modern sedimentological study of this part of the succession, Plint (1983a) used the term Bracklesham Formation for Prestwich Beds 12 to 29. More recently, Edwards and Freshney (1987b) assigned various parts of the sequence to formations within the Bracklesham and Bournemouth Groups which 'interdigitate' in Alum Bay, although the latter term has now been superseded (Bristow *et al.*, 1991; see also Figure 5.22).

Following Edwards and Freshney (1987b), Prestwich Bed 29 is included in the Barton Clay and not in the 'Upper Bracklesham Beds' of previous authors (e.g. Curry *et al.*, 1972). This reflects its lithological affinity with the overlying strata and is compatible with the inclusion of the Huntingbridge Division of Curry *et al.* (1977) in the Barton Clay by Edwards and Freshney (1987a).

Sedimentary cyclicity

The cyclic nature of the Palaeogene succession is demonstrated by the Alum Bay section. King (1981) recognized his 'divisions' A and B here (with no representative of the Bognor Member; Figure 5.21). Division C is also present, but the definition of D and its relationship to C is less clear. King suggested (p. 93) that the top of the C–D sequence here is represented by the sand at the top of Prestwich Bed 7 and that this may be his Whitecliff Bay Member.

Plint (1983a) recognized five cycles in his Bracklesham Formation at Alum Bay (Figure 5.24), the lowest of which commences towards the top of Prestwich 'Bed 12'. Between the cycles of King (1981) and Plint (1983a) are a series of lenticular-bedded and flaser-bedded clays and sands underlain by a pebble horizon at the bottom of Prestwich Bed 8. King (p. 93) referred to a glauconitic unit within this part of the sequence with rare casts of marine macrofossils (echinoids) and pyritized diatoms. It seems likely, therefore, that these beds are also cyclic with a clearly demonstrable transgressive component. In a later paper, Plint (1988a) developed the idea that whilst some of the erosion surfaces in the succession represent transgressive events, others reflect lowstand erosion and channel incision.

Invertebrate macrofauna

Palaeontologically, Alum Bay is an important section. King (1981) recorded a number of molluscs from his 'Oldhaven Formation' and the London Clay but only up to the higher part of cycle B of the latter. The Barton Clay has a rich and well-preserved macrofauna. A number of species are listed in White (1921, p. 96) but there is no recent published research on this fauna. In contrast with the sections at Bracklesham and Whitecliff Bays, the 'Bracklesham Beds' have no recorded macrofauna except very close to the base, an indication of the relatively 'continental' aspect of this more westerly section. Brachiopods are not particularly common in the local Palaeogene strata. Hence, the occurrence of *Discinisca* attached to *Astarte* valves towards the base of the London Clay is of some interest (Muir-Wood, 1939).

Macroflora

The macrofloral remains in the Alum Bay section are particularly important and contribute to our understanding of early Tertiary vegetation and

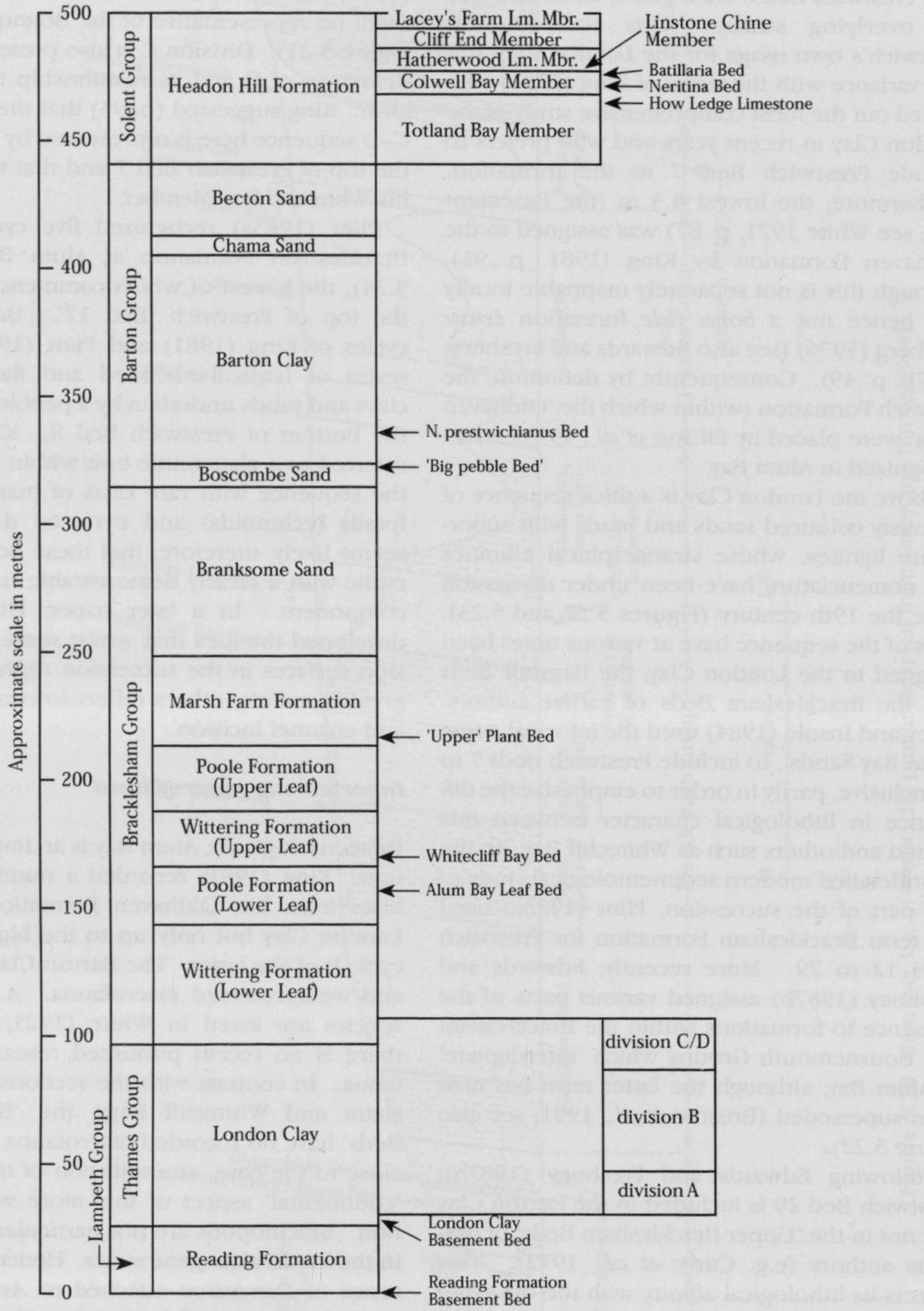

Figure 5.19 Lithostratigraphical succession in Alum Bay and its extension into Headon Hill, Isle of Wight (after Edwards and Freshney, 1987b).

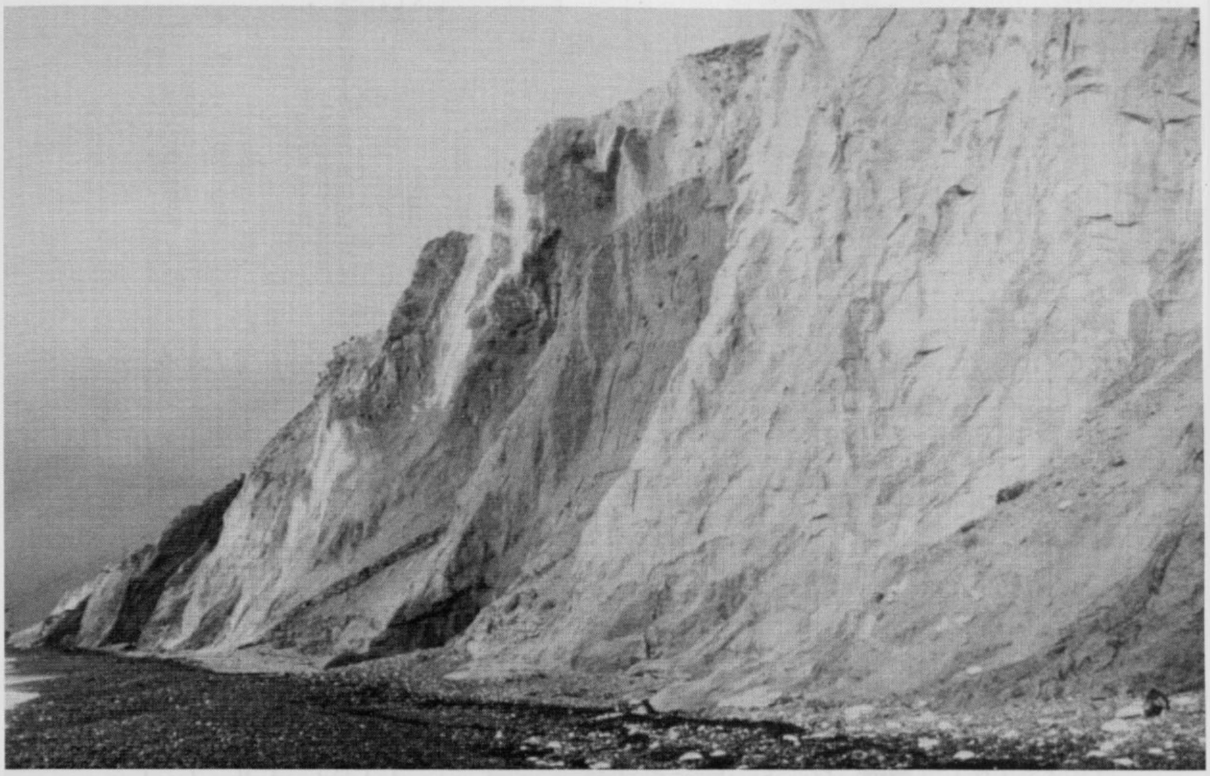

Figure 5.20 Part of the Bracklesham Group succession in Alum Bay, looking northwards towards the junction with the Barton Group a little south of the base of the chair lift. (Photograph: B. Daley.)

climate. The best-known plant horizon is the 'Alum Bay Leaf Bed' (see Figure 5.22, Prestwich Bed 17), an almost white 'pipe-clay' some 1.4 m in thickness. Leaves have been studied from this horizon since the 19th century (e.g. De la Harpe and Salter, 1862; Gardner and von Ettinghausen, 1879) but are less common now than they once were. The flora has been reviewed by Crane (1977, 1978). Most of the leaves have entire margins, an indication of tropicality. The angiosperm families particularly represented are the Lauraceae, Leguminosae and Moracae.

Crane (1977) found a second plant bed higher up the succession (towards the base of Prestwich Bed 24; Figure 5.22) which contains leaves with well-preserved cuticles. From this horizon, he identified a fern, *Osmunda lignitum*, a conifer and eight angiosperms.

Microfauna

The microfauna of the section has been studied in some detail. No nummulitids have been found in the 'Alum Bay Sands' but are present in the overlying Barton Clay. Numerous *Nummulites prestwichianus* occur in a bed formerly used to define the base of the Barton Clay, whilst *N. rectus* occurs somewhat higher up, in the upper part of the 'Lower Barton Beds' of Gardner *et al.* (1888).

Other microfaunal work on the section includes that on ostracods by Haskins (1970). Foraminifera were investigated by Bowen (1954), Kaasschieter (1961) and more recently, Murray and Wright (1974), as part of a wider comprehensive investigation of Palaeogene foraminifera in the Hampshire Basin. Although absent from the 'Alum Bay Sands', a number of foraminiferal assemblages occur in the London Clay and Barton Clay. Lower diversity assemblages characterize the London Clay, and Murray and Wright (1974) interpret them as representing shallow, slightly hyposaline (32–33%), shelf conditions. Faunas devoid of planktonic species are indicative of a restricted situation with limited connections with the open sea. The presence of planktonic species, by contrast, suggests improved circulation, cf. the 'Planktonic Datum' of Wright (1972), which in Alum Bay falls just above the base of King's cycle B. Most genera from the Barton Clay are typical shelf forms living on a fine substrate in turbid water of

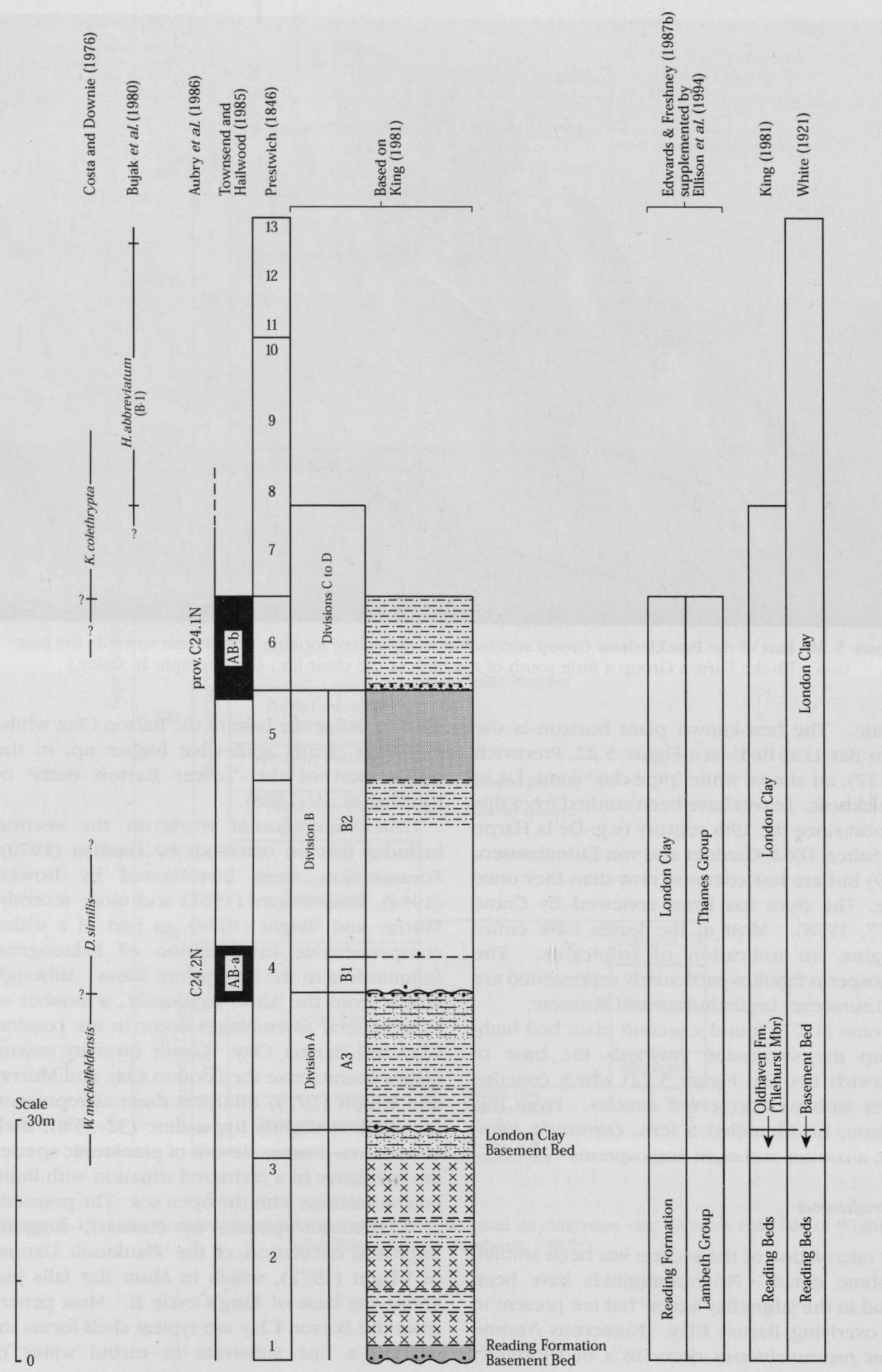

Figure 5.21 Lithostratigraphical, biostratigraphical and magnetostratigraphical succession of the Reading Formation and London Clay, Alum Bay, Isle of Wight (after King, 1981 and other authors).

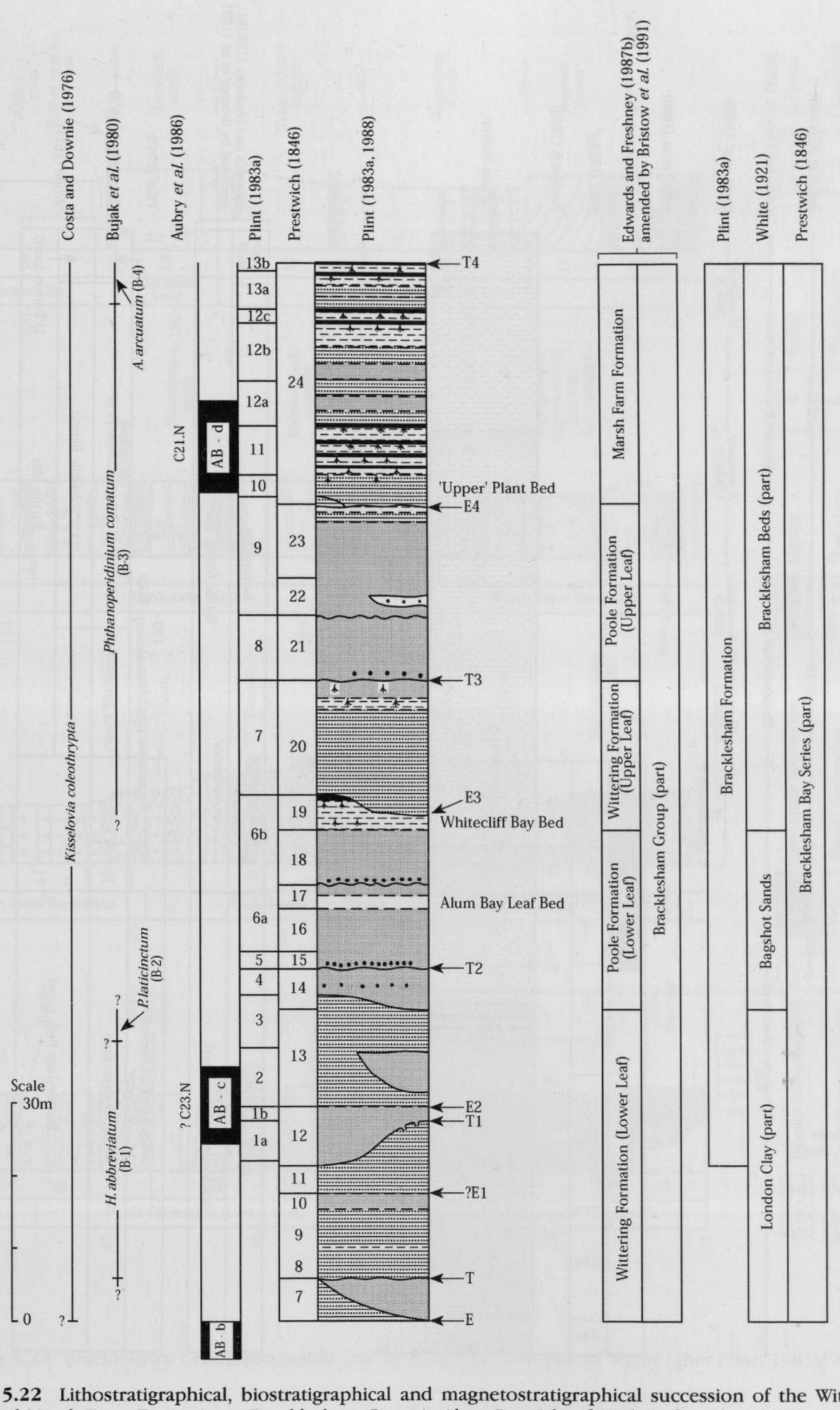

Figure 5.22 Lithostratigraphical, biostratigraphical and magnetostratigraphical succession of the Wittering, Poole and Marsh Farm Formations (Bracklesham Group), Alum Bay, Isle of Wight (after Plint, 1983a; Edwards and Freshney, 1987b and other authors).

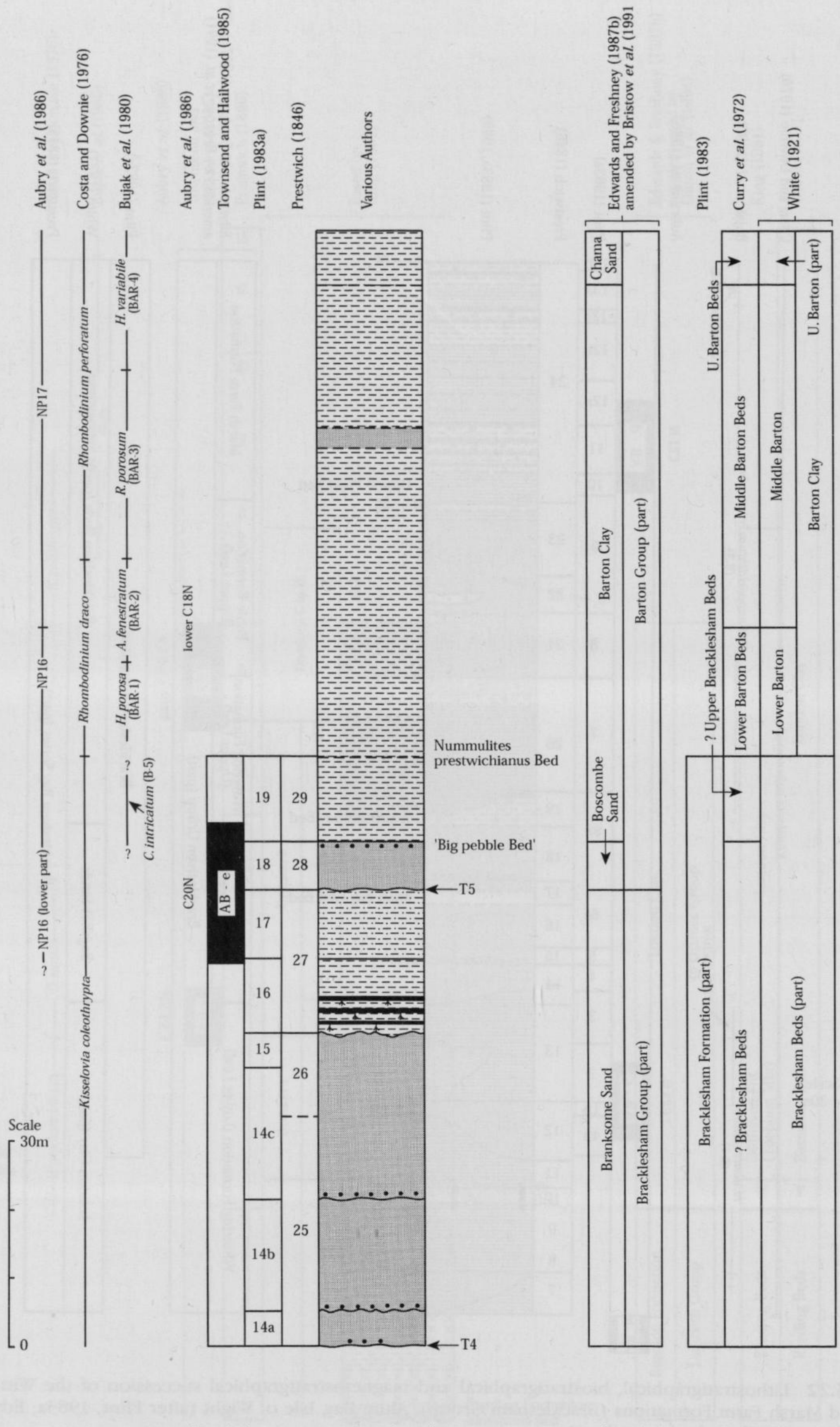

Figure 5.23 Lithostratigraphical, biostratigraphical and magnetostratigraphical succession of the Branksome Sand (Bracklesham Group) and Barton Clay and Chama Sand (Barton Group) in Alum Bay, Isle of Wight (after various authors).

