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THE SEDIMENTOLOGY, PETROLOGY AND STRATIGRAPHY OF THE UPPER GREENSAND IN S.W. ENGLAND

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University of Plymouth

THE SEDIMENTOLOGY, PETROLOGY AND STRATIGRAPHY OF THE UPPER GREENSAND IN S.W. ENGLAND

COLIN L. WILLIAMS

Thesis submitted to the Council for National Academic Awards in partial fulfilment of the requirements for the Degree of Doctor of Philosophy.

POLYTECHNIC SOUTH WEST MAY, 1991

DECLARATION

This is to certify that this work submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy under the title "The Sedimentology, Petrology and Stratigraphy of the Upper Greensand in S.W. England" is the result of original work.

All authors and works consulted are fully acknowledged. No part of the work has been accepted in substance for any other degree and is not being concurrently submitted in candidature for any other degree.

CANDIDATE

COLIN L. WILLIAMS

RESEARCH SUPERVISOR

PROF. M.B. HART

DECLARATION

During the course of this research five papers have either been published, or are in press, on the results obtained.

1. Schroeder, R., Simmons, M.D., Hart, M.B. and Williams, C.L. (1986). A Note on the Occurrence of *Orbitolina (Orbitolina) sefini* Henson, 1948 (Foraminiferida) in the Upper Greensand of S.W. England. **Cretaceous Research, 7,** 381-387.

2. Williams, C.L. (1986). The cherts of the Upper Greensand (Cretaceous) of south-east Devon. **IN** Sieveking, G. de G. and Hart, M.B. (eds). The Scientific Study of Flints and Cherts. **Cambridge University Press,** 63-70.

3. Williams, C.L., Hart, M.B. and Leary, P. (1988). Foraminifera and correlation of the Upper Greensand, Branscombe, south-east Devon. **Proceedings of the Ussher Society, 7,** 97-99.

4. Simmons, M.D. and Williams, C.L. (in press) Cretaceous Orbitolinidae (Foraminifera) from Onshore and Offshore South-West England. **Journal of Micropalaeontology.**

5. Simmons, M.D., Williams, C.L. and Hart, M.B. (in press). Sea-level changes across the Albian-Cenomanian boundary in south-west England. **Proceedings of the Ussher Society.**

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ABSTRACT

The Sedimentology, Petrology and Stratigraphy of the Upper Greensand in S.W. England - Colin L. Williams.

A new lithostratigraphic scheme is proposed for those deposits formerly known as the Upper Greensand. In the south and south-west of England the proposed Selborne Group is made up of the proposed Wessex Greensand Formation and Gault Clay Formation as well as the existing Haldon Sands Formation. Four members are proposed and type sections are designated.

Lithological logs are presented for sections at Branscombe/Beer Head (Type Section for the Foxmould Sands Member and the Chert Beds Member); Kempstone Rocks, Dunscombe, S.E. Devon (Type Section for the Top Sandstones Member); Whitecliff, Seaton, S.E. Devon; and a small quarry at Dunscombe, S.E. Devon. The sediments found in these sections are divided up into 15 facies. Each facies is described in detail including local variations and associations with other facies. An environmental interpretation is suggested for each facies and it is suggested that the upper part of the Wessex Greensand Formation represents a shallowing upwards sequence which was strongly tidal and storm influenced.

A series of events leading to the formation of chert within the Chert Beds Member is proposed. The gradual replacement of calcite and glauconite combined with void-fill chalcedony and microquartz rim cements are shown to result in a ghost fabric.

A new ammonite occurrence is reported from the Foxmould Sands Member at Branscombe. Identified as *Prohystoceras (Goodhallites) delabechei* it suggests a varicosum Subzone age for the lower part of the Foxmould Sands Member.

23 genera and 32 species of Foraminifera are described. The smaller Foraminifera suggest that the upper part of the Foxmould Sands Member may be as young as dispar Zone but do not allow any further refinement of the age of the Chert Beds Member.

An in depth examination of the occurrence of the large benthonic Foraminiferan *Orbitolina* in S.W. England allowed the identification of members of the *Orbitolina sefini* - *O. concava* plexus. These foraminifera are used to refine the age and correlation of the Selborne Group in S.W. England. 'Orbitolina' occurrences from Wilmington are shown to belong to the sponge genus *Porosphaera.*

The occurrence of both *O. sefini* and *O.*sp. cf. *concava* in S.W. England has allowed the proposal of a colonisation pathway for the Orbitolines from the Iberian Peninsular via the S.W. Approaches to S.W. England rather than by way of the Paris Basin.

Using the techniques of sequence stratigraphy a basin history is presented for S.W. England during Albian/Cenomanian times. A sea-level curve is presented and compared with existing curves.

CHAPTER 1 INTRODUCTION

1.1 Aims and Scope

The mid-Cretaceous Upper Greensand of southwest England has been a subject of interest to geologists since the pioneering days of British geology at the begining of the 19th Century. Its fossil fauna, age, sedimentology, diagenesis and its correlation to other mid-Cretaceous sediments in northwest Europe have been the subject of scientific discussion over the last 200 years or so.

However, despite the interest, the Upper Greensand has been relatively neglected in comparison to the overlying Chalk and Cenomanian Limestone, and the underlying Lower Greensand and Wealden sediments. These units have been the subject of lithostratigraphic revision, intense microfaunal and macrofaunal study, and perhaps most notably, detailed diagenetic and sedimentological analyses using modern techniques of facies analysis and modelling. This study attempts to redress the balance by providing:

(i) A revision of lithostratigraphic nomenclature, dividing the Upper Greensand into correlatable formations and members which are formally defined using stratotypes.

(ii) A detailed sedimentological study in order to determine the environments of deposition.

(iii) A study of the diagenetic processes operating within the Upper Greensand, particularly those leading to the formation of chert nodules.

(iv) A review of the biostratigraphy of the Upper Greensand, focusing on the foraminiferal fauna recovered during the course of this study, and the implications for biostratigraphic correlation.

(v) A preliminary attempt at using the conclusions from all the above studies in a modern sequence stratigraphy context. The wider implications of the stratigraphy of the Upper Greensand are considered with reference to eustatic changes in sea-level and Albian -Cenomanian basin history in northwest Europe.

The individual aims of this project listed above are each detailed in subsequent chapters, following a more general introduction in this first chapter.

This study can only be considered as a preliminary review of Upper Greensand sedimentology and stratigraphy. Not least, there is still much work to be done on the Upper Greensand and its equivalents in other parts of southern England.

1.2 General Introduction

The area of study comprises the outcrops of Upper Greensand in southwest England (see Fig. 1.1). This effectively includes the southeast part of Devon and the extreme southwest part of Dorset. The general geology of this area is documented in a number of publications, notably Edmonds *et al.* (1975) and Durrance and Laming (1982).

It can be seen from Figure 1.1 that in the study area, the Upper Greensand rests unconformably on Devonian, Carboniferous, Permian and

GEOLOGICAL MAP OF SOUTHEAST DEVON

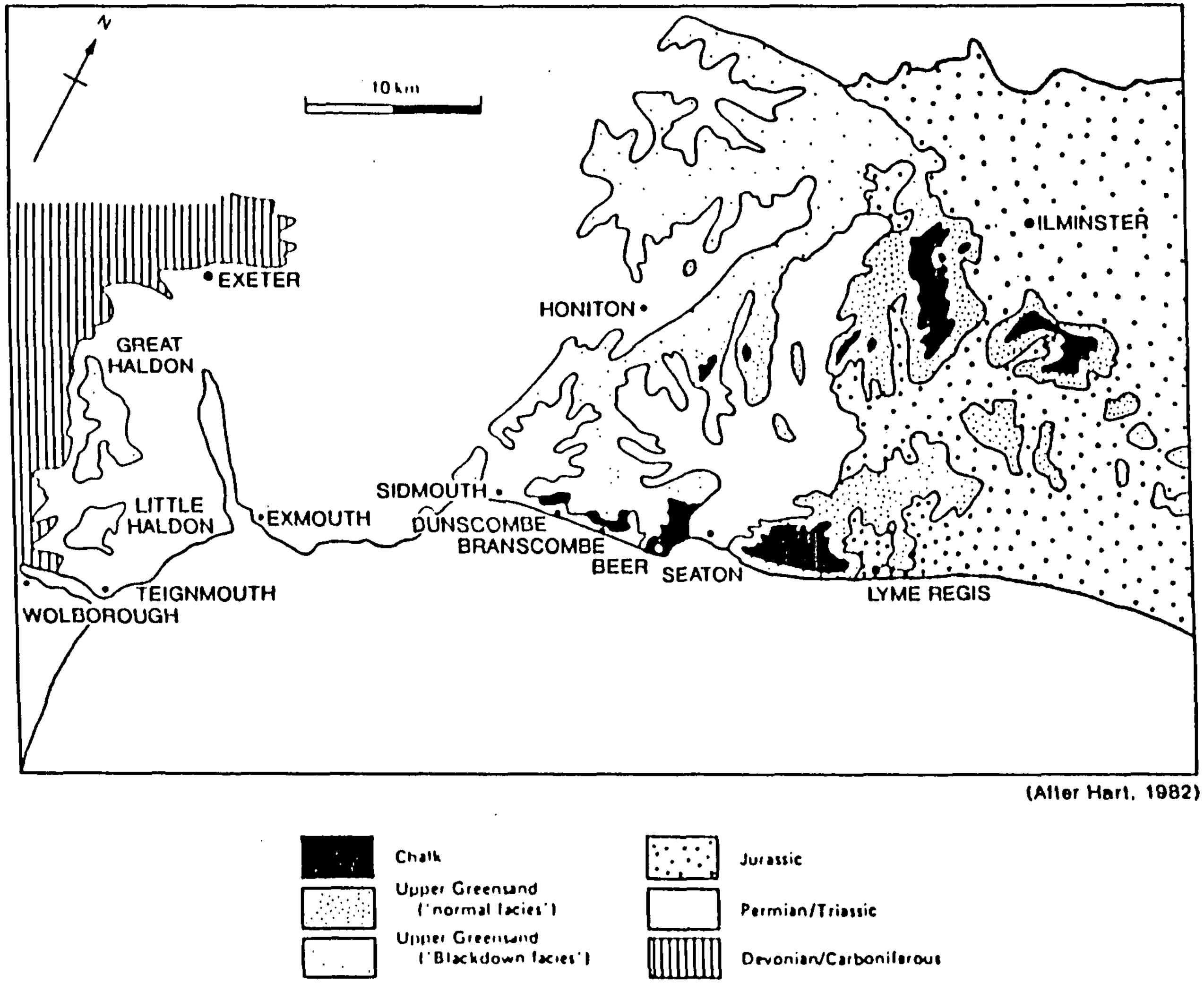


Figure 1.1

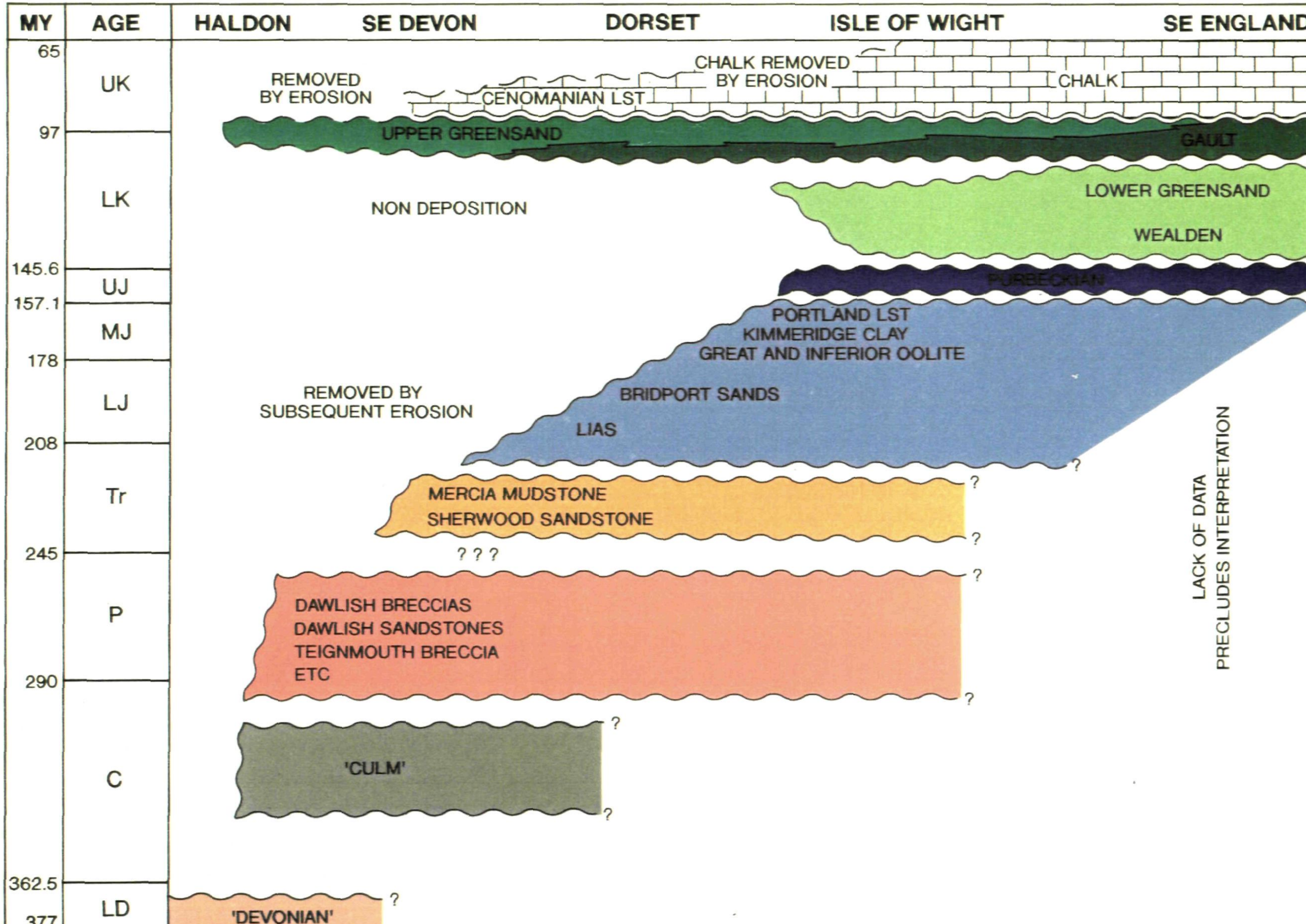
Triassic sediments. In an easterly direction from the study area, the Upper Greensand overlies progressively younger rocks; the result of pre mid-Cretaceous uplift, tilting and erosion. This relationship can clearly be seen in Figure 1.2 a chronostratigraphic summary chart for the Wessex Basin.

Figure 1.2 shows that the Upper Greensand both overlies and is the lateral equivalent of the Gault Clay. The boundary between these two units is diachronous (cf. Rawson *et al.*, 1978). The Gault Clay - Upper Greensand couplet has been regarded as a major transgressive - regressive cycle (sequence) following restricted sedimentation in the Early Cretaceous over southern England (eg. Rawson *et al.*, 1978; Anderton *et al.*, 1979; Hancock, 1989). The overlying Cenomanian Limestone and equivalents is transgressive (Garrison *et al.*, 1987). These relationships are more fully discussed in Chapter 6.

The term "Upper Greensand" has come to be accepted as referring to the glauconitic sands, silts, calcarenites, limestones and cherts lying immeadiately beneath the Late Cretaceous Chalk. It's age is largely Late Albian. In the study area extension into the Early Cenomanian has been proposed by some (eg. Hart, 1971, 1973b; Carter and Hart, 1977) but refuted by others (eg. Hamblin and Wood, 1976). This is more fully discussed in subsequent chapters. Certainly Early Cenomanian Upper Greensand in the form of the Eggardon Grit occurs in the east of the study area (Kennedy, 1970).

The term 'Greensand' probably originated with William Smith, between the years 1800 and 1812, to describe the sands which were found between the Chalk and the Gault Clay. Although Smiths' earliest 'Table

SIMPLIFIED CHRONOSTRATIGRAPHY SUMMARY CHART FOR WESSEX BASIN / SOUTHERN ENGLAND



Does not include all non-occurrance due to Tertiary-Recent erosion

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LEGEND TO PALAEOGEOGRAPHIC, ISOPACH AND TECTONIC MAPS AND TO STRATIGRAPHIC CORRELATION CHARTS

LITHOLOGICAL SYMBOLS

- Sand and conglomerate
- Sand
- Sand and shale
- Carbonate and sand
- Carbonate
- Carbonate and shale
- Shale, some carbonate
- Shale
- Organic shale
- Halite
- Sulphate
- Oolitic iron ore
- Coal
- Volcanics
- Instrusives

DEPOSITIONAL ENVIRONMENTS

- Areas of non-deposition
- Uninterpreted areas
- Continental, lacustrine
- Deltaic, coastal and shallow-marine clastics
- Shallow-marine shale
- Deeper-marine shale
- Deeper-marine clastics
- Carbonates, mainly shallow-marine
- Evaporites

TECTONIC SYMBOLS

- Normal fault
- Transcurrent fault
- Steep reverse and thrust faults, active deformation front of fold belt
- Fold axis
- Continental slope
- Sea mount
- Sea floor spreading axis
- Caledonian deformation front
- Position of future Variscan deformation front
- Position of future Alpine deformation front
- Approx. boundary between Penninic and Austro-Alpine domains

SPECIAL SYMBOLS ON PALAEOGEOGRAPHIC MAPS

- Direction of clastic influx
- Direction of marine incursion
- Direction of intra-basinal clastic transport
- ------ Erosional edge of map interval
- 300 Thickness of map interval in metres

STRATIGRAPHIC CORRELATION CHARTS

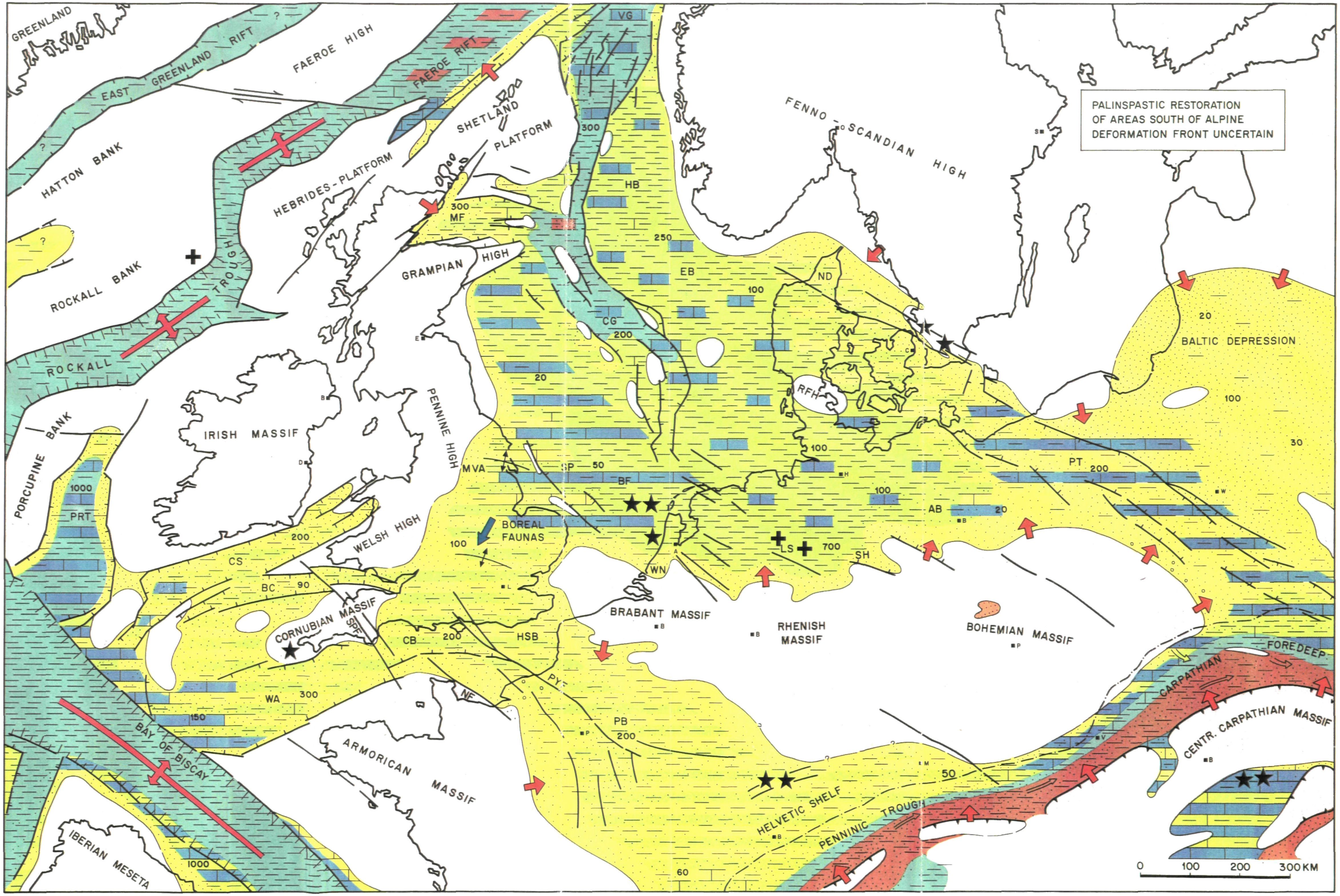
- Low angle unconformity
- High angle unconformity
- Erosional hiatus
- R Rift induced
- W Wrench induced
- i Inversion
- F Folding, thrusting
- U Regional uplift
- —||— Tuffaceous series

ISOPACH MAPS

Colour scale for increasing thickness of map interval; contour interval specified on each map

- Thickness of map interval unknown or only locally known
- Map interval eroded
- ------ Erosional edge of map interval

ENCL. 39.



ENCL. 22. APTIAN-ALBIAN PALAEOGEOGRAPHY. (Main sources: Czerminski and Pajchlowa, 1975; Diener, 1967; Gwinner, 1971; Mégnien, 1980; Schott, 1967; Slaczka, 1976). (from Ziegler, 1982)

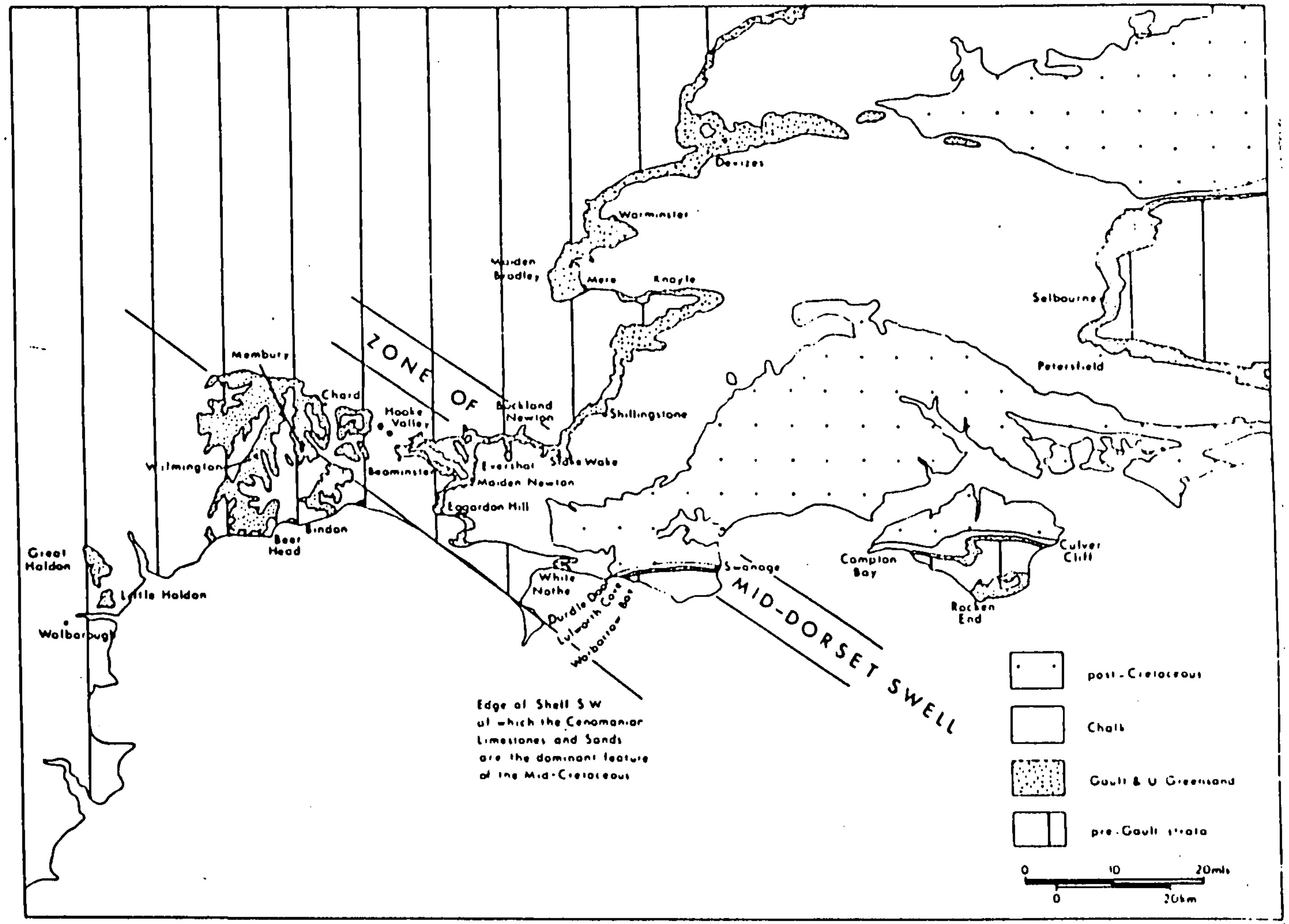
of Strata' (1799) referred to these beds as 'Sand', his close friend the Rev. J. Townsend, published a book in 1813 in which they were called 'Greensand'.

Unfortunately this clear beginning became confused by a series of errors and compromises (see Chapter 2 for details). By the 1820's the term 'Greensand' was being freely used to describe the sands both above and below the Gault Clay. In an attempt to end this confusion Fitton (1824) published a letter proposing the use of the terms 'Upper Greensand' and 'Lower Greensand' for the sands above and below the Gault Clay respectively.

Fitton's recommendations were eventually adopted by the Geological Survey in 1839. The term "Upper Greensand" has been in common use since that time. However, it lacks a modern formal definition, and recommendations are made in Chapter 2 to use the precisely typified term "Wessex Greensand Formation" in the study area. The Upper Greensand is found over much of southern England in surface exposures and the subsurface, with its outcrop pattern being controlled by Tertiary and Quarternary erosion (Figure 1.3). A large number of local and commercial names have been used to describe local lithological variations (Figure 1.4).

The thickness of the Upper Greensand varies across southern England (Figure 1.5). Some 54m of Greensand and Malmstone occur in Wiltshire (Fitton, 1836; Jukes-Browne and Hill, 1900). In Berkshire the Malmstone becomes thicker (Hinde, 1885; Jukes-Browne, 1889) but when traced through Oxfordshire and Buckinghamshire the Upper Greensand gradually thins out and disappears (Jukes-Browne and Hill, 1900). In

OUTCROP PATTERN OF THE UPPER GREENSAND AND COEVAL GAULT IN SOUTHERN ENGLAND



(After Carter and Hart, 1977)

Figure 1.3

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MALM ROCK OR MALM OR MALMSTONE	SILICEOUS EQUIVALENT OF UPPER GREENSAND IN HAMPSHIRE, SUSSEX AND BERKSHIRE
FREESTONE	QUARRYMAN'S TERM: USED FOR EASILY QUARRIED ROCK
FIRESTONE	TERM USED AS EQUIVALENT TO UPPER GREENSAND IN S. AND S.E. ENGLAND
TOP SANDSTONES CHERT BEDS FOXMOULD	BASIC SUCCESSION IN S.W. ENGLAND
COWSTONES	BASAL UNIT OF UPPER GREENSAND IN S. DORSET
PASSAGE BEDS	SERIES OF BEDS BETWEEN GAULT CLAY AND UPPER GREENSAND ON THE ISLE OF WIGHT

FIG. 1.4: SOME EXAMPLES OF LOCAL AND COMMERCIAL NOMENCLATURE USED FOR THE UPPER GREENSAND.

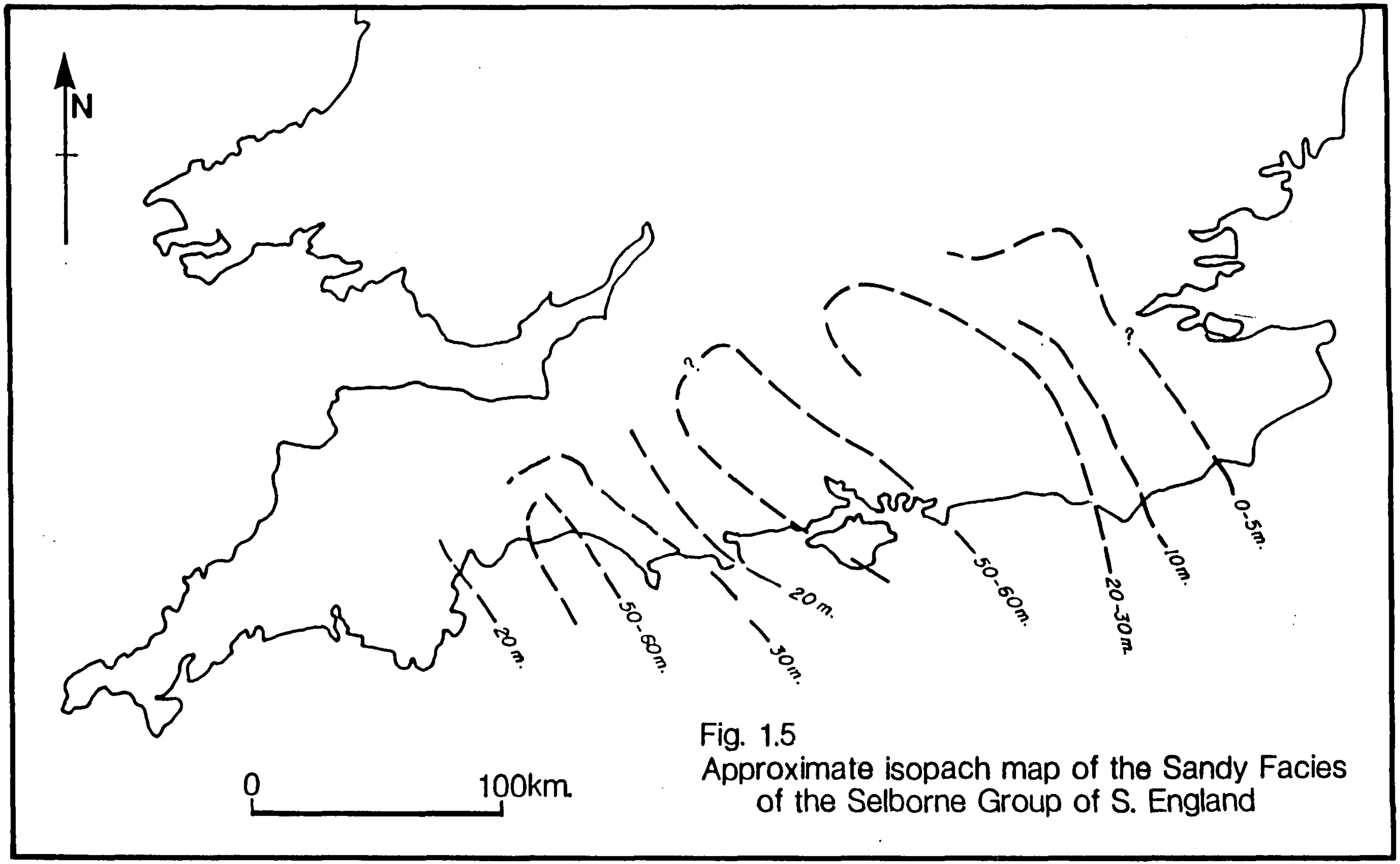


Fig. 1.5
Approximate isopach map of the Sandy Facies of the Selborne Group of S. England

Hertfordshire only 2m of greenish silt represents the Upper Greensand (Jukes-Browne and Hill, 1900).

In the area of the Weald, although natural exposures are relatively rare, a great lithological variety occurs. Three broad rock types can be recognised: poorly consolidated siltstones that are transitional down into the Gault, the Malmstone and an upper clayey sandstone with glauconite. The Upper Greensand is thickest in the west of this area, about 67m at Selbourne, thinning northwards to 27m at Guildford, southwards to 34m at Midhurst (Gallois, 1965) and eastwards to 10m at Eastbourne (Barrois, 1876).

At the base of the Upper Greensand in the Isle of Wight a series of sandy clays and marls, the Passage Beds, occur (White, 1921). These are succeeded by sandstones with concretions and chert courses. In south Dorset the Upper Greensand increases in thickness south-westwards and sands with limestone concretions are succeeded by Foxmould, Chert Beds and Top Sandstones/Eggardon Grit of the Devon/Dorset border region, the main area of study documented herein (see Garrison *et al.*, 1987 for a recent review of lithologies.)

In the southwest of England the Upper Greensand is found capping many of the hills in southeast Devon. Outliers also occur in the Haldon Hills and the Bovey Basin. Two facies were recognised by Tresise (1960), separated by a line running from Sidmouth, north-eastwards to Yarcombe. To the east of this line the calcareous 'Normal Facies' is found while to the west the non-calcareous 'Blackdown Facies' may be seen.

The outliers seen in the Haldon Hills consist of a sequence of non-calcareous sands and gravels which often contain cherts (Haldon Sands Formation - Hamblin and Wood, 1976; Selwood *et al.*, 1984). At Wolborough, on the edge of the Bovey Basin, there occurs an exception to the 'Blackdown Facies' in the form of a series of orbitoline-rich limestones (Edwards, 1979; Selwood *et al.*, 1984).

Many workers have considered that during Albian times western Europe consisted of a number of highs and massifs surrounded by mainly shallow seas (Figure 1.6)(see Ziegler, 1982 for an overview). Across central Europe a series of linked massifs, the Brabant, Rhenish and Bohemian Massifs acted as a barrier between the northern 'Boreal Sea and the southern Tethys Ocean. To the east and west of these massifs mixing of the two seas was possible, although in the west the Armorican Massif created another barrier only allowing a relatively narrow seaway between the northern and southern water bodies. A second seaway existed between the Armorican Massif and the Iberian Meseta.

The Upper Greensand and it's equivalents was deposited in a series of basins to the north and northwest of the Armorican Massif. The area of deposition was bounded to the west, northwest and north by the Cornubian Massif and the Welsh and Pennine Highs (Figure 1.6).

The tectonic events influencing southern England at this time were all Alpine in origin, but may have been influenced by older structures (Ziegler, 1982).

After the early Aptian Austrian tectonic phase the Bay of Biscay opened (Ziegler, 1978). Rifting and transform faulting in this area was probably combined with marginal uplift and erosion. This erosion led to the shedding of clastics eastwards into the Celtic Sea Trough and Wessex Basin.

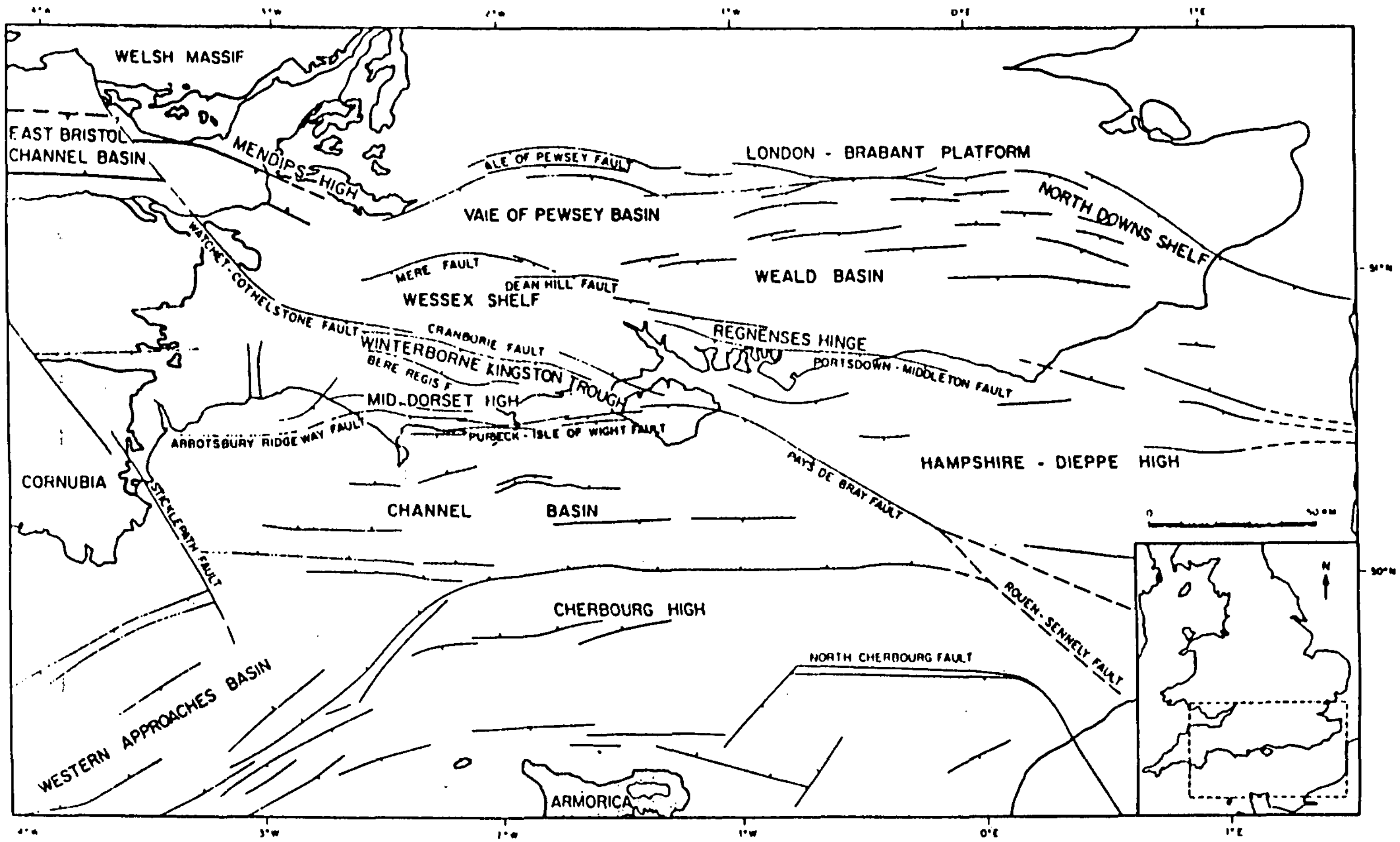
Ziegler (1978) considered that at this time, the Celtic Sea, Bristol Channel and Western Approaches Troughs were largely inactive.

Lake and Karner (1987) divided the Wessex Basin, which includes the main area of study, into four sub-basins (see Figure 1.7). These sub-basins relate to the reactivation of Hercynian basement structures. They attributed the pre-Aptian (pre Lower Greensand) uplift and erosion to thermal effects associated with the opening of the Bay of Biscay. Subsequent subsidence led to the enlargement of the Weald Sub-Basin to cover southwest England.

Southern England was affected by intra-Cretaceous folding and faulting. Most of these earth movements occurred in post-Wealden/pre-Aptian times (House, 1961; Phillips, 1964). They are typified by the folds and faults seen in the Weymouth area. Hart (1971) suggested that the mid-Cenomanian non-sequence he recognised in southern England on microfaunal evidence equated with the intra-Cretaceous folding recognised by Smith (1957a) and Durrance and Hamblin (1969). Drummond (1970) considered the absence of the dispar Zone (latest Albian) over central Dorset was related to gentle uplift of the Mid-Dorset Swell during this time. Kennedy (1970) also noted a condensation of the *dispar* Zone over the Mid-Dorset Swell.

Full discussions of previous studies on the Upper Greensand are given at the begining of each relevant chapter.

MAJOR MESOZOIC STRUCTURAL FEATURES IN THE WESSEX BASIN, SOUTHERN ENGLAND



(After Lake and Karner, 1987)

Figure 1.7

1.3 Methodology

The interpretations made in this study are the result of the analysis of two sets of data. The first is a review of all the relevant published information. The second is a new study of the sedimentology, diagenesis and biostratigraphy of the Upper Greensand in the area of southeast Devon.

With respect to the new study, attention has focussed on three sections along the southeast Devon coast: Branscombe, Dunscombe and Seaton (see Figure 1.1), although all other suitable sections in the study area (eg. those in the Haldon Hills) have been considered before the interpretations were made.

Each of the main sections was examined, measured and logged with special attention being paid to bed form, sedimentary structures, gross mineral content and macrofossil content. A sample was taken from each bed with occasionally several samples from one bed (total 198 samples). These samples were taken as deep as possible from the outcrop surface in order to avoid the most heavily weathered rock.

The samples varied widely in competance from hard, brittle chert to soft easily disaggregated, muddy sand. A sub-sample from each was, as far as practicable, disaggregated, washed and dried, then sieved into fraction sizes and examined for microfauna. It was, of course, not possible to do this with the cherts and some of the harder nodules. Where a microfauna was present an attempt was made to pick a minimum of 300 specimens in order to gain a representative sample (Murray, 1973). Relatively few samples, however, contained microfossils and of those that did it was seldom possible to obtain 300 specimens even after carefully processing and picking a kilogram of original sample. The samples that contained a microfauna were picked using a damp brush and picking tray under a binocular microscope. All the size fractions were examined in detail (500, 250 and 180mm sieve sizes) including the finest residue in the bottom tray.

A sub-sample from each sample was also prepared as a standard thin section. In many cases this required the impreganation of the sample with resin before cutting. Each of these thin sections was examined in order to discover details of its mineral content, microfacies and diagenetic history. Additional thin sections (212) were prepared from cherts and other lithologies in order to work out the diagenetic sequence and also to obtain median sections of the orbitoline foraminifera.

CHAPTER 2 LITHOSTRATIGRAPHY

2.1 Previous Work

See Figure 2.1 for a summary of lithostratigraphic terminology.

Over much of its outcrop in the south of England the Upper Greensand lies stratigraphically between the Gault Clay and the Chalk. The Chalk was used as an easily available source of lime for building by the early Saxon invaders and the word was probably derived from the Saxon word for lime - cealc (German - Kalk). The word gradually became softened to 'Chalk' and as it was a specific appelation to a particular rock type it naturally became a geological term. In Germany this was not possible as the word did not have a specific meaning and another term was used to describe the rock type 'Kreide'.

The lithological unit usually found below the Upper Greensand has been variously spelt as Gault, Galt or Golt. This term is a provincial name for a 'stiff blue clay' that occurs in Cambridgeshire, Suffolk and Hertfordshire. Although the word's origin is in doubt, it may have been derived from the German word 'Kalt' (cold); forming a cold soil.

The Rev. John Michell used the term 'Golt' in 1788 or 1789 for a 'stiff blue clay' that occurred beneath the Chalk. William Smith, working in the Bath area in 1799, described the rocks beneath the Chalk as 'sand' and 'clay'. Thomas Webster's letters (written in 1811 but not published until 1816) in which he described the geology of the Isle of Wight, refer to the Gault Clay as the 'Blue Marle'. This name was adopted by William Smith in his 'Map of England and Wales' (1815).

Smith next used the term 'Brickearth' for the Gault Clay in his 'Stratigraphical System of Organised Fossils' (1817) but by 1819, in the maps published that year, he referred to it as the 'Golt Brickearth'.

The term 'Greensand' probably originated with William Smith between 1800 and 1812 and both he and Thomas Webster always used it for the green sands which lie between the Chalk and the Gault Clay. Smith referred to these beds simply as 'sand' in his 'Table of Strata' (1799).

In the Rev. J. Townsend's work 'The Character of Moses Established for Veracity as an Historian' (1813) all the Cretaceous strata below the Chalk were listed as 'The Sand'. He further divided these sands into 'green, grey and red sand'. Although he was aware of the presence of clay and brickearth between the grey and red sands he seemed to consider this to be a local phenomenon. He did, however, specifically mention the presence of 'firestone' within the grey sands.

The terms 'Firestone' or 'Calcareous Malmstone' were used to describe a rock type that was quarried for use as hearthstones. This variety of Malmstone (Malm or Malmrock) contains up to 25% calcareous material. It is usually more compact with a higher specific gravity than pure siliceous Malmstones. Malmstone was a provincial name, used in the counties of Sussex and Hampshire, for a fine grained siliceous rock.

John Middleton published an essay entitled 'Outlines of the Mineral Strata of Great Britain' (1812) in which he presented a list of terms for the Cretaceous rocks. He used the term 'firestone' rather than greensand and regarded it as part of the Chalk.

In 1818 William Phillips presented a paper to the Geological Society (published 1821) in which he described the Chalk cliffs near Dover. He described the subdivisions of the Chalk and placed the 'Blue Marl' beneath the 'Grey Chalk'. He then proceeded to describe the 'Blue Marl' as resting on 'the greensand'. This 'greensand' he equated with Smith's 'Greensand', although Smith had always described it as occurring above the 'Blue Marl'.

Also in 1818, Mantell published 'A Sketch of the Geological Structures of the South-Eastern part of Sussex'. In this work he equated the 'Blue Marl' with the 'Chalk Marl' and placed the 'Greensand' below this unit. In what was apparently an attempt to match his work with Smith's, he then placed a 'Brickearth' below the 'Greensand' and a 'Blue Clay' or 'Oak Tree Soil' below that, saying that the 'Brickearth' only occurred locally. To make this sequence fit the observed facts at Eastbourne he had to assume that the 'Blue Marl' or Gault Clay was absent and that his 'Greensand' thus underlay the Chalk.

Both Phillips and Mantell assumed that there was only one 'Greensand' and that this occurred below the 'Blue Marl'. Their ideas were followed and extended by other workers. Buckland (1818) arranged the lithological units into formations but the 'Greensand' included both the Upper and Lower Greensand of the present day.

Phillips and Coneybeare (1822) published a series of lithological sections. In the section for the Weald their 'Chalk Marl' included the Malm Rock, Firestone (the present Upper Greensand) and the Gault Clay. Their 'Greensand' was the equivalent of the present day Lower Greensand. In the section for Dorset their 'Greensand' was the equivalent of the present Upper Greensand, their Weald Clay was the present Gault Clay and their Iron Sand was the equivalent of the present day Lower Greensand.

Mantell (1822) referred to Phillip's observation that 'the Greensand' lies under the Blue Chalk Marl at Folkestone. He also reiterated his own idea that the Blue Chalk Marl (Gault Clay) was absent at Eastbourne and elsewhere to explain the obvious 'Greensand' which underlies the Chalk. Mantell also grouped various sands and clays into a 'Greensand Formation'.

Two schools of thought thus existed at that time. The erroneous idea that 'the Greensand' always lay below the Gault Clay wherever it occurred and the correct observation that the 'Greensand' occurred both above and below the Gault Clay, with the present-day Upper Greensand lying above the Gault Clay.

Fitton (1824) published an account of the beds between the Chalk and the Purbeck Limestone in south-east England and correlated them with strata found on the Isle of Wight. He also observed that there were, in fact, three sand units separated by two clay units (the Gault Clay and the older Weald Clay) as opposed to the two sand units quoted by Phillips and Coneybeare. Although the sands below the Gault Clay had been described originally with other names (Iron Sand, Ferruginous Sands and Carstone), Fitton suggested the retention of the name 'Greensand'.

Subsequently, in a letter published in the Annals of Philosophy, Fitton attempted to end the controversy over the use of the name 'Greensand'. He reported that it had been suggested to him that the names Upper Greensand and Lower Greensand should be used in place of the terms 'Firestone' and 'Greensand' that he had used previously. He went on to say, however, that he considered that the use of the term 'Greensand' had led to so much misunderstanding that both units should be renamed and he proposed the names Merstham Beds ('Firestone' or 'Upper Greensand') and Shanklin Sands ('Greensand' or 'Lower Greensand').

Webster read a paper to the Geological Society in November 1824 in which he reviewed the confusion which had occurred over the use of the term 'Greensand'. In early 1825 Webster published his 'Reply to Dr. Fitton'. He confirmed the precedence of the sands below the Chalk to the name of 'Greensand' and described it as "a stone composed of siliceous grains, mica and dark green particles with a calcareous cement". He proposed that the Upper Greensand, Gault Clay and Lower Greensand be placed in a ' Greensand Formation'.

Murchison (1825) examined the geology of the western end of the Weald and used the terms Upper and Lower Greensand as proposed by Webster, but replaced the term 'Blue Marl' with Gault Clay.

De la Beche (1826) described the "Greensands below the Chalk" in southeast Devon using the subdivisions Foxmould Sands and Chert Beds; the former being a local name and the latter presumably being lithologically descriptive. These subdivisions subsequently became well established.

Mantell (1827) attempted to correct some of the errors contained in his earlier work by adopting the names proposed by Fitton in his letter to the Annals of Philosophy. However, he still bracketed the Grey Marl, Firestone, Upper Greensand or Merstham Beds and the Gault Clay or Folkestone Marl together as Chalk. He also used Fitton's term 'Shanklin Sands' instead of 'Green or Chlorite Sand', for the Lower Greensand.

Martin (1828) chose to use the names Malm, Gault and Shanklin Sands and placed them together in a 'Glauconite Group'. He further subdivided the Malm into Upper Greensand and Malm-rock and the Shanklin Sands into Ferruginous Sand and Lower Greensand. This modification meant that three diferent schemes were in use, all of which had overlapping elements when the names used were listed.