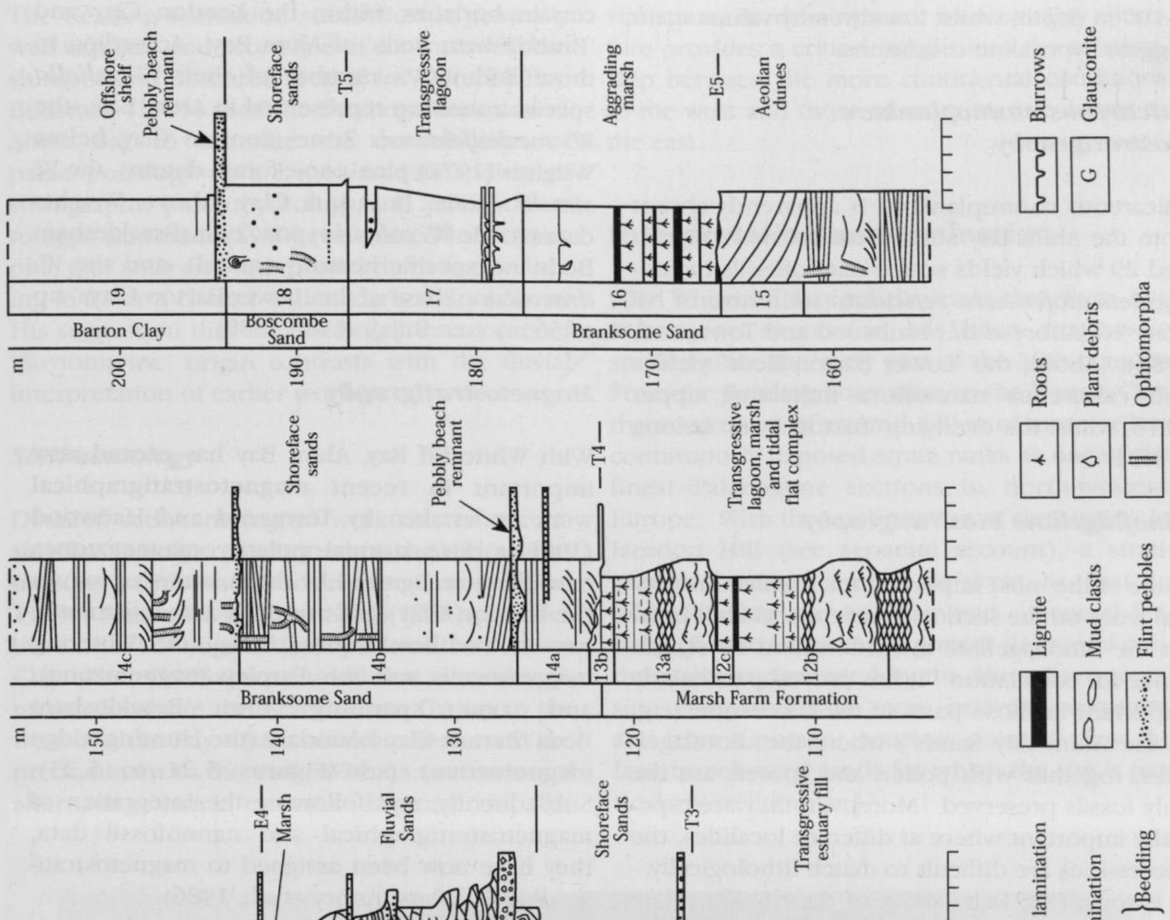

Figure 5.24 Bracklesham Group succession and facies in Alum Bay, Isle of Wight (after Plint, 1983a, 1988a).

1–100 m depth, whilst low-diversity values again suggest hyposaline conditions.

Calcareous nannoplankton biostratigraphy

Calcareous nannoplankton is apparently absent from the Alum Bay succession below Prestwich Bed 29 which yields scarce nannofossils including *Reticulofenestra reticulata* indicative of NP Zone 16 (Aubry *et al.*, Hailwood and Townsend, 1986). Above, the 'Lower Barton Beds' yield a rich calcareous nannoflora indicating upper NP16, whilst the overlying 'Barton Beds' belong to NP17.

Dinoflagellate biostratigraphy

Some of the most important micropalaeontological work on the section in recent years has been on the dinoflagellate microflora and its significance for correlation. It has proved particularly important in those parts of the succession (e.g. in the 'Alum Bay Sands') where the dinoflagellates, together with pollen and spores, are the only fossils preserved. Moreover, they are especially important where at different localities, the successions are difficult to match lithologically.

Eaton's (1971a,b) study of the dinoflagellate cysts and acritarchs enabled him to establish five microplankton zones which could be used to correlate the 'Bracklesham Beds' of Alum and Whitecliff Bays. At Alum Bay, the relationship of these zones to the lithological succession (using Prestwich Bed numbers) is as follows: Zone 1 (Beds 8 to 13, in part); Zone 2 (Beds 13, in part, to 15, in part); Zone 3 (Beds 15, in part, to 24, in part); Zone 4 (Beds 24, in part, to 28, in part); Zone 5 (Beds 28, in part, to 29). These he described in some detail in a later paper (Eaton, 1976), whilst they are formally defined in Bujak *et al.* (1980). Current lithostratigraphical usage means that Eaton's uppermost zone partially falls within the Barton Clay.

Of the five dinoflagellate zones which Bujak *et al.* (1980) recognized from the Barton Beds, four have been found at Alum Bay (Figure 5.23). The uppermost zone is not represented because, the authors suggest, marine strata of this age are absent from the section.

The important zonal dinoflagellate genus *Wetzeliella* is represented by *Wetzeliella* (*Apectodinium*) *homomorpha*, which, according to Costa and Downie (1976), is abundant at certain horizons within the London Clay and 'Bracklesham Beds' of Alum Bay. According to these authors, a number of their *Wetzeliella* species zones are represented in Alum Bay: the *W. meckelfeldensis* Zone (London Clay, below Wright's (1972) planktonic foram datum), the *W. similis* Zone (London Clay, above Wrights datum), the *W. coleothrypta* Zone (Bracklesham Beds, no specific horizon named), and the *W. draco* Zone (base of the 'Lower Barton Clays' up to 36 m) (see Bujak *et al.*, 1980).

Magnetostratigraphy

With Whitecliff Bay, Alum Bay has proved very important in recent magnetostratigraphical work undertaken by Townsend and Hailwood (1985). Five normal polarity magnetozones have been recognized by these authors: two in the London Clay (LCI and LCII magnetozones); two in the 'Bracklesham Beds' (the Wittering magnetozone and the Earnley magnetozone); and one spanning the 'Bracklesham Beds'/Barton Clay boundary (the Huntingbridge magnetozone) (see Figures 5.21 to 5.23). Subsequently, and following the integration of magnetostratigraphical and nannofossil data, they have now been assigned to magnetostratigraphical chrons (Aubry *et al.*, 1986).

Detrital mineralogy

Very little mineralogical work has been undertaken on the Alum Bay section. It was sampled by Walder (1964) but not by Morton (1982b) in his recent study of heavy minerals from the Hampshire Basin. Gilkes' (1968, 1978) study of the clay mineralogy contributes to our understanding of contemporary palaeogeography and provenance. The relatively 'continental' 'Bracklesham Beds' of Alum Bay have a predominantly kaolinite/illite mineralogy, derived from the west, not necessarily directly from Cornubia but from the erosion of earlier Eocene sediments. This suite contrasts with the smectite/illite suite of the 'Bracklesham Beds' of Whitecliff Bay.

Palaeopedology

The Reading Formation of Alum Bay has been the subject of the only published comprehensive study to date of fossil gley soils in the local Palaeogene succession (Buurman, 1975, 1980).

The Reading Formation succession is generally well exposed and accessible in contrast with the slumped and obscured section in Whitecliff Bay. Buurman (1975) used the Reading Formation of Alum Bay to examine the contribution of palaeopedology to a better understanding of stratigraphy, palaeohydrology and palaeoclimatology. Buurman (1980) recognized hydromorphic gley soils and interpreted them as developing in a warm climate with a marked dry season. His suggestion that the Reading Formation is of 'fluviomarine' origin contrasts with the fluvial interpretation of earlier workers.

Sedimentology

Detailed sedimentological work on the succession has mainly concentrated on the various formations within the Bracklesham Group (Plint, 1983a; Figure 5.24), since King (1981) provides but a brief lithological description of the London Clay. Plint (1983a) concluded that alluvial sediments dominate the Bracklesham Group to the west of Alum Bay, whilst off-shore sediments are predominant to the east. With its succession of alternating marine, estuarine, lagoonal and alluvial strata, its development in Alum Bay therefore provides a critical insight into the relationship between the more continental conditions to the west and those of more marine aspect to the east.

Interpretation and evaluation

Like Whitecliff Bay to the east, the Alum Bay Palaeogene succession has been extensively studied since the early part of the 19th century. From the Reading Formation to the Barton Clay, the occurrence of around 420 m of more or less continuously exposed strata ranks as one of the finest Palaeogene sections in north-western Europe. With the continuation of the section in Headon Hill (see separate account), a stratigraphical range almost as great as that in Whitecliff Bay may be examined. General features of note include the greater degree of continentality represented by the Alum Bay succession compared with more easterly exposures, and from a popular, touristic point of view, the famous coloured sands for which the site is particularly well known.

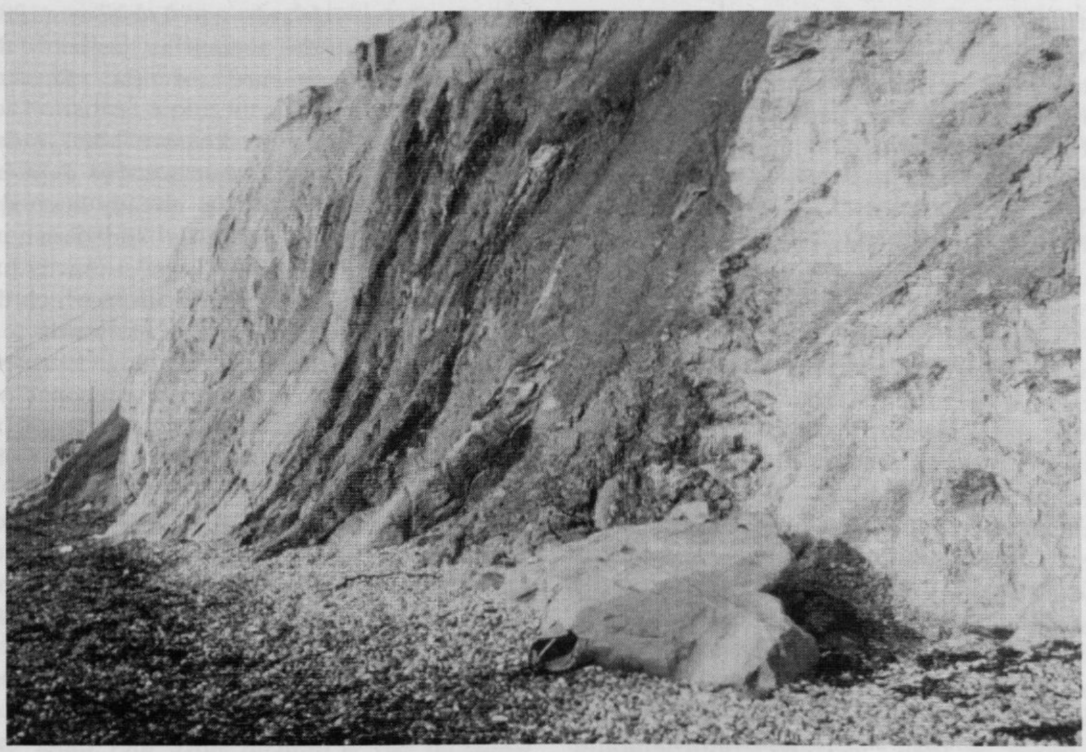

Figure 5.25 Lignite beds in the Marsh Farm Formation (centre left), with the sands at the top of the Poole Formation to the right (both Bracklesham Group) in Alum Bay. (Photograph: B. Daley.)

Stratigraphical definition and terminology

Although the same stratigraphical terminology has been used for Alum Bay and for Whitecliff Bay by many workers, the definition of individual stratigraphical units and their correlation has been a matter for discussion over many years. The London Clay exemplifies the type of difficulty experienced. At Alum Bay, at least three different horizons have been used to define its top, a difficulty that is compounded with the problem of whether or not it should include the Oldhaven Formation of King (1981). Consequently, quite different thicknesses have been attributed to the London Clay, from the 124 m or so of White (1921) to the approximately 71 m of Edwards and Freshney (1986, p. 53). Interestingly, the latter thickness, adopted in this account, follows the original usage of Prestwich (1846) and that in the 1889 Geological Survey Memoir (Bristow *et al.*, 1989).

Difficulties in correlation in part reflect the problem of relating the more marine beds in Whitecliff Bay to the more continental Alum Bay sequence. This is particularly true of the thick sequence of mainly sands and muds succeeding London Clay, included in the 'Bracklesham Beds' of White (1921) and the Bracklesham Formation of Plint (1983a). As Edwards and Freshney (1986, p. 46) pointed out, Plint used the term Bracklesham Formation chronostratigraphically to describe a laterally variable 'packet' of strata between the London Clay Formation of King (1981) and the 'Barton Formation' of Curry *et al.* (1978) and is invalid lithostratigraphically. Indeed, the use of Bracklesham Beds or Bracklesham Formation for the Alum Bay section appears to reflect more a desire for stratal continuity or persistence than the recognition of lateral differences.

Not that all have followed this practice. Bristow *et al.* (1889) used the term 'Lower Bagshot Sands' for 202 m of strata above Prestwich Bed 6 in Alum Bay, whilst, more recently, Daley and Insole (1984) adopted the informal term 'Alum Bay Sands' for some 230 m of the succession culminating in the coarse conglomerate below the Barton Clay. Edwards and Freshney (1987b, p. 56) considered the Alum Bay section to represent a zone of interdigitation between the dominantly fluvial to barrier shoreline sands of their 'westerly' Bournemouth Group and the laminated clays and sands of the Bracklesham Group more extensively developed in Whitecliff Bay. Strata included by Edwards and Freshney in the Bournemouth Group are Prestwich Beds 14–18, 21–23 and 25–27. More recently (Bristow *et al.*, 1991), it has been argued that there is insignificant justification for having two groups and that their formations should all be assigned to the Bracklesham Group.

Little disagreement now exists over defining the base of the Barton Clay. The muds above the coarse conglomerate at the top of Prestwich Bed 28 are included in the latter, following Freshney and Edwards (1987a, pp. 64–5). Formerly, the base of the formation had been placed at the *N. prestwichianus* horizon by Curry *et al.* (1972) and earlier authors, following Gardner *et al.* (1888) (see also discussion of the Whitecliff Bay site elsewhere in this volume).

Comparison with other sites

Apart from the problems of definition and nomenclature, the succession of Alum Bay differs in various ways from those of other local Palaeogene sites. The Reading Formation is only half the thickness of that at Whitecliff Bay, yet what it lacks in quantity it makes up for in quality. In designating it as the Hampshire Basin hypostratotype, Edwards and Freshney (1986, p. 47) referred to the section as 'probably the best natural exposure of the Reading Formation'.

Comparison of the thickness of the London Clay in Alum Bay with other sections depends partly on definitions, as has already been discussed. Following Edwards and Freshney (1987b), it is, at some 71 m, almost exactly half of the 142.3 m of Whitecliff Bay from which the formation continues to thicken eastwards (e.g. around 155 m at Sheppey; see King, 1981, pp. 52–4). The westward thinning (see isopachyte map in King 1981, fig. 40) is also apparent from individual London Clay cycles. King's cycles (divisions) A and B thin from 37.5 m and 39.8 m in Whitecliff Bay to 16 m and 38 m respectively in Alum Bay. The London Clay of Alum is nevertheless thicker than in Dorset to the west, where, for example, only 28 m occurs in the Bere Heath borehole (SY 860921).

Correlating the strata between the London Clay and Barton Clay with the succession in Whitecliff Bay is difficult since they differ in a number of ways (see later discussion of palaeoenvironments and also Figure 5.28). The

Wittering Formation is probably represented at Alum Bay by Prestwich Beds 7–13 and 19–20 whilst the richly glauconitic and fossilferous marine Earnley Sand is absent (Edwards and Freshney, 1987b). These authors consider that the lignitic and laminated sediments of Prestwich Bed 24 correlate with the Marsh Farm Formation, whilst Prestwich Beds 25 and 26 represent shoreface sands of the Branksome Sand Formation, the lateral equivalent of the Selsey Sand found further east. Edwards and Freshney (1987b) have assigned Prestwich Bed 29 to the Boscombe Sand. At Alum Bay, this formation is about the same thickness as at Christchurch but passes eastwards across the Isle of Wight into marine clays.

Unlike the section at Whitecliff Bay, exposures of the Barton Clay are generally good and exhibit a rich and mostly well-preserved invertebrate fauna. At something over 80 m, the formation is twice as thick as at Barton itself.

Macrofossil remains

Apart from the London Clay and the Barton Clay, the Alum Bay section is not well endowed with macrofossil remains. In the Bracklesham Group, macroinvertebrates are rarely found; there are no nummulitids, but rare echinoid casts, together with rich dinoflagellate assemblages, confirm the former existence of marine conditions at various horizons. A plus for the section is the presence of leaf floras at two horizons, where good cuticular preservation provides improved opportunities for taxonomic assessment and comparison with other Eocene floras on the continent and from North America (Crane, 1977, p. 96). Several of the species found also occur in leaf beds at Bournemouth (Collinson and Hooker, 1987, p. 267).

Biostratigraphy and chronostratigraphy

The importance of the Alum Bay section for developing a local dinoflagellate zonation has already been referred to. As Edwards and Freshney (1987a, p. 12) pointed out, however, dinoflagellates are less valuable for correlating in fluctuating marginal marine environments than had previously been realized. This must particularly apply to the Bracklesham Group, although for the more marine Barton Clay the dinoflagellate floras are more reliable. The diachroneity of Eaton's (1971a,b) microplankton zones is indicated by magnetostratigraphical work undertaken by Townsend and Hailwood (1985). They found Eaton's Zone 1/2 and Zone 3/4 boundaries were younger at Alum Bay than at Whitecliff Bay and concluded that changes in the microplankton assemblages forming the basis for Eaton's zones are environmentally influenced. Presumably the 'younger' zonal boundaries in Alum Bay reflect the time taken for the westerly progression of transgressions from a marine area to the east. Townsend and Hailwood also established the diachronous nature of the transgressive surfaces described by Plint (1980, 1983a). Furthermore, the Alum Bay section contributes evidence that the regressive top of the London Clay was markedly diachronous. *D. similis* occurs in the upper part of the London Clay in Alum Bay, whilst the earlier *W. meckelfeldensis* occurs below the top of the unit at Studland and the younger *D. varielongituda* occupies this position in the London Clay (*sensu* King, 1981) of Whitecliff Bay (Costa and Downie, 1976).

No zone fossils occur in the Reading Formation at Alum Bay. Elsewhere, however, this formation has been assigned to the *A. hypercanthum* Zone (Costa *et al.*, 1978) which is approximately equivalent to nannoplankton (NP) Zone 9 and planktonic foraminifera Zone P5 (see Curry *et al.*, 1978).

The occurrence of the three zonal species *W. meckelfeldensis*, *D. similis* and *K. coelothrypta* facilitates correlation not only with other British sections but with Belgium and northern Germany (Costa and Downie, 1976, p. 601). Whether the zones established by Bujak *et al.* (1980) can be as widely used is less clear.

Of all the formations in Alum Bay, the Barton Clay is the easiest to date palaeontologically, since it contains not only *Nummulites* and *W. draco* but some nannoplankton. The suggestion by Curry *et al.* (1978) that the formation was approximately equivalent to nannoplankton Zones 16 and 17 has now been confirmed by Aubry *et al.* (1986). The magnetostratigraphical zones recognized at Alum Bay have already been referred to but their development is of particular significance for sections such as this which are relatively poorly endowed with good zone fossils. Having said this, the importance of combining and relating magnetostratigraphical and palaeontological information is well illustrated by an example from Alum Bay (see below).

Palaeogeography and depositional environments

On the basis of dinoflagellate stratigraphy, Islam (1981, 1983a) concluded that at Alum Bay a surface of erosion/non-deposition occurs between the Wittering and Earnley 'divisions' or cycles. Such a relationship is not surprising since the base of each cycle represents a transgressive and hence erosive event. However, this surface has been shown to correspond with others elsewhere such as that forming the boundary between the Jeper and Panisel Formations in Belgium (Islam, 1981). Significantly, the absence of any record of the magnetostratigraphical unit Chron C22N from the Palaeogene sequence of the London and Hampshire Basins (Aubry *et al.*, 1986) more or less coincides with Islam's surface of erosion/non-deposition. Aubry *et al.* (1986) concluded that this combination of evidence indicates a worldwide drop in sea level, marked by the occurrence of lignites above this 'unconformity' both in Britain and Belgium. Such a regression is recorded locally by the distinctive marker horizon, the 'Whitecliff Bay' Bed, which, according to Edwards and Freshney (1987b, p. 60), may be represented by Prestwich Bed 19 at Alum Bay.

The palaeoenvironmental significance of the Alum Bay section has already been referred to *en passant*. Within the Bracklesham Group in particular, the section represents a vital link between more continental strata to the west and more marine sediments to the east. Plint (1983a, 1988a) considered that this part of the sequence represented a complicated interplay between alluvial, coastal and marine processes in which shoreface sands, lagoonal and marine sediments predominated, with intercalated alluvial and off-shore marine sediments respectively representing the more regressive and transgressive phases of the sedimentary cycles. However, at Alum Bay the effect of the transgressions was more limited. The glauconitic Earnley and Selsey Sands with their marine faunas are not present. The former is represented by beach or shoreface sands (Plint, 1983a; Prestwich Bed 21) whilst the equivalent of the latter comprises shoreface sands (Prestwich Beds 25 and 26) succeeded by a succession of lignites and palaeosols probably representing coastal marshes (Prestwich Bed 27) (Plint, 1983a; Edwards and Freshney, 1986).

Whilst Alum Bay has already been extensively studied, it clearly has potential for more research. This could include modern taxonomic and palaeoecological work on macroinvertebrate faunas such as those of the Barton Clay, whilst a number of horizons could contribute to a broader palaeopedological investigation of the lower Palaeogene strata.

Conclusions

Since the early 19th century, the Palaeogene rocks in Alum Bay have attracted the attention of researchers in many aspects of geology. It helped early geologists begin to understand the stratigraphy of the Tertiary strata in the Hampshire Basin, and more recently has contributed to many aspects of palaeoenvironmental research.

Comprising some 420 m of strata, and representing in excess of 15 million years of deposition, it is stratigraphically more extensive than any other Palaeogene section in Britain apart from that at Whitecliff Bay. Indisputably, it is one of the finest Palaeogene sites in Western Europe. Stratigraphically a 'difficult' section, it exemplifies some of the problems of stratigraphical classification and nomenclature which are a particular feature of paralic successions. The placing of the upper boundary of the London Clay and the lithostratigraphical affinities of the constituent parts of the Bracklesham Group are two examples.

Although generally poorly fossiliferous compared with Whitecliff Bay, the section has proved important from various aspects of correlation. Together with Whitecliff Bay, it facilitated the establishment of a local zonation based on dinoflagellates and contributed to the development of the 'event' stratigraphy of King (1981) and Plint (1983). More recently, the recognition of magnetostratigraphical zones at both Alum Bay and Whitecliff Bays, has shown that both the dinoflagellate zonal boundaries and the surfaces representing transgressive 'events' are diachronous.

Perhaps the most significant aspect of the Alum Bay section is that it provides a major key to the palaeogeographical interpretation of the local Palaeogene strata. It is, in fact, the site that best demonstrates the relationship between the predominantly marine succession of Whitecliff Bay to the east with the more continental succession to the west. This is particularly true at the level for the Bracklesham Group whose constituent formations represent the complicated interplay between alluvial, coastal and marine processes in a paralic situation.

HEADON HILL, ISLE OF WIGHT (SZ 310862)

Highlights

This is the best exposure of the Headon Hill Formation in the west of the Isle of Wight and is the type locality for the formation and three of its members. A wide variety of fossils are present and represent various brackish and freshwater environments. Particularly interesting is the Hatherwood Limestone, only developed well here, with its calcrete and palaeokarst features.

Introduction

This section of the review deals with the succession in Headon Hill (Figure 5.26), the part of Totland Bay–Alum Bay SSSI to the north of Alum Bay Chine (SZ 305856) where the strata are mainly near-horizontal. The Becton Sand (Barton Sand of earlier authors) occurs at the base and is succeeded by part of the Solent Group up to and including the Bembridge Limestone Formation. Most of the section comprises the Headon Hill Formation. Although this unit is predominantly clastic, the presence of freshwater limestones such as the Hatherwood Limestone Member provide a particular focus of interest. Whilst much of the succession is obscured by vegetation, there are some good exposures such as that above Hatherwood Point (Figure 5.27) whilst, at some horizons, the near-horizontal strata provide a considerable opportunity to study lateral facies variation.

Amongst those who made early studies of the section were Webster (1814, 1816), Forbes (1853) and Keeping and Tawney (1881), whose stratigraphical successions were reproduced in Bristow *et al.* (1889) and White (1921).

For many years, little was published on the section, but over the last three decades or so there has been a considerable rebirth of interest. An extensive stratigraphical and palaeoenvironmental study was undertaken by Edwards (1967) whilst other descriptions are given in Stinton (1971a), Insole (1972), Daley and Edwards (1972) and Daley and Insole (1984) and the comprehensive recent review by Daley (1999, pp. 40–45). The macroinvertebrate faunas of the Headon Hill Formation and the Bembridge Limestone Formation were reviewed by Edwards (1967), whilst, more recently, Paul (1989) made a detailed study of the freshwater molluscs from the Hatherwood Limestone Member. The foraminifera have been studied by Murray and Wright (1974) and the Ostracoda by Keen (1977). Vertebrate work has concentrated on the mammalian fauna, including that of Cray (1964, 1973), Insole (1972), Bosma and Insole (1972), Bosma (1974), Hooker (1992) and Hooker *et al.* (1995). Fossil reptiles from the locality have been studied by Rage and Ford (1980). The most important palaeobotanical research undertaken on the section was that by Feist-Castel (1977) on the Charophytes.

Relatively little has been published on the sedimentology, although some descriptions and interpretations occur in the theses of Edwards (1967) and Insole (1972).

This site was also independently selected for its fossil plant, reptiles and mammal content, a more detailed account of which can be found elsewhere in the GCR series (*Mesozoic to Tertiary Palaeobotany of Great Britain* (Cleal and Thomas, in prep.); *Fossil Reptiles of Great Britain* (Benton and Spencer, 1995); *Fossil Mammals and Birds of Great Britain* (Benton *et al.*, in prep)).

Description

To the north of Alum Bay Chine, the Becton Sand crops out above the foreshore. In contrast with the older strata to the south, the formation has a gentle northerly dip. The junction with the Barton Clay is faulted-out.

Further northwards as far as Totland (SZ 320866) and above in Headon Hill (SZ 310862), the remainder of the sequence comprises the lower part of the Solent Group, exposed intermittently in a very shallow E–W trending syncline. At Hatherwood Point (SZ 305860), which provides the best section (Figure 5.27), the strata dip gently eastwards whilst appearing horizontal when viewed from the seaward side. Strata along the northern face of the hill dip southwards at a low angle.

Lithological succession

The succession in Headon Hill is almost 100 m thick, of which some 63 m comprise the Headon Hill Formation (Figure 5.28). Much of the suc-

Figure 5.26 Headon Hill, Isle of Wight. The western end above Hatherwood Point, illustrating the contrast between the near-horizontal strata present and the steeply dipping beds in Alum Bay (front right of photograph). The light-coloured units in Headon Hill comprise, in ascending order, the thin How Ledge Limestone (within the Totland Bay Member), the Hatherwood Limestone Member and, just below the top of the cliff, the Lacy's Farm Limestone Member. (Photograph: B. Daley.)

cession comprises mainly green to grey silty to sandy muds and marls. Sands occur as thin partings within the muds but are better developed at some horizons, such as the Becton Sand at the base of the succession and in the Linstone Chine Member (Headon Hill Formation), particularly where the latter is thicker towards the northern part of Headon Hill. A feature of the section is the occurrence of a number of cream-coloured limestones (Figure 5.29). Some (like the How Ledge Limestone) are lithologically homogeneous. By contrast, the thicker Hatherwood Limestone Member is complex in nature, with irregular internal bedding surfaces, the occurrence of limestone boulders and evidence of pedogenic alteration. It also contains a laterally discontinuous lignite bed. At Hatherwood Point, the top of the section mainly comprises marls which are succeeded by the well-lithified Lacey's Farm Limestone. Younger grey-green laminated muds (Fishbourne Member) and red and green mottled muds (Osborne Marls Member) may be visible further to the north below a thin remnant of the Bembridge Limestone at SZ 317863.

Stratigraphy

Headon Hill has been an important site for stratigraphy and stratigraphical nomenclature since the middle of the 19th century. The Barton Sand was called the Headon Hill Sand by Forbes (1856) and Bristow *et al.* (1889). Below his overlying Osborne Series, Forbes recognized a Headon Series which he subdivided into Lower, Middle and Upper Headon Beds, terms which until recently were widely used.

With the recognition of the need to regulate and standardize stratigraphical terminology (cf. Hedburg, 1976), new terms were introduced to replace these earlier ones and Headon Hill, more than any other site, has encouraged new thought on the stratigraphical subdivisions and nomenclature of this part of the English Palaeogene succession.

Headon Hill was designated by Insole and Daley (1985) the type section (stratotype) for the Headon Hill Formation (see Figure 5.28), a unit encompassing the Headon Beds and Osborne Beds of earlier authors, whose identity as separate units was in doubt as early as the

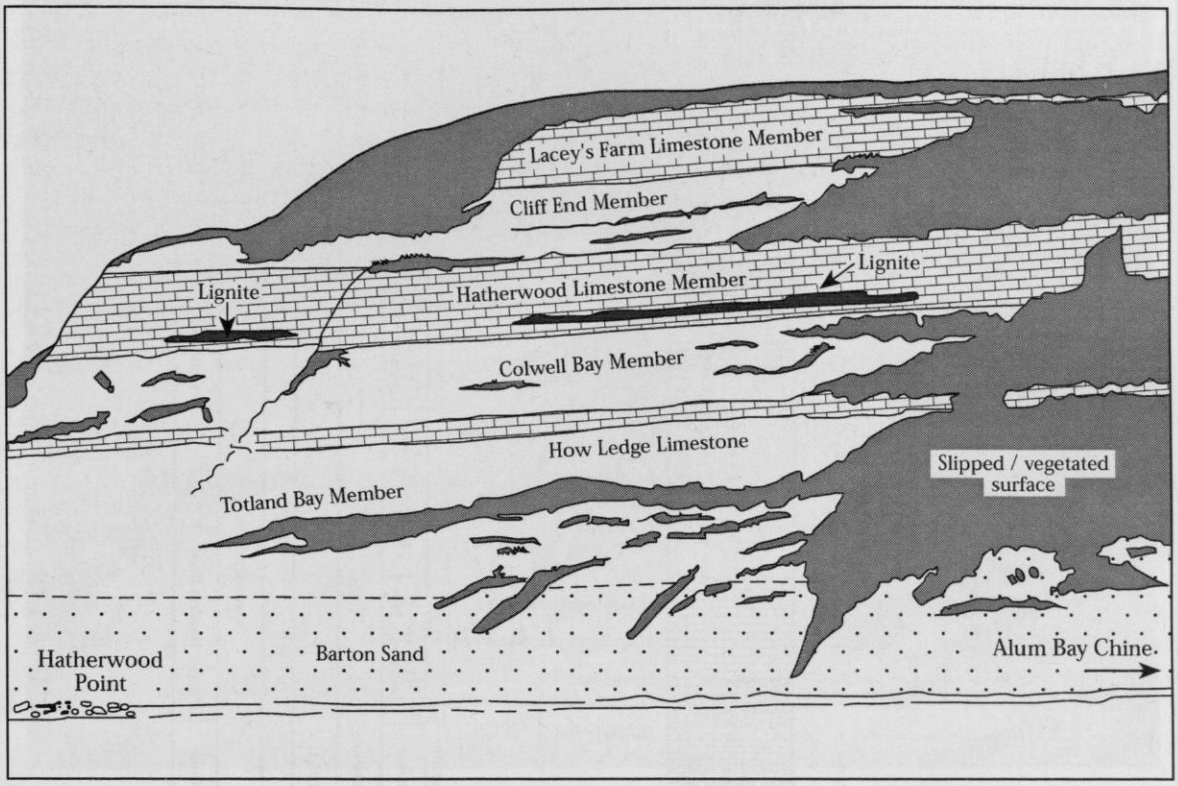

Figure 5.27 Headon Hill, Isle of Wight: a cliff profile at the western end, above Hatherwood Point (adapted from Daley and Insole, 1984).

latter part of the 19th century (Bristow *et al.*, 1889, p. 157). Of the nine members into which the Headon Hill Formation is divided, three have Headon Hill as the type locality: the Totland Bay Member, the Hatherwood Limestone Member and the Lacey's Farm Limestone Member. Headon Hill was chosen for the last of these since the future of the small, now disused pit from which it gets its name, was considered uncertain.

Invertebrate macropalaeontology

Headon Hill is the best palaeontological site at this level in the Eocene succession in Britain. A wide variety of molluscan assemblages have been recognized. Marine influences are apparent in the exposed upper and lower parts of the Colwell Bay Member where assemblages are dominated numerically by cerithiids (*Batillaria* and *Potamides* spp.), oysters (*Ostrea velata*) and corbiculids (*Corbicula obovata*) (Daley and Edwards, 1974). These assemblages are characterized by low species diversity and represent estuarine or lagoonal rather than fully marine conditions. The assemblage of the rarely exposed middle part is more marine in character.

Elsewhere in the formation, a variety of molluscan assemblages reflect freshwater to brackish conditions. Amongst the freshwater assemblages are those characterized by the pulmonates *Galba* and *Planorbina* and which occur mainly in cream-coloured micritic limestones (see for example the paper by Paul (1989) on the molluscan fauna of the Hatherwood Limestone Member). Other freshwater assemblages contain the river snail *Viviparus*, whilst an example of a possibly more brackish water assemblage is the '*Corbicula pulchra* Bed' in the Totland Bay Member. Here the main fossils are *Potamomya*, *Melanopsis*, *Theodoxus* and *Corbicula*. In the Bembridge Limestone, which completes the succession here, species of land snail are associated with freshwater molluscs (Preece, 1976).

A particularly interesting feature of the *Theodoxus* shells is that they retain much of their original pigmentation and portray a variety

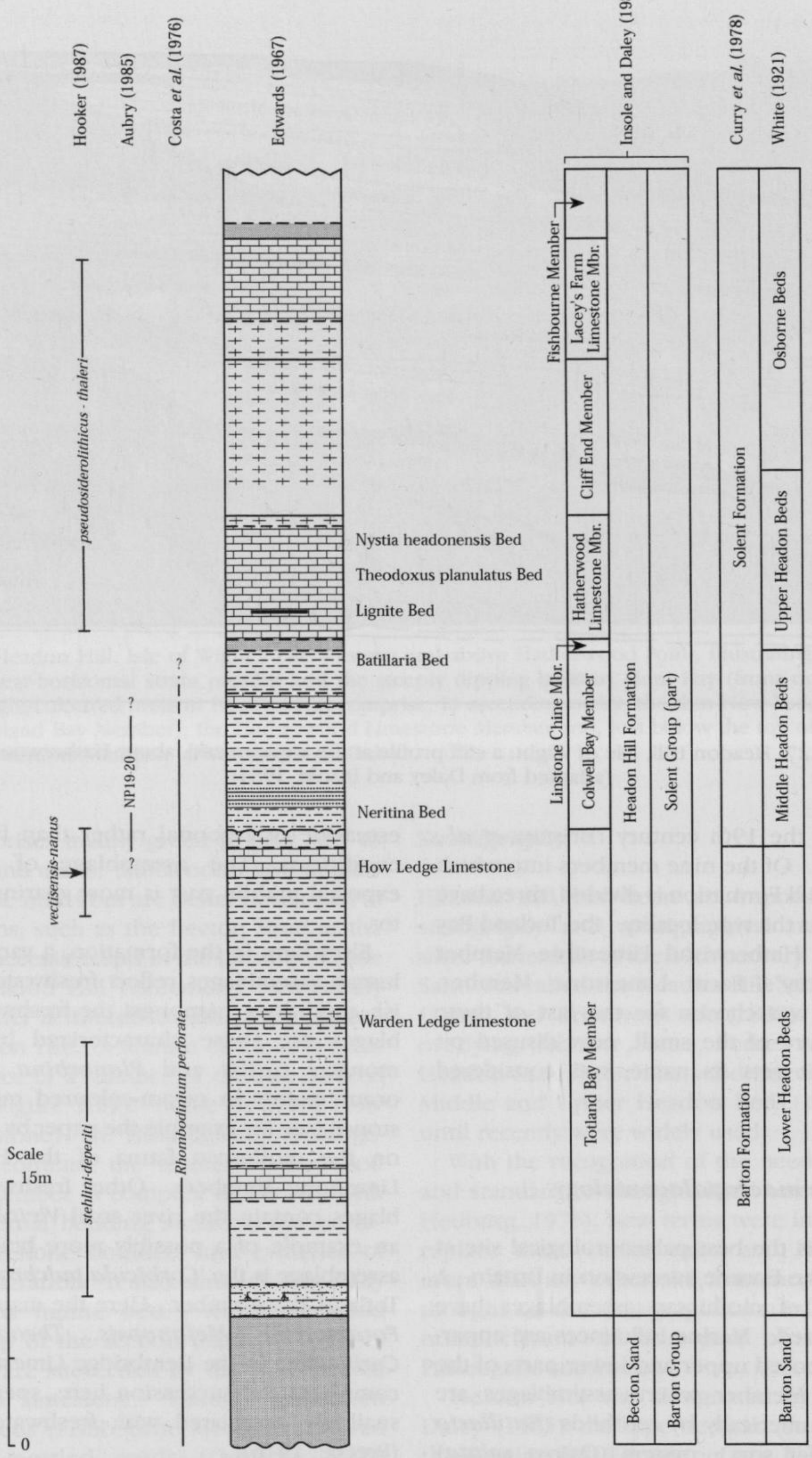

Figure 5.28 Lithostratigraphical succession of the Headon Hill Formation at the western end of Headen Hill, Isle of Wight, above Hatherwood Point (after Edwards, 1967; Insole and Daley, 1985 and other authors) and biostratigraphy (mammal concurrent range zones after Hooker, 1987).

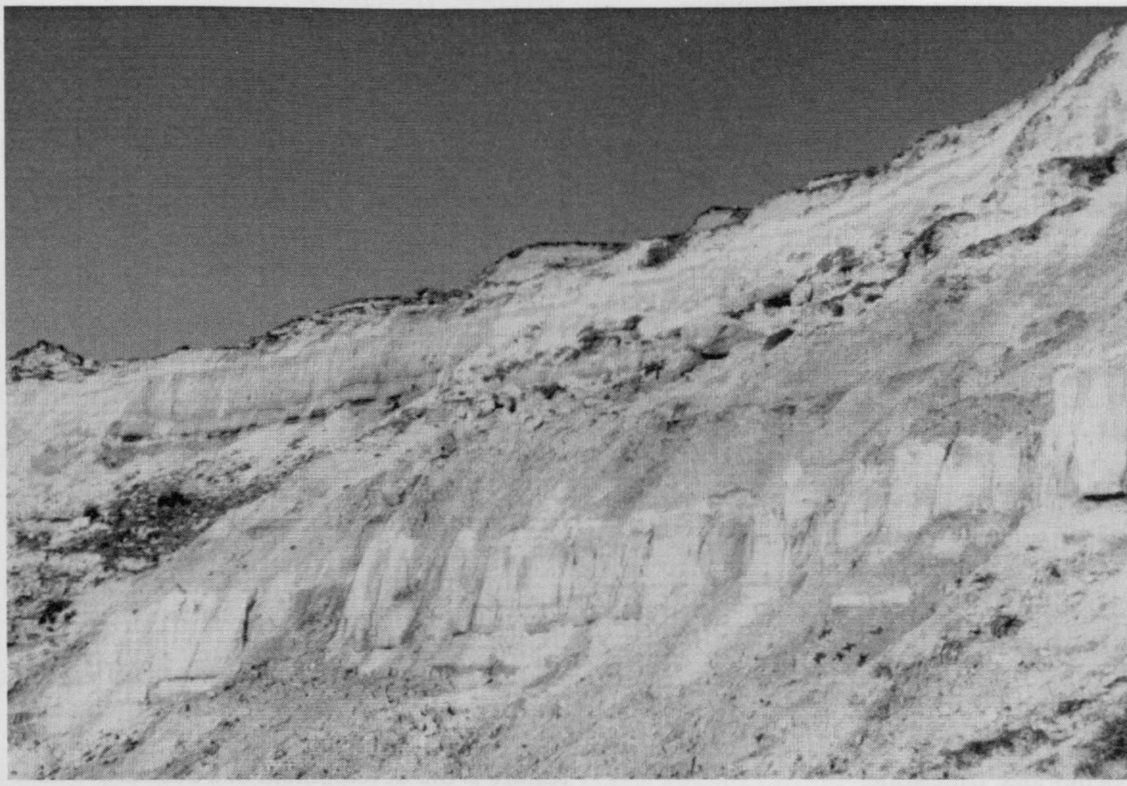

Figure 5.29 Limestones in the Headon Hill Formation at Hatherwood Point, Headon Hill. The How Ledge Limestone (within the Totland Bay Member) occurs towards the middle of the succession illustrated, with the Hatherwood Limestone forming the top of the cliff, above which the Lacy's Farm Limestone is just visible towards the centre and on the extreme left. (Photograph: B. Daley.)

of colour patterns, the nature and significance of which have been investigated by Hill (1986) and, in a broader study of colour pattern preservation in the fossil record, by Hollingworth and Barker (1991).