Mantell (1833) made a move toward uniformity by quoting Websters terminology as synonyms to that he was using. Fitton (1836) adopted the terms Upper and Lower Greensand. Finally, the names Gault Clay and Upper Greensand were adopted by the Geological Survey in 1839 because these lithological names allowed for the separate mapping of sands and clays. Thereafter these terms have been in general use, with the Upper Greensand divided into the Foxmould Sands and Chert Beds as suggested by de la Beche (1826).

Subsequent to the decision of the Geological survey in 1839, there have been few additions to the lithostratigraphy of the Gault Clay - Upper Greensand facies. Meyer (1874) described the lithologies to be seen in southeast Devon and numbered the units within the succession. In 1900 Jukes-Browne and Hill suggested the introduction of the term Selbornian to include both the Gault Clay and the Upper Greensand. This found little favour subsequently. Tresise (1960) noted that the Upper Greensand across Devon west of Sidmouth is largely non-calcareous. He termed this the "Blackdown Facies". Smith (1961a) used the name Top Sandstones for the more sandy facies found at the top of the Chert Beds. Finally the outlier of Upper Greensand on Haldon Hill was formally described as the Haldon Sands Formation by Hamblin and Wood (1976) and divided into four members (See below and Chapter 3).

2.2 New Lithostratigraphic Scheme

2.2.1 Introduction

Although the term Upper Greensand has been in regular use since 1839 (see above), it has never been formally described or subdivided as is the practice in modern lithostratigraphy (Hedberg, 1976; Holland *et al.*, 1978; NASCN, 1983) This is essential for the unit to be mapped, correlated to other coeval sediments of different facies, and for detailed sedimentological studies to take place. A basic premise of this study has therefore been to erect a new lithostratigraphic scheme for the Upper Greensand. This is described in the subsequent sub-chapters.

2.2.2 Selborne Group

Despite the fact that the Upper Greensand in the west of England and the Gault Clay in eastern England are, at least in part, coeval deposits there is no nomenclature to link these two units. Jukes-Browne and Hill (1900) proposed the name Selbornian (from the area around the village of Selborne, Hampshire) to include both the Gault Clay and the Upper Greensand, but this term has not been accepted by other workers, partly because it has chronostratigraphic connotations as well lithostratigraphic meaning.

Hedberg (1976) considered the 'Formation' to be "the primary formal unit of lithostratigraphic classification". He stated that the degree of change in lithology required to erect a new 'Formation' does not have strict rules, but practicality in mapping and delineation on cross sections are important considerations. On these grounds alone it is obvious that the Gault Clay and Upper Greensand should have different 'Formation' names. However, in view of the fact that they are, at least to some extent, coeval and also related in terms of basin history, they should be placed within a lithostratigrahic 'Group'. In memory of Jukes-Browne's enormous contribution to the study of these rock types it is proposed that the group be named the Selborne Group.

"Selborne Group" clearly has a geographic context, but in this case it is quite apt. Around the area of Selborne, Hampshire both the Upper Greensand and Gault Clay are well exposed (Chatwin, 1960). It is also in a position central to the distribution of both facies which outcrop over much of southern England.

The Selborne Group is divided into two main formations: the Gault Clay Formation and the Wessex Greensand Formation (see Figure 2.1 and below). Lateral equivalents of the Wessex Greensand Formation such as the Haldon Sands Formation are also included in the Selborne Group.

The Gault Clay Formation is outside the main scope of this study and is not described in any more detail here. The term Gault Clay is preserved in accordance with the comments of Hedberg (1976) on the preservation of traditional names.

The Haldon Sands Formation is described in detail by Hamblin and Wood (1976) and Selwood *et al.* (1984) and this does not need to be repeated here. However, Hamblin and Wood recognised only four members in the Haldon Sands Formation. These were, in ascending order, the Telegraph Hill Sands Member, the Woodlands Sands Member, the Ashcombe Gravels Member and the Cullum Sands-with-Cherts Member. In the present work these members are retained, but a fifth added. This is the Wolborough Limestone Member, which formally describes the orbitoline-rich limestones outcroping to the west of Haldon near Newton Abbot. This is described in detail in the subsequent subchapter.

2.2.3. Haldon Sands Formation: Wolborough Limestone Member

Type Section

Wolborough, Newton Abbot, Devon, about 400m south of Wolborough church (SX 855 700) (Figure 2.2). Not currently exposed, but well described

SELBORNE GROUP (P)

HALDON SANDS FORMATION
(HAMBLIN AND WOOD, 1976)

WOLBOROUGH	HALDON HILLS
WOLBOROUGH LIMESTONE MEMBER (P)	CULLUM SANDS-WITH-CHERTS MEMBER (H&W, 1976)
	ASHCOMBE GRAVELS MEMBER (H&W, 1976)
	WOODLANDS SANDS MEMBER (H&W, 1976)
	TELEGRAPH HILL SANDS MEMBER (H&W, 1976)

S.E. DEVON

UPPER GREENSAND		WESSEX GREENSAND FORMATION (P)
	TOP SANDSTONES (SMITH, 1961a)	TOP SANDSTONES MEMBER (P)
	CHERT BEDS (DE LA BECHE, 1826)	CHERT BEDS MEMBER (P)
	FOXMOULD (SANDS) (LOCAL NAME USED BY DE LA BECHE, 1826)	FOXMOULD SANDS MEMBER (P)

FIG 2.1: SUMMARY OF EXISTING AND PROPOSED (P) LITHOSTRATIGRAPHIC TERMINOLOGY FOR S.W. ENGLAND.

GEOLOGICAL MAP OF SOUTHEAST DEVON

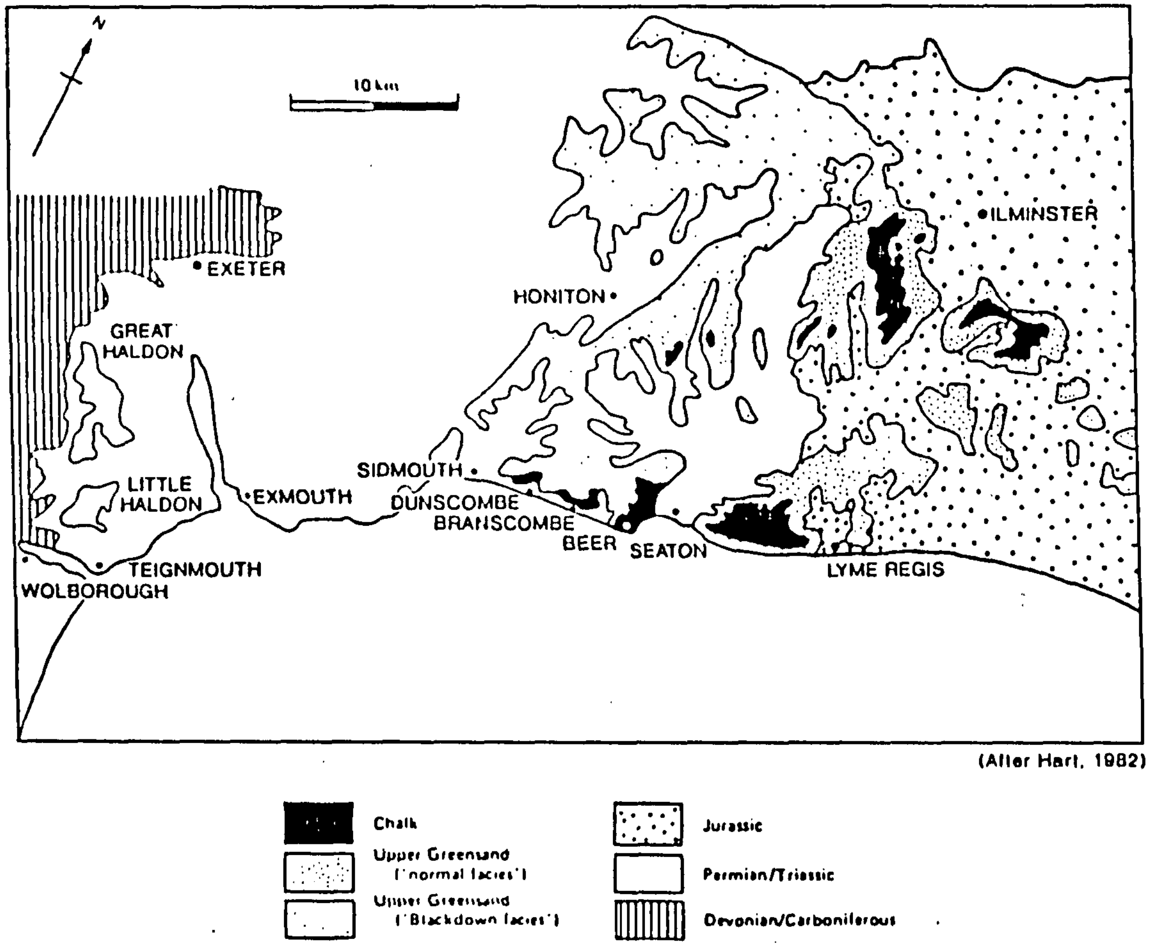


FIG 2.2: LOCATION MAP FOR BRANSCOMBE, DUNSCOMBE AND WOLBOROUGH.

after the digging of an I.G.S. trench in 1974 (Selwood *et al.*, 1984; Edwards, 1979). Overlain by soil and resting unconformably on Devonian Whiteway Slate.

Description

Some 8.5m of gravels, sands and limestones which had slight dips to the east but steepened to 32 degrees at one point. The basal gravels exhibit clasts up to 50mm across and contain some clay. The sands are green, brown or red, glauconitic, fine to medium grained, micaceous and clay-rich. The limestones are pale green/grey, glauconitic, fossiliferous and show some evidence of penecontemporaneous brecciation.

Variation

The basal gravels vary from 0.3m to 1.6m thick, contain clasts 30-50mm across and varying amounts of clay. The sands are medium or fine grained, clay-free to clay-rich and contain varying amounts of clay and fossil material, and are fine to medium grained and massive or rubbly.

Fossils/Age

Within the limestones Selwood *et al.* (1984) reported a bivalve fauna (*Callistina, Glycemeris, Trigonarca* and several trigonid genera), gastropods and serpulid masses as well as the locally abundant orbitoline fauna. Schroeder *et al.* (1986) demonstrated that the orbitolines could be referred to the species *Orbitolina sefini* which according to Schroeder (1985a) has a range from intra-Late Albian to intra-Early Cenomanian. Discussion in chapter 5 of the present work suggests that this fauna is probably Late Albian (Dispar Zone) in age.

2.2.4 Wessex Greensand Formation.

This is the main unit of study within this work. It is divided into three members (see Figure 2.1). In ascending order they are the Foxmould Sands Member, the Chert Beds Member and the Top Sandstones Member. Each is described below and also in greater detail throughout this work.

"Wessex Greensand Formation" is prefered to "Upper Greensand Formation" because of the historical confusion over the term Upper Greensand. Furthermore, the bulk of this formation occurs within Wessex which provides a geographical context.

In addition to the members mentioned above, it is clear that there are other possible members within the Wessex Greensand Formation, if one looks beyond the study area of SE Devon. These include the Eggardon Grit and the Exogyra Sandstone. Chapter 6 includes a brief discussion of how these units relate to the members described in the study area.

2.2.5 Foxmould Sands Member

Type Section

Branscombe to Beer Head, southeast Devon (SY 226 878) (Fig 2.2). Very well exposed except for the base of the section which is only occasionally visible, usually after storm conditions. Overlain by the Chert Beds Member and resting unconformably on Triassic Mercia Mudstones.

Formerly known as the Foxmould Sands (De la Beche, 1826) and described by numerous authors (see chapter 3) notably Meyer, (1874); Jukes-Browne and Hill, (1900); Smith (1973); Williams (1986) and Williams et al., (1988).

Description

Some 30m of green and grey, calcareous, fine to medium grained, clay-rich, glauconitic, well-sorted, silty sands and relatively clay-free, calcareous grey sands and impure limestones. The former have no visible sedimentary structures, abundant evidence of bioturbation and scattered shell debris, while the latter exhibit parallel laminae, small cross-beds and symmetrical ripples. The beds dip to the east at a maximum of 8 degrees.

Variation

The clay-rich green and grey sands vary in thickness from 0.2m to some 5m. Slight variations also occur in glauconite, clay and shell debris content. The latter sometimes occurring as discontinuous horizons. The impure limestones and clay-free sands vary in thickness from 5cms to about 1m. Not all exhibit sedimentary structures and the limestones and sands may occur as lateral equivalents.

To the west of Sidmouth, within the Blackdown Facies of Tresise

(1960), the Foxmould Sands Member does not occur. Moving eastwards from the type section it becomes increasingly difficult to separate this member from the Gault Clay Formation.

Fossils/Age

Exogyra sp. and the serpulid *Rotularia concava* are common in this member and there is a sparse foraminiferal fauna (Williams *et al.*, 1988). The presence of the ammonite *Prohystoceras (Goodhallites) delabechei* suggests a *Varicosum* Subzone age for the lower part of the Foxmould Sands Member type section while the foraminifera suggest that the upper part is at least *Dispar* Zone in age. Further to the east, in west Dorset, the basal Foxmould Sands Member is at least as old as *Cristatum* Subzone (Hancock, 1969).

2.2.6 Chert Beds Member

Type Locality

Branscombe to Beer Head, southeast Devon (SY 226 878) (Fig 2.2). Very well exposed. Overlain by the Top Sandstones Member (see below) and underlain by the Foxmould Sands Member. This member formerly known as the Chert Beds (De la Beche, 1826) and described by numerous authors, notably Meyer (1874), Jukes-Browne and Hill (1900), Smith (1961a,b), Tresise (1960,1961), Smith and Drummond (1962), Hancock (1969), Drummond (1970), Kennedy (1970), Hart (1973), Williams (1986), Garrison *et al.* (1987) and Williams *et al.* (1988).

Description

Some 20m of calcareous sands, shelly sands and conglomerates often with distinctive black tabular/nodular chert horizons. The beds have a slight dip to the east (maximum 8 degrees). They are clean clay-free and exhibit variable competance. Bioturbation is relatively rare, shell debris is common and sedimentary structures occur in all rock types as well as within the cherts (parallel laminae, cross-beds and symmetrical ripples).

Variation

The conglomeratic horizons vary from about 0.25m to 1m in thickness at the type locality. They contain abundant, rounded, intraformational clasts, variable amounts of shell debris and coarse grained sandy matrix. The sands and calcarenites vary in thickness from around 0.4m to 3.3m. They have variable intraformational clast content, shell debris may vary from relatively rare to dominant and chert may be absent or present in varying amounts. Horizons and patches of coarse, rounded quartz, glauconite and heavy minerals also vary in abundance.

To the west of Sidmouth, within the Blackdown Facies of Tresise (1960), the Chert Beds Member *sensu stricto* does not occur and is replaced by non-calcareous, fine sands with cherts and siliceous sandstones often with abundant silicified fossils. Eastwards of the type section the Chert beds Member gradually thins towards the Mid-Dorset Swell (Smith and Drummond, 1962; House, 1963; Kennedy, 1970; Carter and Hart, 1977).

Age/Fossils

Fossils are relatively rare in this member although species of bivalve, especially *Exogyra* sp., are locally common (Jukes-Browne and Hill, 1900). Some suggestion of Cenomanian age (Hart, 1971; Carter and Hart, 1977), using microfauna, has been refuted by the presence of a *Dispar* Zone ammonite fauna near the top of the Wessex Greensand Formation at Shapwick Grange Quarry, southwest Dorset (Hamblin and Wood, 1976). This fauna is most likely from the higher part of the *Dispar* Zone (H.G. Owen pers. comm) and therefore it is possible, probably likely, that the highest part of the Chert Beds Member and the Top Sandstones Member extend into the basal Cenomanian.

2.2.7 Top Sandstones Member

Type Section

Kempstone Rocks (SY 160 881) on the footpath from Weston Mouth to Sidmouth, southeast Devon. Overlain by the Cenomanian Limestone and resting on the Chert Beds Member. Previously described by Jukes-Browne and Hill (1900), and termed the "Top Sandstones" by Smith (1961a) and by most subsequent workers.

Description

Some 5m of poorly sorted calcarenites and quartz arenites. The calcarenites may exhibit 5-15cms thick, normally graded laminae which may have small horizontal burrows at their tops. Other beds show bimodal cross-sets up to 20cms thick. Very poorly sorted quartz arenites also occur, with limited lateral extent, and may have a high clay content.

Variation

To the west of Sidmouth this member is not discernable. To the east in the Branscombe to Beer section, the Top Sandstones Member occurs as 2.5m to 4m of calcareous sand with thin, wavy horizons of green sand. Still further to the east, in Dorset, the Eggardon Grit has a similar stratigraphic position and lithology and probably represents an equivalent of this member (Kennedy, 1970; Drummond, 1970; Carter and Hart, 1977).

Age/Fossils

In southeast Devon fossils are rare in this member, being mostly confined to comminuted shell material. As discussed above it is at least possible that the Top Sandstones Member extends into the basal Cenomanian. Orbitoline foraminifera from this member (and also the topmost Chert Beds Member) provide equivocal evidence for its age, but correlations to the Haldon Hills and also the east indicate an earliest Cenomanian age to be likely (see Chapters 5 and 6).

CHAPTER 3 SEDIMENTOLOGY AND FACIES

3.1 Introduction

In this chapter a review of the available literature concerning sedimentology is presented. Also a number of sections in south east Devon are divided into facies types which, as far as possible, reflect the different environments and energy levels which prevailed at the time of deposition. Sedimentary logs are provided together with descriptions of the rock types, sedimentary structures and other salient features. The various sections are then compared and an overall model of deposition is proposed. The lithostratigraphy proposed in Chapter 2 will be used throughout this chapter and those that follow except when referring to previous workers.

The confusion over nomenclature and the exact stratigraphic position of the Gault and Upper Greensand in southern England, which prevailed in the early part of the 19th century (see chapter 2 for discussion), was largely settled when the names Gault and Greensand were adopted by the Geological Survey in 1839. Most of the work published before this date concentrated on the controversy about nomenclature and relatively little information was presented about the character of the rock types other than simple lithologic descriptions. After this date the published work on lithology and sedimentology can be roughly divided between i) discussions about the coeval nature of the Gault and Upper Greensand; ii) lithological descriptions of various localities sometimes with correlations to other areas; iii) attempts at basinal analysis and depositional models; and iv) more general reviews of the available knowledge for a given area.

3.2 Previous Work

3.2.1 The Coeval Nature of the Gault and Upper Greensand

The first suggestion that the Gault Clay and Upper Greensand were lateral equivalents that had been deposited in different environments was made, almost as an aside, by Godwin-Austen (1850) when he stated that they should be regarded as "arenaceous and argillaceous portions of the same zone". However he presented no evidence to support this declaration. Despite this observation it was generally thought by geologists in the early mid 19th Century that the Gault Clay was an important division of the Cretaceous that was overlain by some representative of the Upper Greensand, and furthermore it was supposed that the Gault Clay was equivalent in age in all areas, while the Upper Greensand was always younger.

The nature of the relationship between the Gault and Upper Greensand gradually became clearer through the 19th century. Meyer (1866) pointed out that the Gault Clay thinned out to the west and suggested that in the region of Lyme Regis it was probably represented by the 'yellowish-brown sand or Foxmould'. This increasing sand content of the Gault Clay to the west was also remarked upon by Strahan (1898).

Early workers on faunal zonation of the Gault Clay such as de Rance (1868) and Price (1874) enabled later workers to decide which zones of the Gault Clay were present in their areas and to demonstrate that not all occurrences of this clay were synchronous. For example Jukes-Browne (1892) showed that the Gault Clay of Devizes was equivalent to only the lower part of the Gault Clay at Folkestone.

Jukes-Browne repeatedly discussed the problem of the Gault Clay and Upper Greensand being two different facies belonging to one time interval (Jukes-Browne, 1892, 1896 and Jukes-Browne and Hill 1900). In 1892 he pointed out the desirability of a new single name for the two rock types and suggested the Devisian.

Jukes-Browne and Hill (1900) reiterated the need for a single name, pointing out that the rocks not only consisted of Gault Clay and Upper Greensand but in some areas appeared as 'Malm Rock' (with very little quartz sand and glauconite) and in others as red chalky limestone and marl ('Red Chalk'). They rejected the use of the French term Albian, on the grounds that many of the lithological units found in France that they regarded as being equivalent in age to the Upper Greensand and Gault Clay in England had been assigned by Barrois (1874) to the Cenomanian. Jukes-Browne and Hill also noted that the name Divesien had been proposed, and had come into general use, for a division of the Oxford Clay. They consequently withdrew Jukes-Browne's previous suggestion of Devisian for the Gault Clay and Upper Greensand as they considered that the similarity between the names would cause confusion and they proposed the name Selbornian which was derived from the name of the village from which Gilbert White wrote his letters, later compiled as 'The Natural History of Selborne' (see Chapter 2). White had made one of the earliest references to the Upper Greensand when he described the 'Freestone' of Hampshire, this being a quarryman's term for the 'Malm Rock'. Jukes-Browne and Hill suggested that terms such as Gault Clay, Upper Greensand and Malmstone would remain in use for lithological descriptions but should be regarded as secondary names of no stratigraphic value.

After 1900 it was generally understood that the Gault and Upper Greensand were diachronous and to some extent equivalent in age but Jukes-Browne's proposals about nomenclature were not adopted (see Chapter 2).

3.2.2 Lithology and Correlation

In the 19th century there were many descriptive/correlative papers published on the Gault and Upper Greensand many of which are mentioned in Chapter 2. In addition the work of Jukes-Browne (1875) and Jukes-Browne and Hill (1886) may be mentioned which suggested that the Cambridge 'Greensand' was not part of the Upper Greensand but the basal unit of the Chalk Marl with the upper part of the Gault Clay having been destroyed by erosion and its fauna reworked into the overlying Cambridge Greensand.

On the Isle of Wight the Upper Greensand was divided into the Chert Beds and an underlying 'Malm Rock', with the 'Passage Beds' at its base passing down into the Gault Clay (Bristow, 1889). The Chert Beds were described as alternations of chert and sand underlain in the central part of the island by a band of 'Freestone' while the 'Malm' consisted of sands with bands or lenticular masses of chert and cherty limestone. Bristow presented a number of measured sections both from the coast (eg. Compton Bay and Culver Cliff) and inland pointing out that the cherts were relatively poorly developed in the east and west of the island compared to the south.

In the Isle of Purbeck and Weymouth areas Strahan (1898) described the Upper Greensand lithology as a glauconitic, quartz sand with some clay, with cherts common in the upper part while to the west of Lulworth a calcareous grit occurred at the top of the Upper Greensand which was apparently derived from the west and north-west. Strahan also noted the difficulty of observing unweathered material suggesting that the Upper Greensand was far more competant when protected from leaching. Strahan also presented measured sections from Punfield, Lulworth Cove, Durdle Door, White Nothe and Holworth House together with notes on lithologies and faunas. Less complete information was given from Ringstead, Osmington Mills, Bincombe, Long Bredy and other surrounding areas.

The Upper Greensand of the Branscombe and Beer Head area was described bed by bed by Meyer (1874). He gave each bed a number; placing beds 1 - 3 in the Gault and beds 4 - 9 in the Upper Greensand.

The Haldon and Blackdown Greensands in the southwest of England were described by Duncan (1879) and Downes (1882). The latter described the lithologies and faunas of the Blackdown and Haldon Greensands. Although his lithological descriptions were cursory and mostly confined to quarrymans terms he did attempt a comparision between sections at Blackdown and Haldon in which he correlated the upper part of the former with the lower part of the latter. This correlation was based upon the similarities in gross lithology and fauna.

The most comprehensive work on the Upper Greensand is certainly the memoir produced by Jukes-Browne and Hill (1900). After giving a general account of the rock types that occurred in their 'Selbornian', they went on to systematically describe each area of England where they could be found. The memoir was completed with examinations of microscopic structure, economic significance of the rock types and sections in northern France. There was also a discussion of the depositional environments of the Upper Greensand, together with a comprehensive faunal list from the Gault Clay and Upper Greensand.

Jukes-Browne and Hill divided their 'Selbornian' into 'Lower Gault'; 'Upper Gault and Upper Greensand (in part)'; 'Merstham or Devizes Beds' (Zone of *Ammonites rostratus*); and the Warminster Beds or Zone of *Pecten asper* and *Cardiaster fossarius*. Their Merstham or Devizes Beds consisted of Marly Clays, Malmstone or Gaize and grey, green and yellow sands. The term Malmstone was used to include the malm, malm-rock and firestone of other authors and it was defined as a fine grained siliceous rock normally containing small amounts of glauconite, mica and quartz although the calcium carbonate content could vary from 2% to 66%. The calcareous Malmstones (firestones) were stated to be much heavier and compact than the low specific gravity siliceous types. In addition concretionary nodules of chert could be present or the Malmstone could pass into a micaceous sandstone with glauconite ('Gaize'). In the south-west of England and in the Isle of Wight they noted that grey, green and yellow sands were the most important constituent of the lower part of the Upper Greensand, which often contained calcareous concretions ('doggers' or 'burr-stones'). These sands were reported to be micaceous, glauconitic and, in their lower parts, silty.

Jukes-Browne and Hill divided their Warminster Beds into three lithologies; greensand and sandstone; fine grey sand with layers or nodules of chert; and light green sand with small calcareous concretions. These beds were said to be confined to the south-western and south central counties of England.

Each area in which the Upper Greensand occurred had a chapter devoted to it in Jukes-Browne and Hill's memoir. The section on the Isle of Wight contained a number of measured sections with lithological details from Gore Cliff, Ventnor, St. Boniface Down, Niton. Culver Point and Compton Bay and from the sections in the south of the island a generalised succession was produced to aid correlation with the other sections. It was shown that cherts were relatively rare in the east and west of the island and the Upper Greensand as a whole was thinner. The chapter was concluded with a list of fossils from the 'Passage Beds' and the Upper Greensand.

The section on 'South Dorset' included measured sections from Punfield Cove, Worbarrow Bay, Lulworth Cove, Durdle Door and Holworth House with all the measurements and lithological details being taken from the work of previous authors. It was noted, however, that the Chert Beds did not occur at Punfield Cove but at Lulworth they were again represented.

Under the heading 'West Dorset, Somerset and Devon' Jukes-Browne and Hill described the generalised lithology of the area as fine, micaceous sand with clay forming the basal unit, which in the west contained lenticular masses of calcareous sandstone. This was succeeded by various sands, which included a rubbly glauconitic sandstone horizon and was capped by a coarse, hard calcareous grit with cherts occurring below the grit in the west of the area.

Coastal sections from Golden Cap to Axmouth were described in the chapter dealing with 'South Dorset and Devon'. The Upper Greensand in this area was broadly divided into basal sands with calcareous concretions (the Cowstone Beds), the Foxmould and the Chert Beds. The Gault Clay and Upper Greensand were reported to overstep the Jurassic succession to the west.

The sections from Seaton to Sidmouth were described in the chapter which Jukes-Browne and Hill devoted to 'South Devon' with lithological details given from Whitecliff, Beer, Branscombe and Dunscombe and the presence of a synclinal flexure between Seaton and Branscombe was also discussed. The absence of the Gault Clay was noted and it was suggested that a general westwards thinning of this clay had continued until its eventual disappearance. The lowermost glauconitic sands and silts, the Foxmould, were shown to rest on red Triassic marls in the Branscombe-Seaton area while the Chert Beds attained their greatest thickness and were often capped by a chert free sand unit below the Cenomanian Limestone. The actual amount of chert recorded within the Chert Beds varied widely even over this relatively small area.

Jukes-Browne and Hill's chapter on 'Devonshire (Inland Sections)' described the outcrop around Axminster, Honiton and the Blackdown and Haldon Hills. They largely agreed with the correlation put forward by Downes (1882).

After the publication of Jukes-Browne and Hill's memoir (1900) there was very little new work reported on the Upper Greensand until the 1940's and 1950's. Exceptions to this were Jukes-Browne's own paper on the Upper Greensand near Chard (1903) and Boswell's examination of the petrography of the Cretaceous rocks of the Haldon Hills (1923). The former gave a somewhat generalised section showing the topmost unit as a hard, nodular, calcareous grit with a waterworn upper surface underlain by a grey sand and sandstone with layers and lumps of chert. Below this was a hard, calcareous, glauconitic sandstone, a glauconitic sand and a basal fine-grained, grey-green sand which contained quartz, glauconite and some mica.

Boswell's work was largely concerned with detrital heavy minerals which he found to be coarse in grain size and abundant in quantity with no significant variation in type or abundance either laterally or vertically. Tourmaline was the most common heavy mineral with large numbers of grains of glauconite, muscovite, andalusite, staurolite and locally kyanite. Boswell noted that tourmaline, muscovite, andalusite and topaz occurred abundantly in the Dartmoor and Cornish granites but suggested that the quantity of staurolite indicated a source area in the metamorphic rocks of Brittany. The absence of biotite, hornblende and pyroxene was regarded as being due to the decomposition of these minerals.

Wright (1947) wrote an account of the Gault and Upper Greensand of the country around Weymouth, Swanage, Corfe and Lulworth in which he proposed the zonation of the Gault and Upper Greensand using the zones and sub-zones of the Albian Stage, as proposed by Spath (1923-1943), on ammonite evidence. Sections were described from Punfield Cove, Worbarrow and Mupe Bays, Lulworth Cove, White Nothe and Osmington. Further information was given on St Oswald's Bay, Durdle Cove and some inland outcrops from Chaldon and Ringstead to Abbotsbury.

Smart (1955) discussed the occurrence of the Upper Greensand in the Alton Pancras disrict in Dorset. He described it as consisting of fine, green sand which became coarser upwards. The top of the Upper Greensand in this area was reported to be a green, hard, nodular sandstone with sporadic phosphatic nodules at its highest level. This phosphatic horizon was penetrated by fissures which were infilled with phosphatic nodules in a matrix of greyish white, calcareous sand. Smart placed the Upper Greensand in the Albian and considered the fissure-fill to be Cenomanian.

There was a considerable amount of work published from the 1950's to the 1980's on the lithology and correlation of the Upper Greensand of southeast Devon and Dorset (Smith 1957a and b, 1961 a and b; Tresise 1960, 1961; Wilson *et al.* 1958; Smith and Drummond 1962; Hancock 1969; Kennedy 1970; Drummond 1970; Hart 1971, 1973; Ali 1974, 1976; Jarvis and Woodroof 1984; Williams 1986; Garrison *et al.* 1987; Williams *et al.* 1988.

Smith (1957a) noted the blocky appearance of the uppermost beds of the Upper Greensand and that these beds seemed to be rounded in places, presenting the appearance of boulder beds infilled with Cenomaninan deposits. These beds were not developed beneath the Cenomanian Limestone where its lower division was thinnest or thickest which suggested to Smith that thay were blocks washed a short distance from the crest of the ridge and rounded by current action. As these blocky beds were infilled with Cenomanian sediments he concluded that some movement must have occurred before the limestone was deposited. He thought that pebble beds within the Upper Greensand were due to penecontemporaneous erosion and thus supported the hypothesis of uplift occurring while the sands were accumulating. Smith (1957b) also reported on a field meeting in south Devon and Dorset that included visits to the Upper Greensand at Beer, Branscombe and Little Haldon.

An account of the Upper Greensand localities, lithologies and faunas to be found in the country around Bridport and Yeovil was published in 1958 (Wilson *et al.*). They surveyed the area with augers and proved the presence of Gault Clay beneath the Upper Greensand although this was not usually seen at outcrop. The Upper Greensand itself was divided into the basal Foxmould, Chert Beds and topmost Eggardon (or calcareous) Grit. The grit was reported to be Albian in age at its base and Cenomanian at its top, these ages being based on sparse ammonite evidence.

Tresise (1960) made a detailed examination of the lithology of the Upper Greensand in Wessex. He regarded the Upper Greensand as consisting of sands which contained four important components; glauconite, chert, limestone and phosphatic nodules. The successions found on the Devon coast, the Dorset coast and inland Wessex were described with attention being paid to lithological and thickness variations. The evidence of current activity found in the higher beds of the Devon coast was said to be lacking in east Dorset.

Tresise introduced the term 'Blackdown Facies' to describe the non-calcareous sands which he recorded in an area extending from the

Blackdown Hills, eastward to Yarcombe and then south-west to Peak Hill, Sidmouth. The lack of Chalk cover was thought to have allowed accelerated leaching in this area, resulting in the absence of calcareous material.

The abundance of glauconite in the Upper Greensand was seen to vary considerably and it occurred in a variety of forms. The most common form was reported to be dark green, opaque glauconite, which was thought to form by the flocculation of a gelatinous precipitate in sea-water. 'Pigmentary' glauconite, which stained pebble surfaces, was thought to form during periods of low current activity. Similarly, tranquil conditions were thought to prevail during the formation of glassy grains of glauconite. Glauconite was also said to occur as a replacement mineral.

Phosphatic nodules were reported to occur in the Wessex Upper Greensand in a variety of colours and shapes. These were believed to form in conditions of sparse sedimentation and low current activity, by the action of a very weak solution of phosphoric acid in sea-water on calcium carbonate.

Smith (1961a) presented a study of the Cenomanian deposits west of Beer, south-east Devon, and some information on the underlying Upper Greensand was included in this work. Near Branscombe the upper surface of the Upper Greensand was seen to be uneven and consisted of what Smith regarded as shallow, E-W trending channels produced by current scour. He considered that erosion had occurred both before the deposition of the Cenomanian and subsequently after the deposition of his Division A of the Cenomanian. His examination of the lateral variation in the Cenomanian Limestone also led him to postulate a ridge of Upper Greensand at Branscombe Mouth. This ridge would have been periclinal, with a limited extent to the north, and of tectonic origin. He further suggested that a similar ridge could have existed in the Donkey Linhay area to the west of Branscombe Mouth.

Smith (1961b) reported on the detrital mineralogy of the Cretaceous rocks of south-east Devon. He examined the mineralogy of the Upper Greensand pointing out the contrast in quartz content between the Chert Beds (c10%) and the Top Sandstones (c25%). Smith considered that calcarenite would be a more accurate term than sandstone for the Chert Beds . His analysis of the Foxmould revealed a heavy mineral suite distinct from the Chert Beds and Top Sandstones in that it was dominated by zircon. This led him to suggest that direct contributions from the Armorican or Cornubian granites were small and that most of the heavy minerals were derived from pre-Cretaceous sediments, probably the New Red Sandstone. The Chert Beds and Top Sandstones had heavy mineral suites that were largely dominated by tourmaline. This, together with other heavy minerals present, led Smith to suggest that granitic rocks supplied the bulk of the mineral content of the Top Sandstones and that this may have reflected an uplift of the Cornubian Massif.

The 1961 Easter field meeting of the Geologists Association examined the Upper Albian and Cenomanian deposits of Wessex and a report was written by Smith and Drummond (1962). Exposures of the Upper Greensand were seen at Dead Maid Quarry near Mere, sections and blocks to the east and west of Seaton, Warren Hill near Crewkerne, Storridge Hill near Chardstock, Snowdon Hill near Chard, Horn Hill near Beaminster and Evershot. At Dead Maid Quarry calcareous silts with irregular masses of chert and impure limestone made up the Chert Beds. Drummond suggested that the laminae that were seen to curve over the chert masses were the result of differential compaction and not evidence of a mass of chert growing within the sediment.

The field party examined large fallen blocks containing the upper part of the Chert Beds at Culverhole Point below Bindon Landslip to the east of Seaton. The calcarenite contained 'beekitised' oyster shells and irregular masses and slabs often separated by horizons of waterworn pebbles of calcarenite. These 'cobble' horizons indicated penecontemporaneous erosion but no undisputed chert fragments were found to lend credence to a theory of early chert formation. The lower part of the Chert Beds in this area was seen to consist of a fine-grained calcarenite with no pebble beds or conspicuous accumulations of shell fragments. The cherts were of the 'cored' variety, that is they had a hard, black centre and a cream, porous crust. Smith described the basal Chert Beds as buff calcarenites containing siliceous nodules similar to the crust of 'cored' cherts. This basal unit was sandwiched within thin layers of glauconite-rich sand. It was underlain by a nodular, glauconitic, shelly sandstone.

Hancock (1969) examined the heavy mineral content of the Cenomanian Limestone and also made some mention of the Top Sandstones of the Upper Greensand. He concluded that these sands were derived from Devon and Cornwall but that the Dartmoor Granite was not the major source. This conclusion was at variance with most earlier workers. It was based upon the low proportion of euhedral zircons (which suggested no primary source nearby), the scarcity of biotite, monazite and zoned zircons, the flood of tourmaline compared with zircon and that 90% of the assemblage belonged to the stable minerals tourmaline, zircon and rutile. Hancock went on to suggest that the Cornish granites were being eroded and contributing material to the Top Sandstones. This was based on the widespread occurrence of topaz and pleochroic andalucite and the fact that up to 75% of the zircons were unzoned.

Kennedy (1970) described a large number of sections of the uppermost Albian and Cenomanian from locations in the southwest of England.
Ali (1974,1976) discussed the calcareous sands (his 'blocky calcarenite bed' or 'cobble conglomerate bed') at the top of the Upper Greensand of the Beer district in south Devon. He suggested that the unit had affinities with littoral deposits and that the fissure-fill, from the Cenomanian limestone above, could be divided into six lithologies that represented the remains of a complete Cenomanian succession after repeated erosional events.

Jarvis and Woodroof (1984) described the top of the Upper Greensand in the Beer area as the Small Cove Hardground. This consisted of cross-bedded calcarenites penetrated by Thalassinoides burrows. They considered that this burrowing, aided by synsedimentary fracturing, current reworking and bioturbation, had been responsible for the reorientation of some blocks. They agreed with previous workers about the penetration of younger sediments but thought that there was no evidence of subaerial exposure or the formation of beach deposits. They considered that broad shallow troughs and channels in the Upper Greensand had resulted in differences in the thickness of the overlying deposit. Erosion was then thought to have planed off this deposit causing it to pinch-out against 'palaeo-topographic highs'. These 'highs' being the result of the activity of a series of N-S faults which passed through Branscombe Mouth, Beer Beach and Axmouth.

Garrison *et al.* (1987) described the hardgrounds and coarse horizons of intraformational clasts found in the Upper Greensand of southwest England. These horizons were demonstrated to have been subjected to early diagenetic lithification and, in some instances, to have been subsequently exhumed and reworked. Relatively simple hardgrounds were said to be succeeded upwards by more complex horizons and this progression was thought to reflect increasing water depth.

During the same period the western outliers of the Upper Greensand in the Haldon Hills were examined by Hamblin (1968), Durrance and Hamblin (1969 a and b), Hamblin and Wood (1976) and Selwood *et al.* (1984); and in the Bovey Basin by Edwards (1969 and 1979).

Hamblin (1968) and Durrance and Hamblin (1969 a,b) examined the Cretaceous structure of Great Haldon, Devon. Hamblin gave an abstract on mapping in the area in which he stated that the Upper Greensand showed a variation in thickness (70-100ft) which was probably due to variation in deposition and post-depositional erosion. Durrance (and Hamblin) conducted a seismic survey over Great Haldon which revealed variations in thickness of between 84m and 16m in the Upper Greensand. They concluded that the transgression of the Upper Greensand deposits took place over a level surface underlain by Permian breccias. During the period of submergence and deposition a series of folds were thought to have resulted in highs and basins which accounted for the differences in thickness.

Data on the Upper Greensand of the Bovey Basin was reported by Edwards

(1969). In the east of the basin occurred coarse, pebbly, glauconitic sands with fossiliferous cherts belonging to the Upper Greensand. These were found beneath the Aller Gravels which also contained abraded Upper Greensand cherts.

Hamblin and Wood (1976) discussed the stratigraphy of the Haldon Hills and proposed a formal lithostratigraphical classification.
A number of locations were described and, based upon the geographic isolation of this outlier, they proposed the erection of a Haldon Sands Formation. This comprised, in ascending order, the Telegraph Hill Sands Member, the Woodlands Sands Member, the Ashcombe Gravels Member and the Cullum Sands with Cherts Member. The stratotype for each member was unfortunately a temporary section at Woodlands.

The Telegraph Hill Sands Member was described as consisting of poorly consolidated, green and red, well-sorted, glauconitic sands with a locally developed basal conglomerate. The Woodlands Sands Member was comprised of a variable succession of clayey sands, shell rich horizons and siliceous concretions which when compared with the underlying member was found to be less well sorted, clay rich and coarser. The Ashcombe Gravels Member had 'alternating sandy, quartz gravels and coarse, gravelly, quartz sands. The three gravel horizons were reported to be traceable over long distances and Hamblin and Wood suggested that they represented a significant change in sedimentary environment, the finer grade material having been winnowed out by current action. On the western side of Haldon the gravels were seen to be thicker and less well sorted which they considered to indicate that less winnowing had occurred due to the rapid accumulation of sediments nearer to their source on the Dartmoor Massif. The Cullum Sands with

Cherts Member consisted of green and brown sands with cherts of varying vitrification and occassional clay and pebble bands. A comparison was drawn between the tourmaline-rich, coarse sands at the top of this member and the Lower Cenomanian Wilmington Sands.

Finally Hamblin and Wood used their observations to attempt correlations between the Haldon area Upper Greensand and that of the east Devon coast(see Chapter 6 for further discussion).

Edwards (1979) reported on the limestone horizons found in the Upper Greensand at Wolborough, south Devon. Two of these limestone types were exposed in a trench in 1974 and the third was collected as loose erratic material. The trench section was divided into units 1 to 8. Bed No. 6 was a 'pale greenish-yellow, glauconite speckled, rubbly limestone' which was highly fossiliferous. It consisted of detrital quartz, tourmaline, muscovite, glauconite and bioclasts cemented by sparite and patches of micrite. Bed No. 8 was a yellowish-grey, sandy limestone being relatively unfossiliferous. It contained detrital quartz, tourmaline and bioclasts and was cemented by sparite. The third limestone type was a sandy, intraclastic biosparrudite (with some non-intraclastic samples). Edwards thought that the intraclasts were intraformational and represented a period of higher energy deposition.

The memoir for the country around Newton Abbot (Selwood and others, 1984) expanded on the information presented on the Upper Greensand of the area as given by Hamblin and Wood (1976). Details of lithology were given from Bullers Hill Quarry, Cullum Goyle, Woodlands Goyle, Telegraph Hill and various other temporary roadwork cuttings, Summercombe Wood, Smallercombe Goyle, Babcombe Copse, Kingsteignton Bypass and Wolborough.

Dingwall (1971), Smith and Curry (1975) and others examined the geology of the English Channel. Albo-Aptian deposits were said to occur in the central and eastern portions of the English Channel although Dingwall pointed out that seismics could not separate Lower and Upper Greensand and that no Gault Clay was detected. Furthermore there appeared to be no reflecting differences between the Chalk and Upper Geensand.

3.2.3 General Reviews

In the 20th century there have been a number of general geological reviews which included the Upper Greensand among which may be mentioned Woodward and Ussher (1911): Sidmouth and Lyme Regis; Ussher (1913): Newton Abbot; White (1921): Isle of Wight; Chatwin (1960): Hampshire Basin; Edmonds *et al.* (1975): South West England; and Hart (1982): Devon.

3.2.4 Basinal Analysis and Depositional Environments

Many of the publications mentioned in the previous section made some reference to depositional environments and general basin analysis but those described below are considered to be the most important.

One of the earliest references to a specific depositional environment for the Upper Greensand was made by Duncan (1879) in his study of the Haldon Hills. He suggested that deposition in this area had occurred in a high energy, shallow marine environment. This suggestion was incorporated into the overall model put forward by Jukes-Browne and Hill (1900) for the physical and geographical conditions under which the Gault Clay and Upper Greensand were deposited.

They considered that south-east England had suffered greater subsidence than the south-west, which accounted for the shallower water facies in the south west. Using the present heights above sea-level of the base of the Upper Greensand in south-west England it was suggested that Exmoor, with the Brendon and Quantock Hills formed an island or islands during Upper Greensand times. They suggested that the 'Selbornian Sea' was bordered by Dartmoor and that the shoreline stretched from Devon to the north of the peninsular of Cotentin. The muds of the Gault Clay were thought to have originated in rivers draining the 'Belgo-Germanic' land. The muds would have been transported by currents from the south-east "so as to deposit its load in the eastern and central parts of the 'Anglo-Gallic Basin'". Younger 'Malmstone' and 'Gaize' deposits were thought to have formed when the supply of mud diminished.

Tresise (1960) reported a thinning of the Chert Beds at Little Beach, near Branscombe and ascribed this to intra-formational erosion. This erosional phase was also invoked to explain the 'brecciated beds' seen in the area. On the Dorset coast Tresise described the eastward thinning of the Upper Greensand which, he felt, was partly due to the corresponding thickening of the underlying Gault Clay and partly to the condensation of the upper beds of the Upper Greensand. He pointed out the absence of the Chert Beds in the Isle of Purbeck and their reappearance and gradual increase in thickness to the west indicating the presence of a 'Mid-Dorset Swell'.

Tresise constructed a series of lithofacies maps for the Upper Greensand based on distance below the Chalk. He used these maps to give a history of deposition but in places seemed to confuse diagenetic events with sedimentary events, even though he had previously pointed out the difference. Furthermore, as subsequently pointed out by Drummond (1961) he used the diachronous base of the Chalk as his datum and thus largely invalidated them as lithofacies maps.

Smith and Drummond (1962) pointed out the easterly thining of the Chert Beds at Snowdon Hill and Warren Hill which continued, with the result that they did not occur at Evershot. At this locality the top calcareous sandstone rested on the 'Exogyra Rock'. This thining of the Upper Greensand was believed to be the result of late Albian and early Cenomanian uplift and submarine erosion across a 'Mid-Dorset Swell'. The axis of this swell extended NW-SE from Stoke Wake to the Isle of Purbeck.

The transgressive nature of the Cretaceous Sea in south-west England was discussed by Hancock (1969). The progressive overstep of sediments was pointed out which during the Cretaceous extended from the Wessex Basin in the east onto the Cornubian Massif in the west. He suggested that the Haldon Hills and Bovey Basin outcrops marked the western shore during the Albian but mentioned its probable extent northwards, almost to the Mendips.

Kennedy (1970) agreed with Hancock (in House, 1963) and Drummond (in

Smith and Drummond, 1962) about the presence of a Mid-Dorset Swell which ran southwestward from the Evershot-Ansty region to the east of the Isle of Purbeck. He considered that this swell controlled the distribution of Lower Cenomanian and Upper Greensand deposits with the latter thinning out across the structure. Furthermore he demonstrated that the base of the Chalk progressively became younger to the west of the area.

Drummond (1970) thought that the marked thining of the Albian and Cenomanian deposits in Wessex proved the existence of the mid-Dorset swell and he considered that movements along the swell resulted in the cessation of *Mortoniceras inflatum* Zone sedimentation and caused condensation and erosion in the succeeding *Stoliczkaia dispar* Zone. These movements were also thought to be largely responsible for the erosional break between the Upper Greensand and the Lower Chalk.

Some of the publications reviewed in this section will be subsequently discussed in more detail where they are particularly relevant.

3.3 Facies Descriptions

3.3.1 Facies Definition

The term facies has been used in many different senses (see Moore, 1949; Weller, 1958; Teichert, 1958; Krumbein and Sloss, 1963 and Middleton, 1973 and 1978; Walker, 1984 for discussion). Middleton (1978) quoted de Raaf *et al.* (1965) as an example of the correct use of facies. These authors defined each facies objectively using "the total field aspect" of the rocks and then made environmental interpretations of each facies. Middleton considered this methodology to be in accordance with the intentions of Gressly (1838) when he propounded the concept of facies. Teichert (1958), however, after careful referral back to Gressly's work and that of many other European geologists in the 19th century considered that the original intention regarded facies as the sum total of all the primary characteristics of a sedimentary rock from which the environment of deposition may be induced. This latter definition of facies was adopted for use during this work, and in line with Harms *et al.* (1982), it was considered that facies divisions should be kept broad in such a way that small differences were not used to produce a plethora of facies types.

The recognition of those attributes used for facies determination depended on observation and to a certain extent were subjective in the sense that the observer decided which attributes were important. In order to remove this potential subjectivity as far as possible the definition of facies types was arrived at by means of a checklist. The attributes used for this checklist were taken from the descriptions of each unit which were made from field observations, hand specimens and thin sections.

The justifications for the selection or non-selection of the attributes are presented below.

Colour - This attribute was not used as it is susceptible to variation with local diagenetic and weathering events.

Composition - Obviously a large number of categories could have been used for this attribute, involving all occurring minerals and their various percentages. As all units were not examined in thin section the occurrence of minerals of less than 20% was generally not included. The compositional elements used were: clay minerals (>63 fraction), quartz, detrital calcite and glauconite. These elements were split into arbitary percentage classes (20-40%; 41-60%; 61-80%; 81-100%) in order to reflect their importance in a given unit. Composition was included not because it is a direct indicator of depositional events but because it is linked to grain size and mineral availability. However some authigenic minerals such as glauconite do indicate environment.

Cement - The subjective categories of poorly, moderately and well cemented were not used as these were both not measurable objectively and liable to be affected by local weathering conditions. The mineral responsible for cementation was not used as an attribute as it would not reflect a depositional event.

Maximum Grain Size - This parameter was used as it is a reflection of the energy level involved in the depositional event. Where thin bands occurred within units these were recorded seperately.

Sorting - Used in the slightly subjective categories of very poorly sorted, poorly sorted, moderately sorted and well sorted. This feature also reflected the energy level involved in the depositional event.

Grain Shape - Grain shape does not directly reflect the depositional environment of a given unit but is a measure of the sedimentary history of a given mineral grain taking into account it's hardness and other characteristics. This parameter was, therefore, not used as an attribute.

Bed Contacts - The type of bed contacts between units are a direct reflection of the depositional environment prevailing when these units are laid down. These parameters were therefore used as attributes.

Sedimentary Structures - Obviously important as by definition they reflect depositional events or events immediately following sedimentation.

Bioturbation - Not in itself an indicator of depositional mechanism but an important indicator of rate of sedimentation and overall depositional environment (Seilacher, 1967, 1973) and as such was used as an attribute.

Comments - Where observations were made that did not fit into the above categories but were felt to reflect depositional mechanisms these were used as attributes.

3.3.2 Location Details

Sections in the Wessex Greensand Formation were examined from the following localities:

Branscombe Mouth to Beer Head and Pounds Pool; located at SY210882 to SY229885 (Fig. 3.1). This section is designated as the type section for both the Foxmould Sands Member and the Chert Beds Member. It is located on the coast to the east of Branscombe Mouth and with a low tide can be examined as far as The Hall at the eastern end of Pounds Pool. The Wessex Greensand Formation in this area rests on the red and

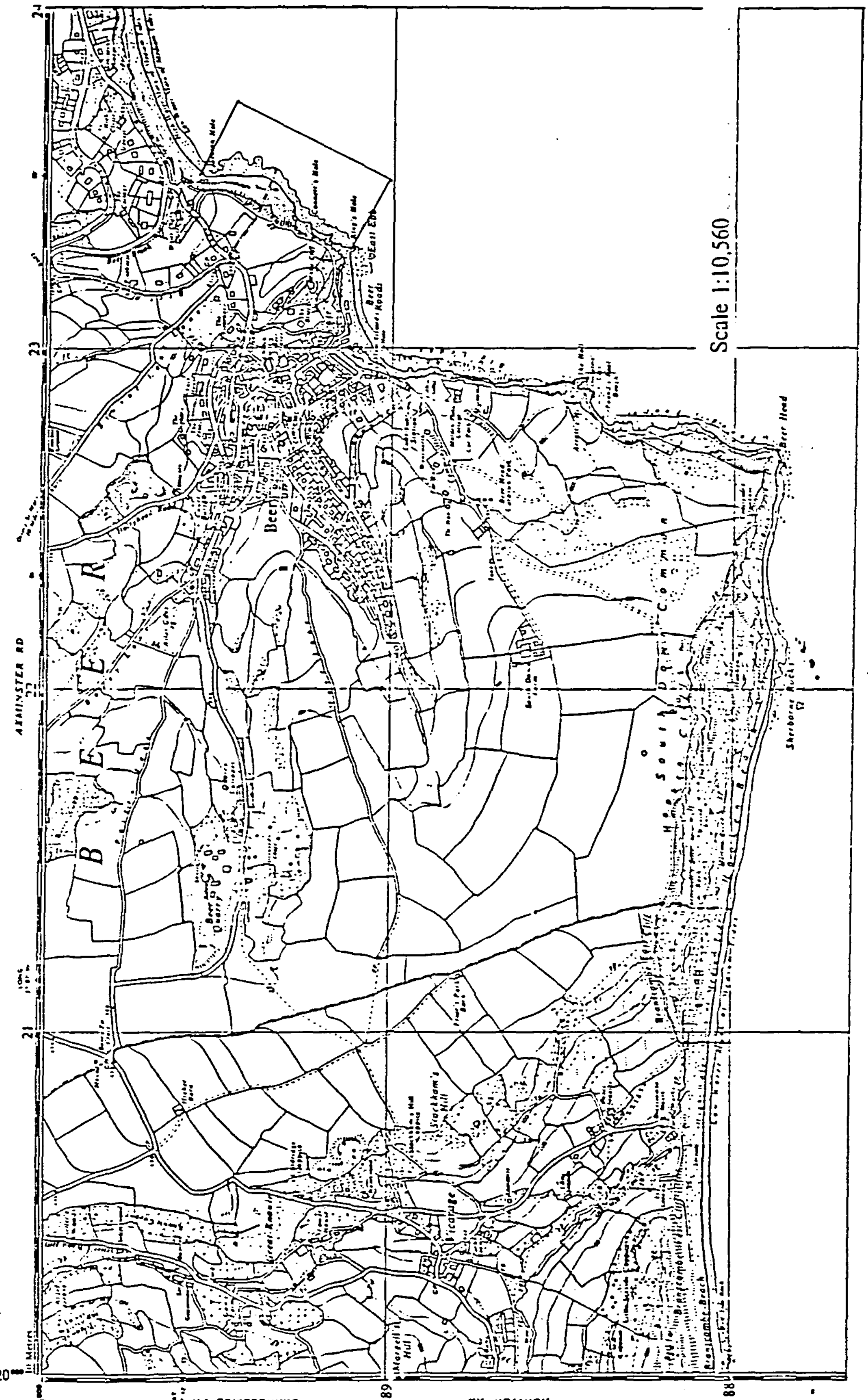


FIG. 3.1: LOCATION MAP: BRANSCOMBE MOUTH TO BEER HEAD AND POUND'S POOL AND WHITECLIFF, SEATON.

green clays of the Triassic Mercia Mudstone Formation but the actual contact is often obscured by slumped and slipped material which has a heavy vegetation cover. As far east as the weathered Chalk peaks, known as 'The Pinnacles', direct access to the Wessex Greensand is difficult and is confined to small cliffs on the foreshore. From 'The Pinnacles' to the eastern end of this area access is generally good with only one gap in the succession that is the result of slumping. There is a dip of about eight degrees to the east which brings progressively higher beds of the Wessex Greensand to beach level until at the eastern end of Pounds Pool the junction with the overlying Cenomanian Limestones is accessible.

Kempstone Rocks, Dunscombe; located at SY881161 (Fig. 3.2); situated to the west of Branscombe Mouth approximately half way along the coastal footpath to Sidmouth. Only the topmost beds of the Wessex Greensand were examined.

Whitecliff, Seaton; located at SY894234 (Fig. 3.1); coastal section which allows the examination of the Chert Beds Member and the Top Sandstones Member at very low tide but most of the Foxmould Sands Member is inaccessible due to slumping.

Small Quarry, Dunscombe; located at SY882157 (Fig. 3.2); situated to the west of Branscombe Mouth on the foot path to Dunscombe which leaves the coastal path and although it is partially overgrown a 2m section is accessible.

Graphic logs were drawn for each of these localities (Figs 3.3, 3.4, 3.5 and 3.6) and the rocks were then categorised into facies types

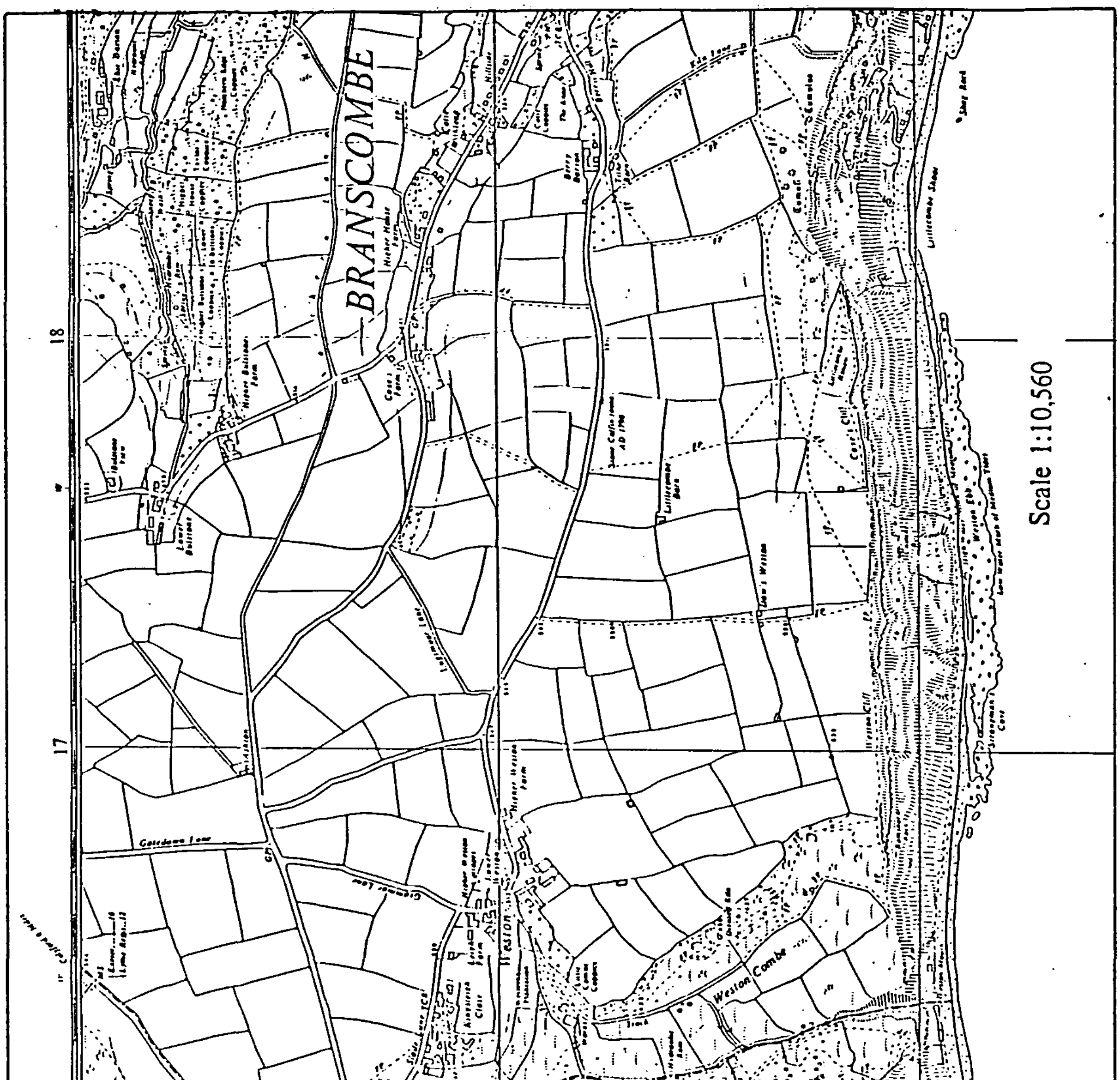
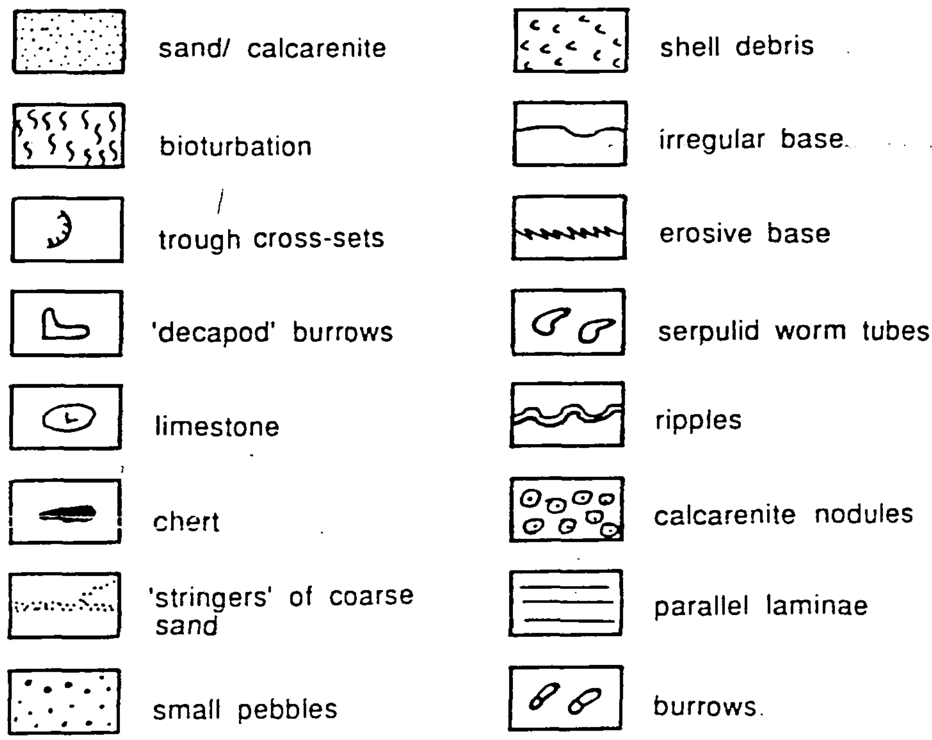


FIG. 3.2 LOCATION MAP: KEMPSTONE ROCKS AND SMALL QUARRY, DUNSCOMBE.

Legend


sand/ calcarenite
bioturbation
trough cross-sets
'decapod' burrows
limestone
chert
'stringers' of coarse sand
small pebbles
shell debris
irregular base
erosive base
serpulid worm tubes
ripples
calcarenite nodules
parallel laminae
burrows.

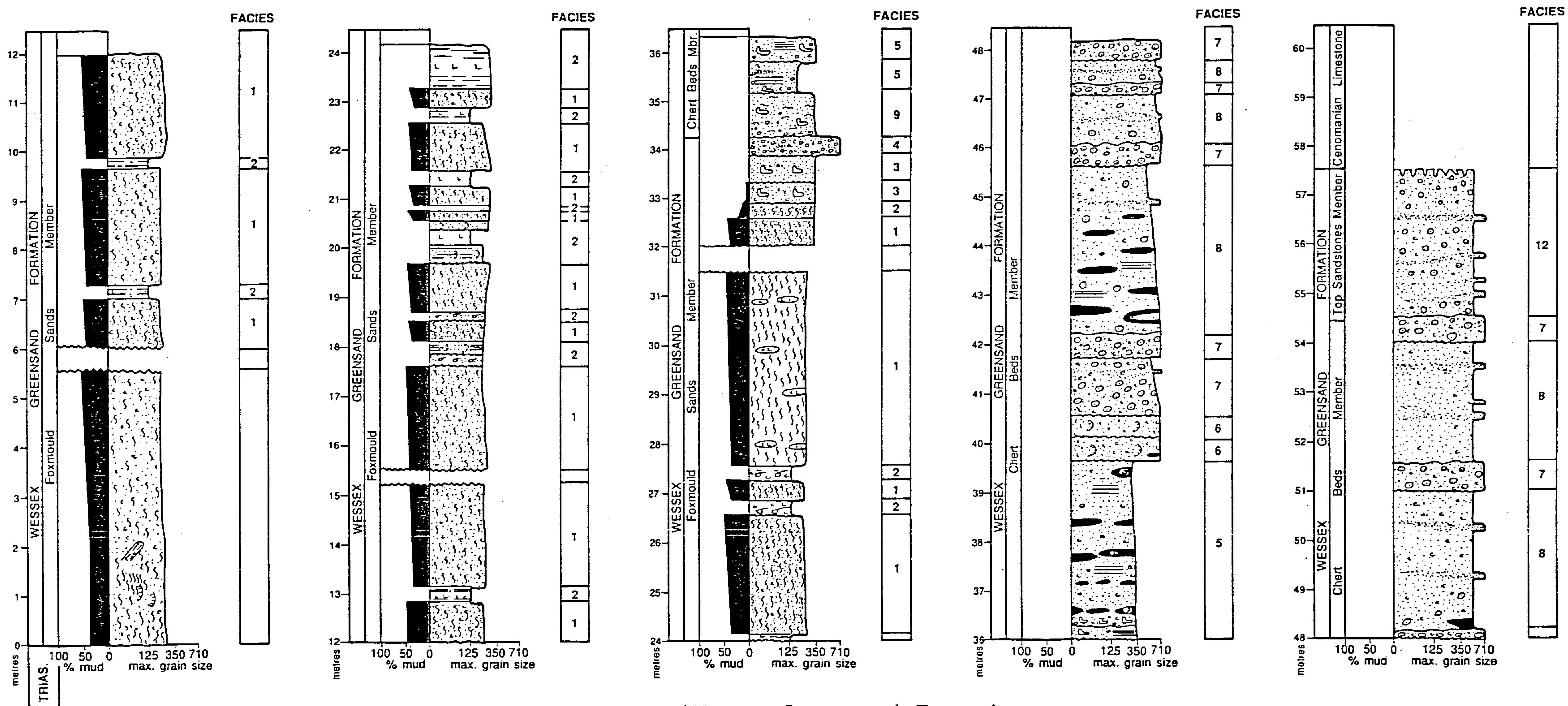


Fig. 3.3 Wessex Greensand Formation, Branscombe. S.E. Devon

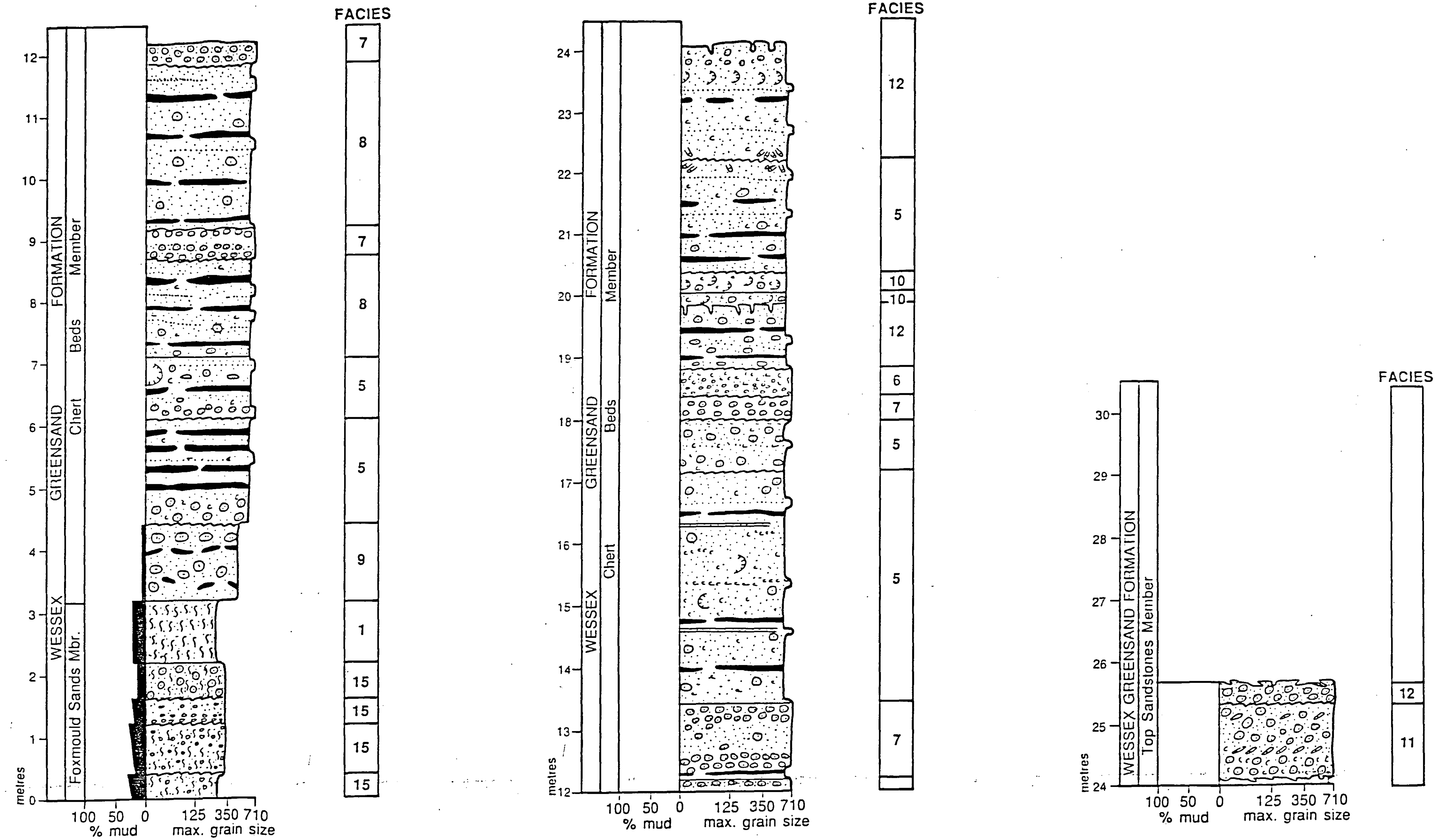


Fig. 3.4 Wessex Greensand Formation, Seaton S.E. Devon

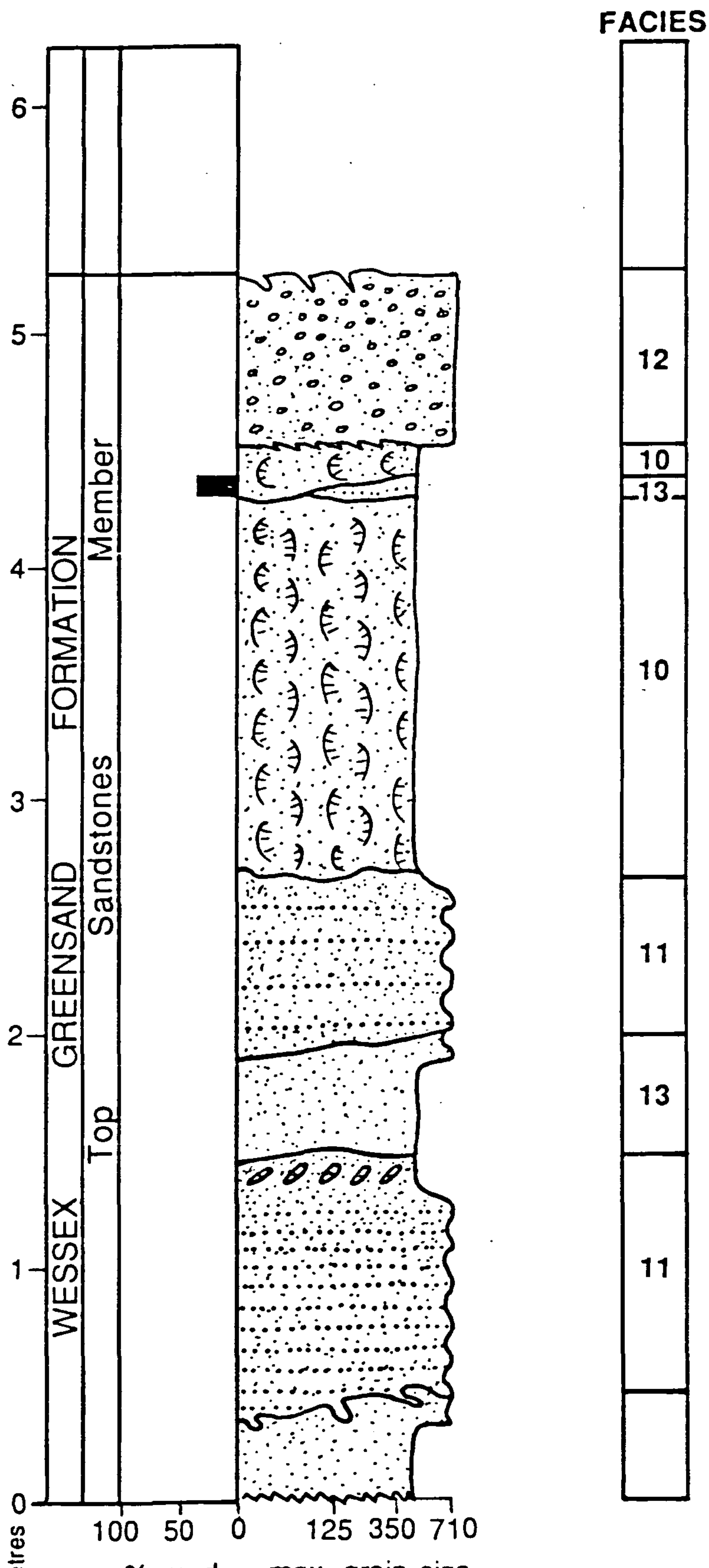


Fig. 3.5 Wessex Greensand Formation, Kempstone Rocks, Dunscombe, S.E. Devon

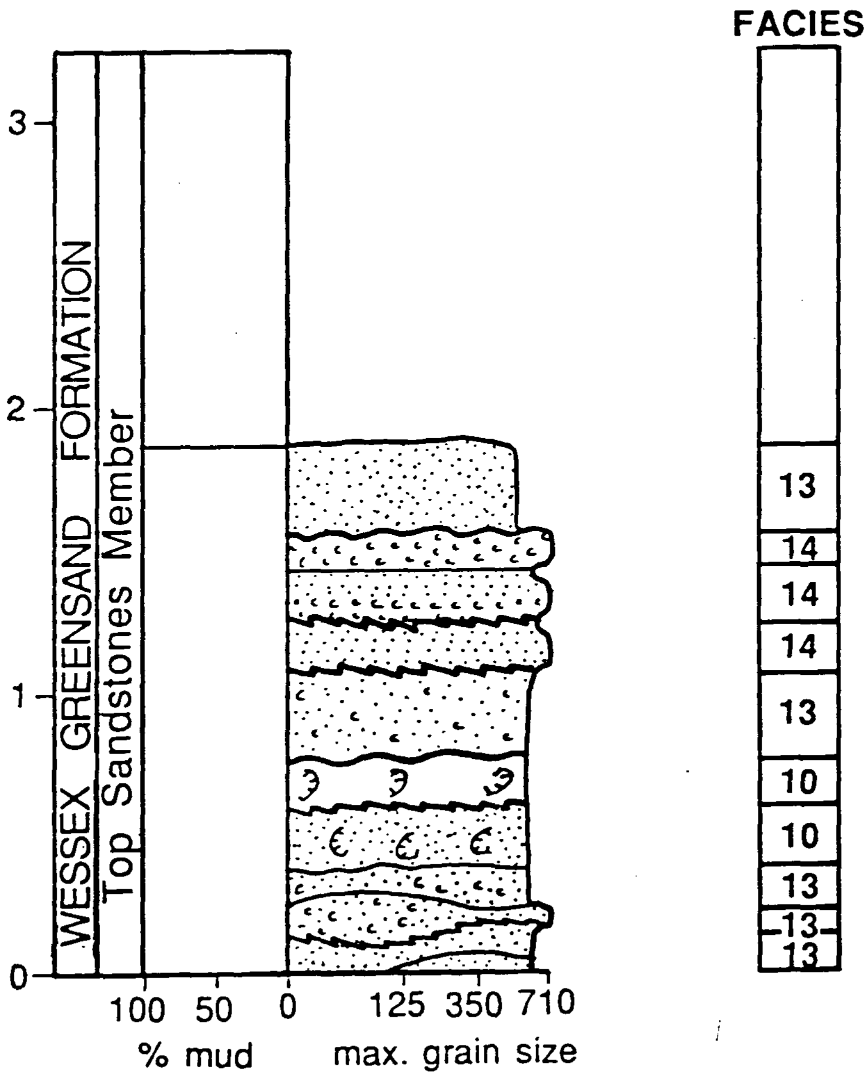


Fig. 3.6 Wessex Greensand Formation, small quarry nr. Dunscombe, S.E. Devon

which are described below.

3.3.3 Facies 1 (Fig 3.7)

Description: Green and grey, calcareous, glauconitic sands with a high (>20%) clay content. Generally the quartz content is 41-60%, the maximum quartz grain size is 250 μ., it is well sorted and moderately to well rounded.

Bed bases are planar or not seen, no sedimentary structures are evident, there is a high degree, of largely horizontal, bioturbation and common scattered shell debris (Fig. 3.8). The serpulid *Rotularia concava* (J. Sowerby) occurs commonly often with *Exogyra* sp..

In thin section (Fig.3.9) the dominant detrital mineral is quartz with glauconite and calcite as the other major constituents (after mud has been removed). Calcite cement occurs in most of the samples and the absence of cement in some samples could be due to recent weathering. In some samples evidence of corrosion of quartz grains can be seen and some quartz detritals show rutile and acicular tourmaline inclusions. Rock fragments of both megacrystalline and microcrystalline quartz occur and some of these grains show undulose extinction indicating that the quartz has been strained and came from a metamorphic source. Calcite generally occurs as organic fragments and glauconite as rounded grains which may show signs of corrosion. Muscovite, zircon and plagioclase feldspar occur as accessory minerals and there are rare tourmaline, biotite, rutile, sphene and microcline feldspar grains.

FIG. 3.7: FACIES 1: FOXMOULD SANDS MEMBER, BRANSCOMBE.

FIG. 3.8: FACIES 1: FOXMOULD SANDS MEMBER, BRANSCOMBE.
BIOTURBATION AND THE SERPULID *Rotularia concava*.

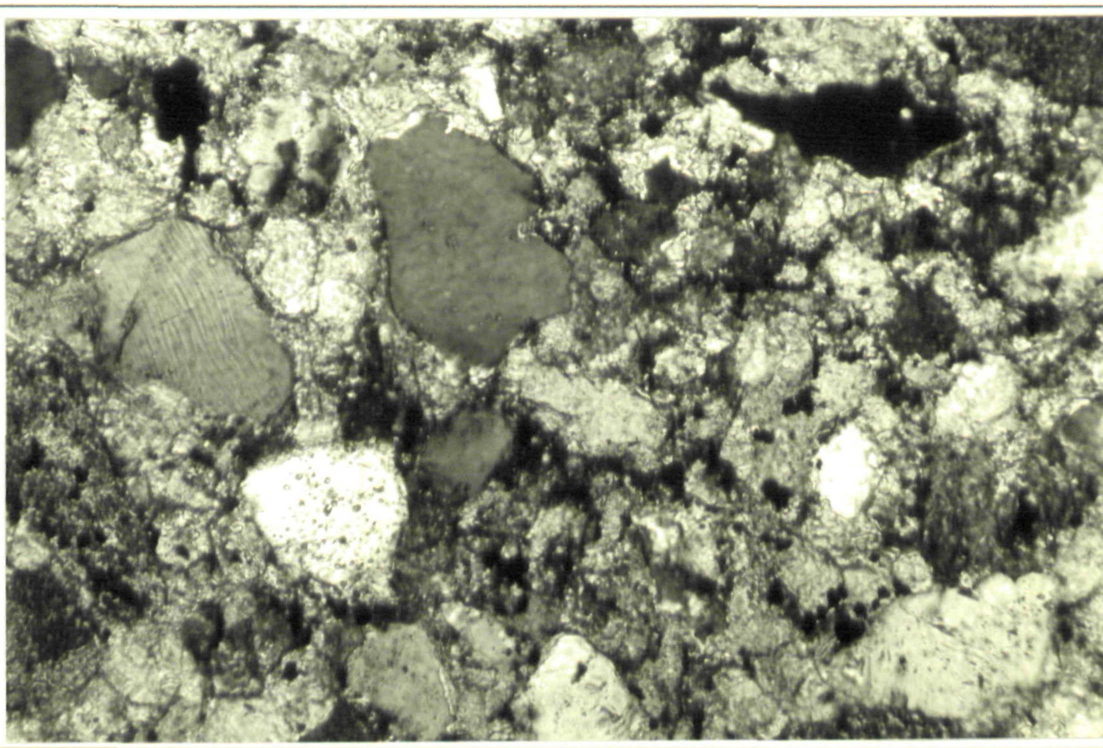


FIG. 3.9: FACIES 1: FOXMOULD SANDS MEMBER, BRANSCOMBE.
THIN SECTION SHOWING DETRITAL QUARTZ AND CALCITE
AND A LARGE GLAUCONITE GRAIN. (F.O.V. 6mm).

Variation: There is a certain amount of variation in the percentage composition of the major minerals; quartz content may be 20-40%, glauconite may be 20-40%, clay content may be 41-60% and shell debris is rare in some beds or occurs in discontinuous horizons. Quartz maximum grain size may be as small as 180 μ or as large as 350 μ. Some beds belonging to this facies contain fish scales and teeth and/or unidentified plant fragments (up to 0.5m long) in the form of black carbonaceous woody material more or less replaced by pyrite and marcasite. Marcasite nodules may also be seen in some beds. Bed thickness varies from 0.2m to some 4m.

Association: Strongly associated with Facies 2 (Fig.3.10)

Interpretation: The presence of planar bases and high clay content together with marine macrofossils and glauconite indicated a relatively low energy, marine environment.

This heterolithic facies, either mixed sand and mud or mud dominated, suggests that the suspension deposition of muds was the normal fairweather process of sedimentation (Aigner and Reineck, 1982). This low deposition rate together with low sediment transport rates and fairly low energy bottom conditions would have provided optimum conditions for glauconite formation (Hein *et al.*,1974). This probably proceeded by the chemical alteration of faecal pellets and/or clay minerals while trapped in a moderately reducing microenvironment. This is further suggested by the presence of marcasite and pyritised plant debris (Deer *et al.*, 1966). The water depth was probably 30-2000m and it's temperature less than 13 degrees celcius (Porrenga, 1967). Further constraints on the water depth are provided by the

FACIES	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	-3	10	0	0	-1	0	-2	-2	0	-1	0	-1	-1	0	1
2	9	-3	1	0	-1	0	-2	-1	-1	-1	0	-1	-1	0	0
3	0	0	0	1	-1	O	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
5	-1	-1	0	0	0	1	0	1	0	0	0	1	0	0	0
6	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0
7	-2	-2	0	0	0	1	-1	5	0	0	0	0	0	0	0
8	-1	-1	0	0	0	0	6	-1	0	0	0	-1	0	0	0
9	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
10	-1	-1	0	0	1	0	-1	0	0	0	0	1	2	0	0
11	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
12	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
13	-1	-1	0	0	0	0	-1	0	0	2	1	0	0	1	0
14	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
15	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

FIG. 3.10: FACIES ASSOCIATIONS: DIFFERENCES BETWEEN OBSERVED NUMBER OF TRANSITIONS AND PREDICTED NUMBER OF TRANSITIONS ASSUMING RANDOM DISTRIBUTION: FOR SECTIONS AT BRANSCOMBE, DUNSCOMBE AND SEATON.

Foraminifera which suggest a water column of 50-200m (Chapter 5).

In this type of environment periodic storm events often result in the deposition of thin (1-5cms) sandstone interbeds from suspension, sand lenses formed by current or wave processes and 1-3cm thick linsen bedding (Reading, 1978; Aigner, 1985). If this was the case here no evidence now remains in this facies as the intense bioturbation would have completely destroyed the thin sandstone structures and thoroughly mixed the sediment. This mechanism might, however, account for the clastic content of the sediment.

The largely horizontal burrowing indicates a preponderance of sediment feeders over suspension feeders (Frey, 1975) which in turn suggests deep water or low energy conditions (Seilacher, 1967). The abundance of bioturbation indicates a high organic content in the sediment which of itself is independent of water depth (Frey, 1971). The plant debris consisted of woody material, now largely pyritised, that had probably floated for some time, became waterlogged and sank to be incorporated into the sediment.

Whether or not the thin sand bodies postulated above occurred in this depositional environment the presence of both sand grade and clay grade material can be used as a guide to bottom current/wave mean flow velocity. Diagrams which depict the relationships between sediment size, mean flow velocity, bed phase boundaries and water depth are usually constructed largely using data collected from flume experiments. Necessarily this means that measurements are made at relatively shallow depths, due to the physical constraints on flume size, and it should be realised that extrapolating bed phase boundaries for much greater depths is dangerous (Harms *et al.*, 1982).

It is known that bed phase boundaries trend upward and to the right in depth/velocity diagrams (Fig.3.11) and that, therefore, the mean flow velocity needed to produce any given bed phase will be higher at greater flow depths. Bearing these limitations in mind some idea may be gained of the mean flow velocities extant in the depositional environment represented by Facies Type 1.

Other evidence suggests that the water depth was measurable in tens of metres and thus using Fig. 3.12 it can be seen that a mean flow velocity in excess of 20cm/sec would be needed to produce any movement of the sand grade material in this facies. Using Fig. 3.11 and remembering constraints of extrapolation to greater depths it can be seen that flow velocities in excess of 20cm/sec acting on sediment of 0.25mm diameter might be expected to produce small ripples, of the type postulated, with the limited amount of sand available.

Occcurrence: Occurs in the Foxmould Sands Member of the Branscombe and Seaton sections; see Figs 3.3 and 3.4.

3.3.3 Facies 2 (Fig.3.13)

Description: Grey, clay-free, sands and impure limestones. Generally the maximum quartz grain size is 180μ or 250μ. Calcitic debris is common and the sediment is well or moderately sorted. There is relatively little glauconite. Sedimentary structures are locally common and include parallel laminae (Fig. 3.14) and/or small cross-beds and/or small symmetrical ripples (Fig. 3.15). Bed bases are

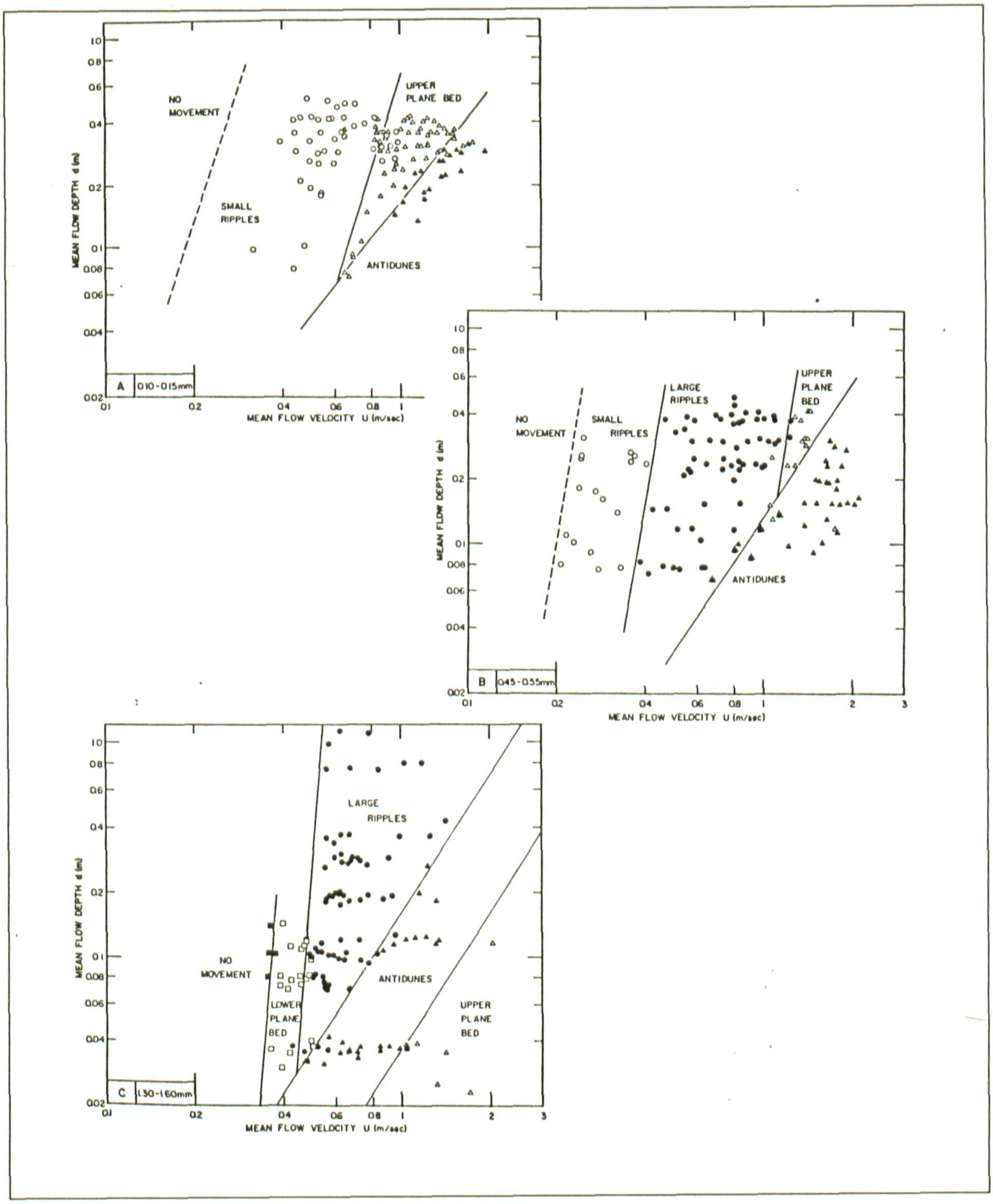


FIG. 3.11: DEPTH-VELOCITY DIAGRAM FOR THREE SAND SIZES. DATA HAS BEEN ADJUSTED TO A WATER TEMPERATURE OF 10 DEGREES C. (AFTER HARMS, 1982)

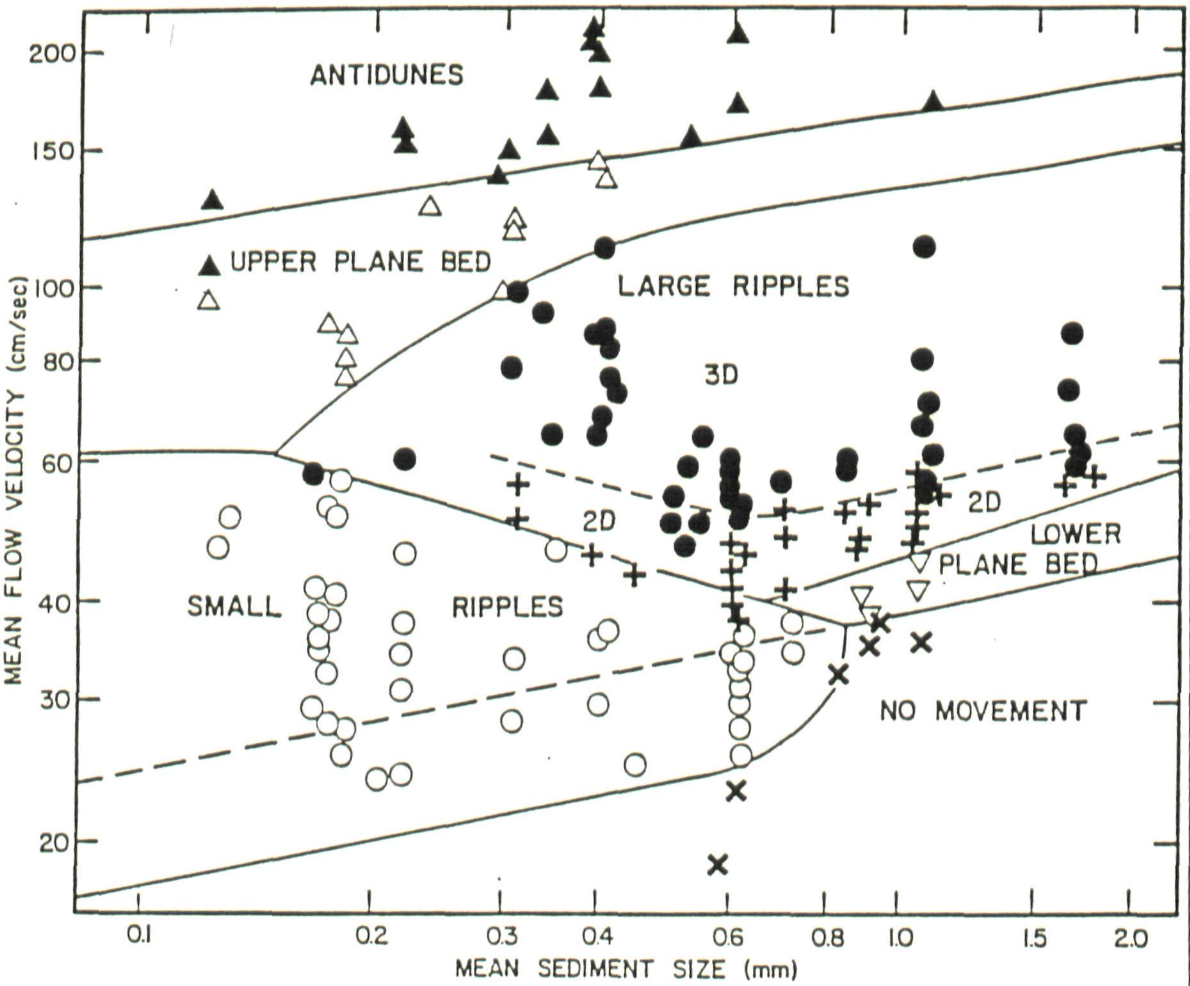


FIG. 3.12: SIZE-VELOCITY DIAGRAM FOR FLOW DEPTHS OF 18-22CMS. ALL DATA ADJUSTED TO A WATER TEMPERATURE OF 10 DEGREES C. (AFTER HARMS, 1982).

FIG. 3.13: FACIES 2: FOXMOULD SANDS MEMBER, BRANSCOMBE.

FIG. 3.14: FACIES 2: FOXMOULD SANDS MEMBER, BRANSCOMBE.

PARALLEL LAMINAE AND WAVE RIPPLES.

FIG. 3.15: FACIES 2: FOXMOULD SANDS MEMBER, BRANSCOMBE.
SMALL WAVE RIPPLES.

FIG. 3.16: FACIES 2: FOXMOULD SANDS MEMBER, BRANSCOMBE.
IMPURE LIMESTONE WITH *Rotularia concava*.

planar or erosive. Large numbers of serpulid worm tubes are often seen aranged in horizontal layers (Fig.3.16).

The impure limestones are bound by a secondary calcite cement but may contain close to 50% quartz detritals (Fig.3.17), whereas the sands vary from calcite cement to silica cement to almost no cement at all. Micas are present in accessory amounts but there is relatively little glauconite compared with Facies Type 1. The detrital quartz present in the samples is medium to fine-grained, fairly well-sorted and subangular to subrounded, although some samples showed a predominance of subangular grains.

Variation: Not all beds show sedimentary structures. Some of the sandy units contain vertical burrows (Fig. 3.18). Some of the impure limestones seen in this facies may be traced laterally as they grade into well cemented calcareous sandstone and then into an uncemented calcareous sand. Bed thickness varies from some cms to about 1m.

Association: Strongly associated with Facies 1 (Fig. 3.10).

Interpretation: The low clay content, erosive bases and sedimentary structures seen in this facies indicate a relatively moderate to high energy depositional environment.

This heterolithic facies is sand dominated although in some instances the bed could be dominated by calcite clasts rather than quartz. This type of deposit is regarded as being deposited from suspension and/or as bedload and is commonly inferred to be the product of intense storm conditions. In addition there may be variable reworking by current and

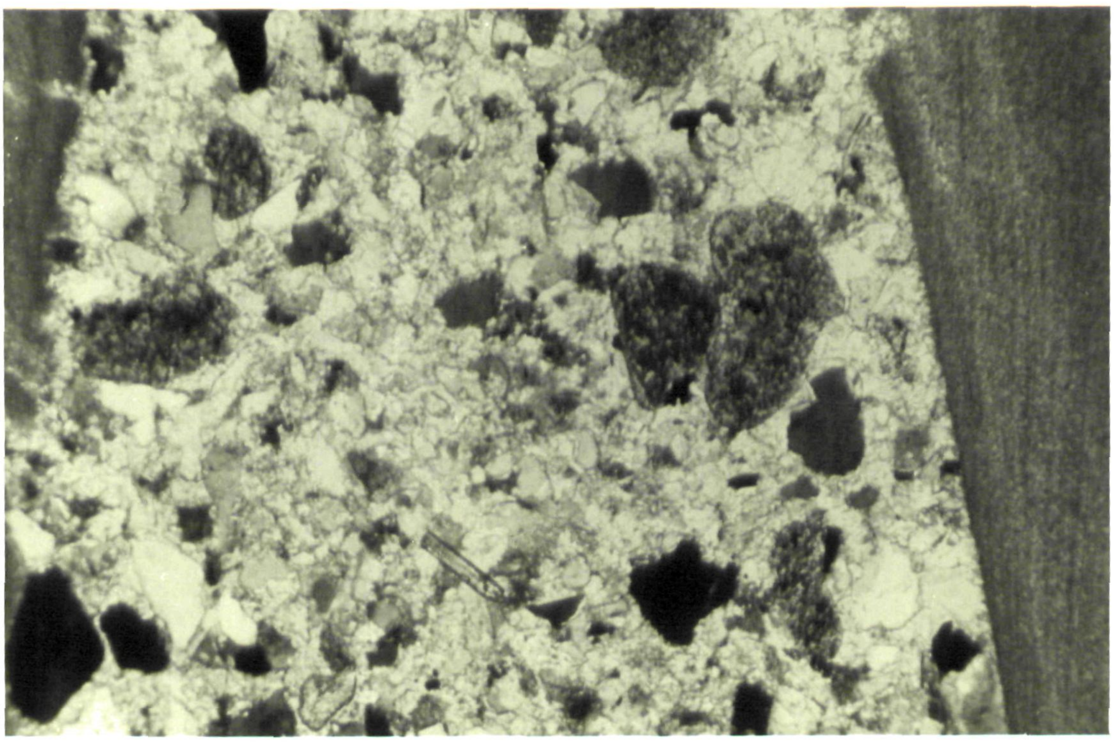


FIG. 3.17. FACIES 2: FOXMOULD SANDS MEMBER, BRANSCOMBE.

THIN SECTION SHOWING QUARTZ DETRITALS, GLAUCONITE AND CALCITE CEMENT. (F.O.V. 1.2 mm).

FIG. 3.18: FACIES 2: FOXMOULD SANDS MEMBER, BRANSCOMBE.

VERTICAL BURROWS.

wave ripples.

The beds observed in Facies type 2 often display parallel laminae which usually reflects upper flow regime conditions with possibly some deposition from suspension as the sand is lifted into the water column either by unidirectional currents or wave action (Reading, 1978; Allen, 1982, 1984).