Microfauna

Headon Hill is an important locality for micro-faunal research. It was one of the two main sections studied by Keen (1977) in his work on the environmental significance of ostracods, which resulted in the recognition of salinity controlled, and hence salinity diagnostic, assemblages. The foraminiferal fauna was studied in some detail by Murray and Wright (1974). They considered that faunas from the Colwell Bay Member were indicative of salinities sometimes close to normal marine levels. Somewhat surprisingly, they found foraminifera in the Hatherwood Limestone, predominantly freshwater in origin but with hydrobiid-rich intervals indicating occasional saline influence (see Paul, 1989). Derived Upper Cretaceous microfossils present in some of their samples confirm that the Chalk had been uplifted by this time and was being eroded.

Vertebrate remains

The importance of Headon Hill from the point of view of vertebrate remains cannot be in doubt. Amongst those found in the Totland Bay Member are freshwater turtles, the alligator *Diplocynodon*, fishes and various mammals. These include rodents described by Bosma (1974), six species from a green silty clay with shell fragments 2.5 m above the base of the member and seven from the grey-green marl immediately below the How Ledge Limestone (Figure 5.28). The latter is now known to be highly productive of vertebrate fossils and from it, Rage and Ford (1980) have described reptiles, including a salamander, lizards and snakes. Recently, a new genus of snake, *Headonophis*, has been described by Holman (1993) from the lignitic clay immediately below the How Ledge Limestone.

Higher up the sequence, at the junction of the Colwell Bay Member and the overlying Linstone Chine Member, is a thin, lenticular, argillaceous sand containing mammal remains which Cray (1973) called the 'Microchoerus Bed'. Amongst species he described from this bed were the primate *Microchoerus erinaceus* and the marsupial *Peratherium*. Other vertebrate material comes from the lignites of the Hatherwood Limestone Member, including turtle and mammal remains. Cray listed 14 mammalian species from the lignite at Hatherwood Point, including the primates *Adapis parisiensis* and *M. erinaceus*, three species of *Palaeotherium* and the creodont *Hyaenodon cf. minor* (Cray, 1973, Table 4, p. 27). A number of rodent species from just above and below the lignite have been described by Bosma (1974). Hooker (1987) has recognized three mammal zones at this locality (see Figure 5.28). More recently, Hooker *et al.* (1995) have described a mammalian fauna from the Bembridge Limestone.

Flora

Headon Hill is not particularly well-endowed with plant fossils, except for Charophytes. Six species were found in cream-coloured marls 1 m above the base of the Totland Bay Member (Feist-Castel, 1977), whilst three species were found in brackish clays and lignites which she referred to the 'Neritina Beds' near the base of the Colwell Bay Member. The Totland Bay Member was sampled by Machin (1971) in her study of pollen and spores from the Palaeogene of the Isle of Wight.

Sedimentology

The section has considerable potential for sedimentological work on paralic brackish to freshwater environments, which mainly comprise those characterized by fine- to medium-grained clastics, but also include freshwater, limestone-producing lakes. Despite the study by Edwards (1967), virtually no modern work on the sedimentology or its environmental implications has been published.

The section contains some of the best representatives of freshwater limestones in the British stratigraphical column. These include the How Ledge Limestone and the Warden Ledge Limestone from the Totland Bay Member. The former is prominent in the cliff face at Hatherwood Point, although at this locality, the Warden Ledge Limestone is thin and poorly exposed.

The best example is the 7–8 m thick Hatherwood Limestone Member that forms a prominent scar towards the upper part of the seaward face of Headon Hill (Figure 5.27 and 5.29). It comprises pale, soft to well-lithified, more or less fossiliferous limestones with subordinate lignites, a facies only developed in Headon Hill. Soft limestones with vertical tubular hollows attributable to the former presence of roots are interbedded with well-lithified hard pans and 'banded' limestones (?pedogenic crusts) with irregular upper surfaces, first described by Jackson (1925).

The near-horizontal nature of this member provides a rare opportunity to study lateral changes in a freshwater limestone. A significant feature is the development of a destructive lateral surface within the member. At Hatherwood Point, where it descends well below the centre of the member, lignites fill the hollows in its very irregular profile (Figure 5.30). Surfaces such as this probably reflect exposure and the existence of solution or karst-type processes.

Fossil soils are well-developed in parts of the Headon Hill section. Halfway up the Cliff End Member at Hatherwood Point, a hard marl (<0.5 m thick) containing knobbly and cylindrical concretions and with a sharp irregular top, passes down into marls with vertical red stripes. Such features are pedogenic in origin and indicative of exposure.

The highest limestone scar above Hatherwood Point is formed by the Lacey's Farm Limestone Member (the Osborne (Beds) Limestone of Edwards (1967) or 'thick concretionary limestone' of White (1921, p. 111)). It comprises hard or soft limestones or calcareous sandstones passing down into very calcareous marls. The limestones are often nodular or rubbly; marked internal surfaces occur, whilst some levels comprise banded limestones or 'crusts'. The top of the member comprises a distinct surface, overlain in places by pebbles or concretions of limestone. The unit as a whole appears to provide a classic example of calcrete profile development.

Figure 5.30 The Hatherwood Limestone Member (Headon Hill Formation) above Hatherwood Point, where a laterally impersistent lignite rests on an irregular internal surface within the limestone. (Photograph: B. Daley.)

Clay mineralogy

Little mineralogical work has been undertaken on the section. It was, however, sampled by Gilkes (1968, 1978) who recorded that, as in all the post-'Bracklesham Beds' sediments on the Island, illite dominates the clay mineralogy suite. He attributed this to either the reworking of older Palaeogene sediments adjacent to the basin of deposition and/or derivation from illites neoformed in the widespread calcareous lakes which existed at this time (cf. Porrenga, 1968; Millot, 1970).

Interpretation and evaluation

The unique sequence exposed in Headon Hill differs in certain respects from other contemporary successions in the Isle of Wight and on the mainland. All the stratigraphical units present occur at other localities, but some are particularly well-exposed here, sometimes with facies significantly different from their occurrences elsewhere. The site, therefore, has a critical contribution to make to our understanding of the depositional environments and Palaeogene palaeogeography.

Comparison with other localities

At the base of the succession, the Becton Sand is 27 m in thickness, compared with about 55 m at Whitecliff Bay and 22 m at the type locality (Barton Cliffs). The Totland Bay Member (27 m) is similar in thickness to the succession at Hordle Cliff (28.3 m), but distinctly thicker than the 8.3 m in Whitecliff Bay, where there are no freshwater limestones such as those present at Headon Hill.

By contrast, the Colwell Bay Member, at something over 9 m, is far thinner than at Whitecliff Bay (30 m). The member is also less marine in Headon Hill, the Brockenhurst Bed being absent. Excellent exposures of the Linstone Chine Member at the Totland end of Headon Hill (around SZ 318865) thin to nothing near Hatherwood Point, whilst its presence is questionable in Whitecliff Bay, from which the overlying Hatherwood Limestone is missing. This member, which shows considerable variation along the length of Headon Hill, reaches some 9 m in thickness but appears to have been eroded further northwards except for a thin (0.5 m) representative at the northern end of Colwell Bay.

The Cliff End Member is thinner than at Whitecliff Bay (13 m), whilst the succeeding Lacy's Farm Limestone Member, although of approximately similar thickness there, lacks the thick limestone development found in Headon Hill. This unit is absent from the Colwell Bay succession. The Fishbourne Member above (3.9 m) is much thinner than at Whitecliff Bay (11 m), whilst the 6.8 m of the Osborne Marls Member is around half its thickness at Cliff End (13.5 m) and King's Quay (approximately 12.2 m), and two-thirds of that in Whitecliff Bay (10.7 m).

The Bembridge Limestone Formation (up to 7.5 m), exposed around grid reference SZ 317863, is slightly thinner than in Whitecliff Bay and a little thicker than at Gurnard Ledge. The presence of lignitic mud in palaeochannels is unique to this locality, but analogous to that in the Hatherwood Limestone Member. The limestone lithologies present resemble those of the other south-western sections such as Prospect Quarry and the now vegetation-concealed exposure at Cliff End.

Stratigraphical significance

Stratigraphically, the Headon Hill section has been important since the 19th century, although some early workers, such as Webster (1814, 1816), failed to fully understand its relationship to other localities. For Forbes (1853, 1856), it was the type section for his Headon Series and, later, Lower, Middle and Upper Headon Beds. Since it is now the type section for the Headon Hill Formation and three constituent members, its significance has been maintained to the present day.

Dating the succession

It has not proved an easy section to date since the predominantly non-marine or marginally marine facies markedly limit the availability of zone fossils. Costa and Downie (1976) do not refer to *Wetzeliella* being identified specifically from Headon Hill, but by analogy with localities such as Whitecliff Bay, the lower part of the succession may be assigned to the *W. perforata* zone. It may include strata of *W. gochtii* age, but since the environments represented above the Colwell Bay Member are incompatible with the occurrence of this fossil, confirmation of this seems unlikely. No calcareous nannofossil zone has been established from Headon Hill material, although the basal part of the Colwell Bay Member at Whitecliff Bay has been assigned to NP Zone 19–20 (Aubry, 1986).

Both in terms of dinoflagellates and nannoplankton, the assignment of late Eocene age to the section seems appropriate. Some have dissented from this view. Bosma (1974) suggested that, on the basis of mammalian studies, much of the succession should be assigned to a new 'Headonian Stage', straddling the Eocene/Oligocene boundary and for which Headon Hill would be the type site. Feist-Castel (1977) also considered that both the Eocene and Oligocene are represented here, the Lower Headon Beds (the Totland Bay Member as used here) being assigned to the Verzenay Charophyte Zone (Eocene) and the younger strata to the Bembridge Charophyte Zone (Oligocene).

Palaeontology

Despite the lack of zone fossils and a scarcity of plant macrofossils, the site is richly endowed palaeontologically. Together, a variety of low-diversity assemblages of molluscs, ostracods and sometimes forams indicate environments of varying salinity from freshwater to almost fully marine conditions. The generally very good molluscan preservation provides excellent opportunities for detailed research, both taxonomic and palaeoecological. An investigation of the freshwater molluscs has now been published (Paul, 1989), but considerable opportunity exists for research on such brackish water fossils as the Cerithiidae (*Potamides*, *Batillaria*, etc.), which occur in profusion at certain levels.

The presence of coloured *Theodoxus* shells has led to research into a relatively unusual aspect of palaeontology. Colour preservation is rare in the fossil record. What makes this site unique is that such large numbers of variably pigmented shells occur, thereby facilitating a detailed study of both the organic chemistry of pigment preservation and the palaeoecological significance of the colour patterns.

Palaeosalinity

In the Headon Hill section, Keen (1977) was able to recognize five of his six, predominantly salinity-related, ostracod assemblages. Only his fully marine *Hazelina* Assemblage (found elsewhere in the Brockenhurst Bed) is missing. His recognition that even in the Colwell Bay Member, salinities did not exceed upper brackish water conditions (*Haplocytheridea* Assemblage; 16.5 to 35%) is compatible with the low-diversity molluscan assemblages present. Murray and Wright's (1974) conclusions are not markedly different. They suggested that the salinities for the Colwell Bay Member were sometimes close to normal marine, whilst conceding that the low-diversity foraminiferal assemblages suggested an abnormal environment.

Keen (1977) and Murray and Wright (1974) were apparently at variance over the interpretation of the Hatherwood Limestone. Keen's work indicated a freshwater derivation whilst the latter authors (p. 36, fig. 15), having identified forams of marine aspect, suggested a lagoonal, intertidal origin. The molluscan faunas can be used to explain this apparent discrepancy, in that whilst such genera as *Galba* indicate freshwater, *Melanoides* and *Theodoxus* are more ambiguous salinity-wise and the hydrobiids represent saline influences. What needs to be remembered is that the carbonate lakes such as that producing the Hatherwood Limestone occurred in a paralic context, where separation from marine or semi-marine influences was from time to time incomplete, allowing the introduction of more saline elements by posthumous transportation or the periodic establishment of more salinity-tolerant communities when suitable conditions were maintained over a longer period. It is worth noting that a similar assemblage of forams to those in the Hatherwood Limestone was found in the predominantly freshwater Bembridge Limestone of Whitecliff Bay.

Palaeogeography and depositional environments

Whilst much palaeoenvironmental analysis of the site has been based on its fossils, the sedimentary features are also valuable for interpretation. It is unfortunate that little of a sedimentological nature has been published, although considerable data may be found in the unpublished thesis of Edwards (1967). Essentially, deposition took place in a predominantly low-energy paralic embayment in which salinity fluctuated, perhaps in part as a result of eustatic changes. The Colwell Bay Member represents the major transgressive event but the evidence suggests that fully marine salinities were not developed here. Faunal evidence clearly shows that freshwater conditions occurred from time to time but the mixing or close juxtaposition of fresh and brackish water assemblages indicates that such freshwater conditions developed within the paralic aqueous complex rather than in separate, isolated lakes.

Some of the most revealing (and sometimes perplexing) palaeogeographical research arises from multidisciplinary studies and for the Headon Hill section this is well exemplified by the work of Hooker *et al.* (1995). In a study of the Bembridge Limestone, they found that such an approach can leave unresolved contradictions. In this case, whilst clear mammalian and land snail evidence suggests the proximity of open woodland to forested areas at the time when the Bembridge Limestone was being deposited, there is no other indication of the presence of trees, including a lack of any pollen evidence for woodland or forest, or indeed any flowering plant pollen.

Palaeopedology

By far the most interesting unit sedimentologically, and particularly so from a palaeopedological point of view, is the Hatherwood Limestone. Within it, Edwards (pers. comm., 1990) recognized features comparable with Quaternary–Recent calcretes from the north-western Mediterranean region but also identified a number of palaeokarst surfaces and the sapping of hardpans which had produced pot-holes and collapse breccias. Such features may be interpreted to suggest an alternation of drier and wetter climatic conditions, a possibility supported by recently published research on the mammalian fauna (Hooker, 1992).

Considerable scope exists for palaeopedological research on the sequence succeeding the Hatherwood Limestone. The Lacey's Farm Limestone appears to have been affected by calcretization, but has not yet been the subject of detailed study. Gley soil development may be reflected in the colour-mottled, variegated muds elsewhere in the succession and these also require investigation.

Conclusions

Headon Hill is a classic site, studied by geologists since early in the 19th century, and was a key locality where early workers such as Forbes first interpreted the local stratigraphy. Nowadays, it is the type section for the Headon Hill Formation and three of its members, whilst its stratigraphical importance is further enhanced by some aspects of the section which contrast markedly with successions of similar age elsewhere.

Palaeontologically, it is no less significant. Although not important biostratigraphically, it contains a wide variety of macrofossil and microfossil assemblages of palaeoenvironmental significance. Molluscs, foraminifera and ostracods have indicated the former presence of a wide variety of freshwater to nearly fully marine environments in a low-energy paralic (coastal) embayment. Amongst the vertebrate fossils found are primates and other mammals.

The section offers excellent opportunities for the study of a wide variety of freshwater and brackish water sediments. The freshwater limestones have attracted particular attention, and of these, the Hatherwood Limestone is the thickest and most interesting. Fossil soils (palaeosols), indicating emergent episodes, are well developed at a number of horizons. From the presence of calcretes, the former periodic existence of climatic drier conditions can be inferred, rather than the continual humid tropical or subtropical climates previously considered characteristic of the local Palaeogene from palaeontological (mainly palaeobotanical) evidence.

COLWELL BAY, ISLE OF WIGHT (SZ 327878–SZ 331887)

Highlights

Seven members of the Headon Hill Formation are represented in Colwell Bay and, for two of these, it is the type section. Particularly well developed is the Colwell Bay Member whose fossils have long been one of the main attractions of the section. The succession contrasts with its time equivalent in Headon Hill and demonstrates how rapidly lateral changes can occur within a small geographical area.

Introduction

From Warden Point (grid reference SZ 325878) to Cliff End (SZ 330980), cliff and limited foreshore sections occur in the Headon Hill Formation of Insole and Daley (1985) from the Totland Member to the Osborne Marls Member. The section is important stratigraphically and for both animal and plant fossils. The Colwell Bay Member (formerly the Middle Headon Beds) has provided a focus of interest since it represents a major transgressive period represented by quite a rich and diverse fauna.

Colwell Bay has been of interest to geologists for many years. Descriptions of the section include those of Bristow *et al.* (1889), White (1921) and Edwards (1967), Stinton (1971a), Insole (1972), Curry *et al.* (1972) and Daley and Edwards (1974). Palaeontological studies include work on the foraminifera by Murray and Wright (1974) and on the plant macrofossils by Chandler (1963a) and Collinson (1978a). Insole and Daley (1985) have designated the site as the stratotype for two members of the Headon Hill Formation. The section has been re-described by Daley (1999, pp. 46–49).

This site was also independently selected for its fossil plant content, a more detailed account of which can be found in the GCR series volume *Mesozoic to Tertiary Palaeobotany of Great Britain* (Cleal and Thomas, in prep.).

Description

The Colwell Bay site comprises a cliff section (Figure 5.31) truncating three chines: from south to north, Colwell Chine, Brambles Chine and Linstone Chine (Figure 5.32). Some foreshore sections may be accessible at low water. With the exception of a small, tight anticline north of Linstone Chine, the strata dip gently northwards.

Lithological succession

Altogether, the succession comprises approximately 33 m from the How Ledge Limestone (Totland Bay Member) to the poorly exposed Osborne Marls Member at the top of the succession at Cliff End (Figure 5.33). However, to the south of Cliff End, well under half of this thickness is present, with the top of the cliff formed mainly by the lowest beds of the Cliff End Member.

Figure 5.31 Colwell Bay, Isle of Wight. To the south of the Brambles Chine (far left), the Headon Hill Formation succession comprises the Colwell Bay Member overlain by the Linstone Chine Formation. (Photograph: B. Daley.)

The essentially clastic sequence comprises a succession of variously coloured muds and sands. Amongst the distinctive lithotypes are the very shelly, muddy sands of the 'Colwell Oyster Bed' (Colwell Bay Member) and the heterolithic Linstone Chine Member. Three thin buff-coloured limestones occur. The How Ledge Limestone outcrops at the bottom of Colwell Chine and the other two at Cliff End.

Stratigraphy

Seven members of the Headon Hill Formation are represented in Colwell Bay (Figure 5.33), but in detail the sequence differs from that further south in Headon Hill. Along most of the section, the Hatherwood Limestone Member is absent and the Cliff End Member rests on the eroded top of the Linstone Chine Member. However, at the northern part of the bay, towards Cliff End, the latter is overlain by a 0.5 m buff *Galba*-bearing limestone, the top of which is truncated by an erosion surface. This thin limestone may be the local representative of some part of the Headon Hill Limestone. The Lacey's Farm Limestone Member is completely absent in Colwell Bay.

Colwell Bay is significant stratigraphically, since it contains the stratotypes for two members in the Headon Hill Formation (Insole and Daley, 1985). The stratotype for the Colwell Bay Member is the cliff section adjacent to Brambles Chine (SZ 330883), whilst that for the Linstone Chine Member is the upper part of the cliff between Brambles and Linstone Chines (around SZ 331884). Formerly called the Middle Headon Beds, the Colwell Bay Member can be divided into a lower, grey, mainly sandy part and an upper, bright green, muddier part. This member contains the 'Neritina Bed' followed by the 'Venus Bed', although between Colwell and Brambles Chines, the latter is replaced by the

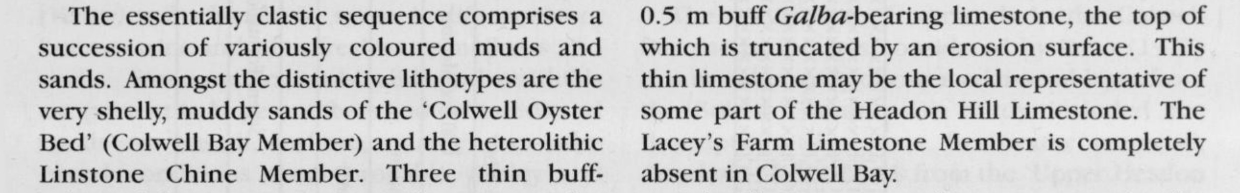

Figure 5.32 Colwell Bay, Isle of Wight: cliff profile (after N. Edwards, pers. comm.; Daley and Insole, 1984).

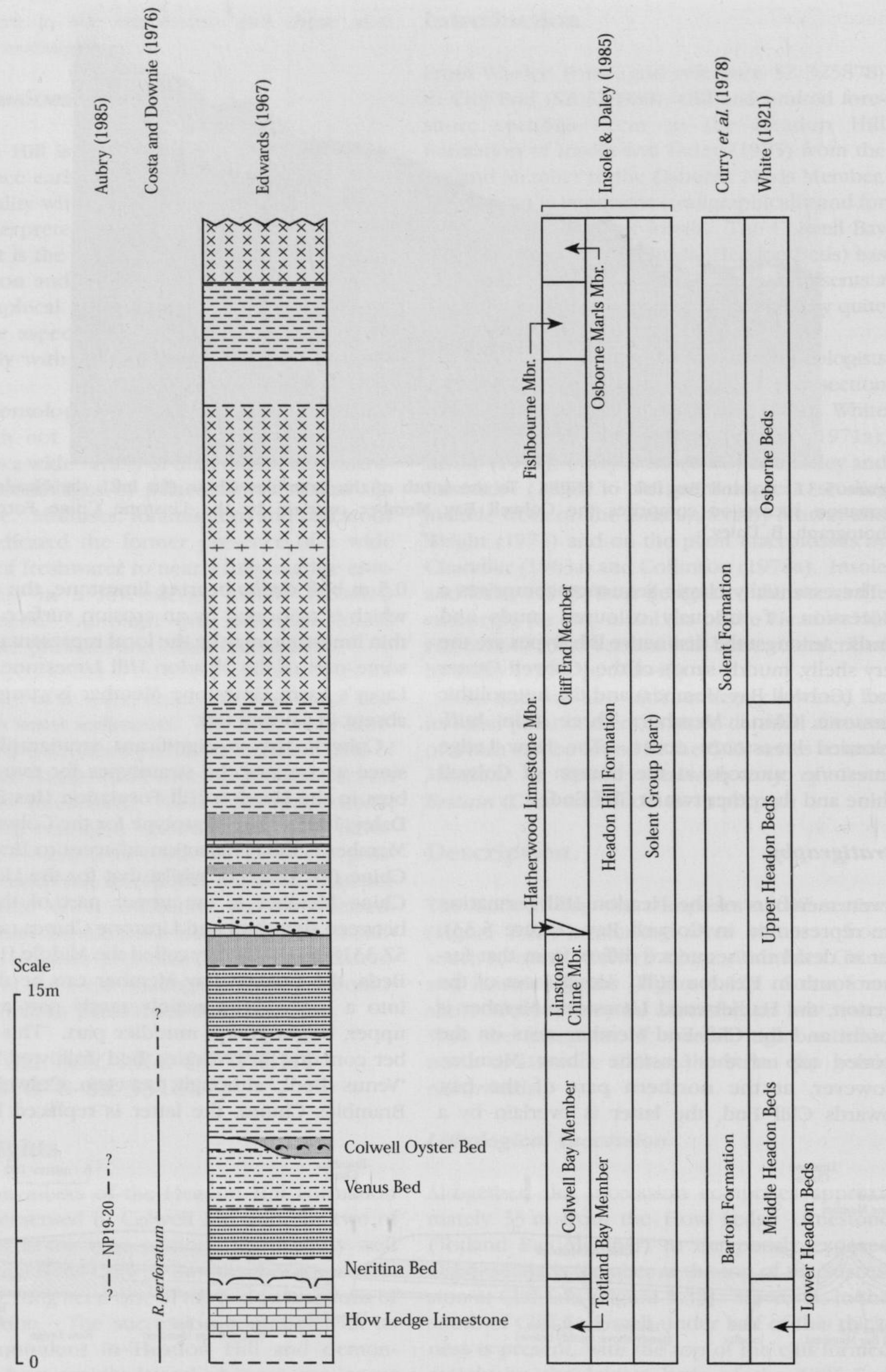

Figure 5.33 Lithostratigraphical and biostratigraphical succession of the Headon Hill Formation, Colwell Bay, Isle of Wight (after Edwards, 1967; Insole and Daley, 1985 and other authors).

lenticular 'Oyster Bed', thought to have originated as a tidal-channel fill (cf. White, 1921). The marine Brockenhurst Bed does not occur in Colwell Bay, but the brackish water 'Neritina Bed' is its probable equivalent (Vella, 1969).