The ripples show a variation in crest height (1-7mm) but are fairly evenly spaced (crest spacing 25-28mm). Individual ripples are symmetrical in cross-section but vary from a well rounded form to a flattened rounded form. This variation occurs both from ripple to ripple and along the crest of individual ripples. The ripple crest lines are parallel to subparallel and indicate water motion along a NW/SE vector.

The features exhibited by the ripples suggest both wave and current genesis (Amos and Collins, 1978; Clifton, 1976; Allen, 1982 Allen, 1981) that is they have a well rounded symmetrical form but show changes in crest height along their length. If an open coast and deep water wave are assumed the symmetric form indicates a water depth of >5m. In fact the depth was probably much greater, as indicated by the apparent high glauconite production seen in Facies Type 1 which occurs both above and below the rippled beds. The relative scarcity of burrows could be explained by the lack of mud and therefore of organic material available as food. The beds of Facies Type 2 were presumably too thick to be reworked by the resident infauna in the time available before further burial and it seems probable that after resumption of Facies Type 1 conditions the infauna recolonised the muds from further seawards.

The probable overall environment of formation for this facies was a high energy storm event generating offshore bottom currents and large onshore waves which reached below the normal wave base to the sediment/water interface (Reading, 1986; Aigner and Reineck, 1982; Aigner 1985). The currents probably carried a flood of detrital quartz and carbonate grains which were laid down in upper flow regime parallel laminae onto the eroded sea-floor (Allen, 1984). As the strength of the offshore currents diminished the bed tops were subjected to some current and wave reworking before the wave base returned to its normal position in the water column where it was unable to directly influence the bottom sediments.

Where increased clay content is observed towards the top of these units it probably reflected the return to normal bottom conditions as clay material lifted into the water column settled back out of suspension (Aigner, 1985). The cemented vertical burrows occasionally observed may represent attempts by suspension feeding organisms to colonise the substrate but presumably this became an unsuitable environment for them when mud deposition resumed.

Referring to Fig. 3.12 it may be seen that in order to produce upper plane bed parallel laminae in the range of sediment sizes found in this facies a mean flow velocity of over 60cm/sec would be necessary and in the larger grain sizes over 80cm/sec. These velocities are greater than those for normal condition currents (Fig. 3.19) and suggest storm surge conditions involving both bottom currents and wave action.

Transporting agency	Typical speed (m s^{-1})
Mass flows	
creeping soils	1×10^{-9}–3×10^{-8}
rock slides/avalanches	$\lesssim 10.0$
debris flows	$\lesssim 1.0$
Rivers	
normal flow stages	0.5–1.0
flood stages	1.0–5.0
Wind	
breeze	1.0
gale/hurricane	10.0–20.0
Wind-generated waves	
maximum orbital velocity	$\lesssim 1.0$
Tidal currents	
open ocean	0.01–0.1
offshore in restricted sea	0.5
estuaries	$\lesssim 3.0$
Oceanic currents	
thermohaline	0.1–1.0
wind-generated	0.1–0.5
storm surge	$\lesssim 1.0$
Turbidity currents	
small, low concentration	0.1–1.0
large, high concentration	1.0–10.0
Glaciers	
at equilibrium	3×10^{-7}–3×10^{-6}

FIG. 3.19: TYPICAL SPEEDS OF THE MAIN SEDIMENT TRANSPORTING AGENTS.

(AFTER ALLEN, 1984).

Occurrence: Occurs in the Foxmould Sands Member of the Branscombe section; see Fig.3.3.

3.3.3 Facies 3 (Fig. 3.20)

Description: Grey, calcareous, medium grained, moderately sorted sandstones which may be packed with shell fragments and/or exhibit linear concentrations of glauconite grains. Beds have erosive bases and contain hard, irregular, hollow concretions suggestive of decapod burrows. Iron stained veins are common.

Variation: Beds vary in thickness from 0.4m to 0.6m.. Shell debris may be abundant or rare.

Association: No marked association due to low occurrence.

Interpretation: The presence of erosive bases and the lenses and 'stringers' of coarse sediment suggests a relatively moderate to high energy environment.

This facies appears to be similar to Facies Types 9 and 5 and the processes involved in the formation of the coarse lenses and 'stringers' were probably those described for Facies Type 8 with Facies Type 3 probably representing a more distal expression of Type 8.

Referring to Fig. 3.11 for an approximation of the mean flow velocities involved in the deposition of this facies suggests that the bulk of the beds were laid down in velocities greater than 30cm/sec

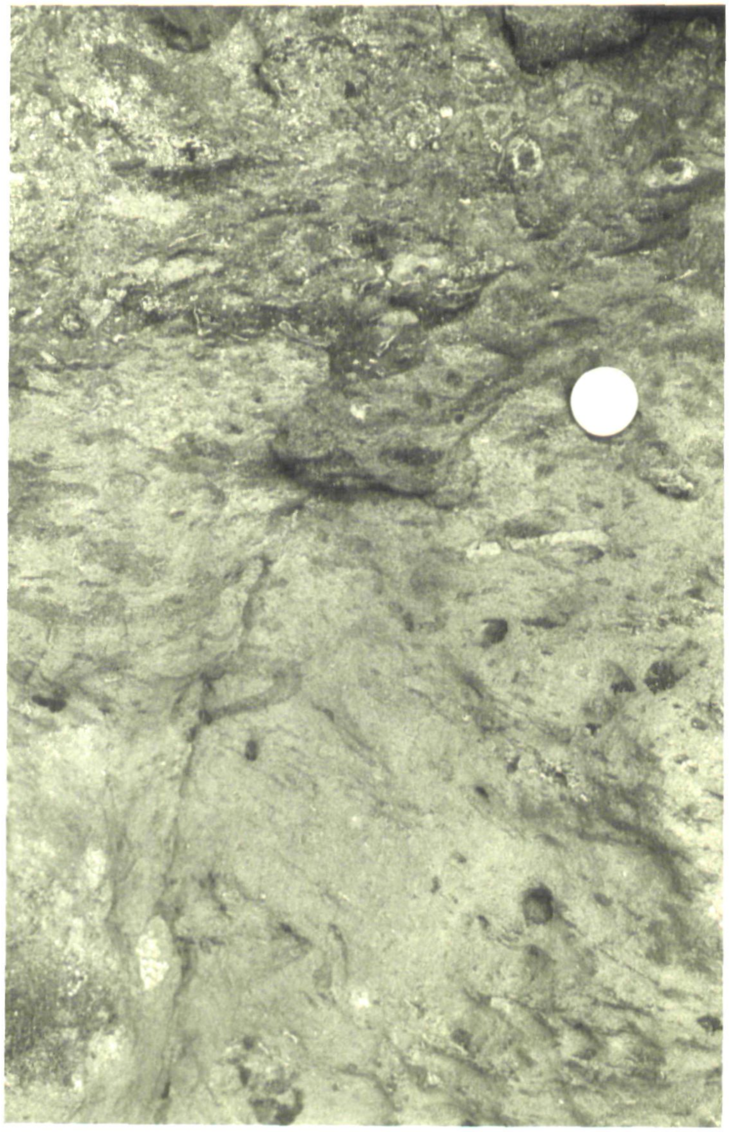


FIG. 3.20: FACIES 3: FOXMOULD SANDS MEMBER, BRANSCOMBE.

while the coarser horizons were deposited by higher velocities of the order of 1m/sec. These figures are extremely tentative as no internal sedimentary structures were observed that could be used as a guide to the type of deposition.

Occurrence: Occurs in the Foxmould Sands member of the Branscombe section; see Fig. 3.3.

3.3.3 Facies 4 (Fig. 3.21)

Description: Coarse grained, well rounded, glauconitic sands with abundant organic debris and sub-rounded clasts of a medium grained sandstone with a much lower glauconite content. Small encrusting bryozoa can be seen near the irregular bed top and the bed base is erosive.

Variation: Only one bed visible for a limited lateral extent.

Association: No marked association due to low occurrence.

Interpretation: The erosive base, large grain size, poor sorting and the presence of abundant intraformational clasts all suggest relatively high energy conditions.

This facies is sand dominated but displays no internal structure being essentially made up of a jumble of partially rounded intraformational clasts infilled with coarse sand. The presence of encrusting bryozoa on the irregular bed top suggests that sedimentation ceased for some time allowing the suspension feeders time to colonise.

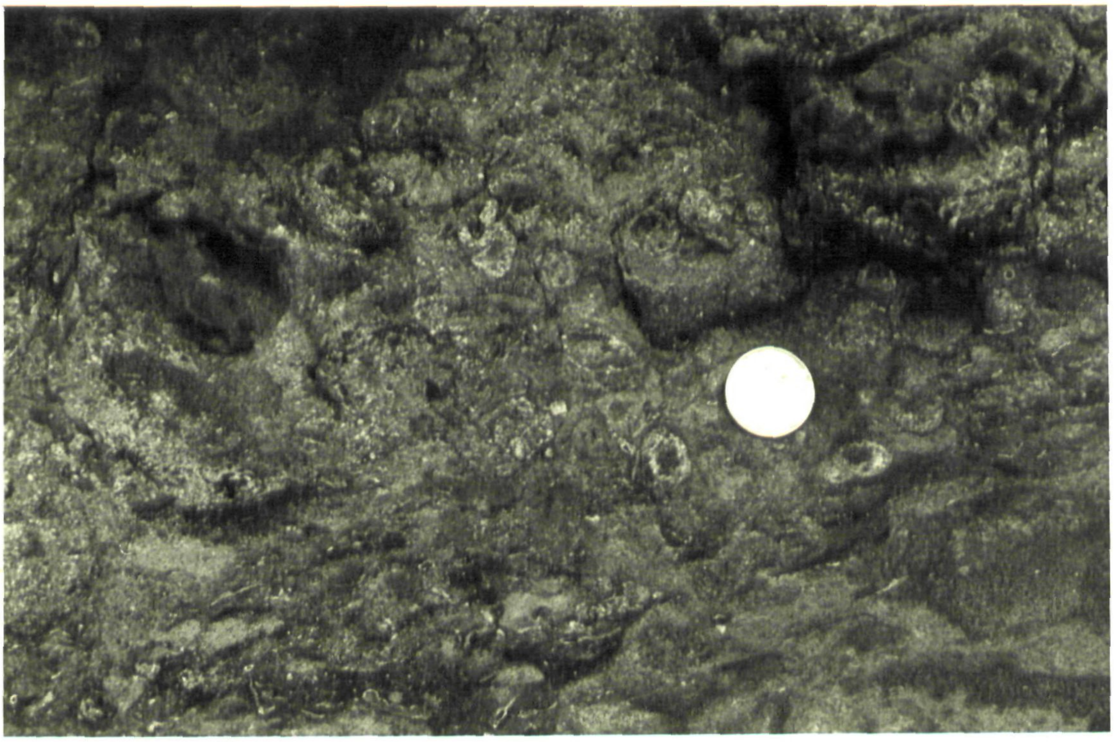


FIG. 3.21: FACIES 4: FOXMOULD SANDS MEMBER, BRANSCOMBE.
SHOWING ABUNDANT SHELL DEBRIS AND INTRAFORMATIONAL CLASTS.

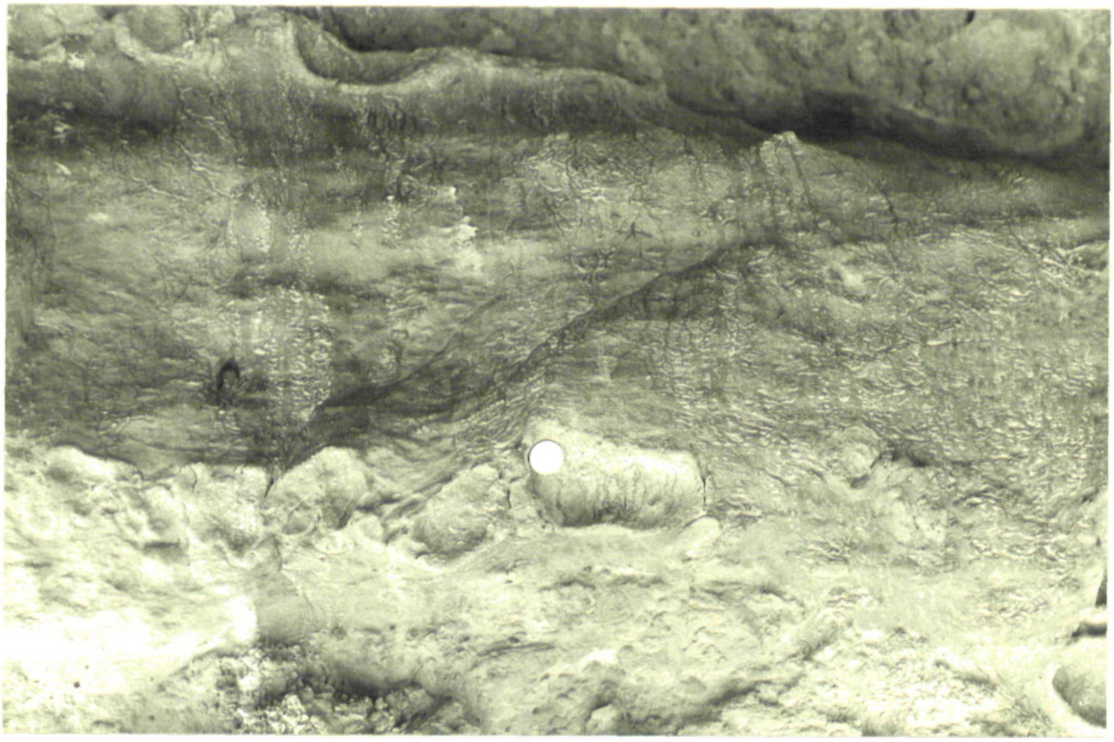


FIG. 3.22: FACIES 5: CHERT BEDS MEMBER, BRANSCOMBE.
CALCAREOUS SANDS WITH 'DECAPOD' BURROWS.

Local erosion must have occurred to produce the intraformational clasts and the energy required to create these clasts and transport them must have been considerable. They probably represent sediment that was not fully cemented and thus relatively easily rounded. Using Fig. 3.11 as a guide it is probable that bottom mean flow velocities in excess of 1m/sec were involved and these were probably generated by extreme storm surge wave and current conditions.

Occurrence: Occurs in the Foxmould Sands Member of the Branscombe section; see Fig. 3.3.

3.3.3 Facies 5 (Fig. 3.22)

Description: Massive, buff calcareous sands which are moderately sorted and medium grained. They have erosive or irregular bases and display patches and horizons (1-3mm thick) of coarse quartz grains, glauconite and heavy minerals which may persist laterally or form anastomosing patterns. The 'decapod burrow' concretions seen in facies 9 and 3 are locally common. The quartz detritals seen in this calcarenite tended to be angular and etched (Fig. 3.23). Glauconite was relatively rare and 'cherty' microquartz grains occurred especially in horizons that had an incipient quartz cement. Abundant comminuted calcitic debris was present together with some larger shell debris.

Variation: This facies may contain nodular /tabular dark brown to black cherts (Figs 3.24, 3.25). These cherts tend to be laterally impersistant and often display a hard white envelope of siliceous material. Shell fragments, bimodal cross-sets, parallel laminae and

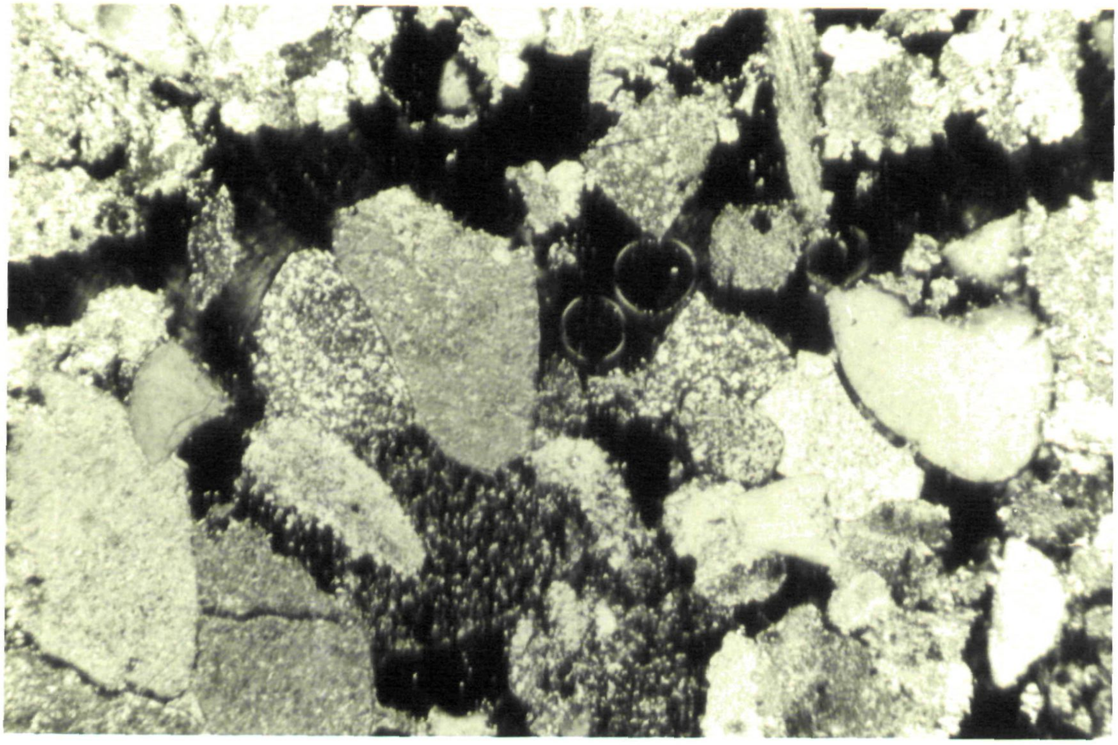


FIG. 3.23: FACIES 5: CHERT BEDS MEMBER, BRANSCOMBE.
THIN SECTION SHOWING ETCHED, ANGULAR QUARTZ AND CALCITE DEBRIS (F.O.V. 1.2 mm).

FIG. 3.24: FACIES 5: CHERT BEDS MEMBER, BRANSCOMBE.
IRREGULAR CHERT BED.

FIG. 3.25: FACIES 5: CHERT BEDS MEMBER, BRANSCOME.

DISCONTINUOUS CHERTS.

coarse, well rounded quartz grains are all seen preserved within cherts (see Chapter 4). Shell debris is seen in varying amounts together with echinoid spines and bryozoan fragments. Some beds appear more nodular than massive and some are coarser grained and well sorted.

Association: No marked association (Fig. 3.10).

Interpretation: The erosive bases, sedimentary structures and coarse 'stringers' all suggest a moderate to high energy environment.

This clastic facies has elements of both the cross-bedded and flat-bedded subfacies. The small trough cross-sets preserved within cherts probably represent megaripples and they can be seen in some instances to be bimodal, suggesting a tidal origin. The parallel lamination may have been wave and/or current formed under high energy conditions. A discussion of the origin of the lenses and 'stringers' of coarse material is to be found in the analysis of Facies Type 8.

Using Fig. 3.11 a mean flow velocity of around 80cm/sec would have been needed to produce these structures with velocities in excess of 1m/sec needed to produce the coarse horizons probably with an element of winnowing.

The overall picture for this facies is of a moderate to high energy bottom environment with both tidal and stronger storm surge currents transporting the calcarenite as megaripples and by suspension to produce the parallel laminae. The coarse horizons represent relatively short lived higher energy events while the presence of 'decapod' burrows suggests that bottom conditions could be relatively stable at least long enough for the burrow-making organisms to colonise the area.

Occurrence: Occurs in the Chert Beds Member of the sections at Branscombe and Seaton; see Figs 3.3 and 3.4.

3.3.3 Facies 6 (Fig. 3.26)

Description: Coarse grained, very poorly sorted sands/calcarenites (approximate composition 20-40% quartz; 61-80% detrital calcite) with abundant, large shell fragments and debris (Fig 3.27). Beds in this facies tend to fine upwards and have highly erosive bases (Fig. 3.28).

Variation: Cross-bedding may be seen in beds belonging to this facies. Around 0.3m thick (Branscombe).

Association: No marked association (Fig. 3.10).

Interpretation: The coarseness of the sand, the poor sorting, the abundance of coarse shell debris and the erosive bases to the beds together suggests a high energy depositional environment.

The fining upwards indicates a gradual decline in energy level which is supported by the parallel laminae near the base of the bed giving way upwards to barely discernable, small, trough cross-sets (10cm maximum set thickness) (Allen, 1983).

Using Fig 3.11 it seems probable that maximum velocity flows of the

FIG. 3.26 FACIES 6: CHERT BEDS MEMBER, BRANSCOMBE.

STORM UNITS.

FIG. 3.27: FACIES 6: CHERT BEDS MEMBER, BRANSCOMBE. STORM UNIT.

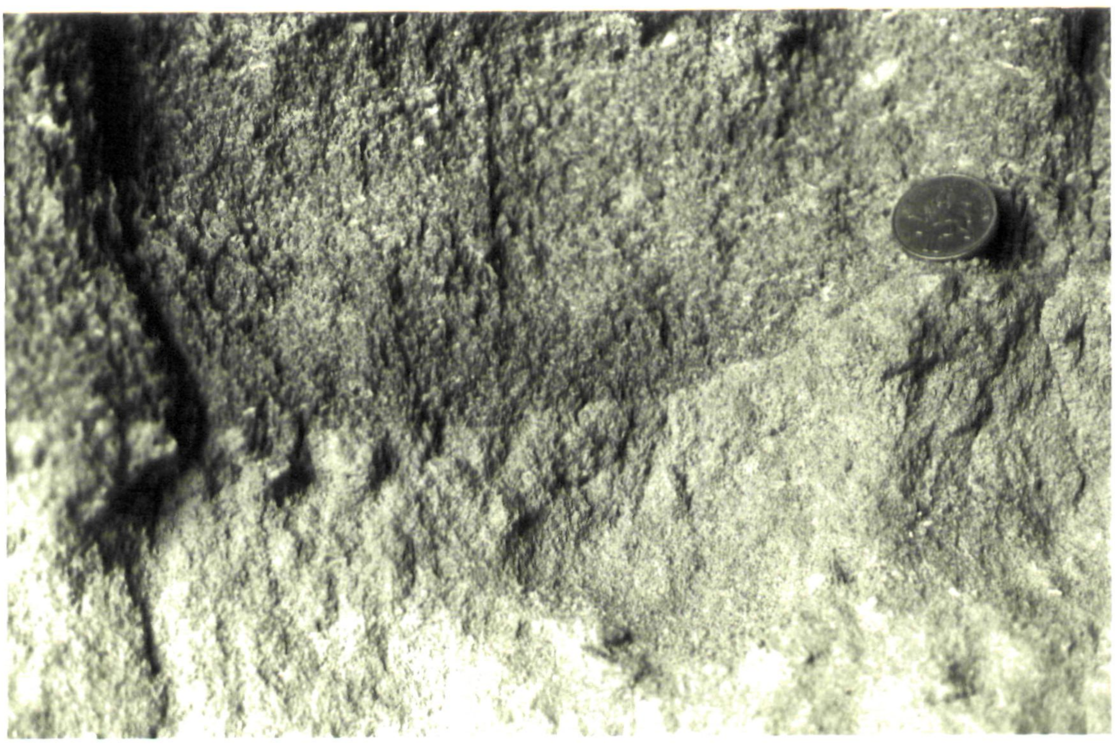


FIG. 3.28. FACIES 6: CHERT BEDS MEMBER, BRANSCOMBE.

EROSIVE BASE OF STORM UNIT.

order of 1m/sec were involved at the outset of this energy event which then declined in intensity. A high energy storm event was probably responsible for these deposits either by storm waves 'touching bottom' and creating a lag coquina deposit (Brenner and Davis, 1973, Aigner, 1985) and/or by means of an offshore storm surge density current, probably in conjunction with wave activity, being erosive, winnowing and transporting sediment and organic debris from nearer shore (Walker, 1979).

Occurrence: Occurs in the Chert Beds Member of the sections at Branscombe and Seaton; see Figs 3.3 and 3.4.

3.3.3 Facies 7 (Fig. 3.29)

Description: Irregular, nodular/cobble beds with erosive bases. The matrix between the cobbles consists of coarse, poorly sorted sands with angular/sub-angular quartz grains, glauconite and heavy minerals. The nodules largely consist of calcareous detrital material, the bulk of which is fine to medium grained, fairly well sorted and subangular to subrounded (Fig. 3.30). Individual grains of quartz are often etched and corroded. There is also a small amount of glauconite, rare feldspar (usually being replaced by calcite), rutile, sphene, mica and polycrystalline quartz rock fragments which often show undulose extinction and have numerous inclusions and vacuoles which suggests a metamorphic source. In addition calcite grains are found which have been partially replaced by microquartz crystals.

The matrix between the nodules is made up of two distinct sands; a light grey calcarenite which exhibits varying degrees of calcite

FIG. 3.29: FACIES 7: CHERT BEDS MEMBER, BRANSCOMBE.

NODULAR, CALCAREOUS SANDS.

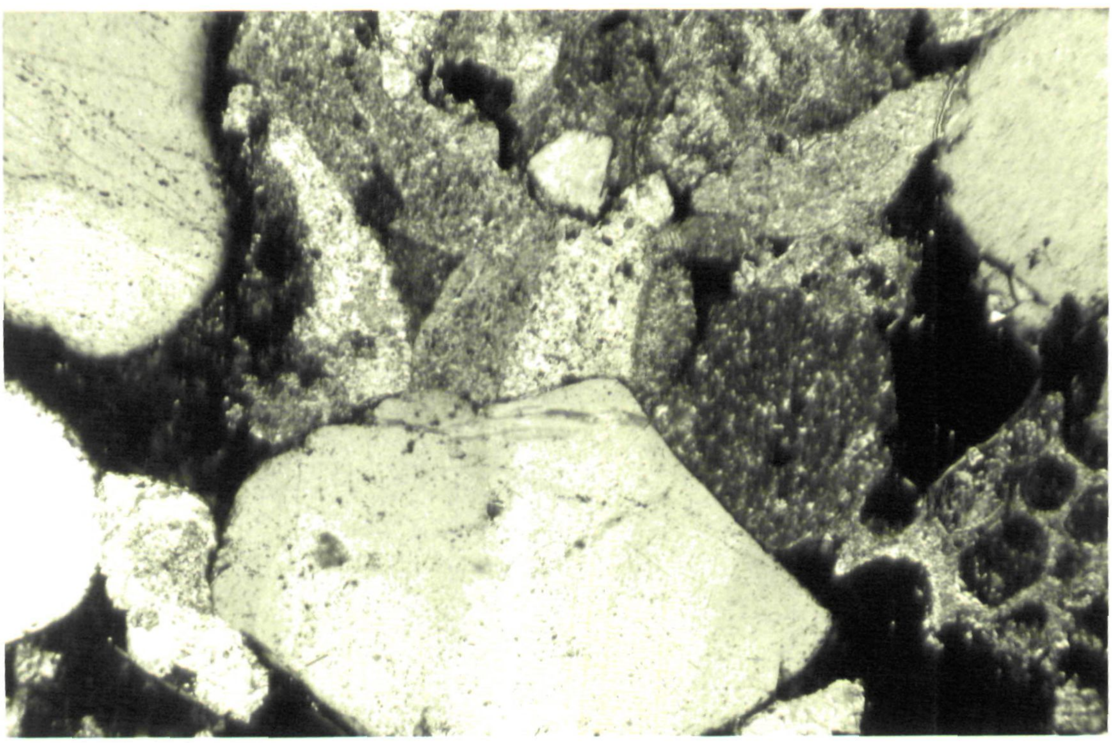


FIG. 3.30. FACIES 7: CHERT BEDS MEMBER, BRANSCOMBE.

THIN SECTION SHOWING CALCITE AND QUARTZ DETRITALS

(F.O.V. 1.2mm).

cementation and a second sand type which contains relatively little calcite, is poorly sorted, poorly cemented and contains large numbers of coarse, rounded to subrounded quartz grains (Fig. 3.33). This sand also often contains abundant coarse shell debris (Fig. 3.31).

Variation: The beds in this facies vary in thickness from 0.5m to 1.2m (Branscombe). The amount of shell debris varies and it may occur in extremely shell-rich horizons. The cobbles vary in size from <1cm. to 30 cms. Fish teeth may be seen in the matrix sands and some beds have symmetrically rippled tops. Shattered and flexed tabular sands may be seen (Fig. 3.32).

Association: Shows a marked association with Facies 8 (Fig. 3.10).

Interpretation: The erosive bases, abundant intraformational clasts and coarse poorly sorted matrix all indicate a very high energy level.

All the constituents of this facies also occur in the much more vertically extensive Facies Type 8 from which they were probably largely derived. The original calcarenite was probably in the initial stages of lithification when it was eroded by the high energy event (Garrison *et al.*, 1987). These lithified units were torn loose from the sea-bed and reworked but were probably not transported very far, if at all, before the energy level dropped.This resulted in the jumbled mass of rounded and/or tabular calcarenites mixed-up with their uncemented equivalents with the coarser grained matrix and the larger organic fragments being transported in from nearer the shoreline or winnowed out of the coarse horizons seen in Facies Type 8.

FIG. 3.31: FACIES 7: CHERT BEDS MEMBER, BRANSCOMBE.

COARSE, NODULAR, SHELLY BED WITH WAVE RIPPLED TOP.

FIG. 3.32: FACIES 7: CHERT BEDS MEMBER, BRANSCOMBE.

SHATTERED AND FLEXED TABULAR SANDS.

FIG. 3.33. FACIES 7: CHERT BEDS MEMBER, BRANSCOMBE.

COARSE MATRIX SAND AROUND NODULAR,

CALCAREOUS SAND.

The energy event was certainly stronger than the generally prevailing conditions and was probably caused by a storm of unusual magnitude which produced wind-driven onshore waves and/or powerful offshore bottom density currents (Walker, 1979). The top surfaces of the beds are often irregular as might be expected, but are sometimes capped by thin wave-rippled beds which indicates lower energy conditions when waves reworked the sediment/water interface prior to the return to more normal conditions.

The forces involved in the production of this facies type must have been well in excess of normal and probably fell into the category of hurricane (see later discussion) with the bottom current and/or wave orbital energy touching bottom probably measurable as several metres per second.

Occurrence: Occurs in the Chert Beds Member of the sections at Branscombe and Seaton; see Figs 3.3 and 3.4.

3.3.3 Facies 8 (Fig. 3.34)

Description: Buff/grey, fine to medium grained calcarenites with scattered shell fragments. Medium to coarse grained sand horizons with an irregular and anatomosing pattern. The bases of the beds are generally draped over the unit below. This facies type contains the same lithological elements as Facies Type 7, medium grained calcarenites with varying degrees of cementation and coarse grained poorly sorted sands. The calcarenites which make-up the bulk of this facies are indistinguishable from the calcarenite nodules seen in Facies Type 7.

FIG. 3.34: FACIES 7 & 8: CHERT BEDS MEMBER, BRANSCOMBE.

Variation: Beds of this facies may contain irregular cherts and the amount of coarse sand and the number of intraformational clasts varies considerably. Locally shell debris is seen in discontinuous horizons.

Association: Shows a marked association with Facies 7 (Figs 3.10 and 3.34).

Interpretation: The presence of coarse horizons and parallel laminae suggests a moderate to high energy environment.

The bases of the beds are not considered to be true indicators of energy level as they essentially cover beds of much coarser material of Facies Type 7 which usually had irregular tops and which the prevailing conditions which produced Type 8 could not have moved.

Type 8 is a clastic facies, largely massive in appearance, with many coarse anatomosing 'stringers' and occasional traces of parallel laminae. The calcarenites which make up the bulk of this facies are indistinguisable from the calcarenite nodules and matrix seen in Facies Type 7 which strongly suggests that they acted as a source for Type 7 during very high energy events.

The overall appearance of the beds belonging to Facies Type 8 is similar to that seen in Type 5 but the thin coarse horizons are much more extensive. The grain size is similar, suggesting similar energy levels but the higher levels of energy needed to produce the coarse horizons must have been far more frequent. It is suggested, therefore, that these two facies represent a continuum with Facies Type 5 being more distal.

The presence of parallel laminae in Facies Type 8 indicates that high energy bottom currents or wave action were responsible for deposition with possibly some material from suspension. The coarse anastomosing bands are thought to be the product of similar processes but during much higher mean velocity flows with the material being derived from an onshore direction with some component of winnowing.

The cessation of a mean velocity flow sufficient for the deposition of the coarse bands would mean a return to the more prevalent energy conditions and the finer sediment would then cover the coarser. It seems probable that as the energy level rose some planing-off of the calcarenite in places penetrated to the previous coarse-grained horizon while winnowing and depositing more coarse sand. This many-times-repeated process resulted in the irregular and anastomosing geometry of the coarse-grained 'stringers' (Fig 3.35) and also accounts for the local coarsening upwards.

Facies Types 9, 5, and 8 are therefore regarded as being largely examples of the normal fair weather depositional regime which seems to have had a tidal component suggesting the movement of megaripples both on and offshore at different times. In addition, however, the presence of parallel laminae suggested somewhat higher energy conditions possibly connected with wave action.

Occurrence: Occurs in the Chert Beds Member of the sections at Branscombe and Seaton; see Figs 3.3 and 3.4.

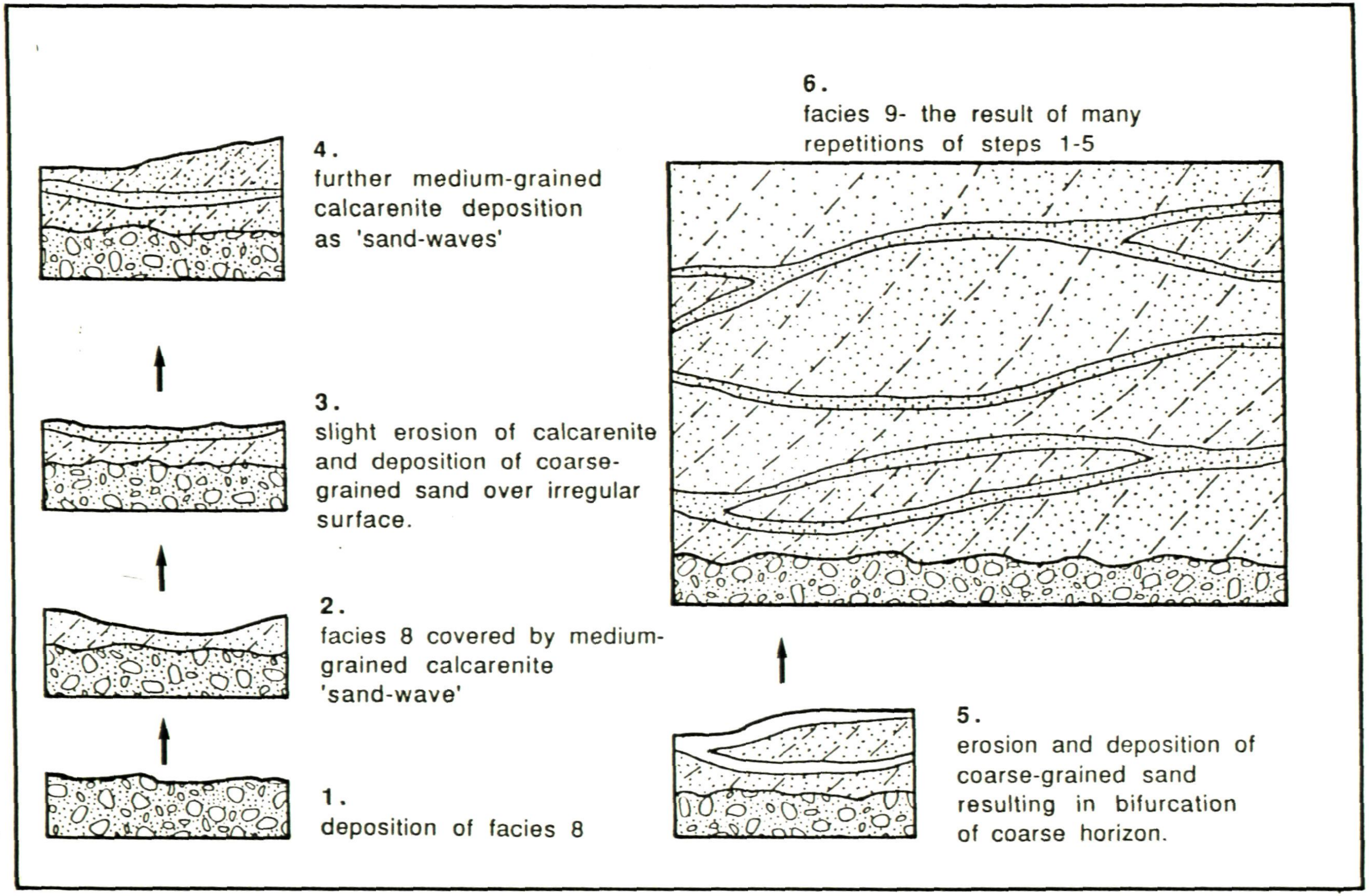


Fig. 3.35 Hypothesis for the formation of coarse, anastomosing sands in Facies 8

3.3.3 Facies 9

Description: Massive, grey/buff calcarenite, moderately sorted, medium grained, sub-angular quartz and common comminuted shell fragments and echinoid debris. Rounded intraformational clasts may be seen at the bases of beds which are planar or irregular.

There is abundant evidence of horizontal burrowing and the concretions seen in Facies 3 are locally common (Fig. 3.36) often occurring in linear horizons which are laterally persistant.

Variation: Only one bed in this facies at each of the localities. The description above broadly covers both beds but at Seaton scattered chert nodules may also be seen.

Association: Shows a moderate association with Facies 5 (Fig. 3.10).

Interpretation: The planar/irregular base and the presence of horizontal bioturbation suggests that this facies was laid down under low to moderate energy conditions.

The absence of internal sedimentary structures made it difficult to arrive at an estimation of the mean velocity flows but this facies is regarded as a more distal expression of the facies represented by Types 5 and 8.

Occurrence: Occurs in the Chert Beds Member of the sections at Branscombe and Seaton; see Figs 3.3 and 3.4.

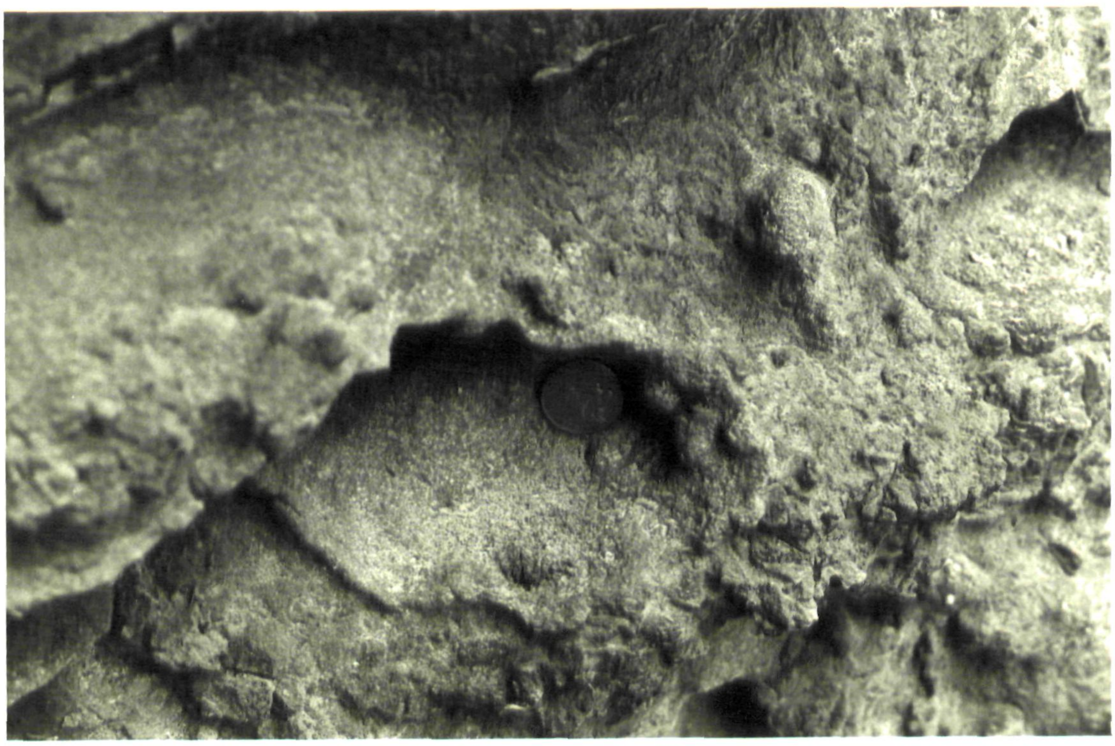


FIG. 3.36. FACIES 9: CHERT BEDS MEMBER, BRANSCOMBE.

? DECAPOD BURROW.

3.3.3 Facies 10

Description: Medium to coarse grained, poorly sorted, cross bedded (10cms thick sets) sands which truncate against thin horizons of medium grained calcarenites. The quartz grains within the sands are moderately to well rounded and contain about 10% of comminuted shell material. Scattered, rounded, intraformational pebbles (1 - 3cms across) are seen which are made up of fine to medium grained sand/calcarenite.

Variation: The grain size may vary locally from fine to coarse and there may be a tendancy for the sediment within a bed to coarsen upwards. At the Dunscombe localities bimodal cross beds may be seen with each mode occurring in <10cms - 20cms sets indicating movement along a NW/SE vector.

Association: Shows a moderate association with Facies 13 (Fig. 3.10).

Interpretation: The bimodal palaeocurrent directions suggest a tidally dominated environment in which the ebb and flood tides were of similar strength. The energy levels involved in the deposition of this facies were relatively high.

Occurrence: Occurs in the Top Sandstones Member of the sections at Kempstone Rocks and the small quarry at Dunscombe and in the Chert Beds Member at Seaton; see Figs 3.5, 3.6 and 3.4.

3.3.3 Facies 11

Description: Nodular, calcareous sands in which the nodules are fine to medium grained and the matrix is coarse grained and very poorly sorted. There is abundant shell debris.

Variation: Groups of verical or near vertical worm tubes may be seen in horizons. Glauconite is sparse except in some of the nodules. The beds at Kempstone Rocks which are placed in this facies display 5 - 15cms thick, normally graded laminae.

Association: Shows no marked association.

Interpretation: The normally graded laminae together with the coarse grain size at their bases indicates a variation in flow strength of a cyclic nature.

Occurrence: Occurs in the Top Sandstones Member of the sections at Kempstone Rocks and the small quarry at Dunscombe and at Seaton; see Figs 3.5, 3.6 and 3.4.

3.3.3 Facies 12

Description: Coarse to very coarse grained, very poorly sorted calcarenites and sands with horizons of green, poorly sorted medium grained sand. The bed tops are fissured and contain material from the bed above.

Variation: There may be small nodules of finer grained sand scattered throughout a bed. Grain size may be medium; shell debris may be abundant; vertical worm tubes occur locally; encrusting bryozoa, small unbroken echinoids and bivalves, serpulid worm tubes and fish teeth may all be present locally. Bimodal cross sets occur locally and bands of coarse sand appear to infill small channels in the finer material. The hardground surfaces at the tops of beds may display encrusting bryozoa, serpulid worm tubes, pits and depressions (1 - 2cms deep and a few cms across) whose shape suggests that they were echinoid resting places. Some of the bivalves found at the hardground were small, articulated and fairly well preserved while others are larger and usually broken.

Association: No marked association.

Interpretation: This facies is thought to represent periods of hiati in sedimentation, lithification and erosion. A specialised fauna colonised the sea-bed during the time that the hiatus lasted.

Occurrence: Occurs in the Top Sandstones Member of the sections at Kempstone Rocks, Seaton and Branscombe, and in the Chert Beds Member of the section at Seaton; see Figs 3.3, 3.4, and 3.5.

3.3.3 Facies 13

Description: Competant, medium grained sands with no internal structure.

Variation: Beds vary in thickness from about 0.1m to 0.4m. Their bases may be irregular or erosional; there may be scattered shell debris and they usually vary in thickness laterally.

Association: Shows a moderate association with Facies 10 (Fig. 3.10).

Interpretation: The relatively featureless nature of this facies makes it difficult to assign it to any depositional environment.

Occurrence: Occurs in the Top Sandstones Member of the sections at Kempstone Rocks and the small quarry at Dunscombe; see Figs 3.5 and 3.6.

3.3.3 Facies 14

Description: Medium to coarse grained, shelly sands.

Variation: Beds may have erosive bases; be extremely rich in shell material and have asymmetrically rippled tops (average ripple height 14cms and average wave length 45cms).

Association: Shows no marked association.

Interpretation: High energy environment with the sediment being deposited and transported by a unidirectional current.

Occurrence: Occurs in the Top Sandstones Member of the section in the small quarry, Dunscombe; see Fig. 3.6.

3.3.3 Facies 15

Description: Dark green, muddy, fine to medium grained, well sorted, glauconitic matrix sands with abundant, rounded, intraformational clasts. Beds contain shell debris, have erosional bases and there is evidence of bioturbation. The sands making up the intraclasts are indistinguishable from those making up the matrix.

Variation: The size of the intraclasts varies both from bed to bed and within a bed (maximum 20cms across) although most beds have clasts up to only 4cms across . The amount of shell material and the degree of bioturbation also varies considerably.

Association: Shows no marked association.

Interpretation: The rounded clasts suggest an initial high energy environment for this facies when already lithified sea-floor was ripped up and transported, probably only a short distance, and then re-deposited. Relatively low energy conditions then prevailed so that sediment infilled the interstices between the intraformational clasts.

Occurrence: Occurs in the Foxmould Sands Member of the section at Seaton; see Fig. 3.4.

3.4 Correlation and Modelling

Analysis of the facies present in the section at Branscombe suggests a number of generalised conclusions about the environmental changes which occurred during the time period represented by the Wessex Greensand Formation.

1) Over the time period concerned there was a general increase in the energy levels ambient at the time of sediment deposition from probably less than 20cm/sec. in Facies Type 1 to a current and/or orbital velocity well in excess of 1m/sec. in Facies Type 7.

2) This increase in energy levels reflected a decreasing water depth as the shoreline prograded towards the area.

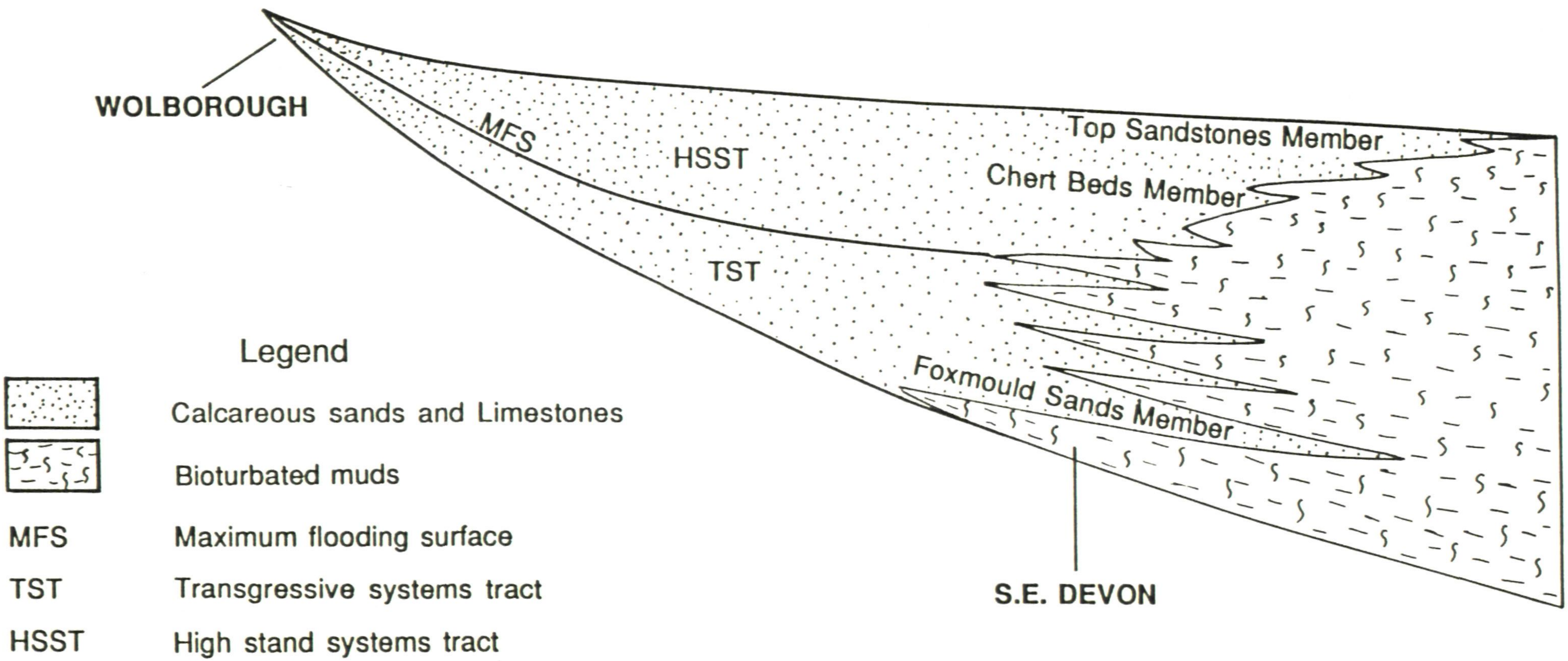
3) The normal, fairweather depositional regime is represented by Facies Types 1 and probably the bulk of Facies Types 9, 5 and 8. Storm events of varying intensity and duration are represented by Facies Types 2, 6 and 7.

These conclusions are summarised in the model proposed for the sedimentary environments over time at the various localities examined in this work (Fig. 3.37).

The fairweather depositional environment offshore was dominated by mud deposition from suspension and the water depth was probably in excess of 30m with a deposition rate slow enough to allow the formation of glauconite. Bottom energy conditions were low, with waves unable to touch bottom and bottom currents of negligible strength. The muds had a high organic content and supported a large, soft-bodied infauna.

Further inshore the ambient energy levels were too great to allow mud deposition and the calcarenite was probably deposited under tidal influence although there is also evidence for the deposition of sand grade material from suspension by wave processes. There appear to have

Fig. 3.37 Diagrammatic representation of the sedimentary model for the Selborne Group, S.W. England



been periodic high energy events perhaps with a mean velocity flow of ~1m/sec. which caused some planing off of bottom structures and the deposition of thin, coarse grained horizons. As the water depth decreased these coarse horizons became more common.

Facies Types 7, 6 and 2 are thought to represent increasingly distal expressions of storm deposition. Allen (1984) presented a speculative physical model for storm sedimentation (Fig. 3.38) in which he proposed five stages of storm development over a shelf that was being supplied with mud and sand grade material from the shore.

Pre-storm stage - gentle winds and small surface waves.

Storm growth - rapid growth in wind strength and thus wave size and period.

Full storm - wind and wave conditions relatively constant for a significant interval.

Storm decay - windspeed and wave conditions decline towards pre-storm levels.

Post-storm - resembles pre-storm.

Theoretical, semi-quantitative models for laminar currents in a water body acted on by the wind show that the summation of a wind drift current and the opposing gradient current caused by 'set-up' produce an observable current which flows in the wind direction in approximately the upper third of a water body and at 180 degrees below this layer. In turbulent flows much more complex models are proposed (see Allen, 1984) but one of the important points brought out by these various mathematical models is that the water velocity is generally only a few per cent of wind speed.

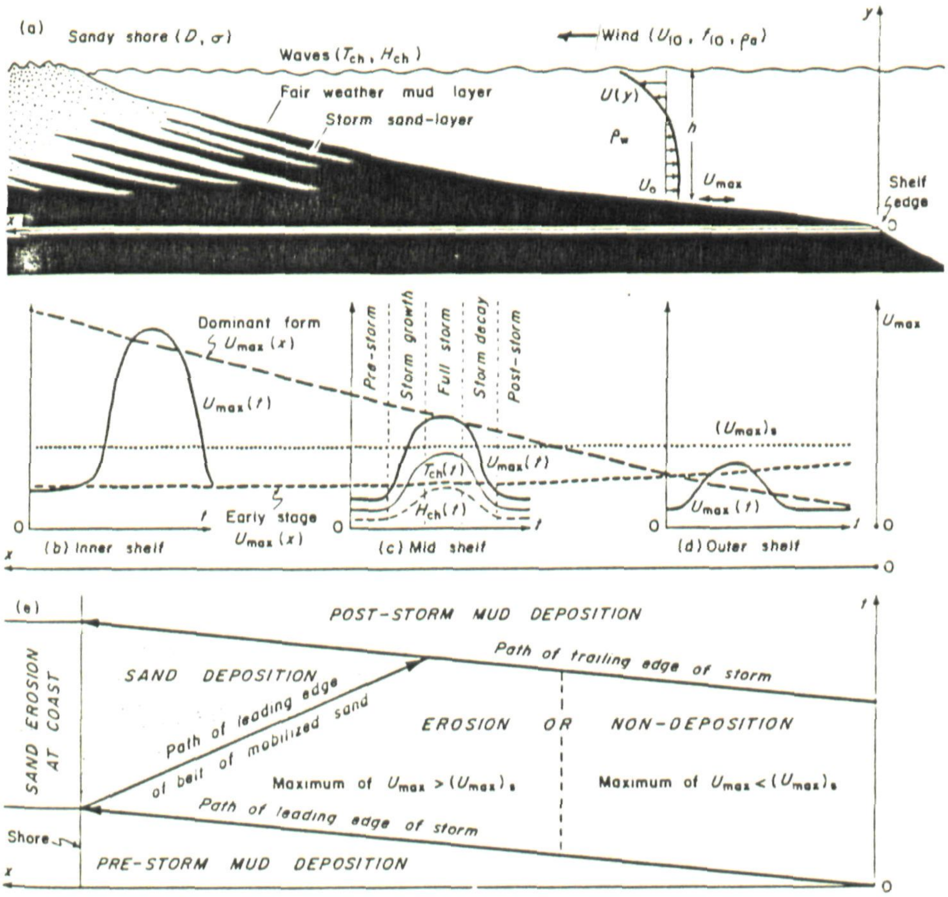


FIG. 3.38: A SPECULATIVE PHYSICAL MODEL FOR STORM SEDIMENTATION (AFTER ALLEN, 1984).

A) DEFINITION DIAGRAM FOR A SHELF WITH SANDY SHORE AFFECTED BY A STORM TRAVELLING ACROSS THE SHELF FROM DEEPER WATER.

B),C),D) VARIATION OF WAVE-RELATED CURRENTS WITH TIME AND WITH DISTANCE ACROSS THE SHELF.

E) THE MOVEMENT OF THE MARGINS OF THE STORM AND OF THE LEADING EDGE OF THE ZONE OF STORM-MOBILISED SAND.

Measurements of wind induced, near-bed, offshore currents have been quoted at 0.81m/sec (Gienapp, 1973) which was about double the fair weather flow; 0.8m/sec. pulsing to 1.6m/sec (Murray, 1970b) and 1.5m/sec (Forristal *et al.*, 1977) under hurricane conditions measured between 6m and 60m depth. These figures suggest that the proposed mechanisms for deposition in the Branscombe section are feasible.

Allen's model assumes that during fair weather mud was deposited except at depths which had current/wave action sufficiently strong to prevent mud leaving suspension and to keep sand in motion. This is comparable with the model proposed for Branscombe.

During a storm U_{max} (maximum horizontal orbital velocity) of a near-bed water particle, would first increase rapidly with time and then steady for a time before gradually declining.

$$U_{max} = \frac{n\ H}{T\sin(kh)}$$

Where H = wave height

h = water depth

T = wave period

$k = 2\ n/L$ where L = wavelength

U_{max} is thus linearly dependent on wave height and has an inverse relationship to wave period and water depth. The expected wave heights in the open sea as a function of wind speed are shown in Fig. 3.39.

The inverse relationship with water depth means that the most powerful wave-related currents will be generated in the shallowest water. Allen points out, however, that as a storm travels shorewards the changes in

Expected wave height in the open sea as a function of Beaufort wind force or wind speed at height of 10 m above the sea surface. After Frost (1966)

Mean wind speed at of 10 m ($m\ s^{-1}$)	Beaufort wind force	Descriptive term	Probable height of waves in open sea * (m)
0	0	calm	0
1.5	1	light air	0.1
3.3	2	light breeze	0.2
5.3	3	gentle breeze	0.6
7.5	4	moderate breeze	1.0
9.6	5	fresh breeze	2.0
11.9	6	strong breeze	3.0
14.3	7	near gale	4.0
16.7	8	gale	5.5
19.1	9	strong gale	7.0
21.7	10	storm	9.0
24.1	11	violent storm	11.5
26.8	12	hurricane	≥14.0

* Heights less than tabulated values in inshore waters.

FIG. 3.39: EXPECTED WAVE HEIGHT IN THE OPEN SEA AS A FUNCTION OF WIND SPEED AT HEIGHT OF 10M ABOVE THE SEA SURFACE (FROM ALLEN, 1984)

U_{max} will be out of phase with this relationship; that is the storm will reach the outer shelf first and U_{max} may well be greater in deeper water than inshore. The inverse relationship would be restored when the storm reached shallower waters.

Sand grade material would be maintained as a dispersed load through the action of U_{max}.

$$\frac{mg}{(\sigma - p)\, gD} = 50{,}000 \left(\frac{pU^2_{max}}{(\sigma - p)\, gD} \quad \frac{V^{0.5}}{U_{max}\; T^{0.5}} \right)^{0.25}$$

Where v = fluid kinematic viscosity

D = particle diameter

m = sediment load

σ = angular velocity of particles

p = fluid density

This dispersed load then travels away from shore at a rate comparable to U_o (velocity of offshore wind-induced bottom current). Thus the distance that the sand travels is determined by the behaviour of U_o during the storm or because depth becomes so great that U_{max} falls below the critical value $(U_{max})_s$ needed to entrain the sand. The value of U_o is generally lower than the speed travelled by the storm centre and thus storm duration may be the main control on seaward spreading of sand. Using his model Allen discussed the sedimentary regimes likely to occur during a storm and these will now be compared with those observed in the section at Branscombe.

Pre-storm - Allens model proposed mud deposition where water depth was too great for sand deposition and the energy level was low enough to permit settling out of mud. This mud depositional environment finds it's equivalent in Facies Type 1 while the inshore equivalents are largely represented by facies Types 9, 5 and 8.

During Storm - Allen suggested that mud might be eroded or at least remain in suspension in deeper water. The control being the magnitude of U_{max} ie water depth and storm intensity. Mud could be deposited as laminae in the deepest water but as sedimentation rates were likely to be low, bioturbation rates were high.

In the model Allen suggested that the mid-shelf was likely to have thin allochthonous sands interbedded with thicker autochthonous muds (Facies Type 2 interbedded with Type 1). Allen considered that the storm sands should show sharp and often erosional bases which reflected moderate values of U_{max}. The beds should be relatively thin because of the relatively short period of sand deposition; they should ordinarily be normally graded since deposition occurs mainly during the storm decay phase; wave-current ripples may be present on the tops of the sand beds and there may be internal climbing ripple lamination. Facies Type 2 beds usually have sharp and/or erosional bases and are relatively thin although they tend to become thicker and more frequent upwards, thus supporting a shallowing model. Some of the beds do show wave/current ripples at their tops but no evidence of climbing ripple cross lamination was seen. The subsequent diagenesis made it difficult to see any evidence of internal grading but some evidence of an increase in mud content upwards through a bed is seen.

Allen's model suggested that inner shelf storm deposits should be relatively thick, allochthonous sands, possibly alternating with thinner autochthonous muds. Most of the sand beds should have sharp or erosional bases; they may show off-shore directed channel-type deposits; the coarse beds may be relatively thick because sand deposition occurs for relatively long periods; the high values of U_{max} should result in parallel laminae followed upward by wave related cross laminae and possibly a wave-current rippled top. The beds proposed to be the result of storm sedimentation at Branscombe are comparable to some extent but there was no evidence of interbedded muds and the fair weather environment is considered to have been far too energetic to allow mud deposition. Facies Types 6 and 7 showed sharp and often erosional extremely bases. The nature of the deposits made observation of internal structure difficult but evidence of parallel laminae could be seen in Type 6 and wave rippled tops were seen in Type 7. No evidence of channel-like structures was seen.

Type 7, as discussed above, is thought to have been the result of very high velocity wave/current action that resulted in the break-up of partially lithified sediments. Otherwise the various facies observed at Branscombe fitted moderately well with Allen's model.

The amount of sand deposited at any given point is proportional to the product of the duration of the regime of sand deposition and the deposition rate. Allen (1984) presented a theoretical example of calculations made for four different wind speeds which gave indications of wave period and height and U_o (Fig.3.40).

Wind speed U_{10} ($m\ s^{-1}$)	Wave period T (s)	Wave height H (m)	Friction coefficient of sea surface f_{10}	Velocity of near-bed offshore currents U_0 ($m\ s^{-1}$)	Reach of sand away from shore: distance (km)	Reach of sand away from shore: depth (m)	Sand transported offshore during storm ($kg\ m^{-1}$)
30	9.5	9.95	2.16×10^{-2}	0.0865	20.45	54.54	3.43×10^{7}
20	7.7	3.58	1.68×10^{-2}	0.0508	10.94	29.18	8.02×10^{6}
15	6.7	2.34	1.44×10^{-2}	0.0353	7.53	20.09	2.85×10^{6}
10	5.4	1.30	1.12×10^{-2}	0.0207	4.38	11.69	9.74×10^{5}

FIG. 3.40: PRINCIPAL CONDITIONS RESULTS FOR STORM SAND-LAYERS DEPOSITED ON A UNIFORMLY SLOPING SHELF (AFTER ALLEN, 1984).

These calculations, for a sand of 125 μ diameter, suggested that large quantities of sand could be moved many kilometres offshore during a storm into depths measured in decimetres. Which supports the feasability of the storm depositional model for many of the facies in the Branscombe section.

The Foxmould Sands Member in the Seaton section (Fig. 3.4) was deposited in a relatively low energy, marine environment (Facies 1) that was subjected to periods of high energy that ripped up the already lithified sea-floor (Facies 15). The Chert Beds Member displays a similar succession to that seen at Branscombe; representing a tidally dominated shallowing sea (Facies 9, 5 and 8) which was subject to violent storms (Facies 6 and 7). There is also more indication at Seaton of long periods without active sedimentation (Facies 12).

The two small sections at Dunscombe (Fig. 3.6) show sediments that were probably deposited in high energy, tidally dominated shallow water close to shore.

CHAPTER 4 DIAGENESIS

4.1 Introduction

This chapter presents an historical review of work on the diagenesis of the Wessex Greensand Formation and reports the results of thin section analyses undertaken to study the diagenetic processes which have taken place in the Wessex Greensand Formation. The occurrence of secondary calcite and silica is described, particularly with respect to chert formation, a series of events are suggested to explain chert formation and an attempt is made to explain these events in geochemical terms.

Most of the workers on the Wessex Greensand Formation in the 19th century were concerned with basic lithological descriptions, stratigraphy and the examination of fossils. However, some mention was made of the weathered condition of many of the Wessex Greensand Formation outcrops and comments were made on the origin of some of the mineral components, such as glauconite, phosphates and cherts. The sections below deal with the occurrence in the Wessex Greensand of (i) secondary silica and chert formation, and (ii) secondary calcite.

4.2 Secondary Silica and Chert

4.2.1 Previous Work

Hinde (1885) specifically addressed the problem of chert formation and considered that what he called 'Sponge Beds' in the Upper Greensand occurred in two separate forms. The first form was the Malmstone which was described as a porous, siliceous rock which usually contained some calcium carbonate. The porosity of this rock was reported to be largely due to cavities left after the dissolution of sponge spicules. Hinde suggested that these dissolved spicules could have provided some of the silica for the matrix which consisted of amorphous silica, minute globules and chalcedonic silica. Sponge spicules which had been altered to glauconite or amorphous silica were also seen in the Malmstone.

The second type of 'Sponge Bed' was that described from the Isle of Wight as a siliceo-calcareous rock with cherts. Hinde described two types of chert. The first consisted of spicules in a chalcedonic matrix, while the second was made up of spicules and chalcedony in an amorphous matrix. Some spicules were described as being replaced by glauconite within chert cavities and others as being replaced by calcite in the calcite matrix. Hinde claimed that similar 'Sponge Beds' occurred in the Blackdown and Haldon Hills. He suggested that the porous envelopes around the cherts were a result of the silica of the spicules being dissolved and deposited in the chert and he rejected the view that the silica originated directly from sea-water "attracted from the exterior medium by animal matter".

Strahan (1898) quoted the work of Hinde (1885) on chert formation in his own work in the Isle of Purbeck and furthermore suggested that much of the outcrop was decalcified, as evidenced by sand moulds of shells and shells converted to chalcedony. He also thought that the presence of glauconite grains within cherts showed that the glauconite was formed before the silicification of the "Sponge Beds ". Watts (in Strahan) reported on a brownish grey chert from the Upper Greensand of Abbotsbury which consisted of cryptocrystalline silica with traces of organisms such as sponge spicules and foraminifera but no other minerals. Watts suggested that the chert could be a silicified limestone as a way of explaining how the organic remains could have become embedded. He proposed a sequence of diagenetic events starting with the replacement of the organisms by silica and followed by the deposition of fibrous silica around them with the final deposition of coarser fibrous silica in the remaining voids.

Hill (in Jukes-Browne and Hill, 1900) described the progressive alteration of colloidal silica into chalcedony within cherts and concluded from his investigations that although a certain amount of water bearing silica percolated from bed to bed, the bulk of the chalcedonic silica in the cherts was the result of the alteration of the colloidal form in situ. His ideas on chert formation largely followed those of Hinde (1885); large numbers of sponge spicules were thought to have contributed to globular colloidal silica in horizons now occuppied by chert. Hill further decided that there was no evidence for the cherts having been formed by the direct replacement of limestone.

The irregularly shaped, silicified nodules found in the Chert Beds near Bridport and Yeovil were thought by Welch (in Wilson *et al.* 1958) to be secondary in origin. It was suggested that silica derived from the chert had replaced the calcium carbonate in the fossils in and just below the Chert Beds and that the carbonate had migrated downwards to form the limestone concretions or 'cowstones'.

Tresise (1960) reported that chert and glauconite rich sediments were almost mututally exclusive in S.E. Devon and it was thought that this might be due to the fact that both required silica in solution and that a tranquil environment favoured chert formation while current activity favoured glauconite formation. Tresise described the cherts of the Upper Greensand as "botryoidal masses of chalcedonic silica in a metacolloidal state" with acicular chalcedony in the interstices and he drew a distinction between them and siliceous sandstone, with clastic grains cemented by secondary silica (Tresise, 1961). He considered true chert to be primary in origin, formed in tranquil waters and attributed the absence of chert from the Top Sandstones Member to increasing current activity.

The usual morphology of chert nodules was described as a compact, glassy core surrounded by a porous, siliceous envelope. Tresise claimed that this envelope was not a transitional form between the chert core and the surrounding sediment. He reported that both the envelope and the core were dominantly composed of chalcedonic silica. He noted three cavity types in the marginal envelope; original cavities, sponge spicule solution cavities and irregular cavities produced by the dissolution of calcareous material.

Tresise pointed out that detrital grains were rare within the chert and suggested that this ruled out the mechanism of silica cementation of the surrounding sediment as a method of chert formation. Where angular quartz grains did occur they often showed secondary growth in optical continuity, whereas glauconite grains resembled those seen in the surrounding sediment. Relatively rare calcareous organic remains were also reported within the cherts (foraminifera, fragments of echinoid test and bivalve shells). This material was observed to be still calcareous or partially/wholly siliceous. This observation did not support his theory of chert formation.

Tresise considered that the cherts were made up of masses of 'metacolloidal silica', which could produce internal cavities due to contraction. These cavities could be seen completely infilled with acicular chalcedony or remaining as a void often with a granular quartz lining.

Tresise examined three theories for the formation of chert in the greensands of southern England, those of Hinde (1885), Richardson 1947) and Humphries (1956).

Richardson (1948) had demonstrated the silicification by percolating solutions, of limestone masses found within the Aptian Bargate Beds. He suggested that silica had been electrolytically precipitated in a shallow sea and this gradually replaced the limestone masses which were an early diagenetic product. Tresise rejected this theory of formation on the grounds that although limestone did occur in the Upper Greensand he had not observed any evidence of its transformation into chert.

The observations made by Hinde had led him to suggest that chert was an organic deposit originating from the solution and reprecipitation of masses of sponge spicules. Tresise considered that this theory had been largely based on circumstantial evidence. His own work had found that sponge spicules only occurred in relatively limited numbers and he thought that even Hinde's descriptions suggested that the siliceous matrix formed before the spicules had been dissolved.

The study of the cherts of the Hythe beds conducted by Humphries had led him to the conclusion that they were contemporaneous in origin, being formed from a gel precipitated on the sea-floor. He suggested that precipitation might have been caused by electrolytes in sea-water or by the action of algae or bacteria. Tresise thought that this was the most likely mechanism to account for the formation of the cherts within the Upper Greensand. The precipitation of a mass of silica gel accounted for the colloform structures he had observed in the cherts, the metacolloidal nature of the silica, the general lack of detrital grains, the relative rarity of sponge spicules and the perfect preservation of spicule casts in the marginal envelopes of the cherts. Despite the fact that the silica gel theory accounted for this observation, Tresise pointed out that Humphries had assumed that silica existed in sea-water in a colloidal state whereas it was in fact carried in solution, probably as monosilicic acid. Increase in local concentrations of silica would therefore result in the precipitation of calcium and magnesium silicates before electrolytic precipitation of silica gel could occur.

While retaining the silica gel theory as the most likely to account for chert formation Tresise realised that some other means of precipitation must have been responsible. He suggested that a warm climate together with low lying land areas with a heavy vegetation cover would have favoured chemical rather than mechanical weathering. This, in turn, would have resulted in river run-off waters with a high silica content and he suggested a number of possible consequences.

Siliceous organisms, such as diatoms, radiolaria and sponges might have been expected to flourish in offshore waters (even though he pointed out that modern organisms did not appear to be controlled by such a simple correlation). Where river and sea-water mixed a decrease in silica content would have occurred, as seen in similar modern environments, due to both dilution and the adsorption of silica onto colloidal matter and suspended solids in the river waters. Tresise suggested that some of these small flocculated masses could have settled to the sea-floor and been converted to glauconite by the adsorption of potassium and other ions. Some of this silica could have precipitated as a gel, possibly aided by the presence of ammonium salts produced by organic decay. Sponge beds would have provided a suitable environment for this gel formation and would have accounted for the presence of sponge spicules in the chert and its sporadic occurrence. The postulated build-up of silica and/or ammonium concentrations would have required low energy conditions.

Tresise thought that the cherts were formed not by the simple dehydration and contraction of the gel masses but depended on the diagenetic relocation of the opaline silica found in the sponge spicules which were distributed in the sediment. This mobilised silica was thought to have been precipitated as chalcedony within the voids produced by the contraction of the gel.

The alternating bands of chert and calcarenite that commonly occur in S.E. Devon were thought to be the result of a diffusion gradient. Silica deposited in the chert horizon would have resulted in an influx of silica bearing solutions to replace the impoverished fluids. At the chert horizon silica would have tended to replace calcium carbonate and in the limestone horizon calcium carbonate would have tended to replace silica as this was taken into solution. Drawing upon previous workers investigations of silica solubility Tresise suggested that these gradients could have been caused by either local variations in pH or temperature.

4.2.2 Secondary Silica - Foxmould Sands Member

In the Foxmould Sands Member secondary silica is almost entirely restricted to the relatively mud-free, storm-sorted calcareous sand horizons of Facies 2. Occasional thin (up to 3cm thick), clean quartz sands in these deposits are cemented by small secondary quartz crystals. This is in contrast to the rest of this Member where cement is usually of secondary calcite if present at all.

In the storm-sorted calcareous sands bivalve shells and fragments are common, as are the coiled calcareous tubes of the serpulid *Rotularia concava*. The latter are abundant in some horizons and are often welded together to form discontinuous limestone bands. Voids tend to occur within these serpulids and these spaces are frequently infilled with secondary silica (Fig. 4.1).

Chalcedony, a cryptocrystalline fibrous type of silica is the form taken by the secondary void-fill and very little evidence is seen of microquartz replacement of calcite. This passive filling of voids appears to be the limit of secondary silica development and no true cherts are found in the Foxmould Sands Member.

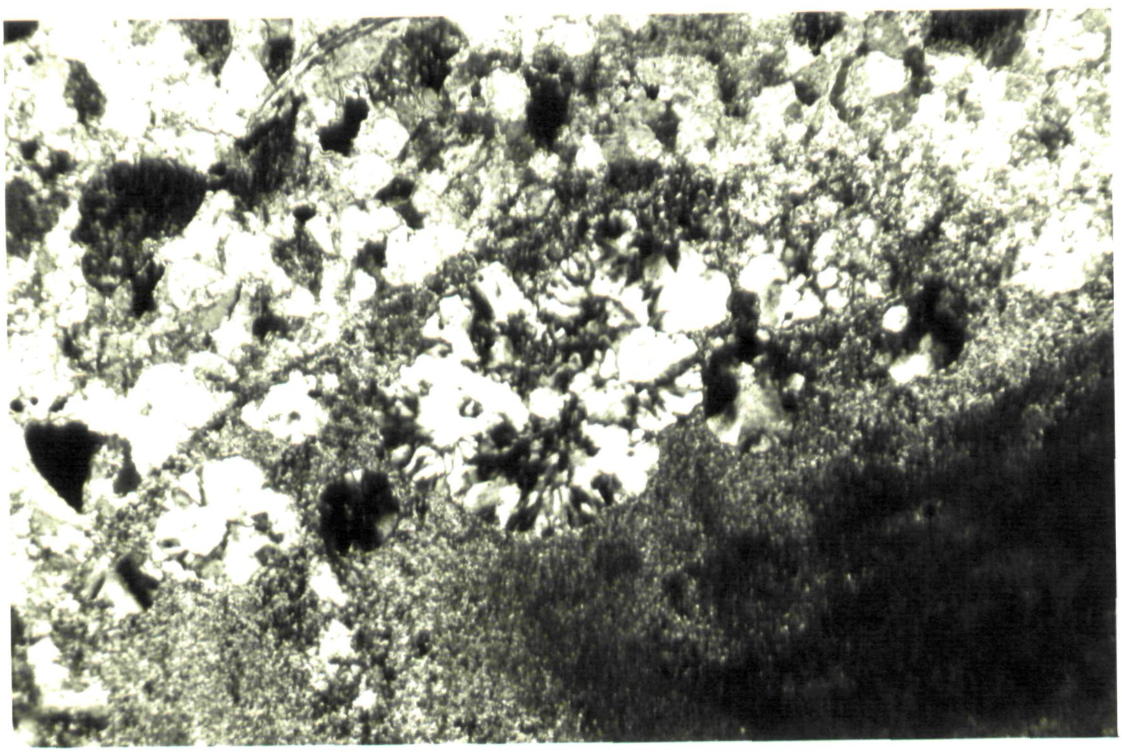


FIG. 4.1: SECONDARY SILICA WITHIN SERPULID WORM TUBES, FOXMOULD SANDS MEMBER, BRANSCOMBE. (F.O.V. 1.2mm).

4.2.3 Secondary Silica - Chert Beds Member

The most obvious secondary silica deposits are the cherts themselves which occur in various morphologies, from irregular nodules to laterally impersistent horizons which vary in thickness (up to 30cms). Sedimentary structures are often preserved within the chert nodules.

The percentage of quartz detritals varies widely in the calcareous sands of the Chert Beds Member. Some cherts contain large numbers of quartz detritals, often remaining unaltered in appearance and with sedimentary structures remaining intact, thus reflecting the nature of their deposition. These well preserved structures suggest a secondary and replacive origin for the chert.

A block of chert which is sectioned and polished appears translucent, allowing a three dimensional view of sedimentary structures when their form is picked out by quartz detritals. An example of the usefulness of this preservation is shown in Fig. 4.2 which illustrates a polished block of chert, taken from Seaton Hole, S.E. Devon. The cross-bedding is picked out by the quartz detritals and silicified shell fragments. In this instance the cross-sets are bimodal and suggest an environment influenced by tidal currents. A detailed examination (Fig. 4.3) reveals the presence of burrows which disturb the laminae. In this sample U-shaped burrows predominate in the upper set, suggesting that the organism was able to cope with the sediment deposition rate by altering the depth of its burrow and keeping the top of the 'U' open to the water/sediment interface.

Sections of cherts typically display a siliceous envelope reaching

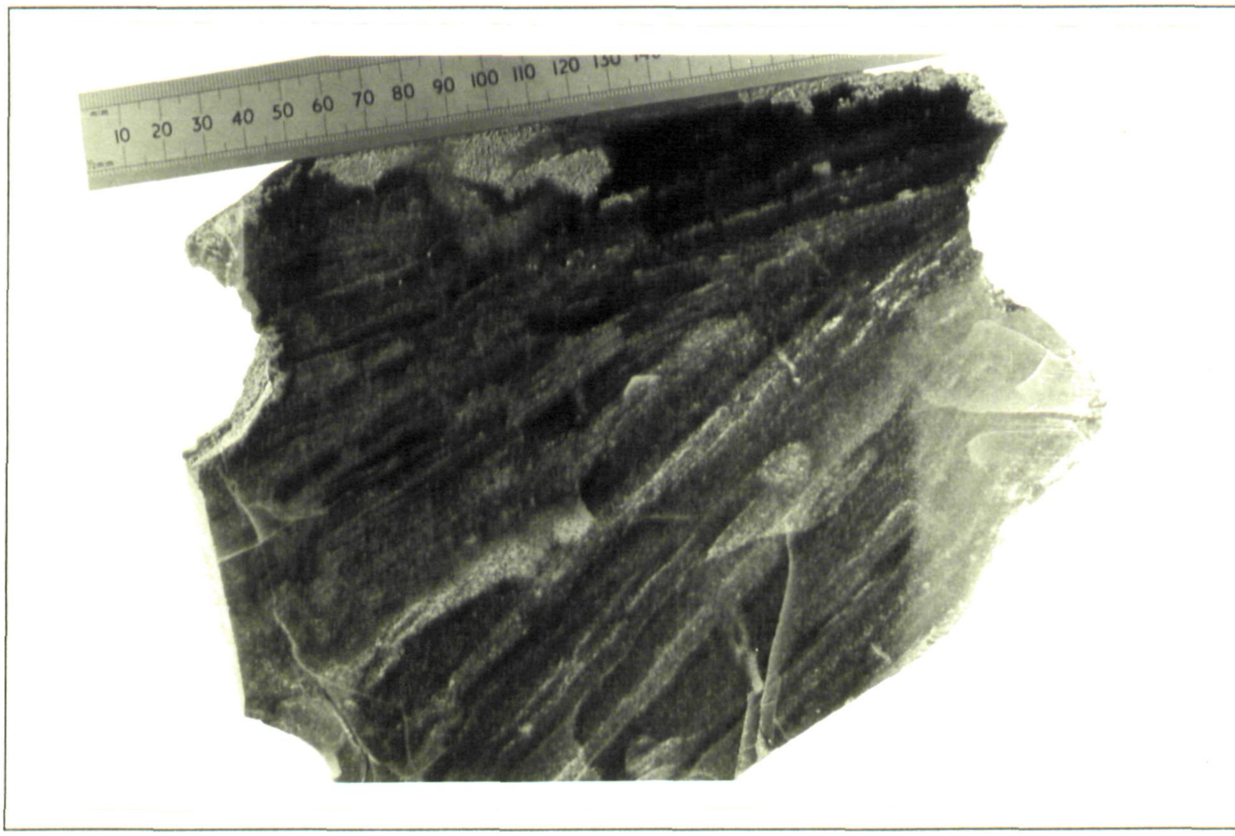


FIG. 4.2: POLISHED BLOCK OF CHERT TAKEN FROM SEATON HOLE, S.E. DEVON. SHOWING BIMODAL CROSS-SETS PICKED OUT BY QUARTZ DETRITALS AND SHELL FRAGMENTS.

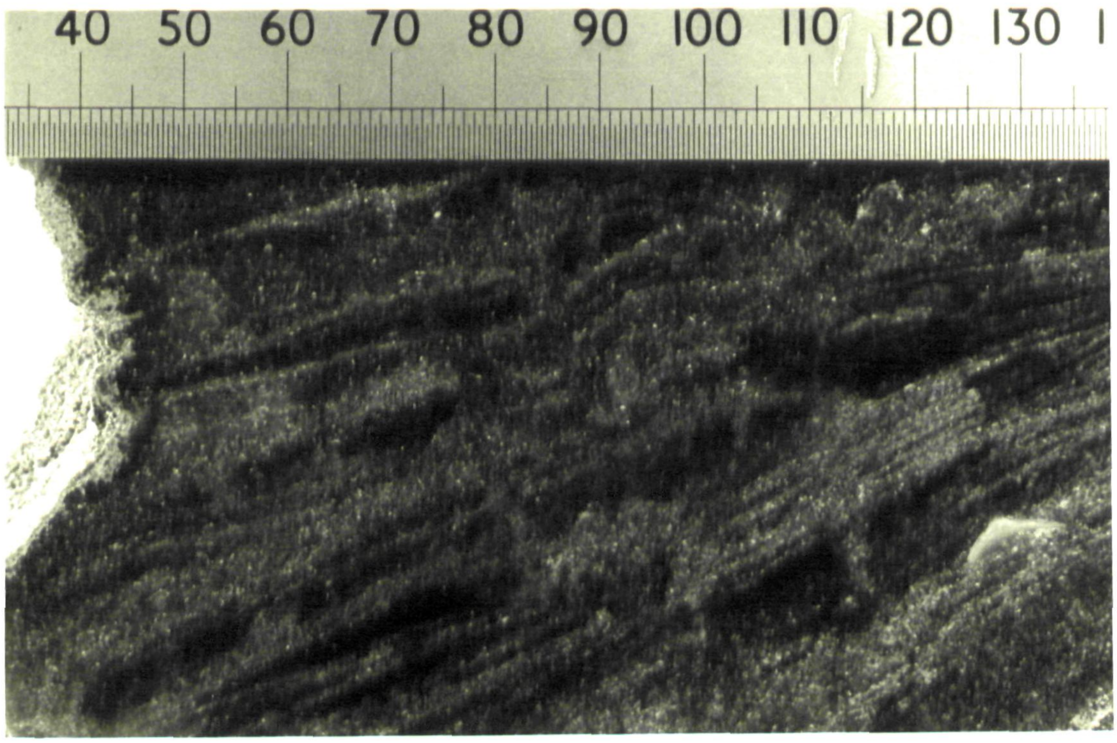


FIG. 4.3: DETAILS OF POLISHED CHERT SHOWING U-SHAPED BURROWS.

into the surrounding calcarenite (Fig. 4.4). Moving outwards from the chert this envelope has a progressively lower silica content. The thickness of this zone varies considerably but is generally measured in centimetres. If the zone around the cherts represents an area adjacent to the maximum development of secondary silica, in which silicification becomes progressively reduced, then an examination of the incidence of secondary silica inwards from the edge of the envelope should reflect the replacive growth of chert within the calcarenite. This process did not always proceed to completion and abundant nodules of partially silicified calcarenite are found in the Chert Beds Member.

A series of thin sections taken across the transition zone reveals the nature of the silica replacement of the calcarenite.

Despite it's name, the Chert Beds Member consists largely of calcareous sands of varying grain size, which reflect the different energy levels obtaining during deposition. The same mineral species occur throughout the calcareous sands but they differ in size, habit and concentration. Quartz detritals may be present in a sample in varying percentages, grain sizes and morphologies. Grain sizes vary from very fine to very coarse, the latter normally being well-rounded and the former sub-angular. The percentage of quartz present varies from 70% to as little as 5%, when the rock is technically a loosely cemented limestone.

Calcite is the other major component and varies from 30% to 95% of the rock. The calcite is made up of organically derived fragments, some of which are recognisable but most of which are comminuted. The organic

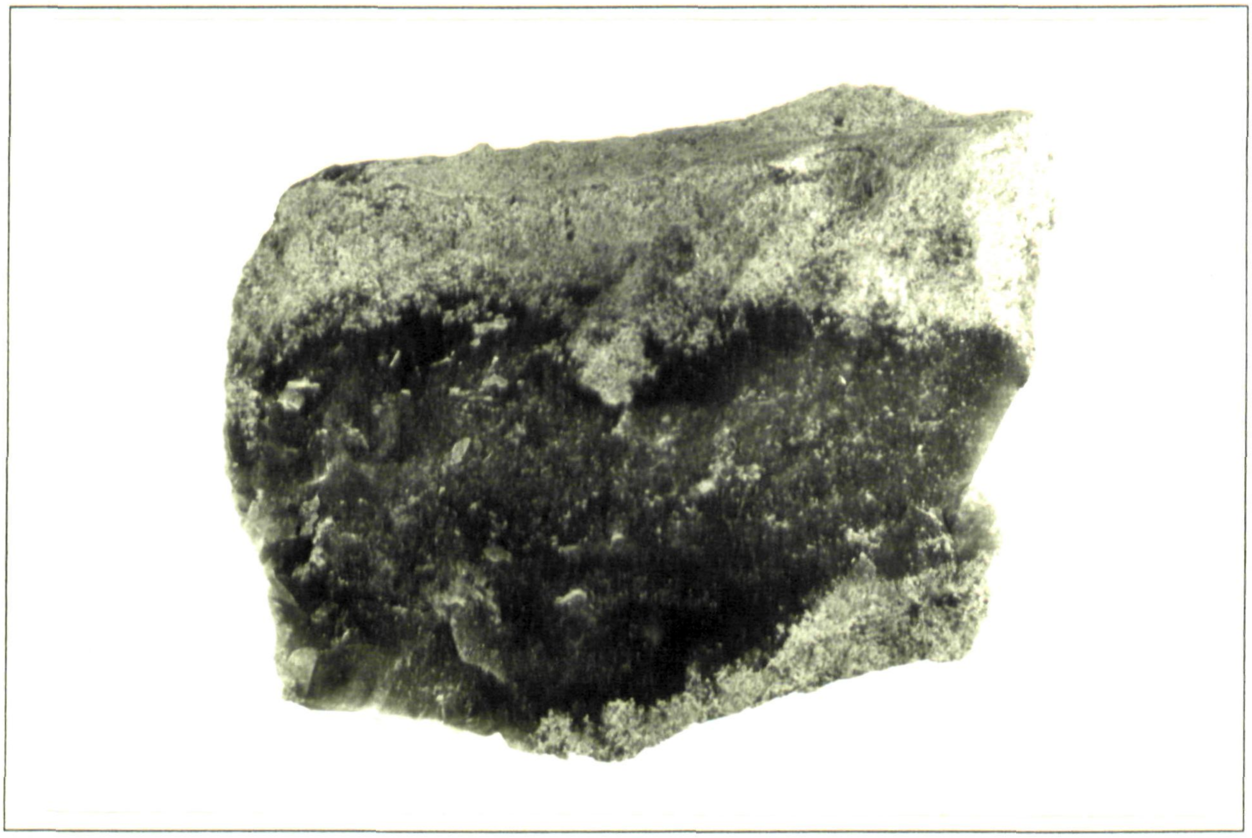


FIG. 4.4: SILICEOUS ENVELOPE AROUND CHERT, SEATON HOLE, S.E. DEVON.

debris consists of molluscs, echinoids, bryozoa and sponges, together with rare foraminifera.

The only accessory mineral of note is glauconite and this normally makes up less than 10% of the rock. Locally small (<1cm) chert fragments may be common and plagioclase feldspar also occurs although this often partially altered to calcite or cherty microquartz. A typical thin section taken from the calcareous sands but not directly associated with chert is shown in Fig. 4.5.

Voids occur within the rock especially in the proximity of calcitic organic fragments. As the chert is approached these tend to be silica infilled with the silica in the form of radiating chalcedony fibres similar to those infilling voids in the Foxmould Sands Member. This passive silica infill of voids is here augmented by the replacement of calcite by microquartz around the edges of the void. This replacement of whole calcite grains with microquartz grains becomes increasingly common near the edge of the chert. Some grains are observed are observed to be completely unaltered, while others have been completely replaced by microquartz. In addition, the amount of chalcedony increases suggesting either a higher incidence of primary voids or the complete dissolution of some calcite grains (Fig. 4.6). Eventually, glauconite grains are seen to have undergone the same process.

Sections taken on the edge of the chert exhibit secondary quartz crystals larger than the replacive microquartz. These crystals form an envelope around quartz detritals and replaced calcite and glauconite grains (Fig 4.7). Within the chert, thin sections reveal microquartz grains and occasional quartz detritals, often enveloped in secondary

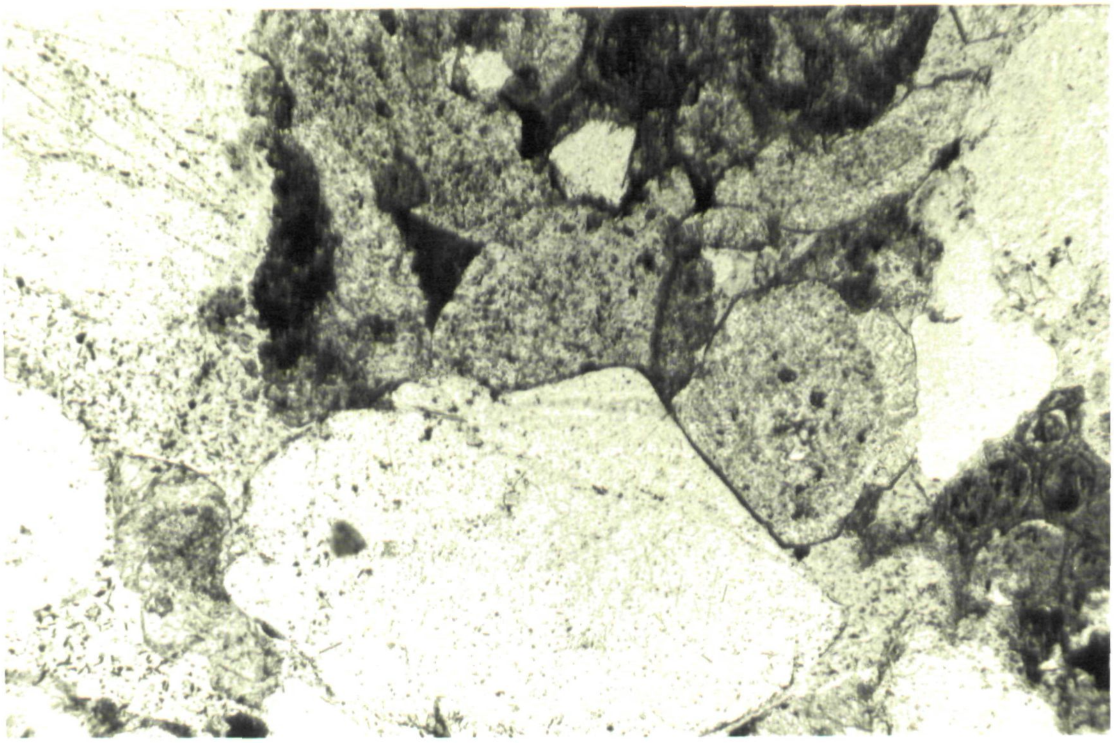


FIG. 4.5: THIN SECTION OF CALCAREOUS SANDS AWAY FROM CHERT, CHERT BEDS MEMBER. SHOWING QUARTZ DETRITALS AND CALCITIC DEBRIS. (F.O.V. 1.2mm).

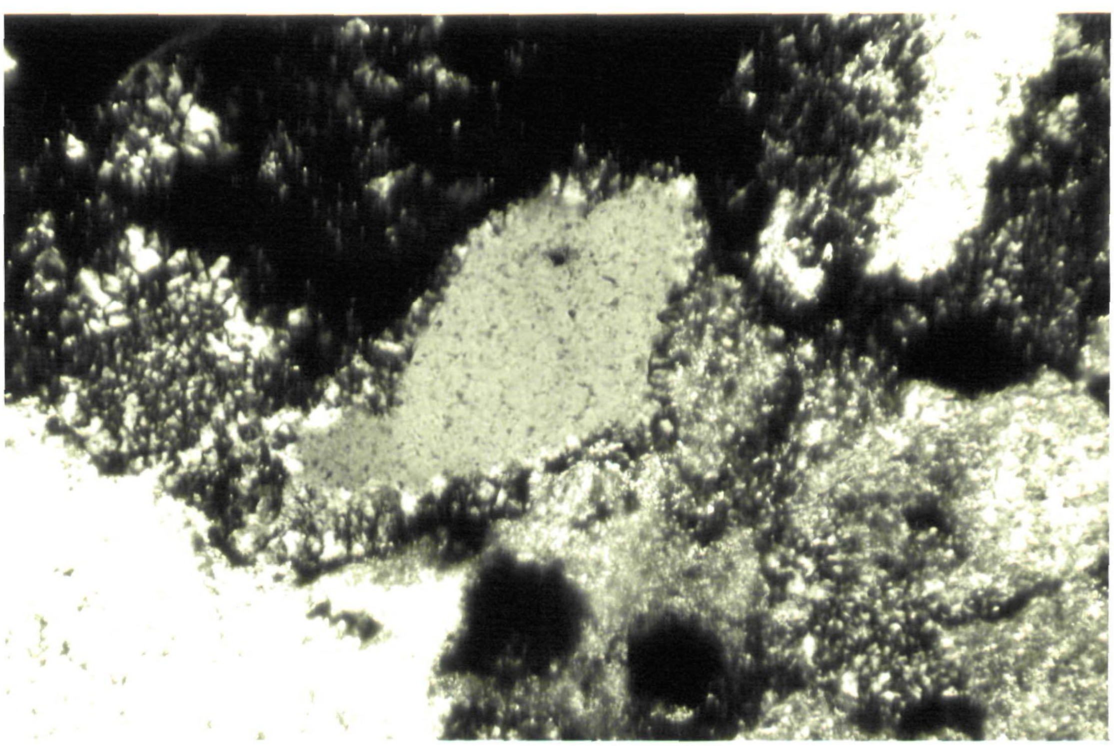


FIG. 4.6: THIN SECTION OF CALCAREOUS SANDS NEAR A CHERT, SHOWING CHALCEDONIC INFILL OF VOIDS AND REPLACEMENT OF CALCITE GRAINS BY MICROQUARTZ. (F.O.V. 0.6mm).

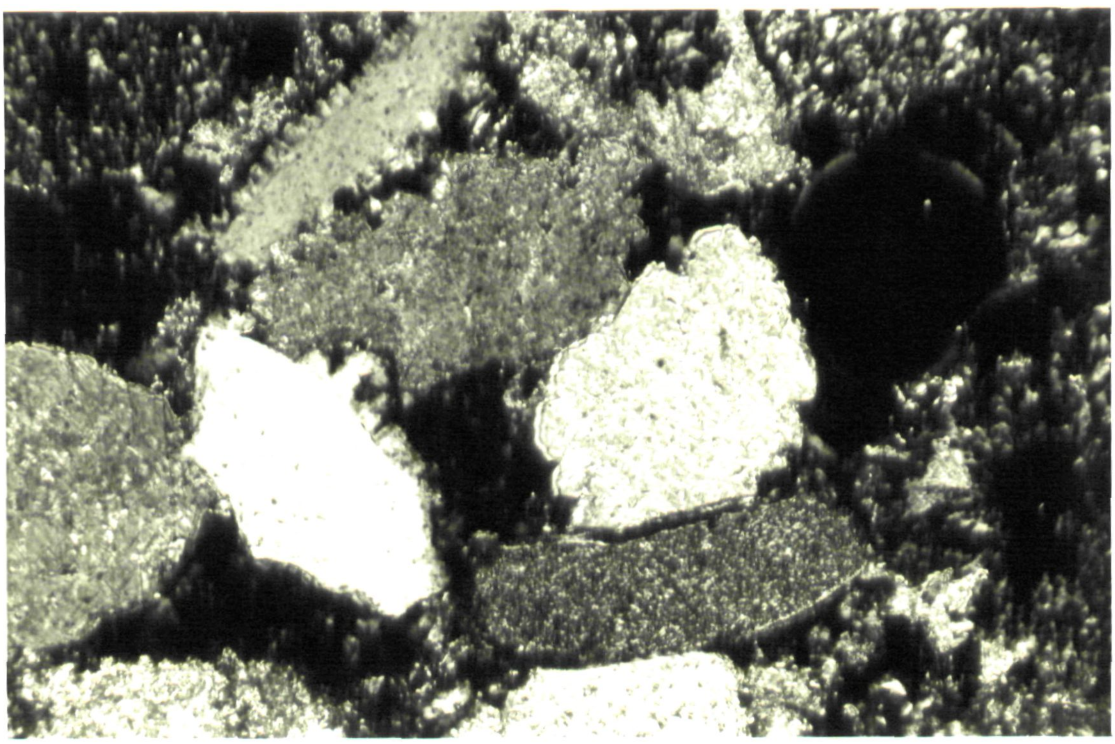


FIG. 4.7: THIN SECTION TAKEN AT THE EDGE OF A CHERT. SHOWING SECONDARY QUARTZ GROWTH ENVELOPING QUARTZ DETRITALS. (F.O.V. 1.2mm).

quartz crystals, with the whole being welded together by chalcedonic quartz (Fig 4.8).

Thus the chert is an imperfect ghost of the original fabric of the calcarenite. Microquartz grains represent former calcite and glauconite grains, while larger secondary quartz grains occur on the periphery of these microquartz grains and outline original quartz detritals. The voids, both original and those left after the dissolution of carbonate material, are filled with chalcedony.

Cherts vary considerably in their quartz detrital content, some having none, some showing partially dissolved grains and others being packed with quartz grains. This variation is a reflection of the varied quartz detrital content found within the calcareous sands of the Chert Beds Member.

It is suggested that this increasing silicification may reflect the sequence of events leading to the formation of chert. The first appearance of secondary silica is in the form of chalcedonic infill of voids, particularly within calcite shell fragments, which in turn act as nuclei for the microquartz replacement of calcite around the edges of the voids. The progressive replacement of calcite by microquartz continues simultaneously with the replacement of glauconite and the deposition of secondary quartz crystals around the quartz detritals and replaced calcite. Chalcedonic infill of voids continues throughout and the original fabric is picked out by the secondary quartz growth around the edges of quartz detritals and microquartz grains.