Invertebrate macrofauna

The fossils of the Colwell Bay Member have always been one of the main attractions of the section. *Theodoxus*, *Potamides*, *Corbicula* and other molluscs occur in the 'Neritina Bed' to the north of Colwell Chine but exposures are usually poor. A particularly good locality for invertebrate fossils is either side of Brambles Chine, where the overlying 'Venus Bed', together with the succeeding bright green muds, is normally well-exposed (see Stinton, 1971a). Curry and Edwards (in Curry *et al.*, 1972) reported some hundred species of mollusc from the 'Venus Bed'. The fauna is predominantly marine, with paired valves of the characteristic *Sinodia (Venus) suborbicularis*, some in life position, but estuarine and a few freshwater molluscs also occur. Since oysters, corbiculids and cerithiids are present in large numbers and echinoids and corals are absent, inshore, muddy river-influenced conditions seem probable (Daley and Edwards, 1974, p. 284). Where the 'Venus Bed' is replaced by the 'Oyster Bed', 90% of the shells are oysters (*Ostrea velata*), together with other species such as '*Murex*' *sexdentatus* and *Nucula headonensis*, and together represent a death assemblage in a sandy matrix.

At other horizons, a number of assemblages are much more taxonomically restricted, although often abundant in individuals. For example, in the remainder of the Colwell Bay Member above the 'Venus Bed', *Theodoxus apertus*, *Potamides pseudocinctus* and *Globularia harrisi* are conspicuous, whilst more characteristic marine elements of the underlying bed are missing (Curry and Edwards, *in* Curry *et al.*, 1972). In the bottom part of the Linstone Chine Member, a nearly monogeneric assemblage of the prolifically occurring brackish water bivalve *Potamomya* is present, whilst in the Cliff End Member above, this genus recurs in abundance, together with *Corbicula* and *Potamides* in certain beds.

Whilst all of these assemblages represent a variety of hyposaline conditions, the presence of *Viviparus* and *Unio* at some other horizons is indicative of freshwater conditions. The latter are also indicated by freshwater pulmonate assemblages comprising *Galba* and *Planorbina* found in thin limestones. They also occur in the 'How Ledge Limestone' (Totland Bay Member) present at the foot of the low cliff just north of Colwell Chine and forming How Ledge on the foreshore south of Brambles Chine.

Microfauna

The foraminifera from Colwell Bay were studied by Bhatia (1955, 1957) and Murray and Wright (1974). The latter authors described two faunules from the Colwell Bay Member. The lower of these, including the 'Oyster Bed', is interpreted as indicating hyposaline estuarine or lagoonal conditions, with very shallow, just subtidal waters. The upper, from a 'green sandy clay', is dominated by *Quinqueloculina impressa*, many of them large, and is thought by Murray and Wright to represent near-normal (>32 parts per thousand) salinities.

The occurrence of ostracods in the Colwell Bay succession was considered by Keen (1977) in a broader study of ostracod assemblages from the Solent Group. His study included the description of a new freshwater ostracod, *Candona cliffendensis* from the 'Upper Headon Beds' of Cliff End at the northern end of Colwell Bay. Another species named after the locality is *Neocyprideis colwellensis* (Jones), which characterizes Keen's (1977) brackish, mesohaline assemblage. Ostracods reflecting higher salinities are found in the Colwell Bay Member, although truly marine salinities were apparently not developed at this time in this area, in contrast with the situation at Whitecliff Bay and in the New Forest (Keen, 1977, p. 426).

Flora

Plant macrofossil remains from the Upper Headon Beds of Colwell Bay have been described by Chandler (1955, 1961a, 1963a) and more recently by Collinson (1978a, 1980b). Chandler (1955) recorded the occurrence of fertile fern-leaf fragments from the Headon Beds and later (Chandler, 1961a) reported the presence of five water plants from the Lower Headon Beds. Collinson (1978a) found plant macrofossils including *Typha*, *Azolla* and seeds of *Potamogeton* in the 'Upper Headon Beds' (probably the Linstone Chine Member) near Linstone Chine. In a subsequent paper

(Collinson, 1980b), she described *Azolla colwellensis* in some detail. Colwell Bay was also extensively sampled by Machin (1971) in her comprehensive study of Palaeogene pollen and spores from the Isle of Wight.

Interpretation and evaluation

Only a limited range of strata are exposed in Colwell Bay, the succession being totally within the Headon Hill Formation. The succession is, however, important both stratigraphically and palaeontologically and contributes significantly to our understanding of contemporary environments and geography.

Dating the succession

The strata in Colwell Bay are now generally considered as being of late Eocene age (Curry *et al.*, 1978), although the Geological Survey Isle of Wight Sheet (1976) still shows them incorrectly as Oligocene. The section appears to be of limited chronostratigraphical value. It has not, as yet, been dated from in-situ material, but the Colwell Bay Member elsewhere has in part been referred to nannoplankton Zone NP 19–20 (Aubry, 1986).

Lithostratigraphy

The section is of lithostratigraphical importance since it is the type locality for two members from the Headon Hill Formation. One of these, the Colwell Bay Member of Insole and Daley (1985) is synonymous with the Lyndhurst Member of Edwards and Freshney (1987b).

Comparison with other localities

The sequence at Colwell Bay differs in a number of ways from successions in the Headon Hill Formation elsewhere. From Colwell Bay to Headon Hill it is apparent that the Totland Bay Member on the west side of the Isle of Wight is far thicker than at Whitecliff Bay. The presence of a number of freshwater limestones, like the How Ledge Limestone, in the west and their absence from the member in the east is a significant lithological difference. Edwards and Freshney (1987a, fig. 39) suggested that the western localities represent alluvial plains with small freshwater lakes, whilst muddy lagoons occurred further north and to the east (presumably including Whitecliff Bay). This is, however, an oversimplification since brackish and freshwater fossils occur within the member on both sides of the Island.

The Colwell Bay Member in Colwell Bay is thicker than at Headon Hill, although the 'Batillaria Bed' which forms the top of the unit at the latter locality is absent. The occurrence of rolled '*Batillaria*' at the base of the overlying unit in Colwell Bay indicates that this absence resulted from contemporaneous erosion. This member is only around 10 m thick here, compared with 30 m in Whitecliff Bay, a reflection of the marked thinning of this marine unit to the west.

Depositional environment and palaeogeography

The absence of the marine Brockenhurst Bed (present to the north towards Lyndhurst and at Whitecliff Bay) suggests that the initial Colwell Bay Member transgression failed to introduce fully marine salinities as far south-west as the Colwell Bay area (see Edwards and Freshney, 1987a, fig. 40). Hence, lower salinities gave rise to the fauna of the apparently contemporaneous 'Neritina Bed'. Murray and Wright (1974) in fact concluded, on the basis of their foraminiferal work, that all faunas, except for one towards the top of the member in Colwell Bay, represented hyposaline conditions with the environment essentially lagoonal or estuarine. The succeeding Linstone Chine Member contains an exceptionally well-preserved variety of structures indicative of intertidal deposition, although the restricted fauna present implies hyposaline waters.

The virtual absence of the freshwater limestones, which form a distinctive feature of the upper part of the succession in Headon Hill, is an important aspect of the section in Colwell Bay. Insole (1972) noted that these limestones are at their thinnest where the Linstone Chine Member is best developed and has suggested that freshwater limestones developed in topographic hollows in a relict sandflat surface. There is, on the other hand, some evidence of erosion at this level which may have locally removed virtually all of the limestone deposited in the Colwell Bay area.

As at Whitecliff Bay, and in the north-eastern sections of Headon Hill, the Cliff End Member rests with a sharp break on the underlying strata. The fauna is clearly indicative of an environment with variable, brackish to freshwater salinities, perhaps a river-influenced lagoon. Why the Lacey's Farm Limestone (the Osborne Beds Limestone of Edwards, 1967) is absent in Colwell Bay is uncertain. It may be that this area was still submerged at the time when emergence further to the south led to its development by a process of calcretization.

Palaeontology

Within recent years, the importance of the site as a water-plant macrofossil locality has been established (Collinson, 1978a, 1980b). Whilst the foraminifera have also been the subject of modern work (Murray and Wright, 1974), a great deal of potential still exists for molluscan macrofossil work, in particular on the taxonomy and palaeoecology of the hyposaline assemblages.

Conclusions

Colwell Bay is a significant section lithostratigraphically. It is the type section for two members of the Headon Hill Formation, whilst the absence of the thick Hatherwood Limestone and Lacey's Farm Limestone illustrates how rapidly lateral changes can occur in a paralic context.

The section provides an opportunity to study a wide variety of environments from freshwater to almost wholly marine conditions. It is particularly famous for the rich faunal assemblages of the Colwell Bay Member (formerly Middle Headon Beds), although it is now known that, for most of the time represented by this unit, conditions were not quite fully marine. The heterolithic lithology of the Linstone Chine Member is a particularly striking example of an intertidal deposit.

Apart from the molluscan fauna of the above and other horizons, Colwell Bay has proved an important locality for microfaunal research on ostracods and foraminifera and for plant macrofossil studies, particularly of water plants. It is therefore considered to be a major palaeontological site.

PROSPECT QUARRY, ISLE OF WIGHT (SZ 385866)

Highlights

Prospect Quarry occurs entirely within the Bembridge Limestone and is the best locality for the study of calcretes within that unit. It is also the major Bembridge Limestone locality for fossil land snails.

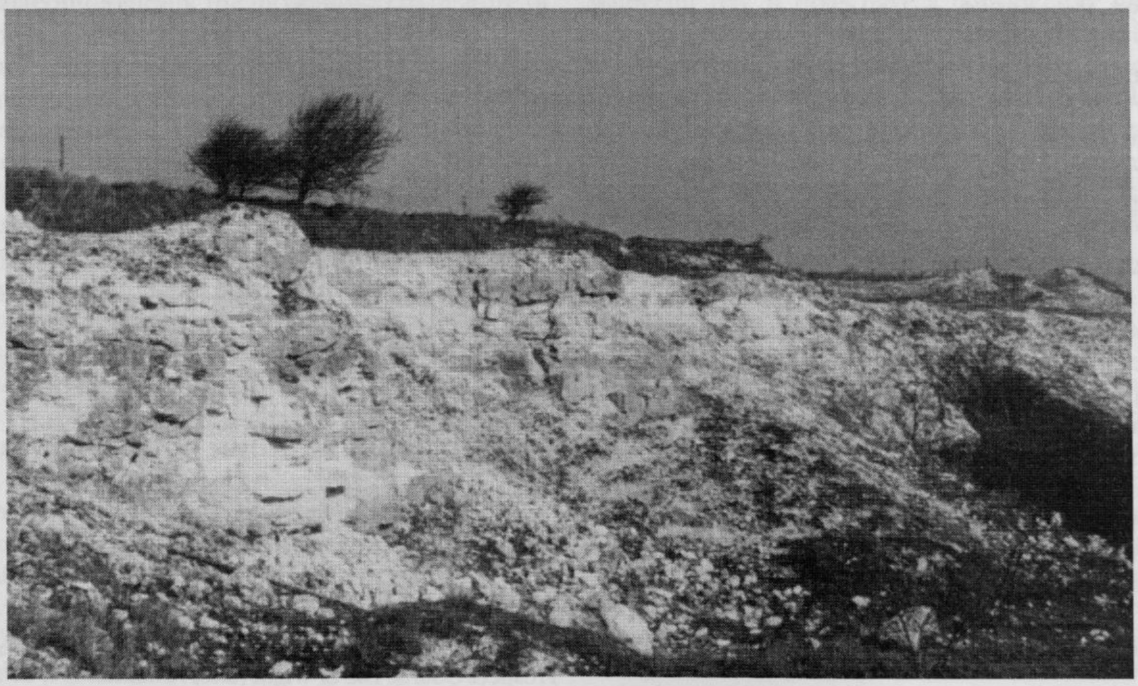

Figure 5.34 Bembridge Limestone in Prospect Quarry, Isle of Wight. (Photograph: B. Daley.)

Introduction

Prospect Quarry (Figure 5.34) is a small quarry in the Bembridge Limestone Formation, some 4.5 km east of Freshwater, Isle of Wight, at grid reference SZ 385866. It is one of two remaining quarries of a number in the formation, including those referred to in White (1921, pp. 119–120). No Bembridge Limestone is visible at any of these other former quarry sites, except for Tapnell Farm Quarry (SZ 377864) where part of the succession is still visible.

This quarry provides the best exposure in the Bembridge Limestone Formation of the pisolitic and laminated facies which are absent or poorly represented at other localities such as Gurnard Ledge (Thorness Bay) to the north and Whitecliff Bay to the east.

No mention of the quarry was made in White (1921) or earlier publications, since it was not opened until 1938 (Pain and Preece, 1968). Apart from the unpublished work of Edwards (1967), who briefly described the stratigraphy and lithologies present, the main interest in the quarry has reflected the molluscan fauna, in particular a diverse fauna of terrestrial gastropods (Pain and Preece, 1968; Jarzembowski, 1976; Preece, 1976). More recent research has centred on the sedimentology, following the recognition that the Bembridge Limestone here has been extensively calcretized (Armenteros *et al.*, 1992, 1997; Daley, 1999, pp. 60–61).

Description

The Bembridge Limestone is exposed in the western and northern part of the quarry in an approximately 40 m long face.

Lithological succession

The succession is up to 4 m in thickness but neither the top nor the bottom of the formation is exposed. The section appears to be in the lower part of the formation, stratigraphically below the muds found towards the middle of the formation at most other localities (Daley and Edwards, 1990). A variety of limestone lithologies are represented, including both well-indurated and soft, poorly lithified rocks (Figure 5.35).

Sedimentology and palaeopedology

Lithological relationships are complex and par-

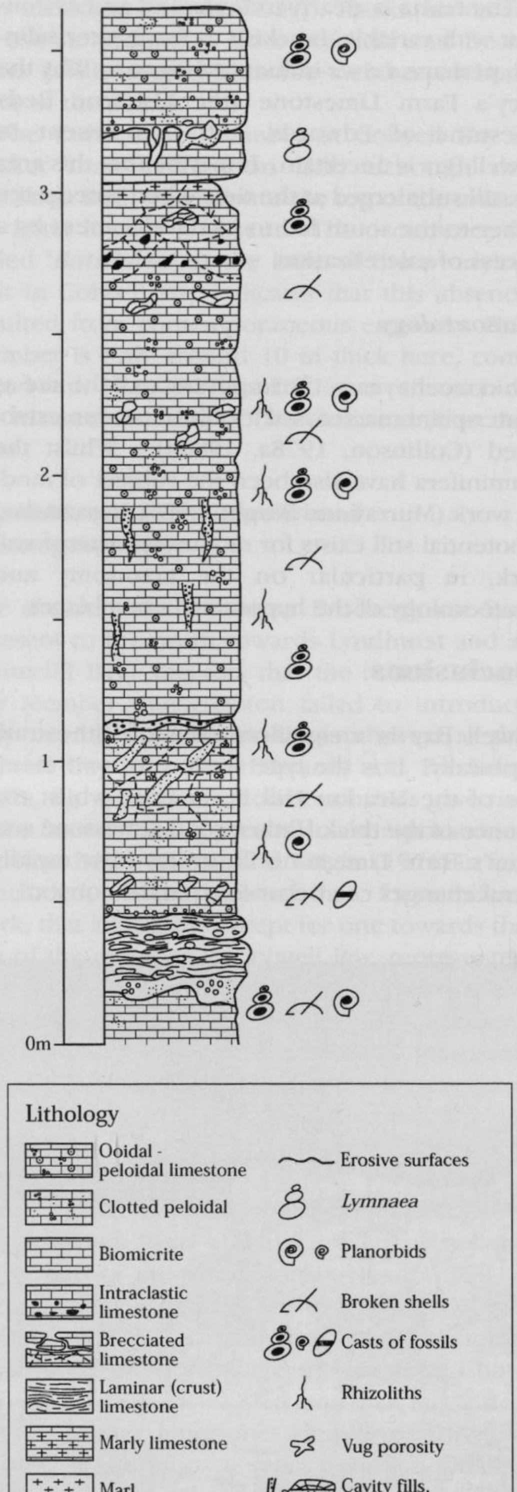

Figure 5.35 Bembridge Limestone succession in Prospect Quarry, Isle of Wight (after Armenteros *et al.*, 1997).

ticularly appear to reflect pedogenic changes associated with calcrete development, whose recognition here has much wider palaeogeographical and palaeoclimatological significance. Certain thin horizons are characterized by irregular, crinkled and contorted laminations, some of which may represent calcified, pedogenic rootlet mats (Wright, 1989, fig. 12; Daley and Edwards, 1990). Some of the indurated limestones contain an ill-sorted mixture of peloidal and coated grains, including quite large pisoliths. Micrites, containing whole and fragmented shells, and intraclasts are also present. Small, soft pseudointraclasts represent remnants of primary lithologies. Contemporaneous breakage and solution added to the complexity. Hollows, veins and other spaces are sometimes filled with coarse sparry calcite or by various mixtures of intraclasts and coated grains. Such cavities are much larger than the 'pseudo-microkarst' features seen in the Bembridge Limestone Formation at Whitecliff Bay, but are probably analogous in origin. Recent work on Prospect Quarry by Armenteros *et al.* (1992, 1997) and Armenteros and Daley (1998) has involved both petrographic and stable isotope work which confirms that the succession here is predominantly of pedogenic facies.

Macropalaeontology

Palaeontologically, the most important feature of the site is its terrestrial gastropod fauna. Pain and Preece (1968) described 12 terrestrial species from the quarry, whilst Preece (1976) listed a total of 25. Aquatic genera are also present, including pulmonates like *Galba* and *Planorbina*, but not in the profusion found, for example, at Whitecliff Bay. Calcareous ovoid-cylindrical trace fossils, once thought to be the eggs of land snails, may be chambers made by insects for pupation or by some unknown organism for hibernation or aestivation (Edwards *et al.*, 1998).

Interpretation and evaluation

Prospect Quarry is the largest of the two remaining inland quarries in the Bembridge Limestone. Although the sequence is incomplete, it exhibits a facies differing from those of Whitecliff Bay and Thorness Bay. Although the diagenetically complex lithologies present are comparable with some in the poorer exposures in Headon Hill and those formerly visible at Cliff End, they are only well exposed in Prospect Quarry.

Palaeogeographical context

Elsewhere in the local Palaeogene strata, the presence of rounded Upper Cretaceous flint pebbles is evidence that older rocks were being eroded during the Eocene. Contemporaneous weathering and soil formation at this site is further evidence of subaerial exposure. Although it has been speculated that the Chalk may have been exposed during the Eocene southwards of a line approximately corresponding to the Isle of Wight Monocline (Plint, 1983a, fig. 12), there is no isopachyte evidence for southward thinning of the Bembridge Limestone (Insole and Daley, 1985, text-fig. 23) to indicate a southerly basin margin. A southward transition to at least periodically subaerial conditions is, however, supported in Prospect Quarry by both palaeontological and lithological evidence.

Significance of the gastropod fauna

At all localities where the Bembridge Limestone is exposed, the presence of large numbers of air-breathing pulmonate gastropods, such as *Galba* in particular, provides evidence of the shallowness of the lake waters. Whilst Prospect Quarry is far less rich in such snails compared with Whitecliff Bay, it does have a considerable terrestrial gastropod fauna, presumably relatively locally derived, which is absent or poorly represented at the more northerly and easterly localities. Prospect Quarry, therefore, appears to reflect a lake margin (palustrine) environment, contrasting with the generally more open lake waters represented at such localities as Thorness and Whitecliff Bays.

Depositional environment

Since both *Galba* and *Planorbina* have little tolerance to even slightly saline waters, it must be assumed that the primary facies here are essentially freshwater in origin. There is, however, increasing evidence that the Bembridge Limestone 'lake' may have been less separate from more saline waters than had hitherto been thought. Part of this evidence comes from the investigations by Marshall *et al.* (1987, 1988) and Armenteros *et al.* (1992) of the distribution of the stable isotopes of C and O in the

Bembridge Limestone of Prospect Quarry. Their distribution is complicated, reflecting both depositional, pedogenic and later diagenetic calcite formations, but some of the diagenetic fluids appear to have included a component of marine and/or brackish waters. This is compatible with the findings of Murray and Wright (1974) whose work on Palaeogene foraminifera revealed the presence of marine elements in the Bembridge Limestone, the recognition by Daley and Edwards (1990) that the presence of hydrobiids at certain horizons in the formation implies some degree of brackishness, and with the occurrence of microlenticular gypsum in the Gurnard section (Daley, 1989).