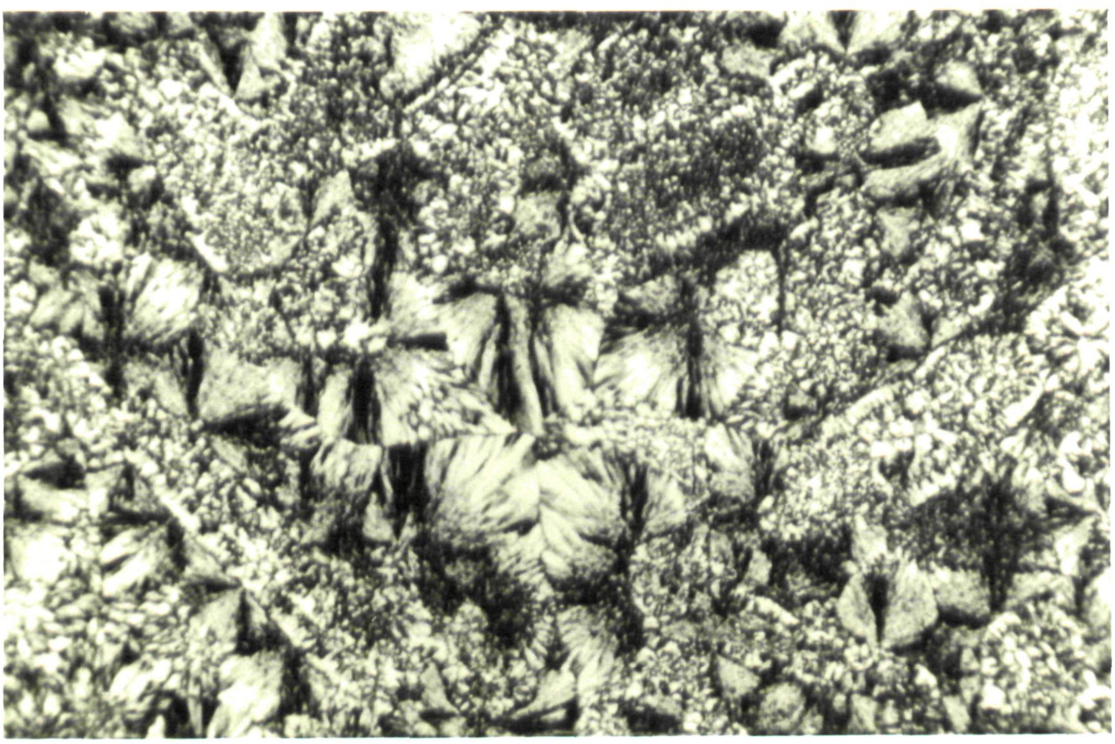


FIG. 4.8: THIN SECTION OF CHERT SHOWING 'GHOST' FABRIC OF MICROQUARTZ GRAINS AND CHALCEDONY. (F.O.V. 1.2 mm).

4.2.4 Chert Genesis - A Discussion

Tresise (1960,1961) examined three major theories of chert formation in relation to the Chert Beds of the Upper Greensand, those of Hinde (1885), Richardson (1947) and Humphries (1956). Hinde thought that cherts originated as sponge spicule masses that were converted to true chert by the solution and reprecipitation of silica. Tresise pointed out the apparent inconsistency in Hindes theory that the spicules were first embedded in siliceous material and then dissolved whereas elsewhere he states that the silica to form the chert is derived from the dissolved spicules. Tresise considered that the silicification by percolating solutions was invalidated in the Chert Beds as he thought that the chert to surrounding sediment change was not transitional. He also stated that there were few quartz detritals in the cherts whereas in a replacement chert many detritals might be expected.

Tresise favoured the silica gel theory (Humphries, 1956) in which the chert is formed by the contraction of a gelatinous mass whose precipitation may have been caused electrolytically or by the action of bacteria or algae. He stated that electrolytic precipitation was not possible in sea-water because of the problem of having a sufficient concentration of monosilicic acid $H_4 Si O_4$ in sea-water. He favoured the precipitation of gel by contact with ammonium salts produced by organic decay combined with the diagenetic redistribution of opaline silica derived from sponge spicules.

Tresise postulated a two-way diffusion gradient in which organic decomposition caused a local lowering on pH, the deposition of silica and the diffusion of silica from nearby which in turn resulted in the dissolution of opaline silica. He further thought that there was a corresponding migration of calcareous material in the opposite direction. He also noted that the diffusion system may have been controlled by pH and/or temperature.

The present work differs on a number of major points with that of Tresise. He states that cherts are absent from beds showing current activity whereas high energy structures have been observed within the cherts. He states that detritals are rare in cherts whereas they have in fact a variable quartz detrital content that reflects the variability seen in the surrounding calcarenites. Tresise also thought that the marginal siliceous envelope seen around cherts was not transitional from chert to sediment whereas the present work clearly demonstrates the transition. Although Tresise states he favours the theory of silica gel formation he in fact includes the classic diffusion of silica ideas to complete his theory of chert formation in the Chert Beds.

Chalcedony, which is seen to infill voids in the Wessex Greensand cherts, appears as a fibrous mineral under the optical microscope but Folk and Weaver (1952) stated that no fibres could be seen under the electron microscope. They concluded that chalcedony was a form of quartz with numerous minute cavities containing water and that this explained the observed properties of chert and chalcedony.They thought that microcrystaline quartz tended to be the replacement product of limestone and was the result of closely associated, multiple initial centres of crystallisation. The chalcedony tended to fill cavities and was thought to result from relatively widely spaced initial centres of crystallisation.

Holdaway and Clayton (1982) pointed out that for silicificaton to occur calcite must be dissolved and silica precipitated. As a ghost calcite grain fabric is preserved in the chert as microquartz it is obvious that dissolution of the calcite occurred simultaneously with the precipitation of silica. Holdaway and Clayton suggested that either some chemical process causes both processes simultaneously or that the dissolution of calcite actually causes silica precipitation. They did not favour the usual, oft quoted, explanation of a local drop in pH which causes undersaturation of calcite in relation to pore waters and supersaturation of silica. Their grounds for rejection were that such pH changes have not been observed in these environments (Berner,1971) and that silica frequently exists in "metastable solution in highly supersaturated conditions with respect to crystalline silica". Furthermore Siever (1957) quoted that solubility of amorphous silica is independant of pH below pH 9.

It is probable that the initiation of carbonate dissolution was caused by the action of bacteria on organic matter in a restricted pore water environment. This restriction was probably caused by the fact that the calcarenite was already partially cemented. Of the various reactions that occur between sedimentary organic matter and bacteria it is probable that the reduction of dissolved oxygen is the most likely to cause calcite dissolution as a result of CO_2 release into the microenvironment (Holdaway and Clayton, 1982).

$$(CH_2O)_{10}(NH_3)_{16}(H_2PO_4) + 138\ O_2 \rightarrow 106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O$$

These workers went on to suggest that the concommitant precipitation of silica may be the result of an increase in the ionic strength of the pore waters or possibly the presence of a "specific mineralising anion" eg. the bicarbonate released by the carbonate dissolution. Once the kinetic barrier to silica precipitation was overcome it is likely that it would nucleate on any available organic material (refs quoted by Holdaway and Clayton, 1982) probably as the result of hydrogen bonds forming between the hydroxyl groups of carbohydrate and silicic acid. It is possible that this nucleation on organic material could explain the deposition of either microquartz or chalcedony (Folk and Weaver, 1952).

Clayton (1986) considered the formation of flints in the Chalk and suggested that aerobic bacteria attack organic matter in the upper part of the sediment down to a depth where oxygen depletion makes it impossible for them to survive. Organic matter oxidation was thought to be continued by sulphate reduction which may be represented as:

$$\text{ORGANIC MATTER} + SO_4 \dashrightarrow \text{SMALLER ORGANIC MOLECULES} + CO_2 + S^{2-}$$

Chemical equilibrium must then be reached by the CO_2 and S^{2-} :

$$S^{2-} + CO_2 + H_20 \rightleftharpoons HS^{-} + HCO_3^{-} \rightleftharpoons H_2S + CO_3^{2-}$$

In the absence of abundant Fe to react with the H_2S it will tend to migrate towards more oxidising conditions where sulphide oxidising bacteria oxidise the sulphide to SO_4^{2-} or native sulphur.

$$H_2S + 2O_2 \dashrightarrow SO_4^{2-} + 2H^{+}$$

Clayton considered that such reactions would take place at a horizon within the sediment where sufficient oxygen was present to allow the survival of the chemolithotropic *Thiobaccili.* These reactions can substantially lower pH values and thus promote the dissolution of carbonate and the concomitant deposition of silica:

$$H^+ + CaCO_3 \rightleftharpoons Ca^+ + HCO_3$$

Clayton's model, therefore, suggested that the silica effectively replaced the calcite along a zone straddling the oxi - anoxic boundary thus producing a tabular body of chert which would explain the observed occurrences in the Wessex Greensand.

In order for the silica to be precipitated it must, of course, be available in the pore waters and probably at high levels of supersaturation. Pittman (1972) reviewed the possible sources of silica in solution: 1) the solution of siliceous shales 2) the devitrification of volcanic glass 3) the decomposition of feldspars 4) biogenic debris releasing silica into solution 5) the precipitation or complexing of silica from river water on contact with sea-water 6) organic complexes 7) precipitation direct from sea-weater 8) pressure solution of silica in areas of high stress and redeposition in areas of low stress.

Bien, Contois and Thomas (1959) also noted that the soluble silica in river water may be up to fifteen times the level of that in sea-water. They consider that this reduction in the sea was due to a) dilution b) biological removal and c) inorganic precipitation. They further suggested that the inorganic precipitation could be due to : 1) the reaction of soluble silica with electrolytes in sea-water to produce insoluble salts or 2) the adsorption of soluble silica with suspended solids or colloids in river water on contact with sea-water electrolytes.

Siever (1957) added two further possibilities as sources of soluble silica; a) deep groundwaters and b) supersaturated hot spring waters.

In the case of the cherts found in the Wessex Greensand of south-west England the source of silica is unlikely to be solutions derived from siliceous shales or deep groundwaters as the chert formation is probably a fairly early diagenetic event. There is no evidence for the presence of volcanic glass or hot spring fluids. Precipitation from sea-water is also unlikely. Pressure solution is a possible source of silica in solution but there is probably not enough quartz present in the calcarenite nor is the sediment likely to have been buried deep enough to produce the necessary overburden pressures in time to act as a source for the chert. There is no evidence for river input in the Chert Beds Member.

This leaves the possible organic complexing of silica, the dissolution of siliceous biogenic debris and the decomposition of feldspars as the most likely sources of silica in solutions of sufficient strength in the pore waters. There is certainly evidence for the latter two possibilities and these are the most probable sources.

The sequence of events in the formation of cherts in the Chert Beds Member of south-west England is therefore thought to be:

1) Silica supersaturation of pore fluids by the dissolution of siliceous biogenic debris and the decomposition of feldspars.

2) Localised action of bacteria on organic matter in a restricted pore water environment resulting in the liberation of CO_2.

3) Consequent initiation of calcite dissolution and resulting silica precipitation.

4) Nucleation of silica on organic debris tending to produce microquartz replacement of calcite grains and chalcedonic void fill.

5) The production of a roughly horizontal silica ghost of the original calcareous sediment.

6) The large numbers of chert horizons may be explained by the nature of the sedimentary environment which repetitively produced the same conditions in the sediment column.

4.3 Secondary Calcite - Previous Work

Tresise (1960) observed that calcareous concretions in the Wessex Greensand Formation were often packed with detrital grains and cemented with calcite which he considered to be derived from fossil fragments taken into solution and then reprecipitated. He thought that this process was controlled by slight variations in pH level which could be caused by organic decay under anaerobic conditions. Pebbles of cemented material were observed suggesting that this was an early diagenetic process. Tresise suggested that the purer limestone nodules could be the result of the recrystallisation of a calcareous sediment and possibly involved the replacement of rare quartz detritals.

The sequence of diagenetic events for the Wolborough limestones of south Devon was worked out by Edwards (1979). Sparry calcite occurred as a cement and in-filled moulds of former aragonitic bioclasts, several of these exhibited micrite envelopes while some syntaxial rim cement also occurred, usually around monocrystalline echinoid fragments. Many of the bioclasts were seen to be silicified and some of the intraclasts had chert-like textures where both carbonate grains and matrix were affected. Edwards proposed a cementation sequence for the Wolborough limestones. Precipitation of small non-ferroan calcite crystals on allochem surfaces and in cavities was an early event completed before intraclasts were formed. After a period of time coarse ferroan calcite filled most of the remaining pores and this process was completed by precipitation of coarse non-ferroan calcite.

Although he noted that the early cement could have been formed in a number of environments Edwards considered that the evidence for dissolution and recrystallisation of aragonite particles suggested exposure to fresh water in a subaerial diagenetic environment. The second ferroan cement was also considered to have formed in the phreatic zone while the late ferroan and non-ferroan cements were considered to have been derived from an external source.

Garrison *et al.* (1987) examined hardgrouds and early lithification in the Late Albian of S.W. England. In all the samples they looked at between two and five generations of cement were observed. They reported the first generation to be either "dog tooth spar" or syntaxial overgrowths while later generations included micritic, fibrous and equant sparry calcites. They considered that there was ample evidence of early lithification under submarine conditions and that the original cements were probably magnesian calcite but may have included aragonite..

4.3.1 Secondary Calcite - This Study

Secondary calcite has probably been largely removed by leaching after the erosion of the Chalk cover from the Wessex Greensand Formation in south-west England, but it still may be seen as a cement in both the Foxmould Sands Member and the Chert Beds Member.

At outcrop most samples of the Foxmould Sands Member are easily disaggregated, contain relatively little true cement and are largely bound together by original void filling clay minerals. Calcite cement does occur, however, and may well have been more important before the leaching of the present outcrop (Fig. 4.9). The cement may occur as an irregular mosaic of small and large calcite crystals with wavy, curved and straight intercrystalline boundaries. This suggests the 'calcitization' of aragonite grains, that is a direct change with no void phase (Bathhurst, 1971). Calcite cement also occurs as small angular crystals which may be seen as void infilling within sepulid worm tubes. Where calcite cement surrounds quartz detritals they often appear to be corroded and etched, probably caused by calcium-rich pore fluids which circulated prior to crystallisation of the cement (Dapples, 1971).

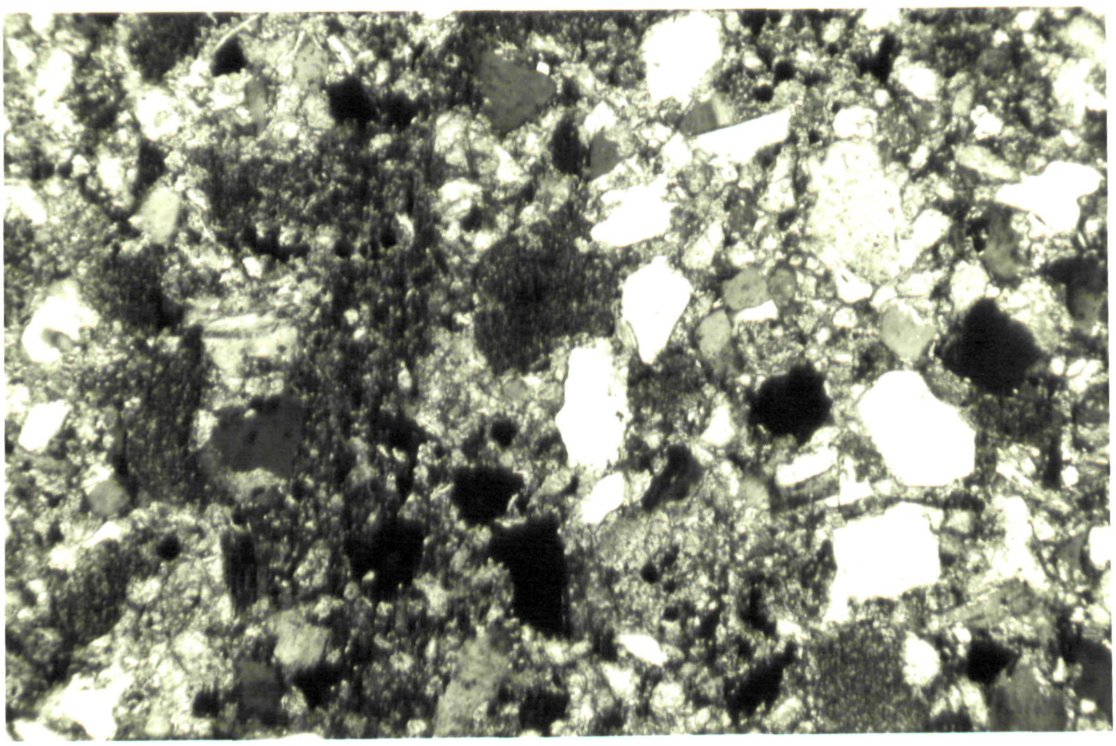


FIG. 4.9: THIN SECTION SHOWING CALCITE CEMENT WITHIN FOXMOULD SANDS MEMBER, BRANSCOMBE. (F.O.V. 1.2 mm).

The calcareous sands of the Chert Beds are usually bound by calcite cement (Fig. 4.10) and plagioclase feldspar grains and glauconite grains may be partially replaced by calcite. Quartz detritals are also seen with etched surfaces which are infilled with calcite and some of the small irregular calcite cement crystals have uneven contacts suggestive of pressure solution.

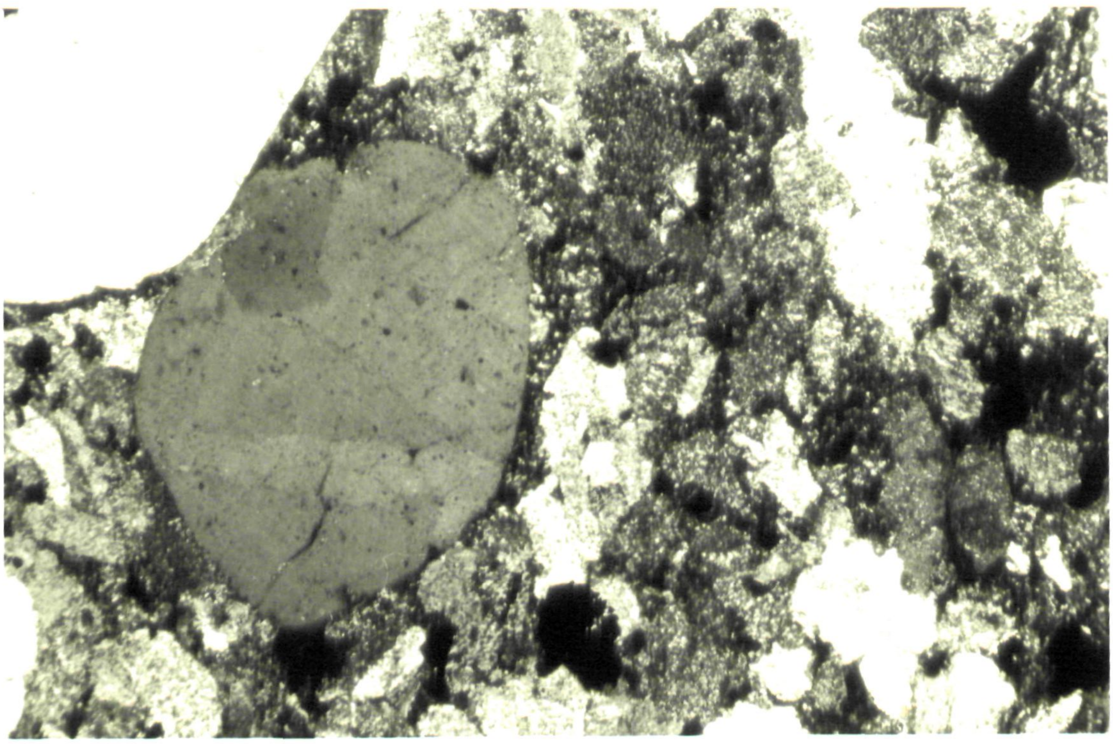


FIG. 4.10: THIN SECTION SHOWING CALCITE CEMENT WITHIN CHERT BEDS MEMBER, BRANSCOMBE. (F.O.V. 3.1 mm).

CHAPTER 5 BIOSTRATIGRAPHY

5.1 Introduction and Previous Work

This chapter is divided into a number of sections which discuss (i) the general faunal references relevant to the Wessex Greensand (ii) general ammonite references, ammonite zonations and a new ammonite occurrence (iii) general references on the Foraminifera, an introduction to the taxonomy and the taxonomy of foraminiferal genera and species collected during this study (iv) a preliminary investigation into the nannofossils found during this study (v) the biostratigraphy and correlation of the Wessex Greensand Formation in south west England and (vi) palaeobiogeography of orbitolinid colonisation pathways into S.W. England

5.2 General Faunal References

Work on the fauna of the Wessex Greensand Formation may be roughly divided into those publications which more or less just listed the fossils to be found and those which attempted to erect a biostratigraphic scheme and use it to correlate between sections.

Much of the important faunal data collected in the 19th century was included in the memoir authored by Jukes-Browne and Hill (1900) and included information from such workers as Godwin-Austen (1842), Fitton (1847), Hinde (1885), Carter (1871), Meyer (1874) and Strahan (1898). Jukes-Browne and Hill also included details of their own collections from the Upper Greensand at many localities.

Publications early in the 20th century which listed the fauna to be found at a given locality included Jukes-Browne (1903), for the Upper Greensand near Chard; Woodward and Ussher (1911), for the area around Sidmouth and Lyme Regis; and White (1921) for the Isle of Wight.

General faunal information may also be found in Arkell (1947) and Smart (1955) for the Dorset area; Wilson *et al.* (1958) for the area around Bridport and Yeovil; Kennedy (1970) for S.W. England; Hamblin and Wood (1976) and Selwood *et al.* (1984) for the Haldon Hills; and Edwards (1979) for the Wolborough Limestone.

In addition to publications dealing specifically with the fauna of the Wessex Greensand Formation of south-west England there have been a large number that examined both macrofauna and microfauna from other locations (of a similar age). These publications have varied in their approach from descriptive to stratigraphic to taxonomic. They include the works of; looking at ammonites Casey (1961), Owen (1971,1975), Spath (1922-1943), Breistoffer (1947), Van Hinte (1976), Juignet and Kennedy (1971), Destombes (1973), Deroo and Destombes and Hancock

(1959, 1969); looking at foraminiferal stratigraphy Price (1977a and b), Magniez-Jannin (1975); ostracod stratigraphy Neale (1978); foraminifera Berthelin (1880), Chapman (1891-1898), Eichenberg (1933), Marie (1939,1941,1965), Khan (1950,1952), ten Dam (1950), Gawar-Biedowa (1969,1972), Hermes (1969), Cushman Foundation (1920-1950), Champney (1978), Ascoli (1976), Price (1975), Loeblich and Tappan (1961), Longoria and Camper (1977), Masters (1977), Robaszynski and Caron (1979), Douglass (1960a-b), Hofker (1963) and Schroeder (1975); ostracods Jones (1849), Jones and Hinde (1890), Chapman and Sherborn (1893), Chapman (1898), Corneul (1848), Mertens (1956), Deroo (1956), Oertli (1958), Kaye (1964-1966), Damotte (1961-1977), Grundel (1967), Kemper *et al.* (1975) and Van der Wiel (1978); nannofossils Davey and Verdier (1971,1973).

The monographs published by the Palaeontographical Society were also a source of data for various fossil groups including; Wright (1862-85) and Spencer (1905-1908) on the Echinodermata; Swinnerton (1936-1952) on belemnites; Hinde (1887-1893) on sponges; Bell (1862) on the malacostracous crustacea; Duncan (1869-1870) and Edwards and Haime (1850) on corals; Davidson (1852-1884) on brachiopods; Lycett (1872-1879) and Woods (1899-1913) on the lamellibranchs.

Many of these works were referred to in the identification of the microfossils mentioned below and where ideas suggested by a specific paper are discussed the paper is cited in the text.

5.3 Ammonites

5.3.1 General Ammonite References

Two faunal groups have attracted special interest because of their potential for stratigraphic correlation and dating: the ammonites and the Foraminifera. Detailed work on the ammonites of the Wessex Greensand Formation has been reported by Wright (in Arkell, 1947) for Dorset; Hancock (1969) and Kennedy (1970) for S.W. England; with other contributions from Smart (1955) for the Alton Pancras district in Dorset; Wilson *et al.* (1958) for the area around Bridport and Yeovil; Hart (1973b) for S.W. England; and Hamblin and Wood (1976) and Selwood *et al.* (1984) for the Haldon Hills.

5.3.2 Ammonite Zonations

One of the earliest attempts at a biozonation of the Upper Greensand was published by Barrois (1876) when he recognised two distinct faunas: the Blackdown fauna which he placed in his Zone of *Ammonites inflatus* and the Warminster fauna which he placed in his Zone of *Pecten asper*.

This scheme was utilised by Jukes-Browne (1892) when he described the sands above the Gault Clay at Devizes as belonging to the older Zone of *Ammonites inflatus* and the younger Zone of *Pecten asper*. In 1900, however, Jukes-Browne and Hill divided their Upper Greensand into the Zone of *Ammonites rostratus* and the younger Zone of *Pecten asper* and *Cardiaster fossarius* . Woodward and Ussher (1911) retained the Zone of *Pecten asper* but placed the Foxmould in the Zone of *Schloenbachia rostrata* while White, (1921) working in the Isle of Wight, divided the Upper Greensand into the Zone of *Cardiaster fossarius* and the underlying Zone of *Mortoniceras rostratum*.

The next major change in biozonation of the Upper Greensand was proposed by Wright (in Arkell, 1947) who placed the largely phosphatised ammonite fauna found in Dorset into the zones and subzones proposed by Spath (1922-1943) (Fig.5.1). *Stoliczkaia dispar* Zone ammonites were seen in every section although none were found belonging to the lower *Arraphoceras substuderi* Subzone. The *Perinquieria inflata* (later *Mortonicera inflatum*) Zone was either suggested or proved at a number of localities. The *Pervinquieria inflata* var. *aequatorialis* Subzone was proved at Punfield; the *Callihoplites auritus* Subzone was proved at Osmington and suggested at Punfield and Worbarrow; the *Hystoceras varicosum* Subzone was proved at Punfield and Osmington; and the *Hystoceras orbigny* Subzone was suggested at Punfield, Worbarrow and Osmington. Although Wright mentioned the phosphatised nature of the *dispar* Zone ammonites, particularly from the 'ammonite bed' found above the Exogyra

ZONES AND SUBZONES (L.F. SPATH)		OCCURRENCES IN DORSET
Stoliczkaia dispar	*Stoliczkaia dispar*	PROVED IN EVERY SECTION.
	Arrhaphoceras substuderi	NO AMMONITES.
Pervinqueria inflata	*Pervinqueria inflata* var. *aequatorialis*	PROVED AT PUNFIELD.
	Callihoplites auritus	PROVED AT OSMINGTON, SUGGESTED AT PUNFIELD AND WORBARROW.
	Hystoceras varicosum	PROVED AT PUNFIELD AND OSMINGTON.
	Hystoceras orbigny	SUGGESTED AT PUNFIELD, WORBARROW AND ?OSMINGTON.
Euhoplites lautus	*Diploceras cristatum*	AMMONITES OF TOP OF LOWER GAULT FOUND LOOSE AT OSMINGTON.
	Anahoplites daviesi	
	Euhoplites lautus-nitidus	
	Diploceras delaruei	

FIG. 5.1: AMMONITE DATING OF THE SELBORNE GROUP IN DORSET. (AFTER WRIGHT, 1947).

Sandstone, he did not consider them to be reworked faunas.

This ammonite based zonal scheme (Spath, 1922-1943) was generally accepted and used by subsequent workers although there was of course disagreement as to which zone a given lithological unit belonged in any given area especially when the zonation was based on correlation rather than the actual occurrence of the zonal fossil.

Smart (1955) clarified the faunal evidence from the Upper Greensand of the Alton Pancras district in Dorset placing the phosphatic nodule horizon and glauconitic sand seen at the top of the succession in the *dispar - perinflatum* Subzone.

In the Bridport and Yeovil areas Wilson *et al.* (1958) placed the lowermost beds of the Upper Greensand in the *inflatum* Zone, based on the presence of *Callihoplites* aff. *auritus* (Spath); the lower part of the Eggardon Grit was placed in the Albian (*dispar - perinflatum* Subzone) on the basis of an ammonite fauna of *Stoliczkaia* cf. *dispar* (d'Orbigny) and *Mortoniceras (Durnovarites)* cf. *subquadratum* (Spath); while the upper part was placed in the Early Cenomanian on the basis of an ammonite fauna of *Anisoceras* cf. *plicatile* (J. Sowerby), *Mantelliceras?*, *Schloenbachia* aff. *nodulosa* (Stieler) and *S.* cf. *subvarians* (Spath).

Hancock (1969) reported the ammonite faunas that had been collected, by various workers, from the Upper Greensand in south-west England, noting that the Haldon Sands had yielded *Mortoniceras (Deiradoceras)* aff. *devonense* (Spath) indicating *inflatum* Zone; the Blackdown Sands had yielded *Hystoceras* spp., *Prohystoceras goodhalli*, *Epihoplites* spp., *Euhoplites alphalautus* and *Mortoniceras devonense* indicating *varicosum* and/or *orbignyi* Subzones. The Foxmould of south-east Devon yielded *Mortoniceras cunningtoni*, *M. devonense*, *M. bipunctatum*, *M. albense*, *Hysteroceras varicosum* and *Callihoplites* aff. *auritus* indicating *varicosum* / *auritus* Subzones. In addition *dispar* Zone ammonites had been reported from the phosphate band below the Glauconitic Marl, Isle of Wight; in a similar position at Punfield, some 4m below the Chalk at White Nothe, and in the Chert Beds near Charmouth. *Mantelliceras mantelli* Zone (early Cenomanian) ammonites had been reported from the top of the Eggardon Grit near Maiden Newton and from the Wilmington Sands.

Kennedy (1970) used the ammonite faunas to date many of the highest horizons of the Upper Greensand in southern England and although many of the localities were outside the present area of study they contributed valuable age determinations.

In the area near Warminster and Mere, Chert Beds of possible *Stoliczkaia dispar* and *Mortoniceras (Durnovarites) perinflatum* Subzone age were overlain by Albian to Cenomanian greensands and locally reworked Cenomanian phosphate horizons. Further south, in the Stour valley, a reworked glauconitic sandstone yielded a phosphatised and unphosphatised *S. dispar* and *M. (D.) perinflatum* Subzone fauna which was succeeded by a glauconitic marl containing a *Hypoturrilites carcitonensis* assemblage fauna (early Cenomanian).

To the south-west, at Evershot, the glauconitic sandstone rested on the Exogyra Sandstone, which yielded a fauna suggestive of *Mortoniceras aequatorialis* or *Callihoplites auritus* Subzone age. Near Maiden Newton the Chert Beds were recorded with a probable *Arrhaphoceras substuderi* Subzone age fauna. These were succeeded by a thin glauconitic sand (which Kennedy considered was all that remained of the *S. dispar* and *M. (D.) perinflatum* Subzone sandstone) and the Eggardon Grit. To the south-west this grit becomes thicker and yielded an early Cenomanian ammonite fauna near it's top.

Reviews of the ammonite zonation of western Europe have been presented by a number of workers (Kennedy and Hancock, 1979; Owen, 1976, 1979); and Owen (1984) listed studies that have been carried out on the ammonite sequences of eastern and southern Europe. In this latter paper, Owen pointed out a number of inconsistencies and errors in the existing ammonite zonation, and suggested that there might be a case for the revision of the scheme.

5.3.3 Ammonite - Present Study

Previous ammonite evidence from the Foxmould Sands Member in S.E. Devon, as cited by Hancock (1969), indicated a *varicosum/auritus* Subzone age.

The only ammonite to be found in the Selborne Group during the present study was recovered from the lower part of the Foxmould Sands Member at Branscombe (Fig.5.2).

It has been identified by Dr H.G. Owen (pers. comm.) as *Prohystoceras (Goodhallites) delabechei* Spath. Preservation was fair to good and assuming it had not been reworked this ammonite suggests a confirmation of *varicosum* Subzone age for the lower part of the Foxmould Sands Member.

5.4 Foraminifera

5.4.1 Previous Work

Detailed work on the Foraminifera of the Wessex Greensand Formation has been reported by Hart (1971), Hart *et al.* (1979a), Hart *et al.* (1979b), Williams *et al.* (1988) and Hart and Williams (1990) for S.E. Devon; Schroeder *et al.* (1986) and Simmons and Williams (in press) for S.W. England; Carter and Hart (1977) for southern England; with contributions from Andrieff *et al.* (1975), Lott *et al.* (1980) and Wilkinson and Halliwell (1980) for the offshore margins of the region.

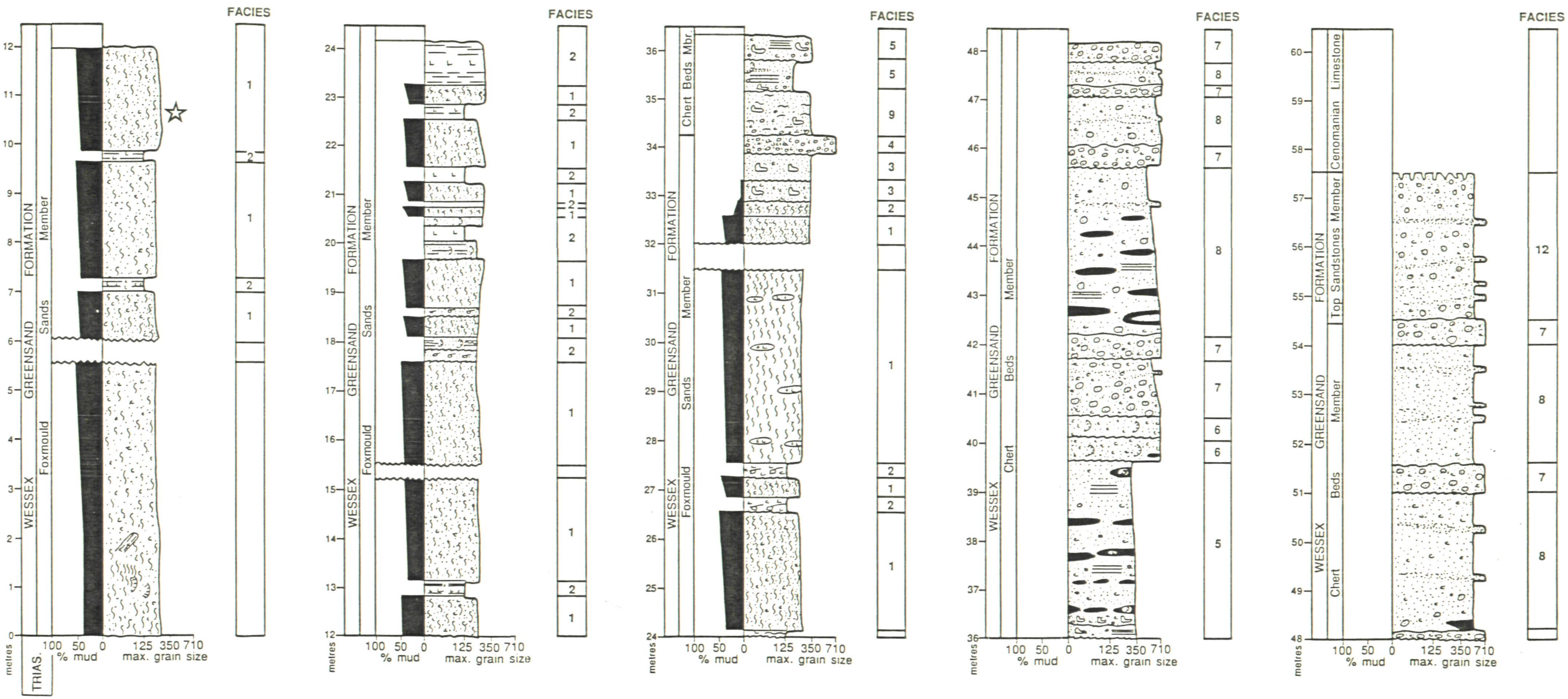


FIG. 5.2: POSITION OF THE AMMONITE *Prohystocreas (Goodhallites) delabechei* IN THE FOXMOULD SANDS MEMBER, BRANSCOMBE, S. DEVON.

By 1970 the Haldon Sands were regarded, mostly on ammonite evidence, as being *inflatum* Zone; the Blackdown Sands as *varicosum/auritus* Subzone; the Foxmould Sands as *varicosum/auritus* Subzone; and the Chert Beds as *dispar* Zone. In 1971, however, Hart discussed the occurrence of the large benthonic foraminiferan *Orbitolina concava* (Lamarck) from localities at Wilmington, Dunscombe, Wolborough, Babcombe (Devon), Antrim (N. Ireland) and Ballon (Sarthe) in western France. He accepted the work of Hofker (1963) which stated that the genus was represented by a single species (*O. lenticularis* (Blumenbach)) (see discussion later) but could belong to a number of 'Form Groups' based on the morphology of the embryonic apparatus. Hofkers 'Form Group IV' (= *O. concava)* was accepted as Cenomanian in age and it was assumed that all occurrences of O. *concava* (= IV) were in rocks of Cenomanian age. The Eggardon Grit, which had been dated as Cenomanian on ammonite evidence (Kennedy, 1970), was correlated by Hart with the horizons containing *O. concava* at Dunscombe and Wilmington.

Hart continued to examine the problem of the age and correlation of the Upper Greensand of S.W. England (1973 b) and presented a synthesis of the available evidence, from both the macrofauna and microfauna. The Exogyra Sandstone found below the Chert Beds (in Dorset) had been dated, on ammonite evidence, as Late Albian *Callihoplites auritus* or *Mortoniceras aequatorialis* Subzone) by Kennedy (1970), who also described a non-phosphatised early Cenomanian ammonite fauna from the

Eggardon Grit. Hart stated that his previous (1971) and forthcoming publications supported the early Cenomanian age for the Eggardon Grit on microfaunal evidence, including the occurrence of *Orbitolina lenticularis* (Blumenbach) (= *O. concava* in this sense).

Given that these ages were accurate, Hart pointed out that if extrapolated westwards to the Beer district then the Chert Beds in that area must represent either all or part of the *S. diapar* Zone (Late Albian) and the *H. carcitanensis* assemblage Zone (Early Cenomanian) of Kennedy (1970). Hart thought it ill advised to accept a single occurrence of *Mortoniceras* gr. *stoliczkaia,* from an unspecified horizon near Charmouth, as sufficient evidence for placing the whole of the Chert Beds in the *S. dispar* Zone.

The *S. dispar* Zone ammonite fauna from the Dorset coast (Wright in Arkell, 1947) was phosphatised and probably reworked and Hart's work had indicated an early Cenomanian age (*H. carcitanensis* assemblage Zone) for the matrix of the 'ammonite bed' from which, it appeared, the *S. dispar* Zone fauna had been collected. Hart used this reworked fauna from the Dorset coast to suggest that there was little evidence of *S. dispar* Zone age Chert Beds in south-west England. This led him to conclude that the Chert Beds were of Early Cenomanian age which he claimed was substantiated by the occurrence of *Orbitolina.*

Much of this work by Hart was based on an examination of the mid -

Cretaceous foraminfera of southern England which had been completed earlier but did not appear in print until later (Carter and Hart, 1977).

The south-west of England was divided, for purposes of study, into the mid-Dorset Swell, the margin of the mid-Dorset Swell and the south-western shelf. Although not primarily concerned with the Upper Greensand, Carter and Hart did date some of the units. On the margin of the mid-Dorset Swell they accepted that the Eggardon Grit was of Early Cenomanian age (their zone 9) and suggested a Late Albian age for the Exogyra Sandstone. In this area they tentatively placed the Chert Beds in the Early Cenomanian.

In south-east Devon the Top Sandstones were equated with the Eggardon Grit and were, therefore, thought to be Early Cenomanian in age. They did not consider these sediments to be diachronous in nature. The chert conglomerate, seen at Lulworth Cove and Durdle Door, was placed in the Cenomanian (their zone 10 to 11i equivalent to the Cenomanian Limestone further west). Based mainly on the occurrence of *Orbitolina* Carter and Hart placed the Chert Beds of south-west England in the Cenomanian (their microfaunal zones 7-8). They considered that much of the macrofaunal evidence for Late Albian age for these sediments had relied on phosphatised, reworked ammonites. The Foxmould which was beneath the Chert Beds was placed in the Late Albian (their zone 6) although the zonal indicators were not found.

The upper part of the outliers found in the Haldon Hills and the limestone seen at Wolborough were placed in the Cenomanian. A decision largely based on the occurrence of *Orbitolina*.

The next major contribution to this debate was made by Hamblin and Wood (1976) when they discussed the stratigraphy of the Haldon Hills and correlated the Upper Greensand members of that area with those in S.E. Devon. The presence of an indigenous late Albian *S. dispar* Zone) ammonite fauna (determined by Dr Hugh Owen) found in the highest part of the Chert Beds or basal Top Sandstone at Shapwick Grange, near Lyme Regis, led Hamblin and Wood to the conclusion that the Chert Beds in south-east Devon were Albian and not Cenomanian. Using their lithostratigraphic correlation, this made the Woodlands Sands Member, at Haldon, Albian in age despite the 'Cenomanian aspect' of the molluscan fauna. They further believed that most of the orbitoline occurrences in Devon, with the exception of Babcombe Copse (and therefore the Cullum Sands-with-Cherts Member) and Smallercombe Goyle, were Albian in age.

Hart *et al.* (1979) examined the Upper Greensand microfauna they found at Shapwick Grange Quarry, east Devon. They described the position in the succession that had yielded the ammonite fauna (Hamblin and Wood, 1976) but stated that their own samples were barren except for one point some way below the ammonite horizon. The ostracods and foraminifera recovered from this sample indicated an Albian-Cenomanian boundary age but the species recorded had either long or imprecisely known ranges, especially in marginal facies. Despite this difficulty it was thought that the results cast some doubt on the dating of the Chert Beds as totally Cenomanian as indicated by Carter and Hart (1977).

Hart and others (1979) reported a bivariate analysis, based on external characteristics only, of the *Orbitolina* fauna from Wolborough in south Devon which suggested a Late Albian-Early Cenomanian age for the Wolborough limestones. The orbitolines found at Bullers Hill Quarry were thought to compare favourably with those from the type Cenomanian of the Sarthe. Other foraminifera and ostracods found in the Wolborough limestone together with some of the microfauna found in the cherts at Bullers Hill were thought to support the Late Albian-Early Cenomanian and Cenomanian dates respectively suggested by the orbitolines.

Schroeder *et al.* (1986) applied the revised taxonomy of the *Orbitolina concava-sefini* group (Schroeder, 1985 a, b) to the orbitoline fauna of south Devon (see later discussion).

Williams *et al.* (1988) examined the Foraminifera of the Wessex Greensand Formation in S.E. Devon (the content of this paper was taken from this study and will be discussed below).

Hart and Williams (1990) examined samples from a borehole on the site of the A303 Honiton-Marsh road and attempted a graphic correlation of the S.E. Devon Wessex Greensand Formation with the Glyndebourne borehole; the results of which did not alter previously held views.

Simmons and Williams (in press) examine the orbitoline occurrences in S.W. England (again the content of this paper is taken from this study and will be discussed below).

5.4.2 Introduction to Taxonomy

Samples from a representative section at Branscombe in S.E. Devon have been examined for foraminifera with a view to refining the age determinations and correlation of the Upper Greensand in S.W. England. In addition examples of the larger foraminiferan *Orbitolina* have been collected and examined from various localities in S.W. England, and as these are the most useful group, they have been treated in the greatest detail.

Of the 80 samples collected from the Branscombe Mouth to Beer Head section only 42 yielded foraminifera and these usually had a poor fauna both in terms of numbers of species and individuals. Indeed some samples contained only a single specimen. In addition the specimens were frequently fragmented, partially dissolved and/or covered with sediment that was difficult to remove. As a result of this combination of few individuals and poor preservation it was not always possible to identify the foraminifera down to species level.

Each of the species found in the section at Branscombe is described with a brief synonomy which covers the original reference and a few of the major or more recent references, especially those where a different generic name was applied. Also included are a diagnosis and some remarks on state of preservation, variation within the population and frequency of occurrence. Finally the stratigraphic range is given and a list of the samples in which the species occurred which may be referenced against the range chart (Fig. 5.3) and sample position (Fig. 5.4).

Recently Loeblich and Tappan (1988) have produced a major revised classification of the Foraminifera and this has been used in the taxonomic descriptions.

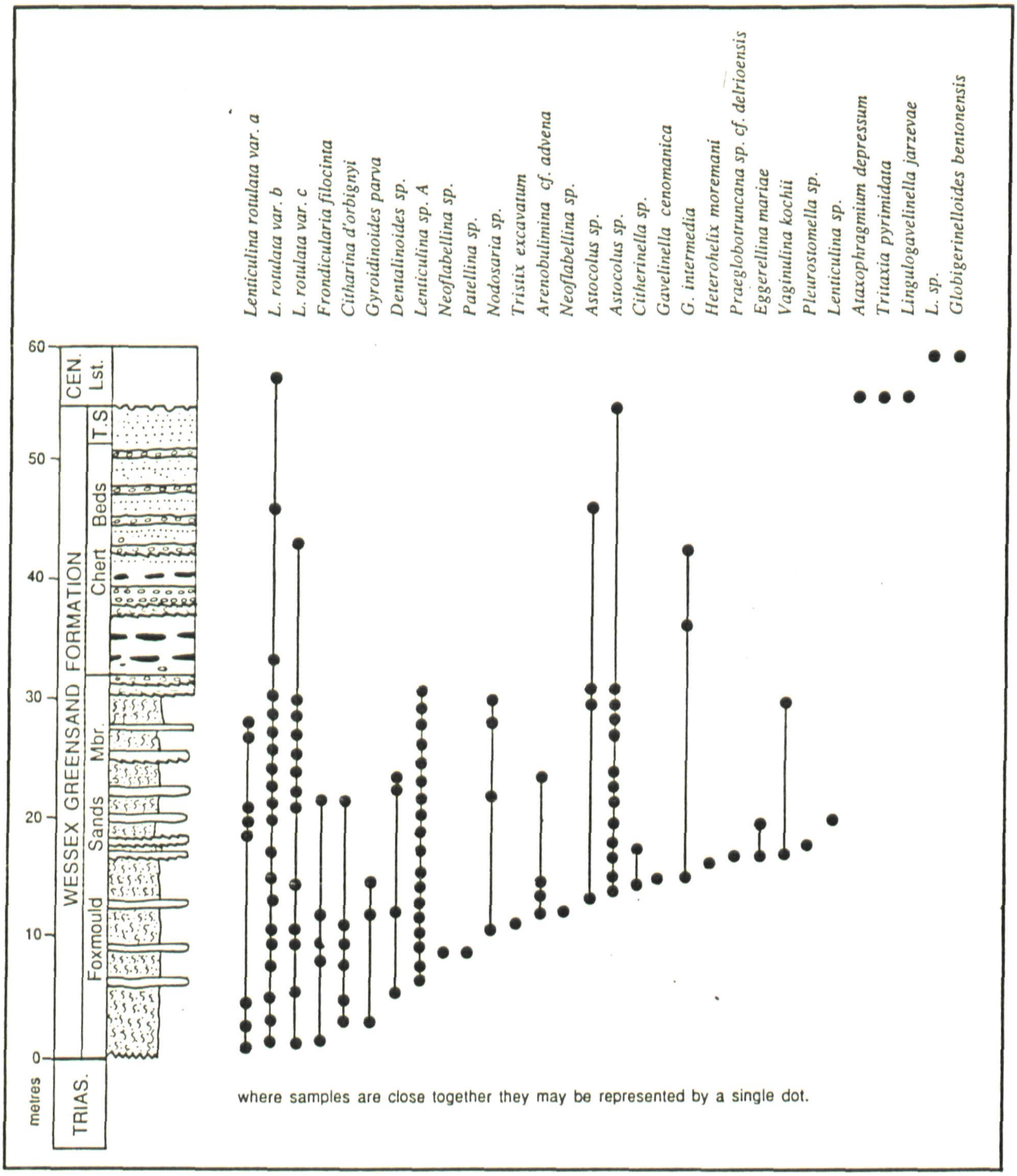


Fig. 5.3 Occurences of foraminifera in the Wessex Greensand Formation, Branscombe, S.E. Devon

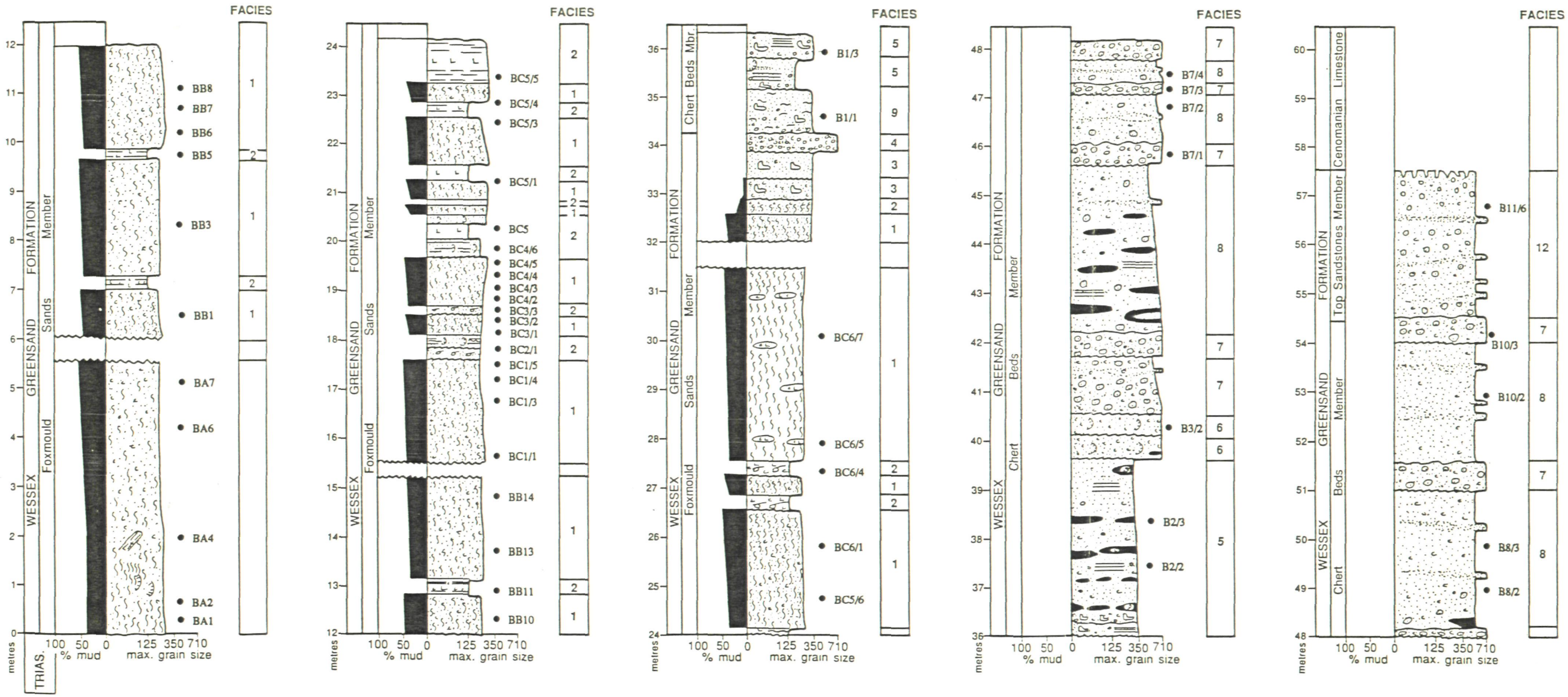


FIG. 5.4: SAMPLE POINTS WHICH YIELDED FORAMINIFERA, WESSEX GREENSAND FORMATION, BRANSCOMBE, S.E. DEVON.