Pedogenesis

The existence of emergent conditions inferred from the nature of the gastropod fauna, is well supported by the particularly fine development of pedogenic facies which dominates the Prospect Quarry sections. Marshall *et al.* (1987, 1988) concluded that the site contained at least seven pedogenic profiles. They identified a number of pedogenic fabrics indicative of calcrete development, a conclusion confirmed by the later, more detailed work of Armenteros *et al.* (1992) and Armenteros *et al.* (1997). The latter authors considered that the few remnants of primary facies probably represented areas that were intermittently water-covered and marshy. Such areas were repeatedly subaerially exposed and subject to pedogenic modification (see Armenteros and Daley (1998) for a detailed description and interpretation). The superimposition of successive pedogenic phases has hindered interpretation and has led to the almost complete obliteration of the primary facies.

Palaeoclimatology

The recognition of calcrete at Prospect Quarry and the consequent inference of dry climatic conditions is compatible with the presence of the thick evaporites of the Gypse in the Paris Basin to the south, with which the Bembridge Limestone has been correlated (Curry *et al.*, 1978). It supports the idea that the former belief in the continuity of humid tropical to subtropical climatic conditions during the Palaeogene is unsustainable. However, recent work on the Bembridge Limestone of Headon Hill by Hooker *et al.* (1995) clearly indicates that there were phases of forest and woodland development and consequently wetter periods. Whilst these authors (p. 450) suggest that their samples are from higher in the succession, the likelihood of wetter phases at the time represented by the Prospect Quarry section may be inferred from the terrestrial gastropod fauna since, according to Preece (1980, p. 178), many land snails are shade-demanding and may indicate the proximity of forest. Consequently, with the lithological evidence for alternating deposition and pedogenic modification (including dissolution), it may reasonably be concluded that the succession represents an alternation of wetter and drier climatic phases.

Conclusions

Although no complete succession of the Bembridge Limestone occurs at Prospect Quarry, the locality is palaeontologically and lithologically significantly different from other major localities where the formation is exposed.

This site represents lake margin (palustrine) and emergent facies of the formation. Land gastropods are much more important here than at any other locality where the formation outcrops. Whilst the original carbonate sediments accumulated in freshwater, isotopic studies suggest the proximity of more saline waters which, together with evidence derived from other localities, calls into question to what extent the Bembridge Limestone 'lake' was separated from coeval brackish or more marine waters.

The recognition that repeated pedogenic modification led to the development of calcretes suggests that the climate was periodically dry whilst the common occurrence of land gastropods appears to indicate the existence of wetter conditions. It therefore seems likely that the succession represents an alternation of drier and wetter climatic phases.

BOULDNOR AND HAMSTEAD CLIFFS AND FORESHORE, ISLE OF WIGHT (SZ 375902–SZ 405920)

Highlights

This is the only site with a more or less complete succession of the Bouldnor Formation and the only place where the Hamstead and Cranmore Members are exposed. These are the youngest rocks of the local Palaeogene succession, with

Figure 5.36 Hamstead Cliffs, Isle of Wight. Cliff and foreshore exposures of the Bembridge Marls Member (Bouldnor Formation), the lighter bands in the cliff representing shell concentrate horizons. (Photograph: B. Daley.)

the site the sole extant exposure of Oligocene age in the Hampshire Basin. It is one of the best localities for the study of low-energy, freshwater and brackish clastic environments and has well-preserved plant macrofossils and macroinvertebrates, particularly gastropods.

Introduction

Bouldnor Cliff and its north-easterly continuation in Hamstead Cliff extends for about 3.2 km as far as Hamstead Ledge. The south-western limit of the site is around map reference SZ 375902 and the north-eastern limit at SZ 405920. It is of considerable stratigraphical and palaeoenvironmental significance, although due to the badly slipped and well-vegetated nature of the cliff section, exposures are intermittent. Except for a very restricted occurrence near Gurnard Ledge, it is the only site where the Hamstead and Cranmore Members of the Bouldnor Formation are exposed and provides the last preserved record of Palaeogene sedimentation in the Hampshire Basin.

This site was also independently selected for its fossil plant content, a more detailed account of which can be found in the GCR series volume *Mesoozoic to Tertiary Palaeobotany of Great Britain* (Cleal and Thomas, in prep.), and its fossil insect content which will be discussed in a future GCR volume.

The section comprises a complete sequence of the Bouldnor Formation, consisting of muds with variable fossil content which have been assigned to three members: the Bembridge Marls Member, the Hamstead Member and the Cranmore Member. The first is seen west of the poor exposures of the underlying Bembridge Limestone forming Hamstead Ledge at the north-eastern end of the section (SZ 403920; Figure 5.36). Although the cliff exposures are intermittent here, the whole of this member is exposed on the foreshore at low water, equinoctial spring tides (Figure 5.37). The Hamstead Member is exposed here, in part along the foreshore and in scattered cliff sections, and the Cranmore Member at the cliff top near the end of Cranmore Avenue (SZ 386906; Figure 5.38), below a capping of Quaternary Gravel. Limited foreshore exposures also occur at the south-western end of the section, towards Yarmouth.

The early descriptions of the cliff section by Forbes (1853) and Bristow *et al.* (1889) remain the most comprehensive due to the very considerable deterioration in exposure which has taken place since the 19th century. No detailed succession of the Hamstead and Cranmore Members has been published since that of Bristow *et al.* (see summary in White, 1921). Daley (1969, 1972c) has redescribed the

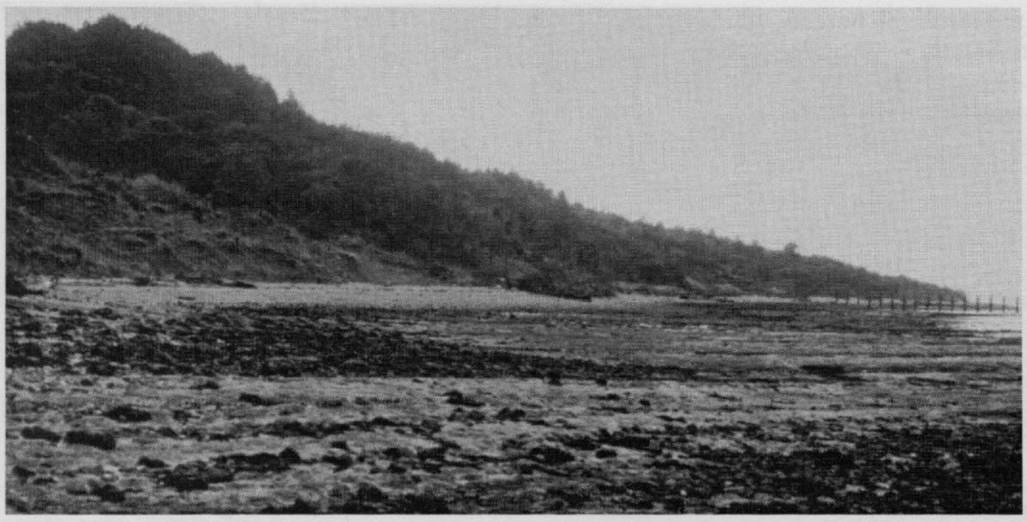

Figure 5.37 View of Hamstead foreshore at low water, equinoctial spring tides. Foreshore exposures provide a continuous section through the whole of the Bembridge Marls Member and the lowest part of the overlying Hamstead Member. (Photograph: B. Daley.)

Bembridge Marls Member, the whole of which is exposed on the foreshore at low water (see also Daley and Edwards, 1974). Brief descriptions of the section as a whole occur in Curry *et al.* (1972) and Daley and Insole (1984); whilst recently the importance of the section has been comprehensively reviewed by Daley (1999, pp. 49–55)..

Recent palaeontological work on the section includes that of Daley (1972b) on macroinvertebrates, Keen (1972a) on the ostracods, Murray and Wright (1974) on the foraminifera, and Ford (1967) and Bosma (1974) on the mammals. Microfloral studies include Machin (1971) on pollen and spores, and Costa and Downie (1976) and Liengjaren *et al.* (1980) on the dinoflagellates. Collinson (1983b) provided details of the stratigraphical distribution of plant beds within the Bembridge Marls Member.

Description

Whilst the site extends laterally for 3.2 km, exposures are intermittent. No complete sequence has ever been measured and there are parts of the succession for which no published description exists.

Lithological succession

Apart from the poorly exposed Bembridge Limestone at the base, the section is entirely within the Bouldnor Formation. It is difficult to determine its thickness but for the site as a whole a composite estimate is almost 110 m. Individual member thicknesses are as follows: the Bembridge Marls Member: 21.5 m; the Hamstead Member: approximately 78 m; and the Cranmore Member: about 9.2 m preserved (Figure 5.39). Above the thin shell bed with *Ostrea* which caps the Bembridge Limestone at Hamstead Ledge, the Bouldnor Formation is predominantly black, grey and green more or less fossiliferous muds and muddy silts, other lithologies being uncommon. There is no representative here of the 'Insect Limestone' which occurs close to the base of the Bembridge Marls Member (Figure 5.40) at all the other major localities where this member is found. Horizons with rough or hackly concretionary ironstone nodules and one continuous ironstone band occur in the lower part of the formation.

Stratigraphy

Forbes (1853, 1856) split the sequence here into the Bembridge Marls and overlying Hamstead Beds, the boundary between them being the carbonaceous mud or so-called 'Black Band' at the base of the latter (see White, 1921, p. 129). These two stratigraphical units were retained by Bristow (1862) and Bristow *et al.* (1889), although in both cases, doubts were expressed as to whether the separation of the two was justified. The complete sequence is, after all, both here and elsewhere, argillaceous throughout.

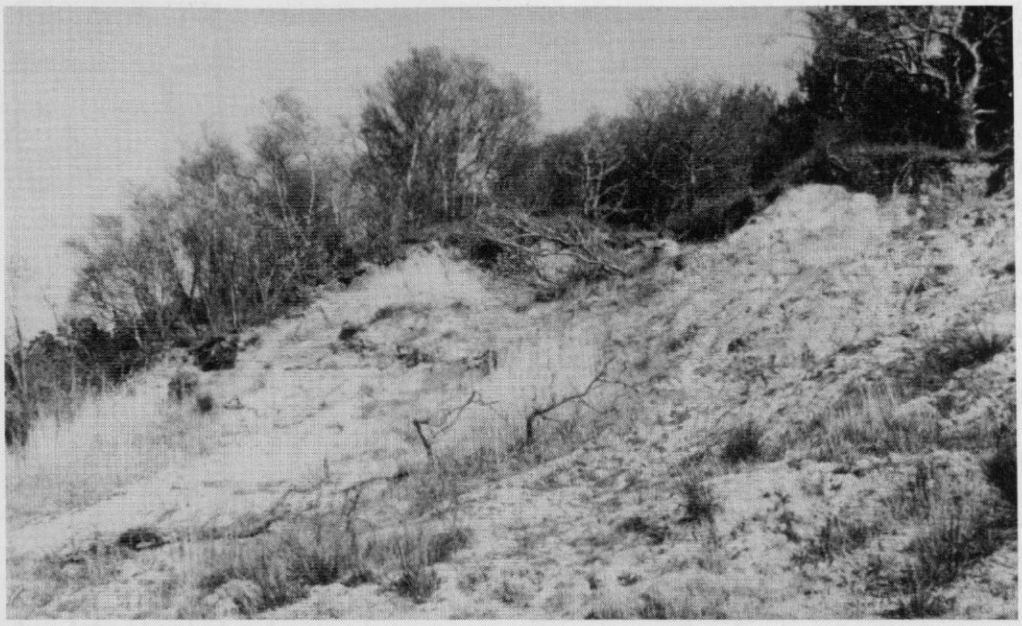

Figure 5.38 Cranmore Member below Quaternary gravel at the top of Bouldnor Cliff, near Cranmore, Isle of Wight. (Photograph: B. Daley.)

Hence, following Hedberg (1976), the similarity of the strata above and below the 'Black Band' denies separate formation status for the Bembridge Marls and Hamstead Beds of the traditional nomenclature scheme. This was recognized by Curry *et al.* (1978) who united both of these units into a single Hamstead Formation, although without a formal definition of its characteristics.

Insole and Daley (1985), in proposing new lithostratigraphical nomenclature, designated the site as the type area for the Bouldnor Formation, a new term used instead of the Hamstead Formation of Curry *et al.* (1978) to avoid nomenclature confusion. The foreshore and cliffs between Hamstead Ledge and Bouldnor were defined as the type area both for the formation and the Hamstead Member (formerly the Lower Hamstead Beds of Bristow *et al.* (1889) and equivalent to the Lower and Middle Hamstead Beds of Keen (1972a)). The stratotype for the Cranmore Member (formerly the Upper Hamstead Beds of Bristow *et al.*, 1889) is the uppermost part of Bouldnor Cliff.

Palaeontology

The Bouldnor and Hamstead site is particularly important palaeontologically, firstly because nowhere else in Britain are rocks of this age and facies preserved (see below) and secondly because it provides an opportunity for the palaeoecologist to study a variety of animal and plant communities from brackish to freshwater environments.

The study of macroinvertebrate assemblages undertaken by Daley (1972b) relied heavily on data derived from this site. A variety of brackish and freshwater assemblages in the Bembridge Marls Member are especially well developed here. In the foreshore exposures, shell preservation is particularly good compared with that frequently encountered elsewhere.

Macroflora

Plant macrofossil assemblages described by Collinson (1983b) from the foreshore exposures west of Hamstead Ledge provide a major contribution to our knowledge of aquatic and marginal aquatic floras of this age and shed considerable light on the conditions under which the lower part of the Bouldnor Formation was deposited. She recognized nine plant macrofossil-bearing horizons; eight are in the Bembridge Marls Member, the ninth being the 'Black Band' at the base of the overlying Hamstead Member. These contain abundant fruits, seeds, fern

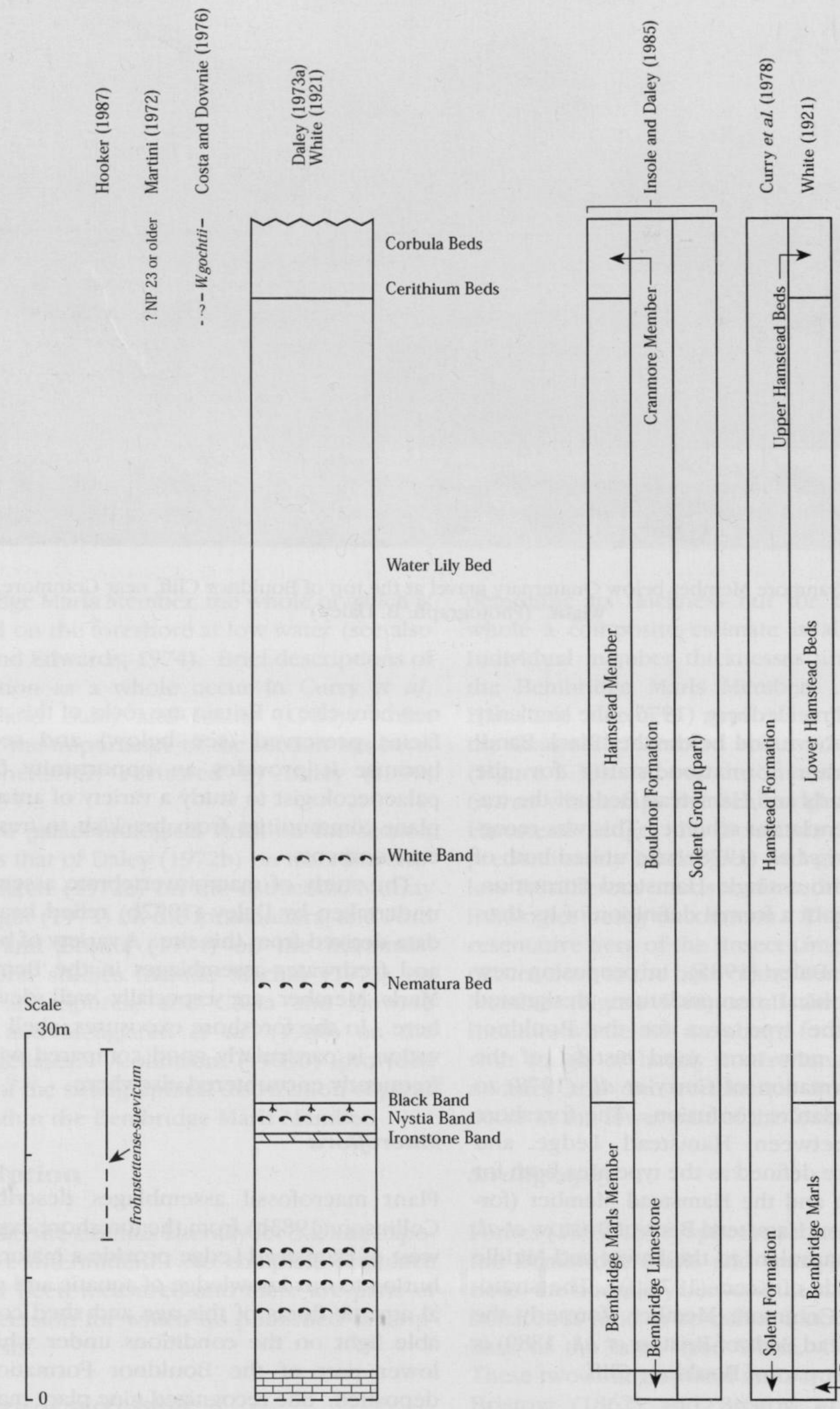

Figure 5.39 Lithostratigraphical succession of the Bouldnor Formation in Bouldnor and Hamstead Cliffs, Isle of Wight, based on the section from Cranmore north-eastwards to Hamstead Ledge (after Daley, 1973a; White, 1921 and other authors). The *frohnstettense–suevicum* Zone (Hooker, 1987) is a mammal concurrent range zone.

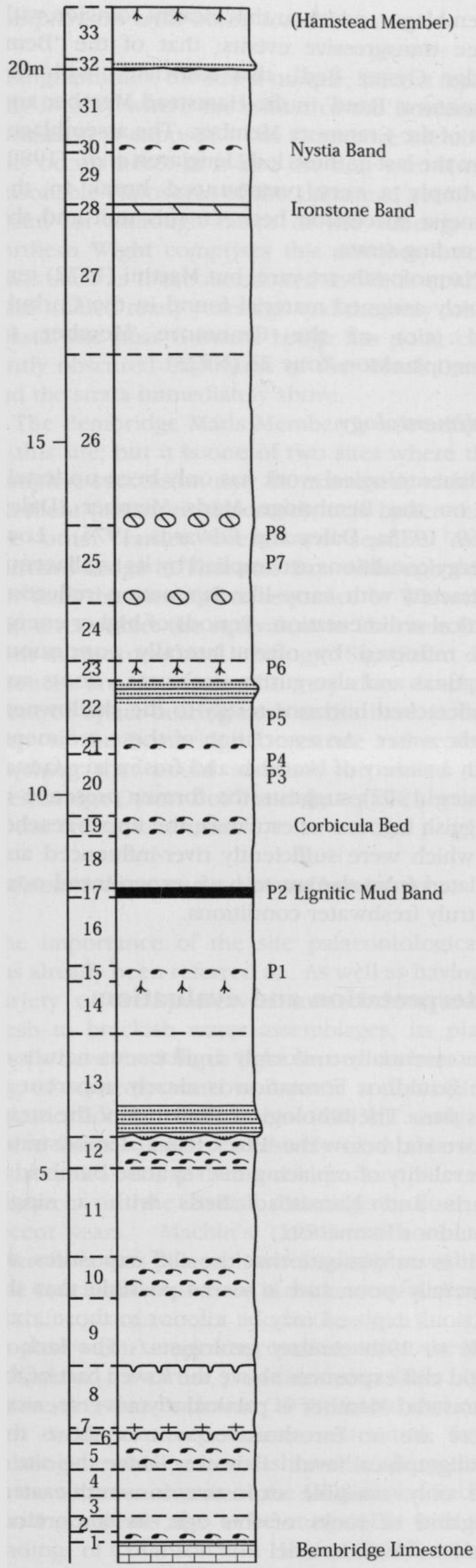

Figure 5.40 Bembridge Marls Member (Bouldnor Formation) succession at Hamstead Ledge, Isle of Wight (after Daley, 1973a), with 'plant beds' (P1 to P9) after Collinson (1983b).

sporangia, megaspores of the water fern *Azolla* and, less commonly, leaves. She also described one new genus and three new species from the locality (see also Collinson, 1980a). The fern sporangia, discussed in more detail elsewhere by Collinson (1978b) occur in all the plant-bearing horizons of the Bembridge Marls Member. They are assigned to the present-day genus *Acrostichum*, characteristic of modern mangrove floras, but extending into freshwater marshes.

At some levels in the Hamstead Member, coniferous leafy shoots and cones of *Sequoiadendron* and *Pinus* are quite abundant and some large logs are common (Collinson and Hooker, 1987). These genera are not part of the swamp flora and Chandler (1978) considered that they might have been derived from some distance. Their abundance does, however, suggest a more proximal hinterland (cf. Schneider, 1992, figs 2 and 3).

More recently, Collinson (1992, pp. 441–2) has discussed the fossil plant remains from this site in the context of floristic changes around the Eocene/Oligocene boundary in western and central Europe.

Vertebrate remains

A particularly significant feature of the Hamstead Member is the presence of vertebrate material, with the larger fossils found mostly not *in situ* but on the foreshore or in foreshore exposures of slumped material. As well as fish, crocodiles, turtles, frogs and lizards, a variety of mammalian fossils have been found. Amongst mammalian genera listed by Ford (1967) are *Entelodon* (pig-like animal), *Bothriodon* and *Brachyodus* (grazers), *Caenotherium* (small and deer-like) and a few carnivores, the largest being *Hyaenodon*. The presence of the insectivore *Butselia biveri* is referred to in Butler (1972). The rodent fauna has recently been described by Bosma (1974) whilst fossil birds found in the vicinity of Bouldnor Cliff were described by Harrison and Walker (1979). Hooker (1987, 1989) listed the mammalian fossils from this site and later dicussed them (Hooker, 1992) in a paper on palaeocommunities. Collinson (1992, fig. 22.1) indicated the position of two 'Mammal levels' (MP) of Brunet *et al.* (1987) in the succession: MP20 below the 'Black Band' and MP21 between the 'Nematura Band' and the 'White Band'.