5.4.3 Taxonomy

Order FORAMINIFERIDA Eichwald, 1830

Suborder TEXTULARIINA Delage and Hérouard, 1896

Superfamily VERNEUILINACEA Cushman, 1911

Family VERNEUILINIDAE Cushman, 1911

Subfamily VERNEUILINOIDINAE Suleymanov, 1973

Genus *Eggerellina* Marie, 1941

Type Species: *Bulimina brevis* d'Orbigny, 1840

Eggerellina mariae ten Dam, 1950 (Plate 1, Fig.3)

1950 *Eggerellina mariae* ten Dam, p.15-16, pl.1, fig. 17.

1977 *Eggerellina mariae* ten Dam; Carter and Hart, p.17, pl.2, fig. 7.

1981 *Eggerellina mariae* ten Dam; Hart *et al.*, p.176, pl.7.2, figs 1,2.

1989 *Eggerellina mariae* ten Dam; Hart *et al.*, p.138, pl.7.2, figs 1,2.

Description: A variable species; test free; sub-conical to sub-ovoid; triserial with inflated and embracing chambers; chambers inflate at various rates, specimens vary from high spiral and narrow to low spiral and wide; normally 6 to 9 chambers per specimen; aperture narrow, hook-shaped and interiomarginal. Test agglutinated, test surface smooth, glossy.

Remarks: *E. mariae* is an extremely variable species ranging from forms that are short and pyramidal to those that are relatively long and narrow. Carter and Hart (1977) were unable to determine distinctive ranges for each of these morphotypes. The specimens collected during this study tended towards the long and narrow form.

Stratigraphic Range and Occurrence: Known from the *C. auritus* Subzone up into the early Turonian. It was first described from the Gault Clay of Holland and widely recorded from southern England by Carter and Hart (1977). At Branscombe it is rare, only occurring as a single specimen in three samples from the middle Foxmould Sands Member; BC1/4, BC1/5 and BC3/2. Preservation was fair to good.

Palaeoenvironment: Deep neritic to upper bathyal (Koutsoukos, 1989).

Family TRITAXIIDAE Plotnikova, 1979

Genus *Tritaxia* Reuss, 1860
Type Species: *Textularia tricarinata* Reuss, 1844

Tritaxia pyramidata Reuss (Plate 1, Fig.1)

1862 *Tritaxia pyramidata* Reuss, p.32, 88, fig. 9a-c.

1928 *Tritaxia pyramidata* Reuss; Franke, p.138, pl.7, fig. 18a-c

1948 *Tritaxia pyramidata* Reuss; Williams-Mitchell, p.98, pl.8, fig. 5a-c.

1950 *Tritaxia pyramidata* Reuss; Ten Dam, p. 12-13.

1953 *Tritaxia pyramidata* Reuss; Barnard and Banner, p.195, pl.7, fig. 1a-b.

1967 *Verneulina variablis* Brady; Fuchs, p.269, pl.3, fig. 2.

1977 *Tritaxia pyramidata* Reuss; Carter and Hart, p.13, pl.2, fig. 15.

1981 *Tritaxia pyramidata* Reuss; Hart *et al.*, p.178, pl.7.3, fig. 2,3.

Description: Test free, triserial in early portions, triangular in cross section, last chamber uniserial, sides slightly concave. In side view species sub-triangular; sutures straight, difficult to observe, generally flush to test surface; last chamber circular in apertural view; greatest width at 0.8 length; wall coarsely agglutinated.

Remarks: May be confused with *Tritaxia singularis* Magniez-Jannin in the early Cretaceous but the latter generally has more excavated sides and a more coarsely agglutinated test(Magniez-Jannin, 1975). *T. pyramidata* shows a wide range of shape and size (Hart *et al.*, 1981).

Stratigraphic Range and Occurrence: Elsewhere in S.W. England Hart

(1970) and Carter and Hart (1977) have recorded this species occasionally from various localities in the Upper Greensand. It is abundant throughout the Albian and Cenomanian of N.W. Europe especially in the chalk facies and is of limited stratigraphic value. At Branscombe a single, poorly preserved, specimen occurred in one sample at the top of the Chert Beds Member, sample B11/6.

Palaeoenvironment: Not known for the Albian - the genus is recorded by Koutsoukos and Hart (1990) as being middle neritic to upper bathyal during the Coniacian.

Superfamily ATAXOPHRAGMIACEA Schwager, 1877

Family ATAXOPHRAGMIIDAE Schwager, 1877

Subfamily ATAXOPHRAGMIINAE Schwager, 1877

Genus *Arenobulimina* Cushman, 1927
Type Species: *Bulimina preslii* Reuss, 1846

Arenobulimina sp. cf. *A. advena* Cushman, 1936 (Plate 1, Fig.2)

Description: Test free, chambers arranged trochospirally; apertural face obliquely truncated, last chamber embraces 0.66 to 0.76 of the test circumference, test circular in cross-section; aperture situated in a slight depression in the apertural face; sutures very weakly depressed; in side view test margins convex, strongly converging umbilically; umbilical margin bluntly pointed; greatest width at 0.66 length; wall agglutinated, test surface almost smooth.

Remarks: In the species *A. advena* there is some variation in the size and outline of adult specimens and the apertural lip is not always present. The internal partitions are simple and extend over the last 1 to 4 chambers.

The specimens collected during this study had an average height of 0.45mm and a maximum width of 0.33mm.

Specimens with complex internal partitions are generally mid-late Cenomanian in age, as reported by Carter and Hart (1977). Forms with simple internal partitions are generally early Cenomanian in age although they are also found in the latest Albian. The possession of such structures is probably a response to environmental factors and, as indicated by Hart (1970) some specimens of *Arenobulimina* have been found in the Upper Greensand of the Isle of Wight.

As indicated by Carter and Hart (1977) there has been an error in the locality and age of the original *"Hagenowella advena"*, initially spotted by Brotzen (1945). The holotype is therefore late Cenomanian in age, and not late Senonian, as reported by Cushman (1936).

Stratigraphic Range and Occurrence: The species *Arenobulimina advena* occurs in the very latest Albian of southern England and is of zonal significance. It's full stratigraphic range is very uppermost Albian to Cenomanian and the type species was described from the Cenomanian of Germany. The specimens collected during this study could not be placed with complete confidence within the species *A. advena* and hence the designation sp. cf.. Because of this designation the age range is probably not reliable. At Branscombe this species occurs in four samples from the middle part of the Foxmould Sands Member; BC5, BB8, BB11, and BB14. It is rare, only one or two specimens per sample but the preservation is fair to good.

Palaeoenvironment: Not known.

Genus *Ataxophragmium* Reuss, 1860

Type Species: *Bulimina variablis* d'Orbigny 1840

Ataxophragmium depressum (Perner), 1892 (Plate 1, Fig.4)

1892 *Bulimina depressa* Perner, p.55, pl.3, fig. 3a-b

1964 *Ataxophragmium depressum* (Perner); Loeblich and Tappan, p.C283, fig. 191.3,4.

Description: Test free, trochospiral, tending to become streptospiral in coiling; chambers low and broad, with internal partitions; wall agglutinated; aperture interiomarginal slit or loop, umbilical in position.

Stratigraphic Range and Occurrence: At Branscombe this species is very rare, occurring as a single, poorly preserved specimen in a sample at the top of the Top Sandstones Member (B11/6). Reported to occur in the Cenomanian of S.E. England (Jarvis *et al.* 1988)

Palaeoenvironment: Not known.

Superfamily ORBITOLINACEA Martin, 1890

Family ORBITOLINIDAE Martin, 1890

Subfamily ORBITOLININAE Martin, 1890

Genus *Orbitolina* d'Orbigny, 1850

Type Species: The type species of *Orbitolina* has been the subject of some debate (Schroeder and Simmons, 1988, 1989; Simmons, 1990).

Several workers, including Douglass (1960 a, b), Hofker (1963, 1966 a, b) and Douglass, Loeblich and Tappan (1964) in the definitive "Treatise on Invertebrate Paleontology", have regarded *Madreporites lenticularis* Blumenbach, 1805 as the type species. According to the 1964 Treatise *Orbulites lenticulata* Lamarck, 1816 (= *Madreporites lenticularis* Blumenbach, 1805) is the type species.However, despite the arguments of Douglass (1960 a), Hofker (1963) and Douglass, Loeblich and Tappan (1964) no original designation of a type species of *Orbitolina* was made by d'Orbigny (1850), nor was the genus monotypic in the original description. Hence *Madreporites lenticularis* (= *Orbitolina lenticularis*) is not automatically the type species.

In their new major work on the classification of Foraminifera Loeblich and Tappan (1988), the type species of *Orbitolina* is given as *Orbulites concava* Lamarck, 1816 citing Parker and Jones (1860). Schroeder and Simmons (1988, 1989), however, contended that Parker and Jones had not made a valid type designation, and recommended that *Orbitolina concava* (= *Orbulites concava* Lamarck, 1816) should be regarded as the valid type species of the genus *Orbitolina* thus obviating the need for a revision of the taxonomy and allowing the genus *Palorbitolina* (type species *Madreporites lenticularis* Blumenbach, 1805) to remain valid. This has been accepted by the I.C.Z.N. (1990). (Freely paraphrased from Simmons, 1990 which contains more detail).

Remarks: As discussed by Schroeder (eg 1962, 1963, 1975) and Hofker (1963, 1966), the internal structure of orbitolinids is the most critical feature for taxonomic separation. Within the Subfamily ORBITOLININAE (*Orbitolina sensu lato*), the most important feature is the macrospheric embryonic apparatus (see Fig.5.5). The structure and size of this delimits genera and species, and allows for the construction of phylogenetic lineages. Hofker (1963, 1966) considered

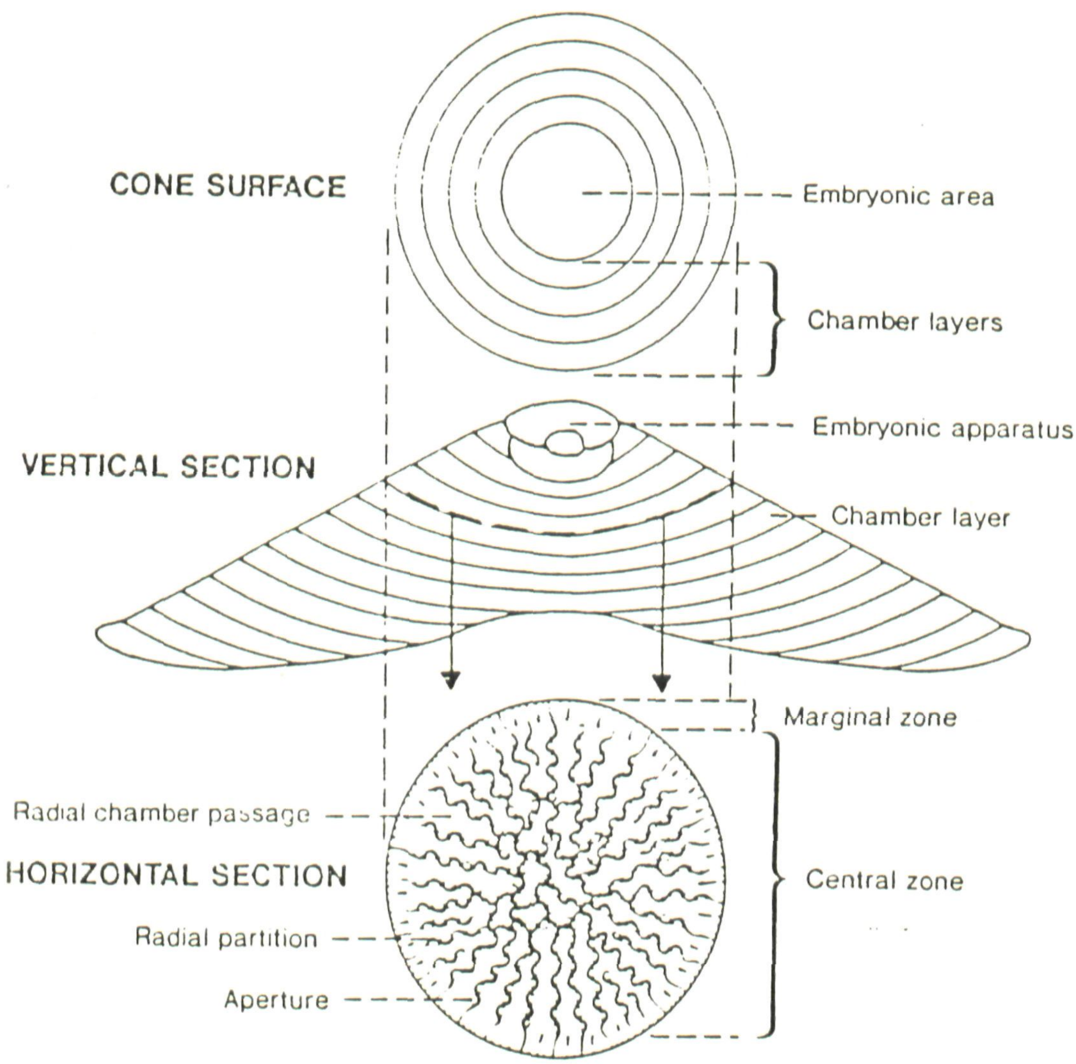


FIG. 5.5: THE MAIN INTERNAL STRUCTURES OF ORBITOLINIDS.

there to be only one phylogenetic lineage within the ORBITOLININAE, and that this could be grouped under one species name - *Orbitolina lenticularis* (Blumenbach). However Schroeder (eg 1975) has shown this to be incorrect. A number of phylogenetic lineages exist within the ORBITOLININAE which allow for separation into distinct genera and short ranging and transitional species. This taxonomy is now widely accepted as being correct.

For further details of the morphological terminology used in describing the orbitolinids see Schroeder (1975) and Arnaud-Vanneau (1980).

Orbitolina sefini Henson, 1948 (Figs 5.6, 5.7)

1948 *Orbitolina concava* (Lamarck) var. *sefini* Henson, 64-65, pl.5, figs 1-2 (non figs 3-4 (= *Orbitolina (Conicorbitolina) conica*)).

1977 *Orbitolina (Orbitolina) concava* (Lamarck): Rey, Bilotte and Peybernès, 378, pl.2, figs 11-12.

1978 *Orbitolina (Orbitolina)* cf. *concava qatarica* Berthou and Schroeder, p.76, pl.4, figs 8-12.

1985 *Orbitolina (Orbitolina) sefini* (Henson): Schroeder, 66-67, pl.30, figs 1-8.

1986 *Orbitolina (Orbitolina) sefini* (Henson): Schroeder *et al.*, 383-385, fig. 2 a-g.

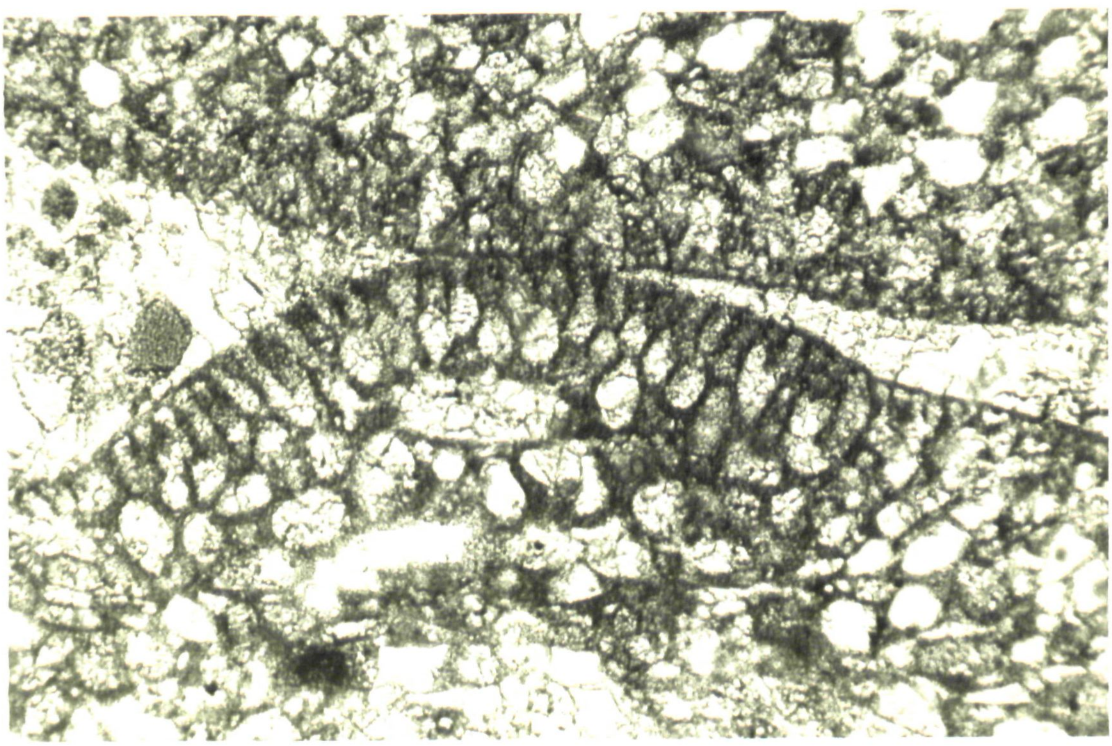


FIG. 5.6. *Orbitolina sefini* SHOWING EMBRYONIC APPARATUS.

WOLBOROUGH LIMESTONE MEMBER.

(X 10)

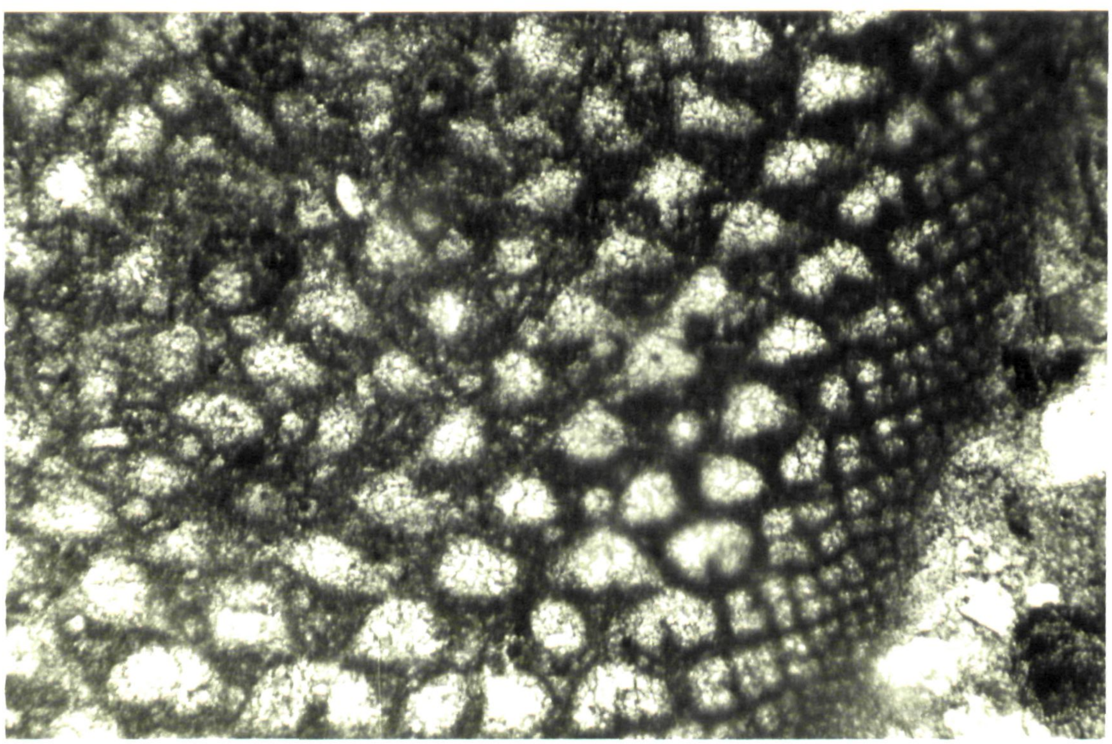


FIG. 5.7: *Orbitolina sefini* SHOWING CHAMBERLETS.

WOLBOROUGH LIMESTONE MEMBER.

(X 10)

Description: The test is either flatly conical, lenticular or "Mexican hat" shaped. Below the apical embryonic apparatus there are numerous chamber layers. The central zone is divided by "wavy" partitions and the marginal zone by horizontal and vertical partitions. The embryonic apparatus is situated at the apex of the test and consists of a protoconch, a deuteroconch with a superembryonic zone of vertical partitions and a subembryonic zone which is also subdivided (after Arnaud-Vanneau, 1980).

The complex embryonic apparatus has a typical diameter of 0.5 to 0.7mm in the megalospheric form (Schroeder, 1985), with an ellipsoidal protoconch surrounded by a subdivided deuteroconch and a considerably thinner, but relatively large, subembryonic zone. Exclusively triangular cross-sections of the radial partitions and chamber passages within the radial zone of the chamber layers are characteristic.

Remarks: *Orbitolina sefini* is the oldest member of the plexus *O. sefini - O. concava* and intermediate forms may occur. *O. sefini* may be distinguished from other orbitolines by the size and complexity of it's embryonic apparatus and from *O. concava* in particular by the latters larger embryonic apparatus (0.7 to 0.9mm with a maximum of 1.1mm quoted by Schroeder, 1985) and the characteristic sub-rectangular cross-sections of chamber passages.

Stratigraphic Range and Occurrence: This species is quoted (Schroeder, 1985) as having a range from intra-Late Albian to intra-Early Cenomanian. In the present study specimens have been recorded from the Wolborough Limestone and from it's equivalent in the road cutting of the Newton Abbot by-pass just north of Newton Abbot (see below for arguments which demonstrate a Late Albian age for these deposits).

Palaeoenvironment: Inner shelf/sub-littoral.

Orbitolina sp. *cf. O. concava* (Fig.5.8)

Description: As for *O. sefini* with the differences mentioned in the remarks above. The specimens collected during this study are poorly preserved and are often silicified (Fig.5.8). However, they can be seen to posses a complex embryonic apparatus divisible into a lenticular protoconch surrounded by a subdivided deuteroconch and a thin subembryonic zone. This indicates that these occurrences can be referred to the genus *Orbitolina*. Of note is the diameter of the embryonic apparatus. It is greater than that of the *O. sefini* specimens from Wolborough having an average value of 0.95mm (see Fig.5.9). This suggests that these specimens are not referable to *O. sefini* and have a closer affinity to *O. concava*. Indeed, the diameter of the embryonic apparatus of the Haldon Hills specimens is slightly greater than that of the topotype specimens of *O. concava* from Ballon, France (see Fig 5.10). Unfortunately the poor preservation of the

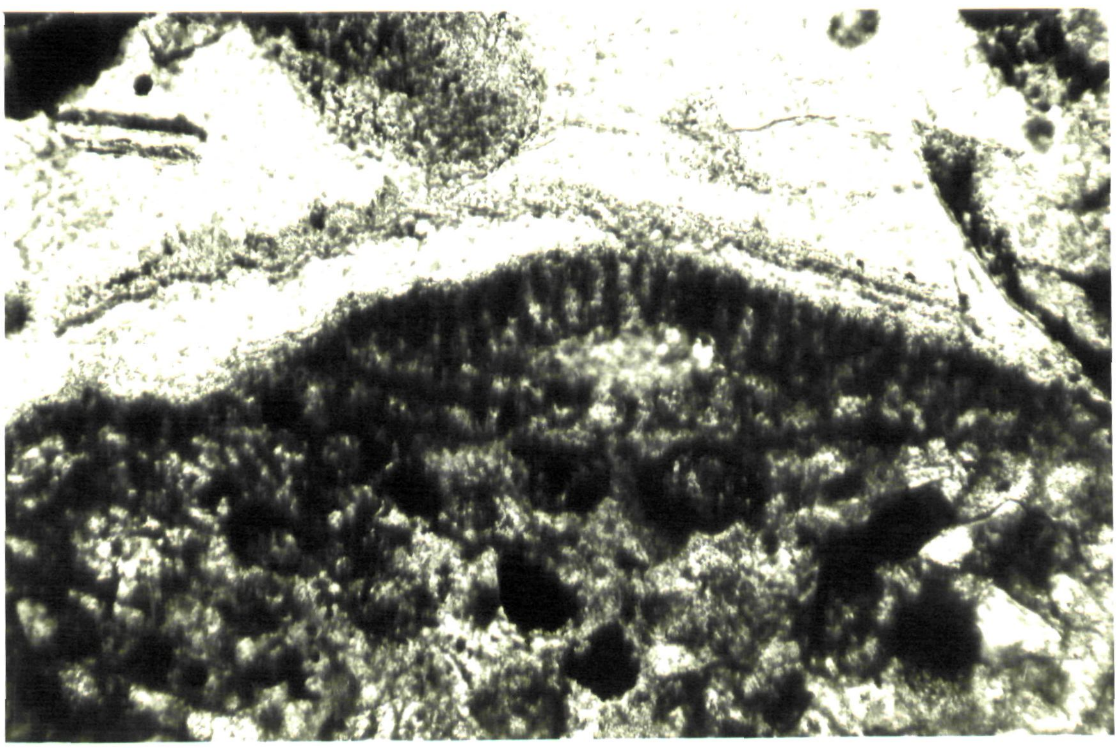


FIG. 5.8: *Orbitolina* sp. cf. *O. concava.*

CULLUM SANDS-WITH-CHERTS MEMBER.

(X 10)

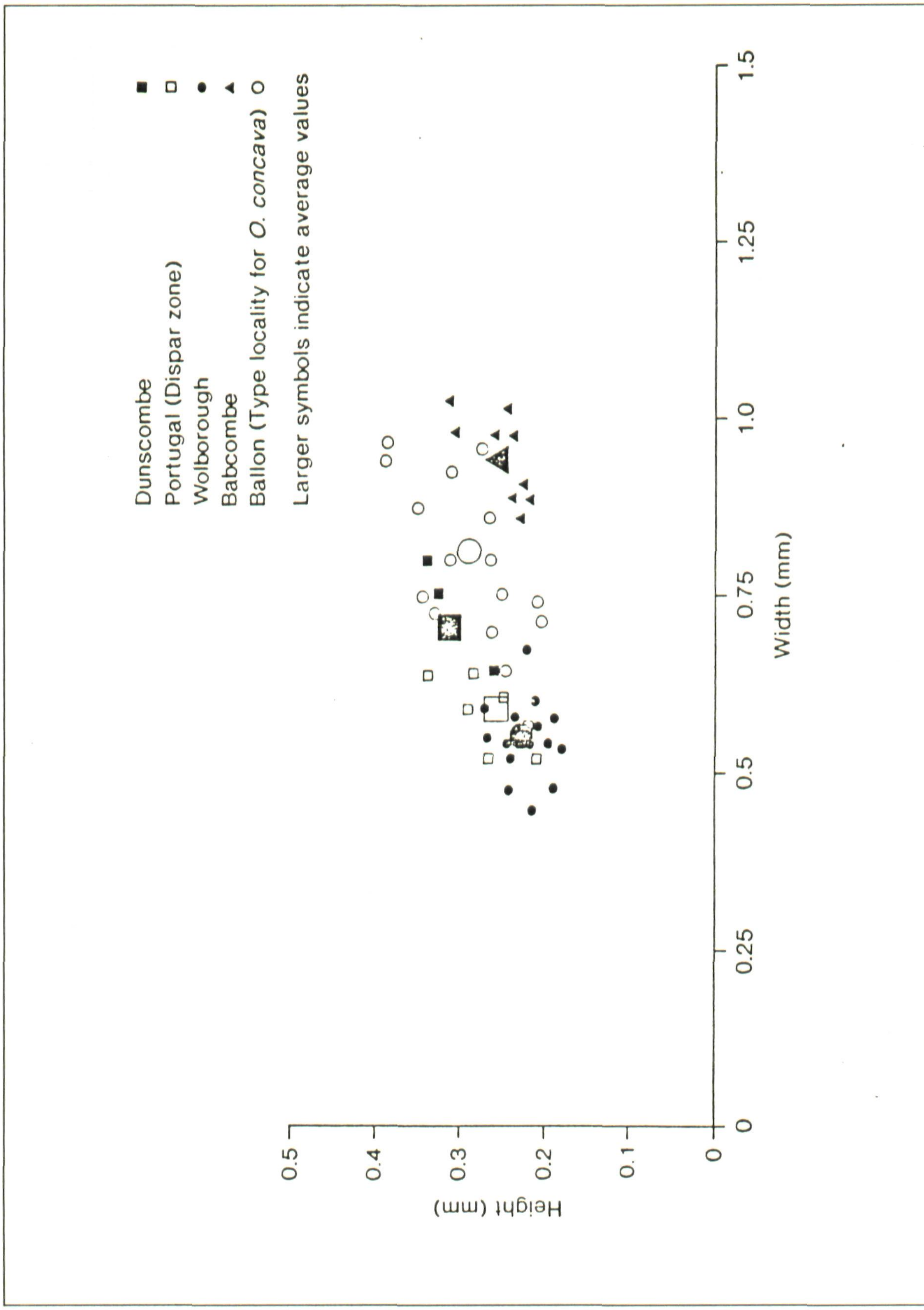


FIG. 5.9: GRAPH OF EMBRYONIC APPARATUS DIMENSIONS FOR ORBITOLINES FROM VARIOUS LOCALITIES.

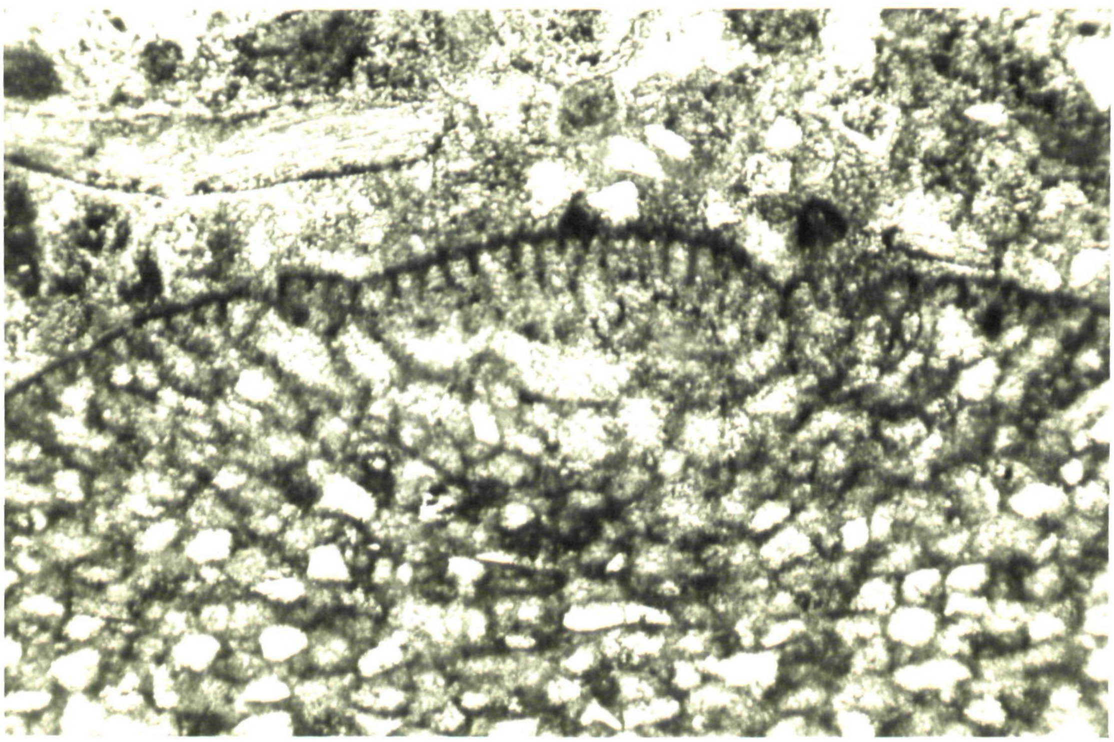


FIG. 5.10: *Orbitolina concava.*

BALLON.

(X 10)

specimens from the Haldon Hills does not allow for recognition of the characteristic sub-rectangular cross-section of chamber passages in *O. concava*. Thus these specimens are referred to *Orbitolina* sp. *cf. O. concava.*

Remarks: In addition to variations within the *O. sefini - O. concava* plexus it should be noted that orbitolinids have been reported from the Early Aptian - Late Barremian (Wealden - Lower Greensand equivalents) of the Fastnet Basin (Ainsworth *et al.,* 1985) and possibly the onshore Faringdon Greensand (Natural History Museum, London, Curry Collection). These belong to the species *Palorbitolina lenticularis* (Simmons and Williams, *in press*). The monotypic genus *Palorbitolina* is distinguished by a relatively simple embryonic apparatus (Schroeder, 1963; 1975). This consists of an apically situated spherical embryonic chamber (a combined proloculus and deuteroconch), and in advanced specimens, peri-embryonic chamberlets. The deuteroconch and peri-embryonic chamberlets typically show a surface division by septa. The lack of a subembryonic zone distinguishes this species from the genus *Orbitolina.*

Stratigraphic Range and Occurrence: *O. concava* has a well defined stratigraphic range in which it is restricted to the Early Cenomanian. In the present study orbitolinids from the Cullum Sands-with-Cherts Member (Haldon Hills) are referred to *Orbitolina* sp.cf. *O. concava.* Other occurrences of orbitolinids, where it was not possible to place them within a species are discussed below .

Palaeoenvironment: Inner shelf/sub-littoral.

Orbitolinid Occurrences: There are relatively numerous records of orbitolinids from the mid-Cretaceous of onshore and offshore S. W. England as well as more questionable records from N. Ireland (Hume, 1897; Hancock, 1961; Reid, 1971).

This study has examined material from Wolborough, the Haldon Hills, Wilmington, the South-East Devon coast and the mid-Cretaceous sediments of the Fastnet Basin.

The most abundant faunas of orbitolinids from onshore South-West England occur in the Selborne Group sediments at Wolborough, near Newton Abbot, South Devon (Fig.5.11) which have been demonstrated to belong to the species *Orbitolina sefini* (Schroeder, *et al.*, 1986). The complex embryonic apparatus of the specimens examined had a typical diameter of between 0.5 and 0.72mm (see Fig.5.9), with an ellipsoidal protoconch (diameter 0.18 to 0.24mm) surrouded by a subdivided deuteroconch and a considerably thinner, but relatively large, subembryonic zone (Fig.5.6).

According to Schroeder (1985a) *O. sefini* has a range from intra-Late Albian to intra-Early Cenomanian. The Wolborough Limestone Member in

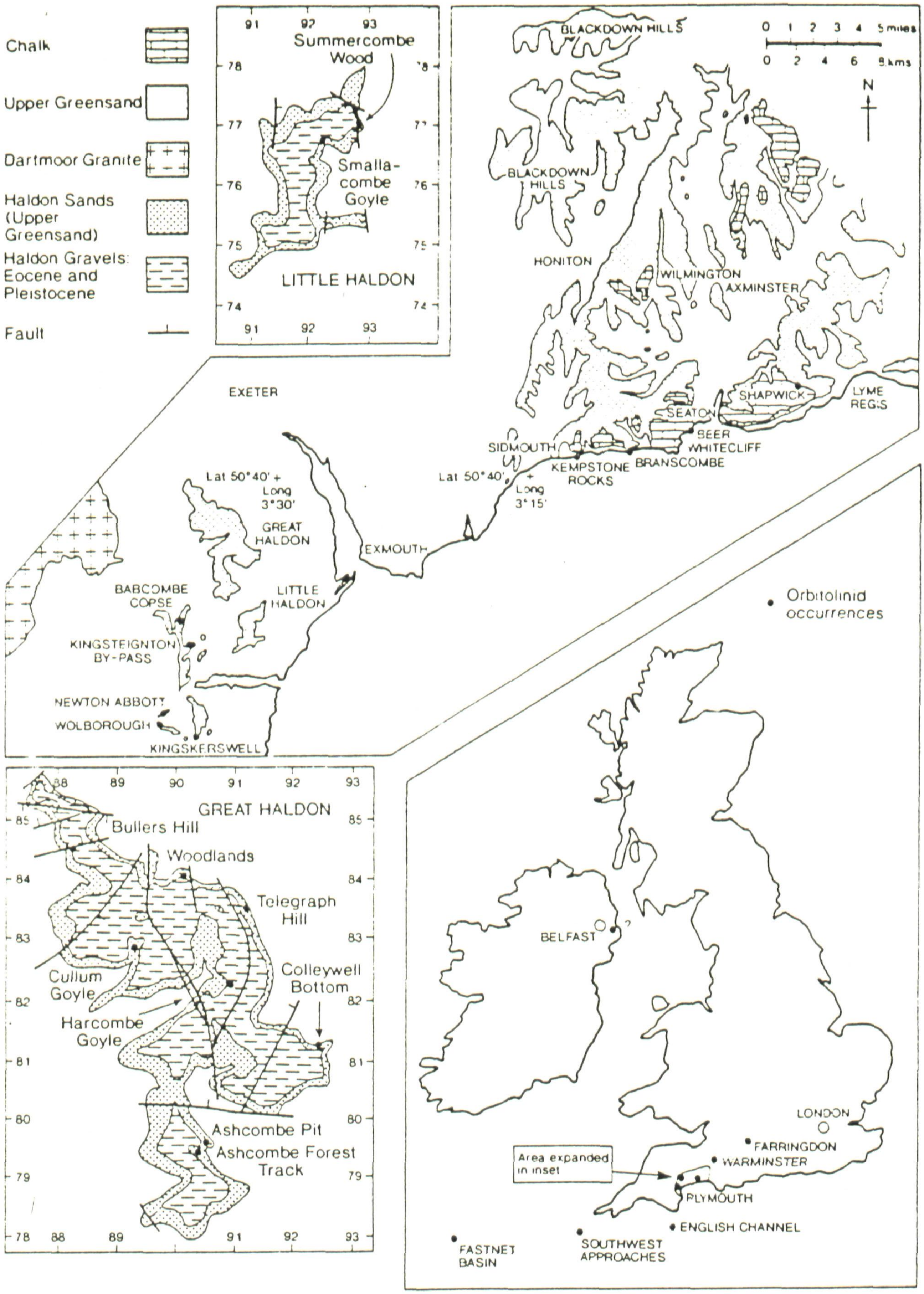


FIG. 5.11: LOCATION MAP OF ORBITOLINE OCCURRENCES.

which *O. sefini* occurs has been correlated with the Woodlands Sands Member of Haldon Hill (Hamblin and Wood, 1976). The Woodlands Sands Member was thought by Hamblin and Wood (1976) to be Late Albian on the basis of a debatable correlation to the Chert Beds Member of South-East Devon, and the presence of two poorly preserved ammonites thought to have their provenance in the Woodlands Sands Member. However, the molluscan fauna found within the Woodlands Sands Member was said to have a Cenomanian aspect. As shown in Fig. 5.9, the embryonic apparatus diameters for *O. sefini* from Wolborough are close to those recorded for Late Albian (*Dispar* Zone) *O. sefini* from Portugal. This tends to confirm a Late Albian age for the Wolborough occurrences.

O. sefini also occurs in the Wolborough Limestone Member equivalent or Woodlands Sands Member equivalent in the road cutting of the Newton Abbot by-pass just north of Newton Abbot (Fig. 5.11).

Orbitolinids are also common at a stratigraphically higher level that at Wolborough in the Selborne Group and Cenomanian Limestone equivalents of the Haldon Hills (see Fig. 5.11). These occurrences are in the Cullum Sands-with-Cherts Member of the Haldon Sands Formation (Hamblin and Wood, 1976). Hamblin and Wood (1976) suggests that this unit correlates with either the non-sequence between the Wessex Greensand Formation and the Cenomanian Limestone, and/or the lower part of the Cenomanian Limestone (Bed A1) (= Beer Head Limestone

Formation, Pounds Pool and Hooken Members of Jarvis and Woodroof, 1984). This correlation indicates an Early Cenomanian age for the Cullum Sands-with-Cherts Member, an age substantiated by the occurrence of Early Cenomanian ammonites in the Haldon section which are thought to have been derived from the Cullum Sands-with-Cherts Member.

Orbitolina concava has a well defined stratigraphic range in which it is restricted to the Early Cenomanian. The likely recognition of this species confirms the results of Hart *et al.* (1979a) who suggested that the Cullum Sands-with-Cherts Member orbitolinids had a close affinity with *O. concava* from the Early Cenomanian of Ballon, whilst the Wolborough orbitolinids had a closer affinity with Late Albian *Orbitolina* from Portugal. This work was based on a comparison of the external dimensions of the orbitolinids, a criterion that is not usually considered valid for speciation of orbitolines.

A limited number of orbitolines have been examined from the Wessex Greensand of the South-East Devon coast. These are specimens collected by Dr Graham Elliot from a level in the uppermost Chert Beds Member or lowermost Top Sandstones Member at Dunscombe and referred to by Hofker (1963) and Carter and Hart (1977). They are housed in the Natural History Museum, London (registration numbers P45079 and P43429). Despite extensive searches by the current author (and Dr M.D. Simmons), the level with *Orbitolina* could not be located on the

South-East Devon coast. A few of the Dunscombe specimens were thin-sectioned and although poorly preserved, the embryonic apparatus of these specimens clearly places them in the *O. sefini* - *O. concava* (Fig. 5.12). Their embryonic apparatus dimensions plot midway between those of *O. sefini* and those of *O. concava* (see Fig. 5.9). The marginal zone of these specimens shows a close similarity to *O. sefini* from Wolborough (Fig. 5.6). However, it must be stressed that the precise identity of these orbitolinids remains uncertain.

Similarly it has not proved possible to provide a precise identification of the orbitolinids found in the glauconitic sands of the Fastnet Basin (Selborne Group) and first mentioned by Ainsworth *et al.* (1985). Loose specimens provided to Dr M.D. Simmons by Dr Ainsworth from the BP well 56/10-1 were thin sectioned, but only poorly preserved embryonic apparatuses were observed. However, these and the nature of the chamber layers suggests that these specimens belong in the *O. sefini* - *O. concava* plexus. Using a variety of microfossil groups, Ainsworth *et al.* (1987) suggested that the sediments containing these orbitolinids were of Early Cenomanian age.

It has not been possible to examine orbitolinid specimens from the Warminster Greensand (Carter and Hart, 1977), or the Hibernian Greensand of Northern Ireland. However, the Early Cenomanian age of the sediments these orbitolinids are recorded from suggests they are likely to be within the *O. sefini* - *O. concava* plexus.

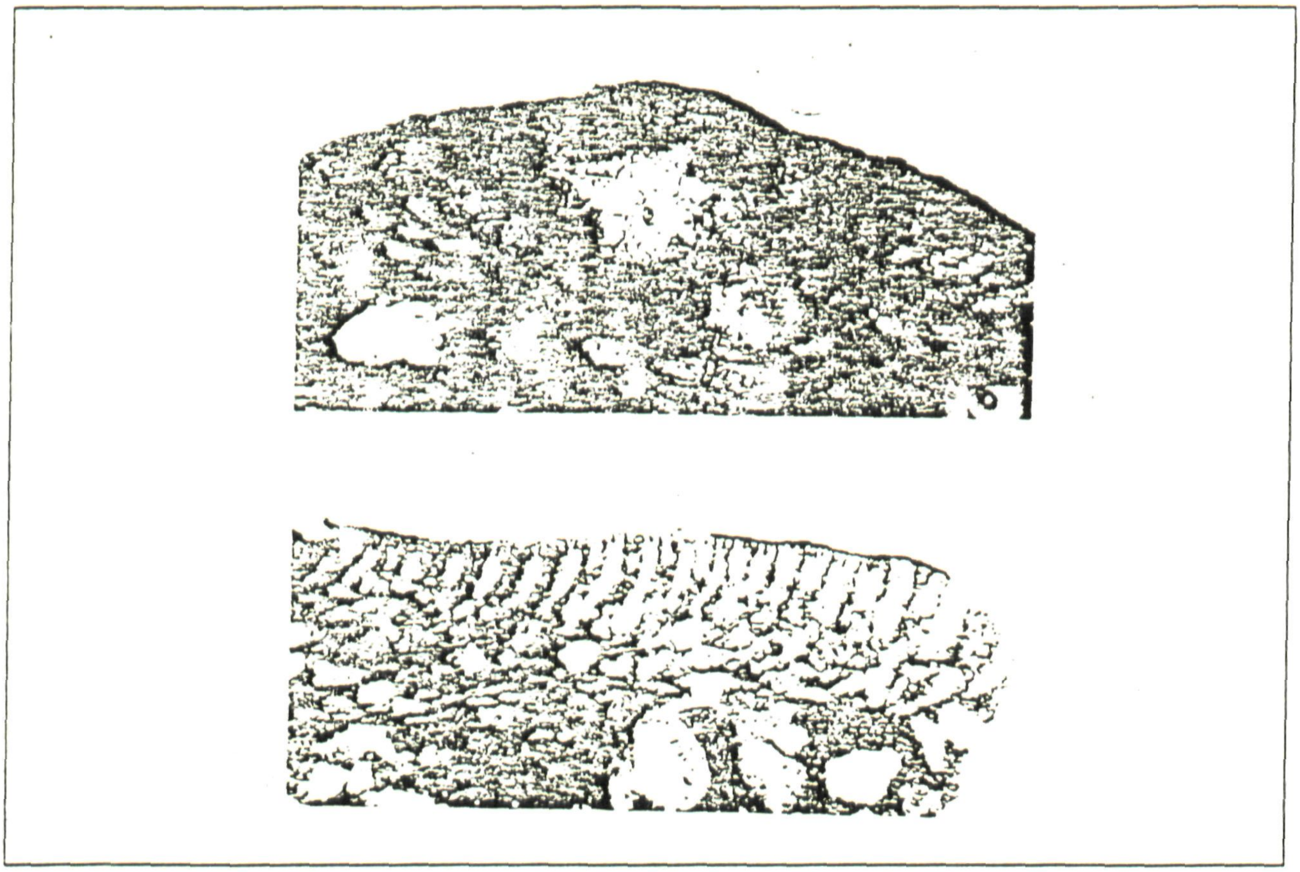


FIG.5.12: *Orbitolina* sp. DUNSCOMBE QUARRY, S.E. DEVON.

ABOVE: DETAIL OF EMBRYONIC APPARATUS (X100).

BELOW: DETAIL OF MARGINAL ZONE (X40).

'Orbitolina' from the Wessex Greensand at Wilmington: Of interest is the record of *Orbitolina* from the Wessex Greensand exposed beneath the Wilmington Sands (Beer Head Limestone Formation equivalent) at Wilmington, East Devon (see Figs. 5.11) (eg Carter and Hart, 1977; Hart, 1982, 1983). The current author and Dr M.D. Simmons have been able to examine specimens from White Hart Pit, Wilmington collected by Prof. Hart, Prof. Murray and Dr Curry (the latter held in the Natural History Museum, London). Whilst these specimens resemble orbitolinid foraminifera externally, thin sections reveal them to have a completely different structure which is non-foraminiferal (see Fig. 5.13).

Comparison with material from other fossil groups in the Natural History Museum, London, shows that these specimens can be referred to the sponge genus *Porosphaera.* Jukes-Browne and Hill (1900) recorded *Porosphaera urceolata* from the uppermost Upper Greensand at Warminister. It is likely that the fossil found by Jukes-Browne and Hill is the same as that found at Wilmington. However, assignment to the species *P. urceolata* (a junior synonym of *P. pileolus* according to Hinde (1904)) is doubtful because this species is typical of the Chalk and is somewhat larger and more spherical than the Wilmington specimens.