Microfauna

Microfaunal studies of the site include research on the foraminifera of the Cranmore Member by Murray and Wright (1974) and the ostracods by Keen (1968, 1971, 1972a). The foraminiferal fauna, though mainly indicative of hyposaline conditions, suggests that open marine conditions existed at the time represented by the upper part of the 'Cerithium Beds'.

The Cranmore Member contains the youngest Palaeogene ostracod fauna in the British Isles. Ten species of polyhaline marine ostracod are present; eight are unique to this horizon, whilst one occurs in the Hamstead Member and another as low as the Bembridge Limestone (Keen, 1972a, p. 313). Ostracods are common at some horizons in the Bembridge Marls Member and thin, lensoid ostracod limestones have been found in one bed described by Daley (1969; see also Daley and Edwards, 1974, p. 286). Keen (1977) referred to low-salinity brackish ostracod faunas in the 'Bembridge Oyster Bed' at the base of the member but gave no detail of ostracod faunas from higher up the succession.

Microflora

Microfloral research on the Bouldnor and Hamstead section includes work on pollen and spores by Machin (1971) and on dinoflagellates by Costa and Downie (1976) and Liengjaren *et al.* (1980). Machin noted a significant, though not sudden, change coinciding with the Bembridge Marls/Hamstead boundary. Above this horizon, most of the forms increasing or coming in for the first time are more characteristically north temperate. Some subtropical genera, by contrast, disappear from the local flora, e.g. the palm *Thrinax*. Costa and Downie (1976), whilst referring to the presence of the dinoflagellate zone fossil *Wetzeliella gochtii* in the Cranmore Member, implied that the base of the zone may be lower in the succession, good dinoflagellate zone fossils being absent between this member and the considerably older Colwell Bay Member. In a more detailed paper, Liengjaren *et al.* (1980) described a number of assemblages, which at this locality coincide with three transgressive events: that of the 'Bembridge Oyster Bed', that associated with the *Nematura* 'Band' in the Hamstead Member and that of the Cranmore Member. The assemblages from the last of these led Liengjaren *et al.* (1980) to imply a very pronounced break in the dinocyst succession between this unit and the preceding strata.

Nannofossils are rare, but Martini (1972) tentatively assigned material found in the Corbula bed (sic) of the Cranmore Member to Nannoplankton Zone 23 (NP23).

Sedimentology

Sedimentological work has only been undertaken on the Bembridge Marls Member (Daley, 1969, 1973a; Daley and Edwards, 1974). Low-energy conditions are implied by its argillaceous character, with varve-like lamination reflecting vertical sedimentation. Periods of higher energy are reflected by often laterally continuous coquinas and also gutter structures. Roots and mudcracked horizons testify to the shallowness of the water. An association of these sediments with a variety of brackish and freshwater faunas (Daley, 1972) suggests the former presence of sluggish lagoons or estuaries, the upper reaches of which were sufficiently river-influenced and isolated from the sea to have experienced near- or truly freshwater conditions.

Interpretation and evaluation

The essentially uniformly argillaceous nature of the Bouldnor Formation is clearly apparent at this site. The lithological similarity of the strata above and below the 'Black Band' demonstrates the validity of replacing the separate Bembridge Marls and Hamstead Beds with a single Bouldnor Formation.

It is unfortunate that the cliff exposures are generally poor and it seems possible that the sections exposed may be inferior to those available to 19th century geologists. The lack of good cliff exposures above the lower part of the Hamstead Member is particularly adverse, since there are no foreshore exposures above this stratigraphical level. However, since the site is the only available exposure in south-eastern England of rocks of this age, its importance remains considerable.

Comparison with other localities

Stratigraphically, the site is unique, since it is the only locality where the whole of the Bouldnor Formation is exposed. The Cranmore Member only occurs here. It is also the only site where reasonable exposures of the Hamstead Member occur, for although much of the subcrop of northern Wight comprises this member, brick-yards such as those mentioned in White (1921) were infilled many years ago and the only other coastal site near Gurnard Ledge has poor, currently obscured exposures of the 'Black Band' and the strata immediately above.

The Bembridge Marls Member is not unique to this site, but it is one of two sites where the complete succession may be examined; with its excellent foreshore exposures, it is better than the other rather overgrown section near Gurnard Ledge in Thorness Bay. Although thinner than the incomplete sequence in Whitecliff Bay, it resembles the equivalent in Thorness Bay, both in thickness and lithology. Significant differences are, however, the very thin development of oyster-bearing rock at the base (a thin 'cap' to the Bembridge Limestone rather than anything that could seriously be called the 'Bembridge Oyster Bed') and that of the absence of the 'Insect Limestone'.

Palaeontology and palaeoclimatology

The importance of the site palaeontologically has already been referred to. As well as having a variety of well-preserved macroinvertebrate, fresh to brackish water assemblages, its plant fossils have shed much light on our understanding of contemporaneous aquatic and marginal aquatic floras. Collinson's (1983b) study of these floras, almost exclusively from this site, must rank as one of the most important pieces of research on the British Palaeogene flora in recent years. Machin's (1971) work on the microflora was palaeoclimatologically revealing. She concluded that there is evidence of a climatic shift towards cooler conditions than the subtropical/warm temperate conditions that she had postulated for earlier, post-Bartonian times. It is interesting that Buchardt (1978) found that oxygen isotope temperatures obtained from Palaeogene shell material showed a sharp drop at the commencement of the Oligocene. Such a cooling appears also to be compatible with the findings of Collinson and Hooker (1987). They concluded that by the beginning of Oligocene times, dense forests of tropical aspect had given way to a more open environment with only scattered trees, whilst Hamstead mammalian faunas show a decrease in arborescent forms and an increase in large ground mammals, especially herbivores with a high fibre diet!

Dating and correlation

Curry *et al.* (1978, table 2) gave an early to middle Oligocene age to the Bouldnor Formation. In fact, correlation with Oligocene strata in other areas of north-western Europe depends to a very considerable extent on material from this site, which was selected by Curry and Hailwood (1986) to typify the English succession spanning the Eocene/Oligocene boundary.

Such workers as Keen (1972a) have stressed the differences between the fossil assemblages of this formation and the older Palaeogene strata of the Hampshire Basin. From his work on the ostracods, Keen considered that this reflected the arrival of a new fauna heralding the Rupelian transgression, which was such a major event over much of north-western Europe (see also Sub-group Lithostratigraphy and Maps, 1980). With this in mind, he placed both the Hamstead and Cranmore Members in the so-called 'Sannoisian Facies' at the base of the Rupelian (Keen, 1971). Cavelier (1964) had earlier established a convincing case for correlating the 'Hamstead Beds' (Hamstead and Cranmore Members) with the Sannoisian of the Paris Basin, which he had placed at the base of the Oligocene. Keen (1972a) placed the Eocene/Oligocene boundary at this site 'somewhere' within the Bembridge Marls Member.

Martini's (1972) tentative assignment of the Cranmore Member to Nannoplankton Zone 23 (NP 23) was based on material from a weathered sample and more recent work indicates that the strata are probably somewhat older. Costa and Downie (1976) assigned this member to the *Wetzeliella gochtii* dinoflagellate Zone, which is also recorded from the Rupel Clay in Belgium.

From their work on dinoflagellates at this site, Liengjaren *et al.* (1980) correlated the Cranmore Member with the Calcaire de Sannois and the lower part of the Marnes à Huitres in the Paris Basin. Dinoflagellate assemblages characterizing the overlying Sables de Fontainbleau are, however, not present here. Liengjaren *et al.* (1980) found that the assemblages from the vicinity of the *Nematura* Band show marked similarities to those of the Argile Verte de Romainville at the base of the Stampian, which has been considered as the Eocene/Oligocene boundary. With this correlation as evidence, they have suggested that the base of the Oligiocene could conveniently be taken as the bottom of the Hamstead Member, some 9 m below the *Nematura* Band (but see Hooker (1992, p. 508) for further discussion and a suggestion that the boundary could be a significant distance below the Nematura Band).

Some attempt has also been made to use the mammalian fossils from lower down the succession for correlation purposes. The presence of *Bothriodon* and *Entelodon* has led to correlation with the Calcaire de Brie in the Paris Basin (Melville and Freshney, 1982), whilst Bosma (1974) suggested a close resemblance of the Hamstead Member mammalian fauna to that from the Horizon of Hoogbutsel in Belgium (base of Upper Tongrian in age) (see also Hooker, 1987).

Depositional environment and palaeogeographical context

The Bouldnor and Hamstead site completes the record of Palaeogene sedimentation in south-eastern England. The pattern of transgression and regression that characterized the whole of the Palaeogene succession is still apparent, although this site demonstrates that the uppermost part of the sequence is essentially non-marine in character. Conditions of deposition are quiet throughout, representing a sluggish fluvial/estuarine/lagoonal complex with salinities varying from brackish to freshwater. Fine sediments are ubiquitous, almost certainly indicating a total lack of local or hinterland tectonism and rejuvenation. Horizontal, sometimes graded laminae represent vertical accretion in essentially still water, whilst gutter structures and laminae with thin organic debris lags and sometimes parallel-orientated gastropod shells indicate periodic lateral water flow. Some of the more laterally extensive shell bands may represent storm events.

Sometimes the water was very shallow, as implied by the presence of desiccation cracks in the brackish water sediments in the lower part of the Bembridge Marls Member and the presence of in-situ rootlets, and in some cases larger roots, higher up the succession. Collinson (1983b) suggested that the plant-rich horizons were laid down in depths of 0.3 to 3.0 m. There is evidence from a variety of criteria that some areas were subaerially exposed. Collinson (1990) referred to the existence of 'tree islands' and the mammalian fauna of the Hamstead Member indicates a woodland/bushland habitat (Hooker, 1992). Possibly, the red-mottled horizons in the Hamstead Member originated in contemporaneous weathering.

Whilst there is evidence from a number of horizons that salinity fluctuated, there are three horizons in particular that represent some degree of transgression. Immediately above the base of the formation the shelly layer with oysters overlying the Bembridge Limestone is the distal (and relatively low salinity) expression of the 'Bembridge Oyster Bed' best seen in Whitecliff Bay. The second occurs at the level of the 'Nematura Band' where a restricted fauna indicates that salinities remained brackish. The third comprises the Cranmore Member at the top of the formation. A concensus, based on evidence from the molluscs, foraminiferids, ostracods and dinoflagellates is that this unit represents a time of fluctuating salinities but that conditions were sometimes fully marine. The 'Corbula Beds', in particular, contain a number of wholly marine elements and such workers as Liengjaren *et al.* (1980) believed that assemblages at this level represent the beginning of a major transgression.

Conclusions

Although the succession is incompletely exposed, the site is of international importance. It is unique, since it is the only locality at which the whole vertical extent of the Bouldnor Formation is exposed. It provides an opportunity to study environments transitional from brackish to freshwater, together with their sediments and associated fossils. A muddy succession throughout represents deposition in a sluggish fluvial/estuary/lagoonal complex occasionally subject to marine inundation (transgression). The site is valuable as a source of information on brackish to freshwater molluscan faunas. It has an important macroflora (particularly water plants) and a variety of vertebrate fossils, including mammals and birds, have been found. The site is uniquely important for correlating the British succession with that of continental Europe.

Ostracods, nannoplankton, dinoflagellates and mammals from the younger part of the formation have been used for this purpose. The upper part of the succession is certainly of Oligocene age, with the Eocene/Oligocene boundary within the formation, either within the Bembridge Marls Member or at the base of the overlying Hamstead Member.

THORNESS BAY AND GURNARD, ISLE OF WIGHT (SZ 436926–SZ 467953)

Highlights

This exposure of the Bouldnor Formation is especially well known for the Bembridge Insect Bed which not only provides the most important insect fauna in the British Palaeogene but is the main source of the 'Bembridge Flora'. It is one of two sites from which evidence for local intra-Palaeogene earth movements is derived.

Introduction

From Gurnard (grid reference SZ467953) south-westwards to beyond Burnt Wood (SZ 436926), intermittent cliff and foreshore exposures occur on both limbs of the shallow Thorness Bay Syncline. Strata from the Osborne Marls Member of the Headon Hill Formation to the 'Black Band' at the base of the Bouldnor Formation, occur here, although the most geologically significant sections are those in the Bembridge Limestone and the lower part of the Bembridge Marls Member. Poor (currently obscured) exposures of the 'Black Band' occur just south of Gurnard Ledge, whilst the uppermost part of the Headon Hill Formation is exposed south-westwards from Burnt Wood.

Thorness Bay, and especially the section near Gurnard Ledge, has attracted geologists since the middle of the 19th century and various aspects of the geology have been described in the *Memoirs of the Geological Survey* (Bristow *et al.*, 1889; White, 1921) and a number of other publications, including the recent comprehensive review by Daley (1999, pp. 55–60).

Much of the early interest was palaeontological, attention being especially focused on the so-called 'Insect Limestone' just above the base of the Bembridge Marls Member. A large collection of insect and plant fossils from this unit was made by a retired sailor, E.J. A'Court Smith. Subsequently, a detailed study of the plant macrofossils contributed in a major way to the description of the 'Bembridge Flora' by Reid and Chandler (1926). An early account of this 'bed'

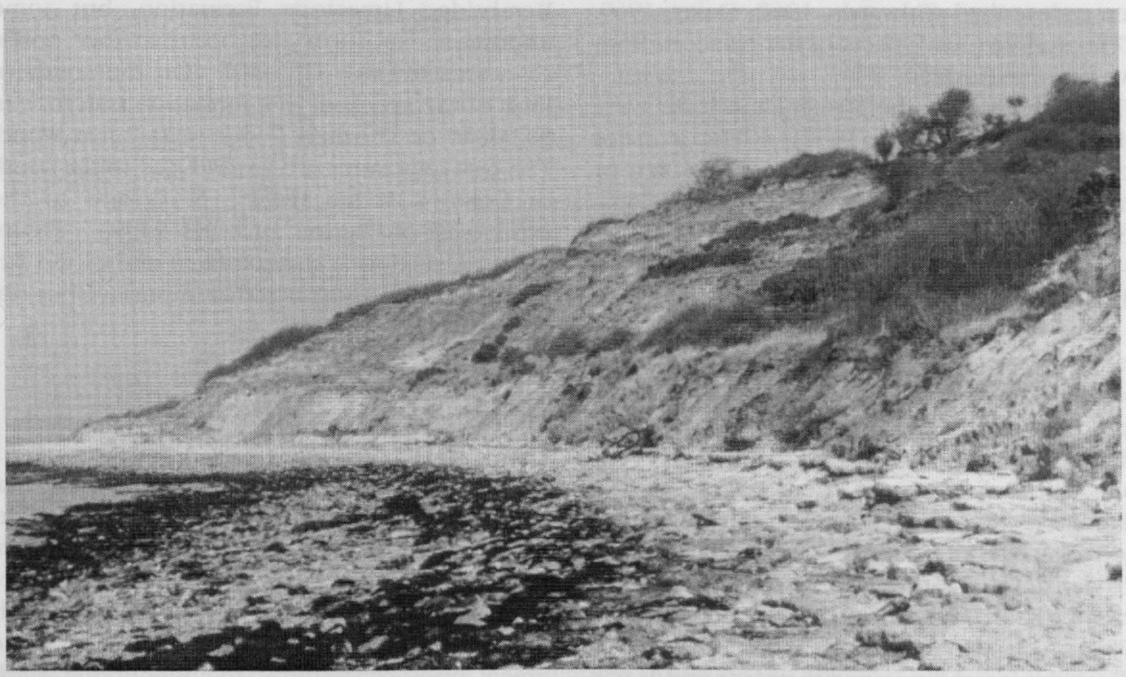

Figure 5.41 Gurnard Cliffs, Isle of Wight. General view from the south. The succession mainly comprises the Bembridge Marls Member which overlies the Bembridge Limestone, present at the base of the cliff (centre left) and on the foreshore (bottom right). (Photograph: B. Daley.)

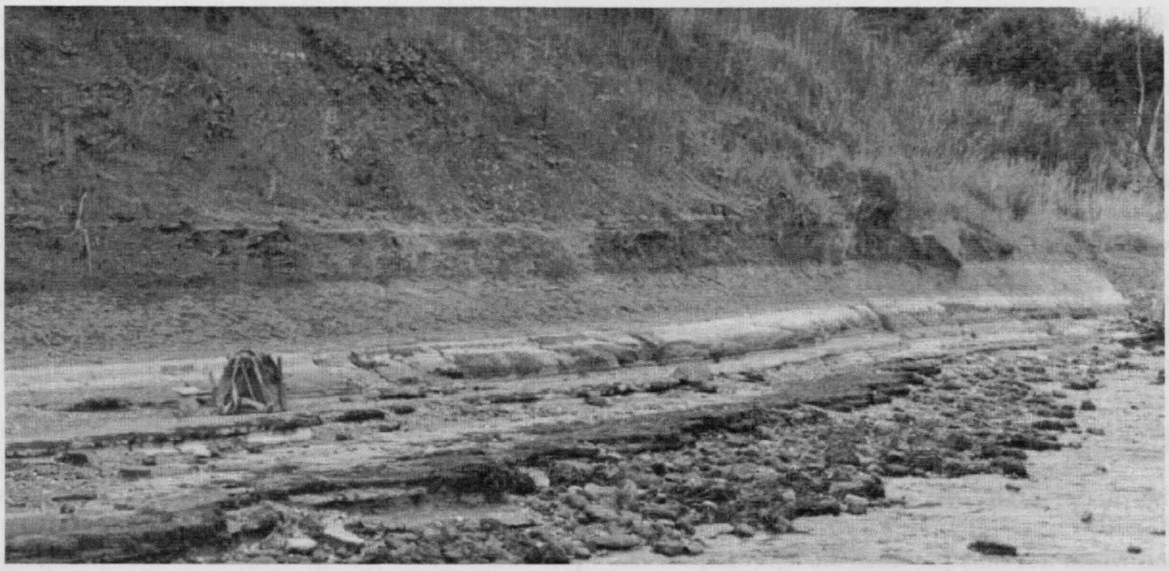

Figure 5.42 Thorness Bay, Isle of Wight. Middle part of the Bembridge Marls Member (Bouldnor Formation) below Thorness Wood. (Photograph: B. Daley.)

with particular reference to its isopods was given by Woodward (1879), although his account of the local succession (p. 343) is upside-down!

Recent years have seen a renewed interest in the geology of Thorness Bay. The succession has been redescribed (Edwards, 1967; Daley, 1969, 1973a) and various aspects of the palaeontology have been researched.

The isopods from the 'Insect Limestone' were redescribed by Martini (1972), whilst a major account of the insect fauna was undertaken by Jarzembowski (1980). Machin (1971) found that the 'Insect Limestone' was the richest microfloral horizon in the local Palaeogene succession, although work by Collinson (1978a) has indicated that plant macrofossils from it are now relatively uncommon. The macroinvertebrate fauna from the Bembridge Marls Member as a whole was described by Daley (1972b, 1973a).

Daley and Edwards (1971) used evidence from Thorness Bay to demonstrate intra-Palaeogene warping. Other references to Thorness Bay include Daley (1972c, 1974), Curry *et al.* (1972), Daley and Edwards (1974), Jarzembowski (1976) and Daley and Insole (1984, pp. 30–1).

Both the insect fauna and the plant fossils will be considered in more detail in separate GCR volumes.

Description

The site traverses the NW–SE trending Thorness Bay Syncline. The northern limit of Thorness Bay comprises Gurnard Ledge, formed from the Bembridge Limestone Formation, but some important exposures also occur further north-eastwards towards Gurnard. On the southern limb of the syncline, this formation outcrops in Saltmead or Thorness Ledge near Burnt Wood. The best exposures are around and to the south of Gurnard Ledge (Figure 5.41) and to the north-west of Pilgrims Park (SZ 449933; Figure 5.42). A section at the southern end of the bay to the west of Burnt Wood is important but not always well-exposed.

Lithological succession

The succession here (Figure 5.43) has a total thickness of less than 30 m. At Gurnard Ledge, the Bembridge Limestone (Figure 5.44) is 6.7 m thick and the Bembridge Marls Member (Figure 5.45) is 21.5 m thick. The succession mainly comprises fine-grained clastics. Black, grey and green muds characterize the Bembridge Marls Member, although marls occur in places, especially lower down the succession, and a very distinctive micritic limestone (the Insect Limestone) is present just above its base. At Gurnard, the Bembridge Limestone (Figure 5.44) is characterized by an upper and lower carbonate unit, comprising buff limestones and marls, separated by a muddy sequence 3.3 m thick. Ferruginous chert concretions occur in the uppermost limestone bed of the lower carbonate unit near Gurnard Ledge. The lithology of the upper unit varies laterally towards the south-west, in part as a result of contemporaneous erosion.

Bembridge Insect Bed

The prime focus of interest in the section has been in the so-called 'Insect Limestone', whose flora and fauna has been famous since the 19th century. The singular form 'Insect Limestone' is in reality a misnomer since, although a more or less *c.* 10 cm thick tabular limestone is often present, discontinuous concretionary limestones and hard marls also occur in places, all within a predominantly argillaceous unit (bed GUR IV of Daley (1973a) near Gurnard Ledge and bed BW IV near Burnt Wood). Recognition of this complexity led Jarzembowski (1980) to prefer the broader term 'Insect Bed' rather than 'Insect Limestone' but in a wider context, the term 'Bembridge Insect Bed' is probably preferable. Within the limestones of the 'Insect Bed', the preservation of extremely delicate biological structure is facilitated by exceptionally fine sediment grain size. Most of the fossils have come from exposures immediately south of Gurnard Ledge, although it is also exposed on the southern side of the Thorness Bay Syncline.

Macroflora

Most of the macrofossils from the 'Bembridge Flora' described by Reid and Chandler (1926) originate from the 'Insect Limestone'. The majority come from the collection of A'Court Smith, obtained from the section over a period of some twenty years (see Woodward, 1879, p. 344). Both Reid and Chandler (1926, p. 3) and more recently Collinson (1983b) have commented on the sparsity of in-situ remains. Amongst the genera described from the 'Insect

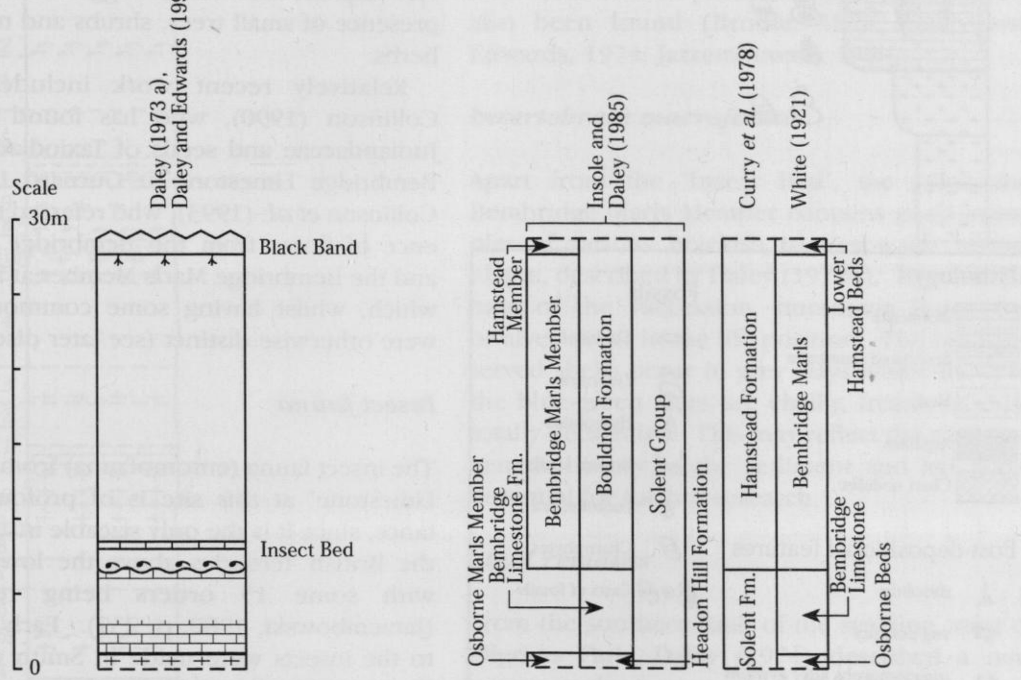

Figure 5.43 Lithostratigraphical succession of the Bembridge Limestone and Bouldnor Formation at the northern end of Thorness Bay and to the north of Gurnard Ledge, Isle of Wight (after Daley, 1973a; Daley and Edwards, 1990).

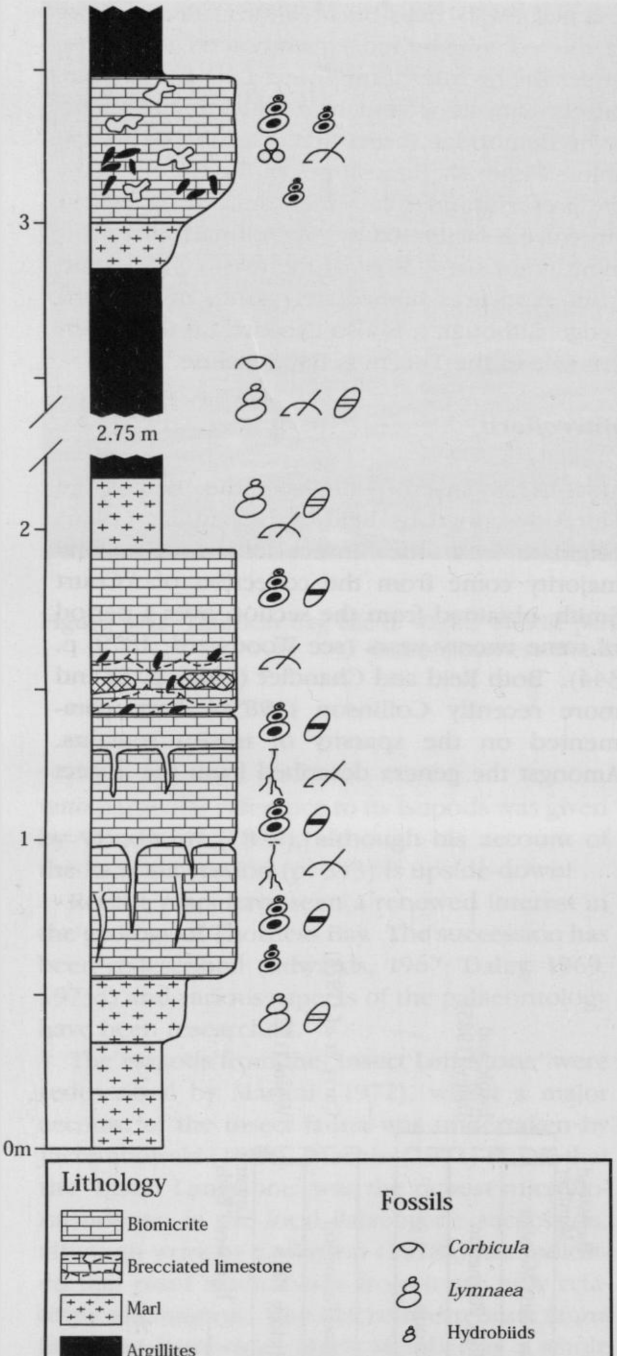

Figure 5.44 Bembridge Limestone succession at Gurnard, Isle of Wight (after Armenteros *et al.*, 1997).

Limestone' are *Engelhardtia*, *Hooleya*, *Typha*, *Ranunculus*, *Abelia* and *Clematis*. Fowler (1975) has made a special study of the fern *Azolla* from this unit.

The total 'Bembridge Flora' described by Reid and Chandler (1926) comprised 108 named species. Some of these came from higher up the Bembridge Marls Member, near Gurnard Ledge. A number (e.g. *Acrostichum, Araucarites, Equisetum* and *Dicotophyllum*) were preserved in ironstone nodules, which are mainly confined to beds with freshwater gastropods. Reid and Chandler (1926) also noted plants from a muddier unit within the Bembridge Limestone Formation. A revision of the Bembridge Flora was undertaken much later by Chandler (1963a) who also considered aspects of the macro- and microflora in a comprehensive review of the Lower Tertiary flora of southern England (Chandler, 1964).

According to Machin (1971), the 'Insect Limestone' in Thorness Bay possibly contains the richest microfossil assemblage of the local Palaeogene strata. Collinson and Hooker (1987) referred to the assemblage as mainly comprising wind-dispersed disseminules. They referred to the common occurrence of water plants such as *Typha* and *Potamogeton* but also were of the view that the assemblage suggested the localized presence of small trees, shrubs and non-aquatic herbs.

Relatively recent work includes that of Collinson (1990), who has found nutlets of Judlandaceae and seeds of Taxiodiaceae in the Bembridge Limestone at Gurnard Ledge, and Collinson *et al.* (1993), who referred to the presence of floras from the Bembridge Limestone and the Bembridge Marls Member at this locality which, whilst having some common features, were otherwise distinct (see later discussion).

Insect fauna

The insect fauna (entomofauna) from the 'Insect Limestone' at this site is of profound importance, since it is the only sizeable insect fauna in the British Tertiaries above the lower Eocene, with some 15 orders being represented (Jarzembowski, 1980, p. 239). Early references to the insects were made in Smith (1874) and Woodward (1878, 1879), whilst a number of authors studied various aspects of the fauna over a number of years prior to 1940 (see the selected resumé of previous work in Jarzembowski,

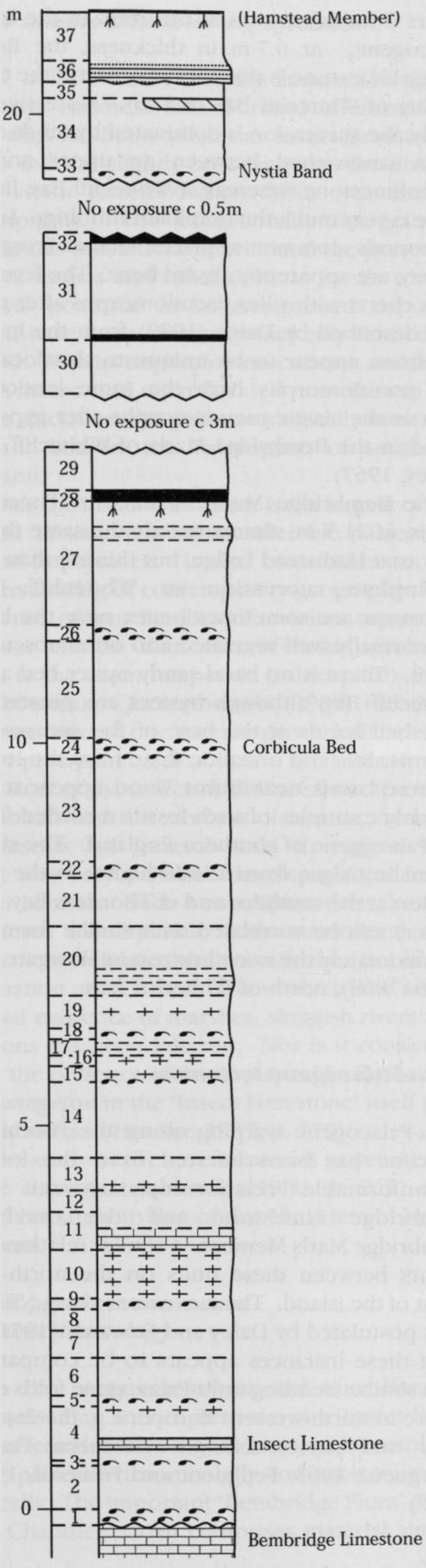

Figure 5.45 Bembridge Marls Member (Bouldnor Formation) succession at Gurnard Ledge, Isle of Wight (after Daley, 1973a).

1980, p. 240). A major contribution to our knowledge of this insect fauna has been made by Jarzembowski (1976, and, more importantly, 1980). As well as reviewing the history of study of the fauna, he describes a number of forms, including new genera and species. Of the insects he examined, 70% belong to the Hymenopera, Diptera and Coleoptera. The first two of these are especially common, with more than 120 species described from this fauna.

Other fossils from the 'Insect Bed'

Amongst other fossils found in the 'Insect Limestone' are an anostracan crustacean, *Branchipodites vectensis* (Woodward, 1879); an isopod crustacean, identified by Martini (1972) as *Eosphaeroma margarum*; a spider, *Eoatypus woodwardii* (McCook, 1888a,b); and an ostracod, *Potamocypris brodiei* (Jones and Sherborn, 1889) which Haskins (1968b) compared with the freshwater genus *Cypridopsis*. Molluscan shells present include the freshwater gastropod *Galba* and the brackish water bivalve *Polymesoda*. Rare portions of bird feathers have also been found (Brodie, 1878; Daley and Edwards, 1974; Jarzembowski, 1980).

Invertebrate macrofauna

Apart from the 'Insect Bed', the remaining Bembridge Marls Member contains good examples of various brackish to freshwater assemblages, described by Daley (1972b). Towards the base of the succession, numerous burrowing bivalves occur in the life position. The best-preserved shells occur in grey clays whilst those in the blue-green clays are chalky, friable or even totally decalcified. This may reflect the early diagenetic history of the sediment and has some potential for further research.

Algal remains

From the southern limb of the syncline, west of Pilgrims Park, Daley (1974) described a new genus and species of shell-encrusting alga, *Epivalvia edwardsii*, from the lower part of the Bembridge Marls Formation (bed THOR III; see Daley, 1973a). Further westwards, as yet undescribed, small stromatolitic/oncolitic algae are well-preserved in the bottom bed of the Bembridge Marls Formation (bed BW I of Daley, 1973a).

Sedimentology

Whilst the stratigraphy of both the Bembridge Marls Member (Daley, 1973a) and the Bembridge Limestone (Daley and Edwards, 1990) of the site is fully documented, relatively little has been published on their sedimentology. The various sections do, however, provide an excellent opportunity to study sedimentation in a sluggish regressive brackish to freshwater environment (see Daley, 1969).

Of work published, Daley (1972c) has described small-scale deformation structures from the 'Insect Limestone', whilst more recently, silica pseudomorphs after microlenticular gypsum have been found in cherts in the Bembridge Limestone to the north-east of Gurnard Ledge (Daley, 1989). The original gypsum crystals are considered to have been pedogenic in origin. Their occurrence provides evidence for a reappraisal of the climate of southern Britain in Palaeogene times.

Intra-Palaeogene tectonism

The tectonic structure of Thorness Bay is superficially simple. Daley and Edwards (1971), however, made a detailed study of the relationship of the Bembridge Limestone Formation and the overlying Bembridge Marls Member following the earlier recognition by Bristow *et al.* (1889) that they were separated by an erosional surface. This study proved an unconformable relationship and demonstrated the occurrence of previously unrecognized intra-Palaeogene folding.

Interpretation and evaluation

Although Thorness Bay contains strata of limited stratigraphical range, from the top of the Headon Hill Formation to the base of the Hamstead Member (Bouldnor Formation), it is one of the most significant of Palaeogene localities, both palaeontologically and palaeoenvironmentally.

Comparison with other localities

Stratigraphically, the Thorness Bay succession differs from other sites at this level in the local Palaeogene. At 6.7 m in thickness, the Bembridge Limestone is thinner here than at the type locality of Whitecliff Bay (8.5 m). More significantly, the succession is dominated by muds and marls sandwiched between an upper and a lower limestone, whereas at Whitecliff Bay, limestone is very much the dominant lithology. Land gastropods, common at places such as Prospect Quarry, are apparently absent here. The ferruginous cherts with silica pseudomorphs after gypsum described by Daley (1989) from the lower limestone appear to be unique to this locality. The pseudomorphs have the same lenticular form as the clastic pseudomorphs after gypsum found in the Bembridge Marls of Whitecliff Bay (Daley, 1967).

The Bembridge Marls Member in Thorness Bay is, at 21.5 m, almost exactly the same thickness as at Hamstead Ledge, but thinner than the incomplete succession in Whitecliff Bay. Exposures are sometimes better near the base but normally well-vegetated and often obscured above. There is no basal sandy oyster bed as at Whitecliff Bay, although oysters are present in two shell bands at the base of the succession. Stromatolitic and oncolitic algae from the lower of these bands near Burnt Wood appear to be the only examples of such fossils recorded from the Palaeogene of southern England. The shell-encrusting algae from a little higher in the succession at the southern end of Thorness Bay (see earlier) can be correlated with similar forms at approximately the same horizon in Howgate Bay (SZ 647868), north of Whitecliff Bay.

Intra-Palaeogene tectonism

Intra-Palaeogene warping along the Porchfield Anticline has been inferred from the locally unconformable relationship between the Bembridge Limestone and the overlying Bembridge Marls Member. A similar relationship occurs between these units on the north-east coast of the island. The movement along NW–SE axes postulated by Daley and Edwards (1971) in both these instances appears to be compatible with similar trending intra-Palaeogene folds elsewhere in north-western Europe, e.g. the Pays de Bray and Artois axes in northern France (Feugueur, 1963; Feugueur and Pomerol, 1963, 1968).

Fossil insects and their significance

There is little doubt that the fame and importance of Thorness and Gurnard is associated with what has been called the 'Insect Limestone' or, to use the slightly broader term, the 'Insect Bed' *sensu* Jarzembowski (1980) (see earlier description). The exceptionally fine-grained limestones present have facilitated the preservation of insects and other delicate fossils whose survival potential in coarser-grained deposits would have been, at most, markedly limited, if not nil. With its important insect fauna and flora (both macro- and microflora), it may claim to be, for its thickness, the palaeontologically most significant bed in the Palaeogene of southern England.

Since the insect fauna here is the largest of the British Tertiary, it is of considerable palaeontological importance. It also contributes to our understanding of contemporary geography. The presence of four families of termites suggests a warmer climate than that of today, probably close to the warm temperate (subtropical)–tropical boundary. Jarzembowski (1980) mentions the presence of one termite genus indicative of lower precipitation than that of modern rain forest. Most of the insects found are from terrestrial habitats and the rareness of aquatic, freshwater insects led Jarzembowski to suggest that there was only a limited development of freshwater habitats. Such a conclusion does, however, seem incompatible with macrofloral and macroinvertebrate studies of the Bouldnor Formation as a whole from which the widespread existence of marshes, sluggish rivers and lagoons has been inferred. Nor is it consistent with the presence of water plants like *Typha* and *Potamogeton* in the 'Insect Limestone' itself (see Collinson and Hooker, 1987, p. 270).

The study of the insect fauna is as yet incomplete since Jarzembowski (1980, p. 240) confined his study to five of the 15 orders of insect present.

Fossil plant remains and palaeoclimatology

Both the plant macroflora and microflora of Thorness Bay, and in particular the 'Insect Bed', are of considerable significance, palaeontologically, palaeoenvironmentally and palaeoclimatologically. The important 'Bembridge Flora' (Reid and Chandler, 1926) comprises material almost exclusively from Thorness Bay and most of this is from the 'Insect Bed', also the richest microfloral source in the local Palaeogene (Machin, 1971). Consequently, the site makes a major contribution, regarding aspects of palaeogeography in which plants provide some degree of explanation.

In considering its significance, Chandler (1964) had no doubt that the Bembridge Flora was tropical in nature, although Reid and Chandler (1926, p. 26) had earlier suggested that it represented warm temperate and subtropical regions. Machin's (1971) interpretation was that the climate was subtropical, perhaps like that of Florida today (i.e. warm temperate eastern margin). The presence in the flora of temperate genera led Chandler (1964) to suggest a derivation from mountains where, at higher altitudes, the temperature would have been cooler. Unfortunately, other geological evidence does not support the existence of contemporary mountains (Daley, 1972a). Recent palaeopedological work, including that of Daley (1989) on the Bembridge Limestone at this site, supports the idea that there were dry climatic periods rather than persistent humid tropical or subtropical conditions as had hitherto been supposed. Recent work by Hooker (1994) on mammalian faunas from the Bembridge Limestone adds some support to this view. The presence of pedogenic gypsum in this formation at this site fits in well with the suggested correlation of the Bembridge Limestone with the Gypse of the Paris Basin (Curry *et al.*, 1978, table 2), the existence of which only 2–3° of latitude further south must indicate a prolonged deficit in precipitation (Daley, 1972a).

Depositional environment

Palaeoenvironmentally, exposures of Bembridge Limestone in Thorness Bay indicate more 'offshore' deposition than that of the land gastropod-rich lithologies at Prospect Quarry, whose pedogenic alteration suggests a more palustrine (lake-margin) situation. The muds with brackish water fossils indicate the proximity of the sea, perhaps more so than at Whitecliff Bay where the argillaceous unit is much thinner. It may be that the lateral interstitial transportation of water from such marine areas provided the saline pore water which on evaporation led to the formation of the microlenticular gypsum referred to above (Armenteros *et al.*, 1997).

As at other localities where the Bembridge Marls Member is present, the Thorness Bay section and particularly its molluscan fauna, illustrates the essentially regressive circumstances under which the unit was deposited. The variety of molluscan associations, particularly lower down the succession, mainly reflect salinity variations, whilst the conformable succession of faunal associations supports the view that deposition was essentially in a sluggish estuary or lagoon (cf. Collinson, 1983b, p. 205) whose salinity varied with the fluctuating influence of the sea. The lower part of the succession indicates that conditions were essentially brackish although where shell-encrusting algae occur, there is the possibility that periodically conditions may have been hypersaline.

Remarkably, very thin beds, characterized by a particular fauna, can be recognized at localities many kilometres apart. By way of example, the thin *Serpulid*-rich unit present here (Daley, 1973a, bed GUR IX, fig. 4) is traceable wherever the lower part of the member is visible, including in Howgate Bay north of Whitecliff Bay. Such cases appear to indicate how rapidly (geologically) circumstances could change over a wide area.

The generally quiescent environment under which the member accumulated is well illustrated by the Thorness Bay succession. Some coquinas, including convex-upward bivalve concentrates, clearly indicate water movement, but shallow-burrowing bivalves in life position and varve-like laminations indicate that for long periods the sediments lay undisturbed. Mud cracks and pyrite 'pins', representing rooted herbaceous vegetation, indicate shallow water, whilst locally there were probably small 'tree islands' with small trees, shrubs and non-aquatic herbs (Collinson and Hooker, 1987, p. 270).

In a more recent paper Collinson *et al.* (1993) concluded that the Bembridge Limestone flora indicated the presence of ponds or lakes with a limited catchment area in comparatively dry surroundings, with warm, clear, calcareous waters including areas of open water and others with emergent vegetation. Collinson *et al.* (1993) considered that the Bembridge Marls Member represented an extensive and persistent marshland with some fluvial influence and some open waters. Mammalian faunas found by these authors indicate the presence of wooded habitats sufficiently close to allow the accumulation of mammal remains but evidence of woodland is hardly evident in the Bembridge Limestone flora and only partly represented by the pollen flora of the Bembridge Marls Member.

Conclusions

Although restricted in its stratigraphical range, Thorness Bay and Gurnard comprises an important site from a number of geological standpoints. It represents brackish and freshwater facies together with a variety of well-preserved molluscan assemblages. It is one of the two sites on the Isle of Wight providing evidence of intra-Palaeogene earth movement.

Its most important component unit is the 'Insect Bed' which is particularly significant both palaeontologically and palaeoclimatologically. This unit contains not only probably the most important insect fauna in the British Palaeogene but is the main source of the 'Bembridge Flora'. For its thickness, there is little doubt that palaeontologically it is one of the richest units in the British Tertiary succession.

From a palaeoclimatological standpoint, evidence from this site indicates that the view that the 'Bembridge Flora' represents a sample of an essentially humid tropical flora can no longer be maintained. It seems that the climate was somewhat less tropical than the London Clay and other earlier Palaeogene floras, perhaps representing subtropical or warm temperate conditions. Mineralogical evidence suggests that from time to time the climate might have been more arid in character.