This is not the first time that *Porosphaera* and *Orbitolina* ahve been confused. According to Hinde (1904), Parker and Jones (1860) records

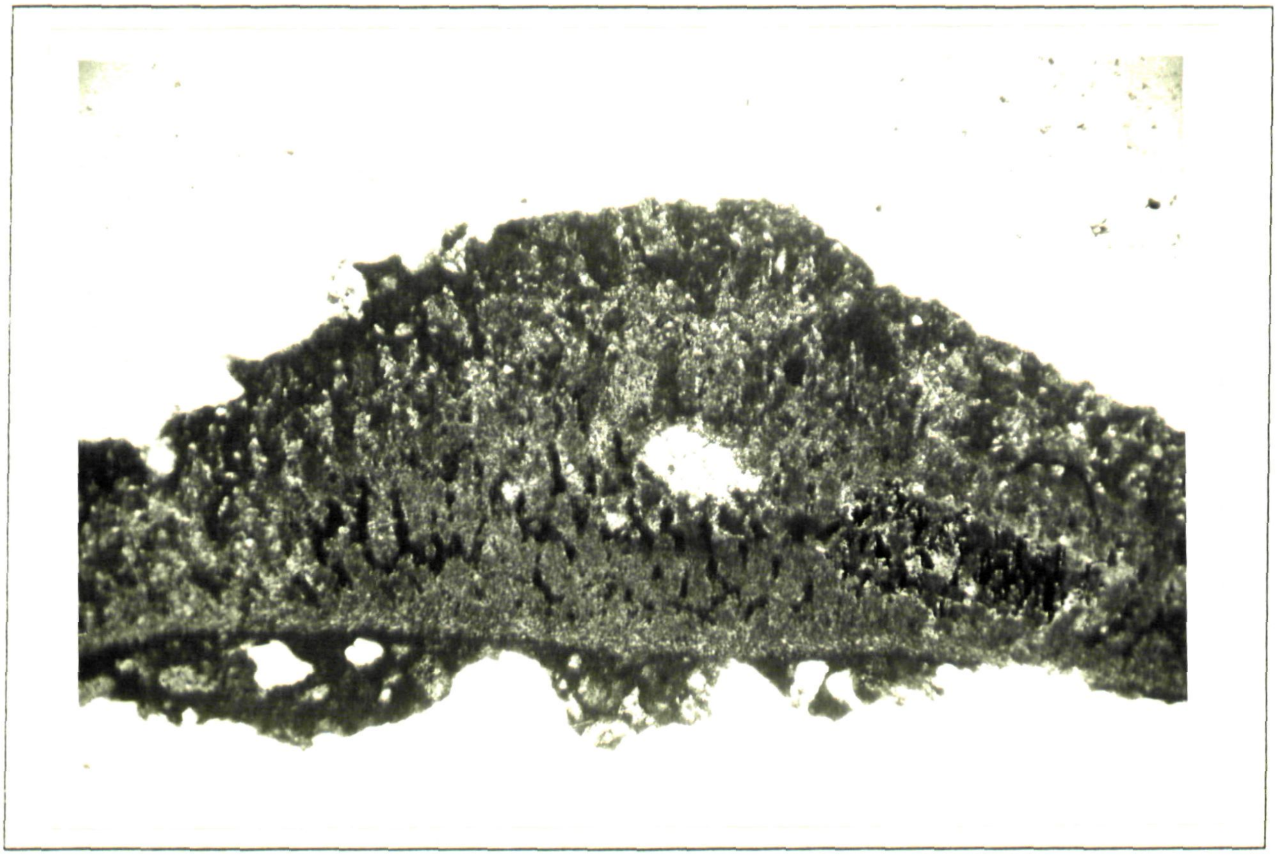


FIG. 5.13: ORBITOLINE HOMEOMORPH: THE SPONGE GENUS *Porosphaera*.

WESSEX GREENSAND FORMATION, WILMINGTON, DEVON. (X20).

of *Orbitolina* are in fact of *Porosphaera*. This is not strictly true. Parker and Jones (1860) mix records of both true *Orbitolina* (eg from the Haldon Hills) with those of *Porosphaera* (eg from the Chalk). It is uncertain if the mention of *Orbitolina* from the Warminster Sands by Parker and Jones (1860) refers to true *Orbitolina* or to *Porosphaera*.

Suborder SPIRILLININA Hohenegger and Piller, 1975

Family PATELLINIDAE Rhumbler, 1906

Subfamily PATELLININAE Rhumbler, 1906

Genus *Patellina* Williamson, 1958
Type Species: *Patellina corrugata*

Patellina sp. (indet) (Plate 3, Fig.2)

Description: Test free, conical, spiral side elevated and evolute, umbilical side flat and involute, elliptical proloculus followed by spirally wound tubular individual second chamber of one to three whorls in microspheric form, proloculus continuous with spiral tube in megalospheric test, smaller in size than that of microspheric generation; wall calcareous, built as a single crystal, finely perforate; aperture a low arch under exterior margin of scroll-like median septum of final chamber at centre of test, median septa of entire test arranged above each other to form columella.

Remarks: Preservation fair, with the outer edge being broken. Height 0.15mm; Diameter 0.35mm.

Stratigraphic Range and Occurrence: At Branscombe this genus occurred as one specimen in one sample from the lower middle Foxmould Sands Member (BB3).

Palaeoenvironment: Middle to outer neritic (Koutsoukos and Hart, 1990)

Suborder LAGENINA Delage and Hèrouard, 1896

Superfamily NODOSARIACEA Ehrenberg, 1838

Family NODOSARIIDAE Ehrenberg, 1838

Subfamily NODOSARIINAE Ehrenberg, 1838

Genus *Dentalinoides* Marie, 1941

Type Species: *Dentalinoides canulina* Marie, 1941

Dentalinoides sp. (indet) (Plate 1, Fig.10)

Description: Test elongate, straight, uniserial, circular in section; sutures horizontal; wall calcareous, perforate; aperture large, rounded, slightly to one side of centre.

Remarks: This genus usually occurred as fragments. Complete specimens measured approximately 1mm in length.

Stratigraphic Range and Occurrence: At Branscombe this species occurred in four samples from the lower and middle Foxmould Sands Member (BA7, BB8, BC4/6 and BC5/1). Usually only as a few fragments per sample.

Palaeoenvironment: Middle to outer neritic (Koutsoukos and Hart, 1990).

Genus *Nodosaria* Lamarck, 1812

Type Species: *Nautilus radicula* Linné, 1812

Nodosaria sp. (indet) (Plate 1, Fig.5)

Description: Test free, multilocular, rectilinear. The chambers may be rounded or flush, with depressed or indistinct sutures. The chambers may increase slightly in size in both width and length on addition. The aperture is radiate and well developed.

Remarks: This Superfamily has been studied in detail by Marie (1938, 1965) and Magniez-Jannin (1975). It has suffered from arbitary splitting into species and as such is not considered to be of stratigraphic value at the present time. The complete specimens collected during this study averaged 1mm in length. Specimens were usually broken.

Stratigraphic Range and Occurrence: The *Nodosaria* as a genus are known from the early Jurassic until the Holocene and are cosmopolitan. The genus seen at Branscombe is rare with only one or two specimens occurring in four samples from the middle and upper portions of the Foxmould Sands Member (BB6, BC4/6, BC6/4 and BC6/7).

Palaeoenvironment:Middle to outer neritic (Koutsoukos and Hart, 1990).

Subfamily FRONDICULARIINAE Reuss, 1860

Genus *Frondicularia* Defrance 1826

Type Species: *Renulina complanata* Defrance, in de Blainville, 1824

Frondicularia filocinta Reuss, 1862 (Plate 2, Fig.1)

1863 *Frondicularia filocinta* Reuss, p.54, pl.4, fig.11.

1880 *Frondicularia ungeri* Reuss; Berthelin, p.61, pl.4, fig.4

1894a *Frondicularia parkeri* Reuss; Chapman, p.157, pl.3, fig.17.

1894a *Frondicularia guestphalica* Reuss; Chapman, p.158, pl.8, fig.4.

1894a *Frondicularia microdiscus* Reuss; Chapman, p.158, pl.4, fig.3.

1894a *Frondicularia perovata* Reuss; Chapman p.158, pl.4, figs.5a,b.

1894a *Frondicularia cordai* Reuss; Chapman, p.159, pl.4, fig.6.

1975 *Frondicularia filocinta* Reuss; Magniez-Jannin, p.201, pl.14, figs.17-22; textfig.108

Description: Test free, compressed, uniserial, palmate; chambers rapidly increasing in size in early part, late chambers increase slowly in size; chamber surface smooth; aperture slightly produced, round, central at greatest height; umbilical boss weak; short longitudinal rib situated umbilically.

Remarks: Divided into six separate species by Chapman (1894a) and into two chronoforms by Magniez-Jannin (1975). Specimens obtained from the Branscombe samples showed some variation in size (length 2-3mm; width up to 1mm) and were generlly poorly preserved.

Stratigraphic Range and Occurrence: Wideranging in the "Gault" facies of France. N. Germany and the U.K. (middle/upper Albian). At Branscombe this species occurs in five samples from the lower to middle Foxmould Sands Member (BA2, BB1, BB6, BB8 and BC4/4).

Palaeoenvironment: Not known.

Genus *Tristix* Macfadyen, 1941

Type Species: *Rhabdogonium liasinum* Berthelin, 1879

Tristix excavatum Reuss (Plate 3, Fig.1)

1863 *Rhabdogonium excavatum* Reuss, p.91, pl.12, fig.8a-c.

1970 *Tristix excavatum* (Reuss); Hart, p.167-168, pl.14, fig.11.

Description: Test free, uniserial, elongate with a slight tapering; faces flush or slightly concave; wall calcareous, hyaline; aperture terminal, rounded to radiate.

Remarks: Preservation good. The specimen collected during the present study measured 0.55mm in length.

Stratigraphic Range and Occurrence: Typical middle to upper Albian species of the Gault Clay. At Branscombe it occurred as one specimen in one sample from the lower Foxmould Sands Member (BB7).

Family VAGINULINIDAE Reuss, 1860

Subfamily Lenticulininae Chapman, Parr and Collins, 1934

Genus *Lenticulina*, Lamarck, 1804

Type Species: *Lenticulites rotulata* Lamarck, 1804

Lenticulina rotulata var. *A*. (Plate 2, Fig.2)

Description: Test free, planispiral, lenticular, biumbonate; swept back sutures are slightly thickened and raised forming slightly concave chambers together produces a slight squaring of the chambers in peripheral view; in general of greater breadth than height; aperture radial at peripheral angle.

Remarks: The raised ribs and squaring of the chambers distinguishes *L. rotulata* var. *A*. from *L. rotulata* var. *B*. The latter is also usually thinner when viewing the apertural face. In the Branscombe material the preservation is poor to fair.

Whole specimens of var. A. measured on average 0.6mm in height and 0.5mm in width.

Stratigraphic Range and Occurrence: The rarest of the three varieties recognised within the species. It occurred in eight samples from the basal to upper Foxmould Sands Member (BA1, BA4, BA6, BC4/2, BC4/4, BC4/6 BC6/1 and BC6/4).

Palaeoenvironment: Neritic to bathyal (Koutsoukos, 1989).

Lenticulina rotularia var. *B* (Plate 2, Fig.3)

Description: The test surface is smooth with a smooth periphery; the degree of enrolment of the test varies considerably as does the height to width ratio; the angle of the test at the periphery is predominantly narrow forming a slight keel.

Remarks: In the Branscombe material this species shows a fair amount of variation in the degree of test enrolment. Preservation is poor to good. Average measurements were height 0.7mm and width 0.5mm.

Stratigraphic Range and Occurrence: At Branscombe this species occurred in twenty-eight samples which ranged from the basal Foxmould Sands Member up into the Cenomanian Limestone (BA1, BA2, BA4, BA6, BA7, BB1, BB5, BB6, BB7, BB10, BB13, BB14, BC2/1, BC4/2, BC4/3, BC4/4, BC4/5, BC4/6, BC5, BC5/1, BC5/6, BC6/1, BC6/4, BC6/5, BC6/7, B1/1, B8/2 and B12/1). It is the most common variety of this species both in terms of the number of samples in which it occurs and in that it is the dominant faunal element within the samples in which it occurs.

Palaeoenvironment: Neritic to bathyal (Koutsoukos, 1989).

Lenticulina rotularia var. *C* (Plate 2, Fig.4)

Description: The test is smooth, with a smooth periphery; test slightly unrolled.This species has all the features of var. B but is so unrolled as to warrant separation from the latter.

Remarks: Variation in the degree of test enrolment means that this variety is probably an end member in a series from variety A to variety C. "Forms" of this species are well known but few people study them systematically. In the Branscombe samples preservation is poor to good. Average measurements were length 0.6mm and width 0.25mm.

Stratigraphic Range and Occurrence: At Branscombe this species occurred in fourteen samples which ranged throughout the Foxmould Sands Member and the middle Chert Beds Member (BA1, BA2, BA7, BB5, BB6, BB13, BB14, BC4/2, BC5/1, BC5/6, BC6/1, BC6/4, B7/2 and B7/3). This variety usually only makes up a relatively small proportion of the population within a slide.

Palaeoenvironment: Neritic to bathyal (Koutsoukos, 1989).

Lenticulina sp. *A.* (Plate 2, Fig.5)

Description: The test is small with a poorly developed keel; the chambers are markedly depressed giving the test a corrugated appearance.

Remarks: Preservation in the Branscombe samples is fair to good. Average measurements 0.5mm in diameter

Stratigraphic Range and Occurrence: At Branscombe this is a common species and occurred in twenty-six samples which ranged from lower to upper Foxmould Sands Member (BA7, BB1, BB5, BB7, BB8, BB10, BB11, BB13, BB14, BC1/3, BC1/4, BC1/5, BC3/2, BC4/2, BC4/3, BC4/4, BC5, BC5/1, BC5/3, BC5/4, BC6/1, BC6/4, BC6/5 and BC6/7).

Palaeoenvironment: Neritic to bathyal (Koutsoukos, 1989).

Lenticulina sp. *B*. (Plate 2, Fig.6)

Description: Small test, unrolled but inner edge of chambers meet proloculus. Aperture slightly produced.

Remarks: Preservation good in Branscombe material. Average measurements 0.65mm.

Stratigraphic Range and Occurrence: At Branscombe this is a rare species which occurred in one sample from the middle Foxmould Sands Member (BC4/2).

Palaeoenvironment: Neritic to bathyal (Koutsoukos, 1989).

Subfamily PALMULINAE Saidova, 1981

Genus *Neoflabellina* Batenstein, 1948

Type Species: *Flabellina rugosa* d'Orbigny, 1840

Neoflabellina sp. (indet) (Plate 2, Fig.7)

Description: Test large, palmate, similar to *Palmula* but with flattened, parallel sides and angular or keeled margins; chambers increase moderately in size on addition with less pronounced sutures in last portion of test.

Remarks: Preservation fair. The specimen collected during this study measured 1.45mm in height and 1mm in width.

Stratigraphic Range and Occurrence: At Branscombe this species occurred as one specimen in one sample from the lower Foxmould Sands Member (BB3).

Palaeoenvironment: Not known - probably neritic to bathyal (Koutsoukos, 1989).

Neoflabellina sp. (indet) (Plate 2, Fig.8)

Description: Chambers increase gradually in size and are moderately inflated; test is markedly compressed.

Remarks: Preservation good. The specimen collected during the present study measured 3.8mm in length and 1.2mm in width.

Stratigraphic Range and Occurrence: At Branscombe this species occurred as on specimen in one sample from the lower middle Foxmould Sands Member (BB8).

Palaeoenvironment:Not known probably neritic to bathyal (Koutsoukos, 1989).

Subfamily MARGINULININAE Wedekind, 1937

Genus *Astacolus* de Montfort, 1808

Type Species: *Astacolus crepidulatus* de Montfort, 1808

Astacolus sp. (indet) (Plate 1, Fig.6)

Description: Test free, elongate, slightly compressed with a sub-triangular terminal chamber; sutures are moderately depressed and subtended at approxiamately 40 degrees to the test; aperture radiate, terminal.

Remarks: Some of the specimens from Branscombe which have the later chambers missing may be lenticulinds. Preservation is poor,with the specimens often being broken or having adhering sediment. Examples collected during this study averaged 0.7mm in length and 0.5mm in width.

Stratigraphic Range and Occurrence: This genus is known from the early Jurassic until the Holocene and is cosmopolitan. At Branscombe it occurs in four samples from the middle and upper Foxmould Sands Member and the middle Chert Beds Member (BC6/5, BC6/7, BB10 and B8/2). It is relatively rare with one or two specimens per sample.

Palaeoenvironment: Not known - probably inner/middle neritic (Koutsoukos, 1989).

Astacolus sp. (indet) (Plate 1, Fig.7)

Description: Test free, elongate, slightly arcuate. Chambers numerous, sutures oblique, highest at outer margin, curved. Aperture radiate, terminal.

Remarks: Samples which contain this species may have only a few broken fragments or practically whole specimens may be a common component of the sparse fauna. Average measurements are length 1.8mm and width 0.5mm.

Stratigraphic Range and Occurrence: At Branscombe this species occurs in twenty samples all but one of which were taken from the middle to upper Foxmould Sands Member with the remaining occurrence being from the upper part of the Chert Beds Member (B11/6, BB11, BB13, BB14, BC1/3, BC1/4, BC1/5, BC2/1, BC3/2, BC4/2, BC4/3, BC4/4, BC4/5, BC4/6, BC5, BC6/1, BC6/4, BC6/5 and BC6/7). Preservation is generally good but the specimens may be broken or have strongly adhering sediment.

Palaeoenvironment: Not known - probably inner/middle neritic (Koutsoukos, 1989).

Subfamily VAGINULININAE Reuss, 1860

Genus *Citharina* d'Orbigny, 1839

Type Species: *Vaginulina (Citharina) strigillata* Reuss, 1846

Citharina d'orbignyi Marie, 1938 (Plate 1, Fig.8)

1863 *Vaginulina discors* Koch; Reuss, p.50, pl.3, figs.10-12.

1938 *Citharina d'orbignyi* Marie, p.95, pl.8, figs 8a,b.

1938 *Citharina* cf. *discors* (Koch); Marie, p.96, pl.8, figs. 10a,b.

1950 *Vaginulina mariei* Khan, p.270, pl.1, fig.16.

1975 *Citharina d'orbignyi* Marie; Magniez-Jannin, p.205, pl.14, figs.2-7.

Description: Test flattened, sub-triangular in outline, chambers numerous, extending nearly to base at inner margin; test surface striated, aperture radiate, at outer margin.

Remarks: This species was reviewed by Magniez-Jannin (1977) who divided it into four chronoforms. It is apparently a rare species.

Stratigraphic Range and Occurrence: Only generally known in southern England, the Paris Basin and N. Germany and usually found in the early or middle Albian. At Branscombe it occurs in six samples, ranging in position from near the base to the middle of the Foxmould Sands Member (BA4, BA6, BB1, BB5, BB7, and BC4/4). It occurs only as a single specimen in each sample and preservation is fair with the individual usually being broken.

Palaeoenvironment: Not known - probably deep neritic (Koutsoukos, 1989).

Genus *Citharinella* Marie, 1938

Type Species: *Flabellina karreri* Berthelin, 1880

Citharinella sp. (indet) (Plate 1, Fig.9)

Description: Test free, lanceolate, chambers low, broad, uniserial. Early chambers extend to proloculus at one side, later chambers chevron-shaped and symmetrical. Aperture terminal and produced.

Remarks: Strongly adhering sediment obscured details of the specimens from Branscombe. Preservation was generally good.

Stratigraphic Range and Occurrence: At Branscombe this species occurs as a single specimen in two samples from the lower middle Foxmould Sands Member (BB13 and BC2/1). Known from the Gault Clay of Germany (Reuss,1863), the *H. dentatus* Zone in Kent (Marie, 1938), the lower and middle Albian of the Aube (Magniez-Jannin, 1977) and from the *L. lyelli* to the *A. intermedius* Subzone in the Weald (Price, 1977).

Palaeoenvironment: Not known - probably middle/outer neritic

Genus *Vaginulina* d'Orbigny, 1826

Type Species: *Nautilus legumen* Linné, 1758

Vaginulina kochii Roemer, 1841 (Plate 2, Fig. 9)

1841 *Vaginulina kochii* Roemer; p.96, pl.15, fig.10.

1863 *Vaginulina eurynota* Reuss; p.90, pl.12, figs.9a,b.

1863 *Vaginulina protosphaera* Reuss; p.90, pl.12, figs.10a,b.

1863 *Vaginulina striolata* Reuss; p.46, pl.3, fig.7.

1863 *Vaginulina strombecki* Reuss; p.46, pl.3, fig.8.

1863 *Vaginulina truncata* Reuss; p.47, pl.3, fig.9.

1880 *Vaginulina comitina* Berthelin; p.38, pl.1, figs.21c,d.

1880 *Vaginulina truncata* Berthelin; p.39, pl.1, figs.25-27.

1894a *Vaginulina arguta* Reuss; Chapman, p.425, pl.8, figs.9a,b.

1894a *Vaginulina comitra* Berthelin; Chapman, p.426, pl.8, fig.11.

1940 *Vaginulina kochii* Roemer; Tappan, p.109, pl.17, figs.2-4.

1975 *Lenticulina/Vaginulina kochii kochii* (Roemer); Magniez - Jannin, p.166, pl.14, figs.26-28, text figs. 90k,a-i

Description: Test free, compressed, elongate; weak ribs are present along sutures and around the margins of the test; chambers uniserial, gradually increase in size; aperture produced, at greatest height of test; umbilical boss small.

Remarks: Many workers have separated this species into many different species and subspecies. The subspecies may be regionally diagnostic morphotypes but this has not been proved. Preservation in the Branscombe samples is fair to good.

Stratigraphic Range and Occurrence: This is a common species that is well known throughout N.W. Europe in the mid-Cretaceous (N. Germany, Baltic, Paris Basin,Holland and the U.K.). At Branscombe this species occurred as single individuals in two samples from the middle and upper Foxmould Sands Member (BC1/5 and BC6/5).

Palaeoenvironment: Not known - probably inner/middle neritic (Koutsoukos, 1989).

Suborder GLOBIGERININA Delage and Hérouard, 1896

Superfamily HETEROHELICACEA Cushman, 1927

Family HETEROHELICIDAE Cushman, 1927

Subfamily HETEROHELICINAE Cushman, 1927

Genus *Heterohelix* Ehrenberg, 1843

Type Species: *Spiroplecta americana* Ehrenberg, 1844

Heterohelix moremani (Cushman) (Plate 3, Fig.4)

1938 *Guembelina moremani* Cushman, p.10, pl.2, figs.1-3.

1940 *Guembelina wahitensis* Tappan, p.115, pl.19, fig.1.

1967 *Heterohelix moremani* Cushman; Pessagno, p.260-261, pl.89, figs.1-2.

1977 *Heterohelix moremani* (Cushman); Carter and Hart, p.26, pl.2, fig.17.

1981 *Heterohelix moremani* (Cushman); Hart *et al.*, p204, pl.7.16, fig.9.

Description: Test free, small, biserial; chambers inflated globular; sutures depressed; aperture a low interiomarginal arch; chambers gradually increasing in size, greatest width at apertural end; test sub-ovate in apertural view, sub-triangular in side view; umbilical margin bluntly pointed; test surface smooth.

Remarks: Often found in shallower water environments when other planktonics are absent. Preservation in the Branscombe samples is good.

Stratigraphic Range and Occurrence: This is a common species that occurs in the middle Albian to upper Cenomanian in the Aube bur is not abundant in southern England until the *S. dispar* Zone. In the Cenomanian it is known from N.W. Europe, N. and S. America and the Atlantic. At Branscombe it occurred as one specimen in one sample from the lower middle Foxmould Sands Member (BC1/1).

Palaeoenvironment: Middle neritic (Koutsoukos and Hart, 1990).

Superfamily PLANOMALINACEA Bolli, Loeblich and Tappan, 1957

Family GLOBIGERINELLOIDIDAE Longoria, 1974

Subfamily GLOBIGERINELLOIDINAE Longoria, 1974

Genus *Globigerinelloides* Cushman and Ten Dam, 1948

Type Species: *Globigerinelloides algeriana* Cushman and ten Dam, 1948

Globigerinelloides bentonensis (Morrow) (Plate 3, Fig.5)

1934 *Anomalina bentonensis* Morrow, p.201, pl.30, figs.4a-b.

1940 *Planulina eaglefordensis* (Moreman); Cushman, p.32, pl.6, figs.4,5.

1977 *Globigerinelloides bentonensis* (Morrow); Carter and Hart, p.27-28, pl.1, figs.19,20.

1981 *Globigerinelloides bentonensis* (Morrow); Hart *et al.*, p.198, pl.7.13, figs7-9.

Description: Test free, planispiral, bi-umbilicate; chambers inflated, gradually increasing in size, approxiamately eight in last whorl; surface is smooth with large simple pores which are low in density; sutures depressed, curved; aperture a broad low interiomarginal equatorial arch with distinct apertural flap, relict flaps are present along inner margins of last whorl.

Remarks: There is a full discussion of the taxonomy of this species in Carter and Hart (1977) and Hart *et al.* (1989). Preservation fair.

Stratigraphic Range and Occurrence: This species occurred as one specimen in one sample from the Cenomanian Limestone (B15/2). A very important stratigraphic marker that only occurs abundantly in the *M. rostratum* Subzone. It occurs sporadically in higher beds.

Palaeoenvironment: Recorded from inner/middle/outer neritic (Koutsoukos and Hart, 1990).

Superfamily ROTALIPORACEA Sigal, 1958

Family HEDBERGELLIDAE Loeblich and Tappan, 1961

Subfamily ROTUNDININAE Bellier and Salaj, 1977

Genus *Praeglobotruncana* Bermúdez, 1952

Type Species: *Globorotalia delrioensis* Plummer, 1931

Praeglobotruncana sp. cf *P. delrioensis*

Description: Test free, trochospiral, biconvex to spiroconvex, umbilicate, periphery rounded to sub-angular with more or less well developed peripheral keel; chambers ovate to sub-angular; wall calcareous, finely perforate, radial in structure, surface smooth to hispid; aperture an interiomarginal, extraumbilical-umbilical arch, bordered by apertural lip.

Remarks: Preservation fair.

Stratigraphic Range and Occurrence: This species occurs from the very top of the Albian to the middle Cenomanian. At Branscombe it occurred as one specimen in one sample from the middle Foxmould Sands Member (BC1/3).

Palaeoenvironment: Not known - probably middle/outer neritic (Koutsoukos and Hart, 1990).

Suborder ROTALIINA Delage and Hérouard, 1896

Superfamily PLUEROSTOMELLACEA Reuss, 1860

Family PLEUROSTOMELLIDAE Reuss, 1860

Subfamily PLEUROSTOMELLINAE Reuss, 1860

Genus *Pleurostomella* Reuss, 1860

Type Species: *Dentalina subnodosa* Reuss, 1851

Pleurostomella sp. (indet). (Plate 3, Fig.6)

Description: Test small, elongate, chambers in early stage biserially arranged , later uniserial; sutures in early stages oblique, later becoming more nearly straight and horizontal, wall calcareous, finely perforate, granular in structure; aperture terminal, with projecting hood at one side, two small teeth on opposite side, and internal tube.

Remarks: Preservation fair to good. The specimens from Branscombe measured 2mm in length and 0.4mm width.

Stratigraphic Range and Occurrence: At Branscombe two specimens occurred in one sample from the middle Foxmould Sands Member (BC2/1).

Palaeoenvironment: Not known.

Superfamily CHILOSTOMELLACEA Brady, 1881

Family GAVELINELLIDAE Hofker, 1956

Subfamily GYROIDINOIDINAE Saidova, 1981

Genus *Gyroidinoides* Brotzen, 1942

Type Species: *Rotalina nitida* Reuss, 1844

Gyroidinoides parva (Khan) (Plate 3, Fig.7)

1898 *Rotalina soldanii* d'Orbigny var. *nitida* Reuss; Chapman, p.9-10, pl.2, figs.2a-c.

1970 *Gyroidinoides parva* (Khan); Hart, p.208-209, pl.22, figs.5-7.

1975 *Valvulineria parva* (Khan); Magniez-Jannin, p.239-246, pl.16, figs.8-17.

Description: Test free, trochospiral, spiral side flattened, umbilical side elevated, periphery rounded; chambers rhomboidal in section, sutures radial to curved, flush to depressed; wall calcareous, perforate, bilamellar, granular in structure; aperture a continuous, low interiomarginal slit extending from periphery to umbilicus, umbilical portion partially obscured by umbilical flap from each chamber.

Remarks: Preservation fair to good.

Stratigraphic Range and Occurrence: This species is mainly known from the Albian of the Anglo-Paris Basin. At Branscombe it occurred as a single specimen in three samples from the lower part of the Foxmould Sands Member (BA4, BB5 and BB14).

Palaeoenvironment: Not known.

Subfamily GAVELINELLINAE Hofker, 1956

Genus *Gavelinella* Brotzen, 1942

Type Species: *Discorbina pertusa* Marsson, 1878

Gavelinella cenomanica (Brotzen) (Plate 3, Fig.9)

1942 *Cibicioloides (Cibicides) cenomanica* Brotzen, p.54, pl.2, figs.2a-c.

1977 *Gavelinella cenomanica* (Brotzen); Carter and Hart, p.46-47, pl.1, figs.27-28.

1981 *Gavelinella cenomanica* (Brotzen); Hart *et al.*, p.192, pl.7.10, figs 9-11.

Description: A low trochospiral species; test free, biconvex, spiral side less concave than umbilical side; test partially involute; periphery very sharply rounded; in spiral view test sub-circular; sutures broad, raised, curved; aperture a low interiomarginal slit extending from near the periphery to the umbilicus; apertural face weakly domed; chambers gradually increase in size with 10 to 11 chambers in the last whorl; a strong spiral ridge extends along the inner margins of the chambers of the spiral side; test surface smooth.

Remarks: This species differs from *G. intermedia* in having a more or less marked rim around the umbilicus (Carter and Hart, 1977). Preservation at Branscombe is good.

Stratigraphic Range and Occurrence: This species occurs in the very top-most Albian of southern England but is not common until the Cenomanian. It is known over N.W. Europe from a variety of clay/sand/chalk facies. At Branscombe two specimens occurred in one sample from the lower middle Foxmould Sands Member (BB13).

Palaeoenvironment: Not known - probably inner/middle neritic

(Koutsoukos, 1989).

Gavelinella intermedia (Berthelin) (Plate 3, Fig.10)

1880 *Anomalina intermedia* Berthelin, p.67, pl.4, figs.14a,b.

1898 *Anomalina ammonoides* Reuss; Chapman, p.3, pl.1, fig.4.

1977 *Gavelinella intermedia* Berthelin; Carter and Hart, p.48, pl.1, figs.33-35.

1981 *Gavelinella intermedia* Berthelin; Hart *et al.* , p.194, pl.7.11, figs 7-9.

Description: A low trochospiral species; test free, partially involute; spiral side flattened, in spiral view test sub-circular; periphery sharply rounded; sutures raised in early chambers, in latter chambers sutures depressed; last chambers weakly inflated; apertural face weakly rounded or flat; in spiral view umbilical side concave, spiral side only weakly convex; aperture a low interiomarginal slit extended from near periphery to umbilicus; chambers gradually increase in size; test surface smooth.

Remarks: Preservation poor to fair.

Stratigraphic Range and Occurrence: This species occurs very abundantly in the Albian and Cenomanian of southern and eastern England as well as N.W. Europe, Italy and Spain. At Branscombe it occurred as single specimens in three samples from the lower middle Foxmould Sands Member (BB14) and the middle Chert Beds Member (B3/2 and B7/1).

Palaeoenvironment: Not known - probably inner/middle neritic (Koutsoukos, 1989).

Genus *Lingulogavelinella* Malapris, 1965

Type Species: *Lingulogavelinella albienensis* Malapris,1965

Lingulogavelinella sp. (indet) (Plate 3, Fig.11)

Description: Test free, trochospiral, periphery broadly rounded, final whorl chambers inflated, sutures distinct, curved. Aperture slit-like, interiomarginal.

Remarks: Preservation good but broken. Specimen collected in this study measured 0.3mm in diameter.

Stratigraphic Range and Occurrence: This species occurred as one specimen in one sample from the Cenomanian Limestone (12/1).

Palaeoenvironment: Not known - probably middle/outer neritic or bathyal (Koutsoukos, 1989).

Lingulogavelinella jarzevae (Vasilenko,1954) (Plate 3, Fig.12)

1954 *Cibicies (Cibicides) jarzevae* Vasilenko, p.121, pl.17, figs 3a-c

1977 *Lingulogavelinella jarzevae* (Vasilenko); Carter and Hart, p.49, pl.1, figs 29-30.

1981 *Lingulogavelinella jarzevae* (Vasilenko); Hart *et al.*, p.208, pl.7.18, figs 11-13.

Description: Test free, trochospiral; spiral side flattened, umbilical side inflated, strongly convex; test involute; sutures radial, depressed; in umbilical view chambers increase rapidly in size, last chamber appears globular, early chambers of last whorl smooth, sutures not depressed; periphery rounded in spiral view, periphery normally rounded in section; in side views chambers on the umbilical side appear concave; aperture an interiomarginal extraumbilical/umbilical narrow slit, on the spiral side relict slits are present giving a 'star-shaped' appearance to the aperture; test surface smooth.

Remarks: Preservation fair.

Stratigraphic Range and Occurrence: This rare species occurs sporadically in the *S. dispar* Zone of southern England up to the top of the early Cenomanian. Also known from Holland, Germany, Denmark and Central Europe. At Branscombe it occurred in one sample from the top of the Top Sandstones Member (B11/6).

Palaeoenvironment: May be an indicator of shallow water conditions (Carter and Hart, 1977).

5.5 Calcareous Nannofossils

A preliminary study has been conducted to assess the value of nannofossil flora in dating the section at Branscombe. Five samples were taken (Fig. 5.14), three from the Foxmould Sands Member and two from the Chert Beds Member.

The Albian-Cenomanian is covered by three nannofossil zones (Fig. 5.15) (Lord, 1982). These are defined by first and last occurrences together with the presence of other important indicator species (Fig. 5.16). In addition the Cenomanian has been further divided (Lord, 1982) into subzones on the basis of first and last occurrences (Fig. 5.17).

In this reconnaissance study the occurrence of nannofossils was found to be patchy, with two samples out of the five yielding significant numbers. In view of the fact that the Chert Beds Member was found to be largely barren of foraminifera it was unexpected and promising that one of these two samples was taken from the middle Chert Beds Member.

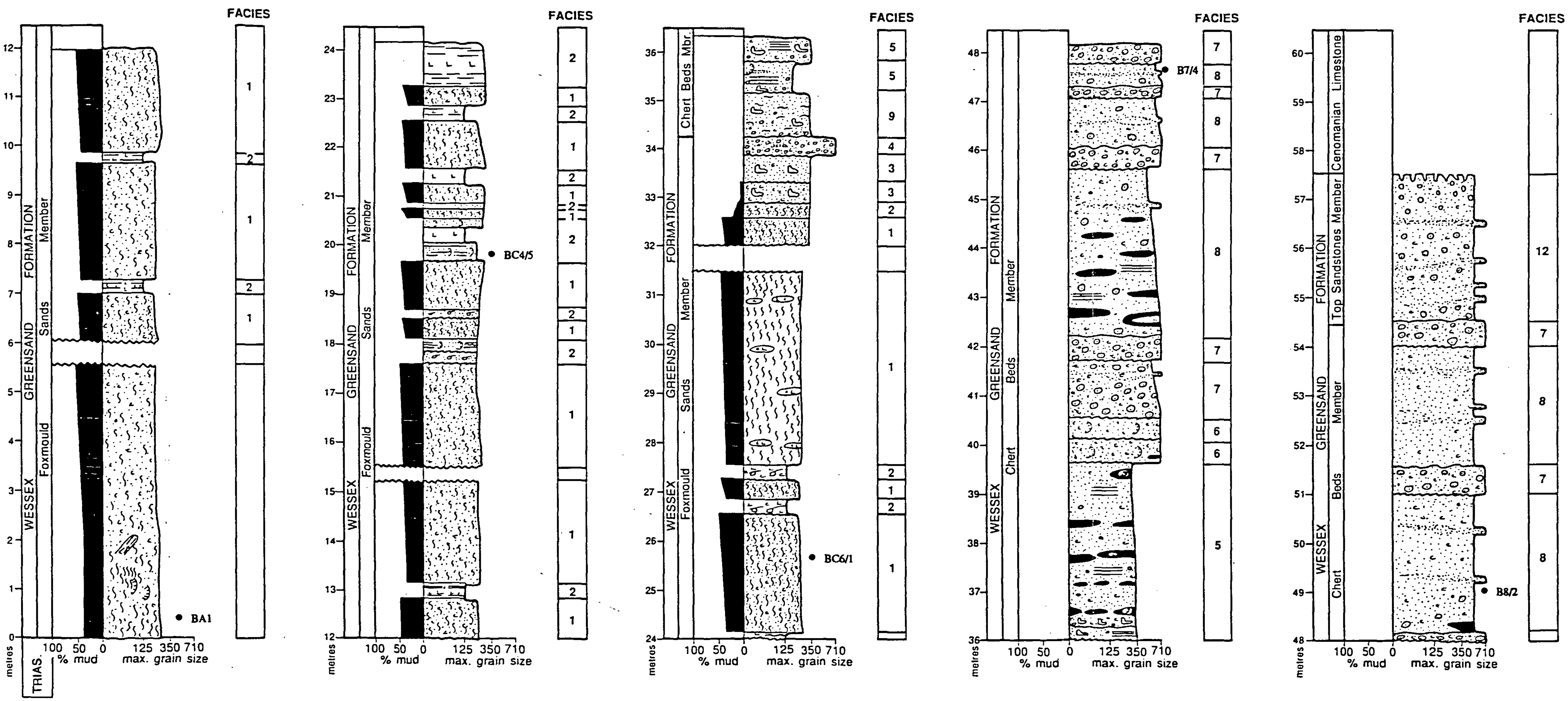


FIG. 5.14: LOCATION OF NANNOFOSSIL SAMPLES. WESSEX GREENSAND FORMATION, BRANSCOMBE, S.E. DEVON.

AGE	AMMONITE ZONE	NF ZONE	NF SUBZONE
TURONIAN			
			Microrhabdulus
	gracile	*E. turriseiffeli*	*decoratus*
	naivculare	ZONE	*Lithraphidites*
CENOMANIAN	*rhotomagense*		*acutum*
	mantelli		*Prediscosphaera*
			spinosa
	dispar		
	inflatum	*Prediscosphaera*	
	lautus	*cretacea*	
ALBIAN	*loricatus*	ZONE	
	dentatus		
	mammillatum	*Parhabdolithus*	
	tardefurcata	*angustus* ZONE	

FIG. 5.15: NANNOFOSSIL ZONAL SCHEME (AFTER LORD, 1982)

1. THE *Parhabdolithus angustus* NF ZONE: INTERVAL FROM THE FIRST OCCURRENCE OF *Parhabdolithus angustus* TO THE BASE OF THE *Prediscosphaera cretacea* NF ZONE AS DEFINED BY THE FIRST OCCURRENCE OF *Prediscosphaera cretacea.*

IMPORTANT SPECIES: *Parhabdolithus achylostaurion, Lithastrinus floralis, Octocychus reinhardtii.*

2. THE *Prediscosphaera cretacea* NF ZONE: INTERVAL FROM THE FIRST OCCURRENCE OF *Prediscosphaera cretacea* TO THE BASE OF THE *Eiffellithus turisseiffeli* NF ZONE AS DEFINED BY THE FIRST OCCURRENCE OF *Eiffellithus turisseiffeli.*

IMPORTANT SPECIES: *Braarudosphaera regularis, Chiastozygus litterarius, Stephanolithion laffittei, Watznaueria barnesae, Podorhabdus albianus, Tranolithus orionatus, Prediscosphaera spinosa.*

3. THE *Eiffellithus turisseiffeli* NF ZONE: BASE OF THE ZONE IS RECOGNISED BY THE FIRST OCCURRENCE OF *Eiffellithus turisseiffeli* TO THE FIRST OCCURRENCE OF *Quadrum gartneri* SUBSPECIES 1.

FIRST OCCURRENCES: *Lithraphidites acutum, Cylindralithus biarcus, C. coronatus, Microrhabdulus decoratus, Corollithion kennedyi, Zygodiscus minimus, Gartnerago obliquum, Pervilithus varius.*

LAST OCCURRENCES: *Lithraphidites acutum, L. alatus, Podorhabdus albianus, Parhabdolithus angustus, P. asper, Microstaurus chiastius, Zygodiscus erectus, Ellipsagelosphaera forbesii, Parhabdolithus infinitus, C. kennedyi, Gartnerago nanum, Cribrosphaera primitiva, Lithraphidites pseudoquadratus, Cretarhabdus striatus.*

FIG. 5.16: NANNOFOSSIL ZONAL SCHEME: FIRST OCCURRENCES AND IMPORTANT SPECIES

3a: THE *Prediscosphaera spinosa* NF SUBZONE: INTERVAL FROM THE FIRST OCCURRENCE OF *Eiffellithus turriseiffeli* TO THE FIRST OCCURRENCE OF *Lithtaphidites acutum.*

FIRST OCCURRENCES: *Corollithion kennedyi, Gartnerago obliquum, Pervilithus varius.*

LAST OCCURRENCES: *Zygodiscus erectus, Ellipsagelosphaera, forbesii.*

3b: THE *Lithraphidites acutum* NF SUBZONE: INTERVAL FROM THE FIRST OCCURRENCE OF *Lithraphidites acutum* TO THE FIRST OCCURRENCE OF *Microrhabdolithus decoratus.*

FIRST OCCURRENCE: *Cylindralithus biacrus.*

LAST OCCURRENCES: *Parhabdolithus asper, Corollithion kennedyi, Gartnerago nanum, Lithraphidites pseudoquadratus.*

3c: THE *Microrhabdolithus decoratus* NF SUBZONE: INTERVAL FROM THE FIRST OCCURRENCE OF *Microrhabdolithus decoratus* TO THE FIRST OCCURRENCE OF *Quadrum gartneri.*

FIRST OCCURRENCES: *Cylindralithus coronatus, Zygodiscus minimus.*

LAST OCCURRENCES: *Lithraphidites acutum, Podorhabdolithus albianus, Parhabdolithus angustus, Microstaurus chiastus, Cretarhabdus striatus.*

FIG. 5.17: NANNOFOSSIL SUBZONES OF THE CENOMANIAN

(AFTER LORD, 1982).

The nannofossils found were generally long ranging forms (Plate 4) and tentative designations are given in Fig. 5.18. The material recovered from these samples is well preserved and despite the fact that it was not possible to assign these samples a place in the Albian-Cenomanian zonal scheme, it is possible that the examination of further samples together with comprehensive taxonomic work will produce a good zonation for the division of the Wessex Greensand Formation.

5.6 Biostratigraphy and Correlation

The stratigraphically useful foraminifera recovered from the Wessex Greensand Formation at Branscombe were all found in the Foxmould Sands Member.

In the lower part of the Foxmould Sands Member *Citharina d'orbigny* with a early to middle Albian stratigraphic range and *Frondicularia filocinta* with a middle to late Albian stratigraphic range together suggest a middle Albian age. However, the remaining species found in the middle Foxmould Sands Member suggest a minimum of late Albian *S. dispar* Zone age (*Arenobulimina* cf. *advena; Heterohelix moremani; Praeglobotruncana* sp. cf *P. delrioensis; Gavellinella cenomanica*).

Only a single specimen of the stratigraphically useful *Ataxophragmium depressum* indicates a Cenomanian age for the top of the Top Sandstones

SAMPLE	NANNOFOSSIL SPECIES	STRATIGRAPHIC RANGE
C45	*Zygodiscus erectus*	SINEMURIAN - CENOMANIAN
C45	*Parhabdolithus asper*	RYAZANIAN - CENOMANIAN
C45	*?Praediscosphaera spinosa*	ALBIAN - CAMPANIAN
B8/2	*Parhabdolithus achylostaurion*	U. APTIAN - TURONIAN
B8/2	*Zygodiscus compactus*	BARREMIAN - CAMPANIAN

FIG. 5.18: NANNOFOSSILS RECOVERED FROM THE WESSEX GREENSAND FORMATION, BRANSCOMBE, S.E. DEVON.

Member. It is obviously unwise to take this occurrence too seriously in view of the danger of contamination and the fact that Cenomanian material penetrates the top of the Wessex Greensand Formation as infill.

Although great care was taken in sampling the small numbers of individuals recovered obviously presents the danger of contamination. This is to some extent obviated by the different species that were found. There is, of course, also the possibility that the specimens of *C. d'orbigny* were reworked and thus give an older age for the lower Foxmould Sands Member.

The stratigraphically useful species thus suggest that the upper part of the Foxmould Sands Member, at least, may be *S. dispar* Zone in age. This casts some doubt on the lithostratigraphic correlation proposed by Hamblin and Wood (1976) between the Haldon Hills and S.E. Devon with regard to the lateral equivalents of the Foxmould Sands Member but does not enable any further correlation of the Chert Beds Member.

The single new ammonite occurrence recorded in this study suggests a confirmation of a *varicosum* Subzone age for the lower part of the Foxmould Sands Member. This evidence, therefore, suggests that the lower part of the Foxmould Sands Member correlates to some extent with the Telegraph Hill Sands Member of the Haldon Hills Formation.

5.6.1 Stratigraphic Significance of Orbitolinid Occurrences

Problems exist with the lithological correlation of the Haldon Hills succession to that of South-East Devon and there has been some disagreement over the chronostratigraphic correlation of the sections. Hart (1971) suggested that the majority of the Chert Beds Member and the Top Sandstones Member of the coastal sections were of Early Cenomanian age, based on the foraminiferal fauna (including *Orbitolina*). By correlation to the Haldon Hills (see Carter and Hart, 1977, Fig. 46) much of the Haldon Hills section is therefore also Early Cenomanian. Hamblin and Wood (1976) whilst agreeing that the upper part of the Haldon Hills section was Cenomanian, considered the majority of the coastal section to be Late Albian. Their argument was based on lithostratigraphic correlation and the occurrence of a *Dispar* Zone (Late Albian) ammonite fauna in the upper Chert Beds Member beds of Shapwick Grange Quarry (Fig. 5.11).

The critical *Dispar* Zone ammonite fauna from Shapwick Grange Quarry is an important line of evidence for suggesting that the majority of the Wessex Greensand Formation is of Late Albian age. Although neither Hart *et al.* (1979b) nor Jarvis *et al.* (1987) could confirm a Late Albian age for the ammonite bearing horizon at Shapwick Grange using a variety of microfossil groups, Owen (pers. comm. to Simmons, 1990) confirms that the ammonite fauna is of latest Albian age (uppermost *Dispar* Zone) and that it is not a remané deposit similar to those known from East Dorset (Carter and Hart, 1977).

Whilst the Shapwick Grange Quarry ammonite fauna indicates that the Chert Beds Member must be Late Albian (contrary to the view of Hart 1971, *et seq.*) it does not rule out the possibility that the Top Sandstones Member is Early Cenomanian. This was suggested by Kennedy (1970) who provided ammonite evidence that the Eggardon Grit was, at least in part, Early Cenomanian. The Top Sandstones Member is the lateral equivalent of the Eggardon Grit (see Fig. 5.19), although note that this coarse, sandy facies at the top of the Wessex Greensand Formation is likely to be diachronous.

The orbitolinids found in the Selborne Group of South-West England give some useful indications about the correlation of this marginal facies between localities. The Wolborough orbitolinids can be assigned to *O. sefini* which suggests an intra-Late Albian - intra-Early Cenomanian age. In fact, the embryonic apparatus measurements plot very close to those for Late Albian *O. sefini* from Portugal (see Fig. 5.9). This tends to support the Late Albian age ascribed to these sediments by Hamblin and Wood (1976) and their tentative correlation to the Late Albian Woodlands Sands Member of the Haldon Sands Formation of Haldon Hill. It is clear that the orbitolinids from the Cullum Sands-with Cherts Member of Haldon Hill belong to a separate, younger population (*O.* cf. *concava*), most likely Early Cenomanian. Again, this confirms the age ascribed to this unit by Hamblin and Wood

(1976).

However, the critical question of the correlation of the Haldon Hills section to that of the South-East Devon coast still remains essentially unanswered. The simplistic correlation of the orbitolinid-rich Cullum Sands-with-Cherts Member to the orbitolinid bearing Top Sandstones Member/uppermost Chert Beds Member at Dunscombe on the South-East Devon coast is thought unlikely, and in any case, the orbitolinids studied from Dunscombe cannot be identified at present. Rather, the definite Early Cenomanian age suggested for the Cullum Sands-with-Cherts Member indicates a correlation with the lower part of the Beer Head Limestone to be likely. The present author suggests that lithologically, the Ashcombe Gravels Member correlates with the Top Sandstones Member and upper Chert Beds Member (Fig. 5..19). These correlations are in broad agreement with some of the suggestions of Hamblin and Wood (1976).

It is known that embryonic apparatus size in orbitolinids increases with time within a phylogenetic lineage (eg Schroeder, 1975; Gûsic, 1981), thus within the *O. sefini* - *O. concava* plexus it may be assummed that greater embryonic apparatus size indicates a younger age. Therefore Figure 5.9 suggests that three distinct populations of *Orbitolina* occur in the Selborne Group of South-West England: the Wolborough Late Albian population, which is older than the Dunscombe population, which in turn is older than the Early Cenomanian Babcombe

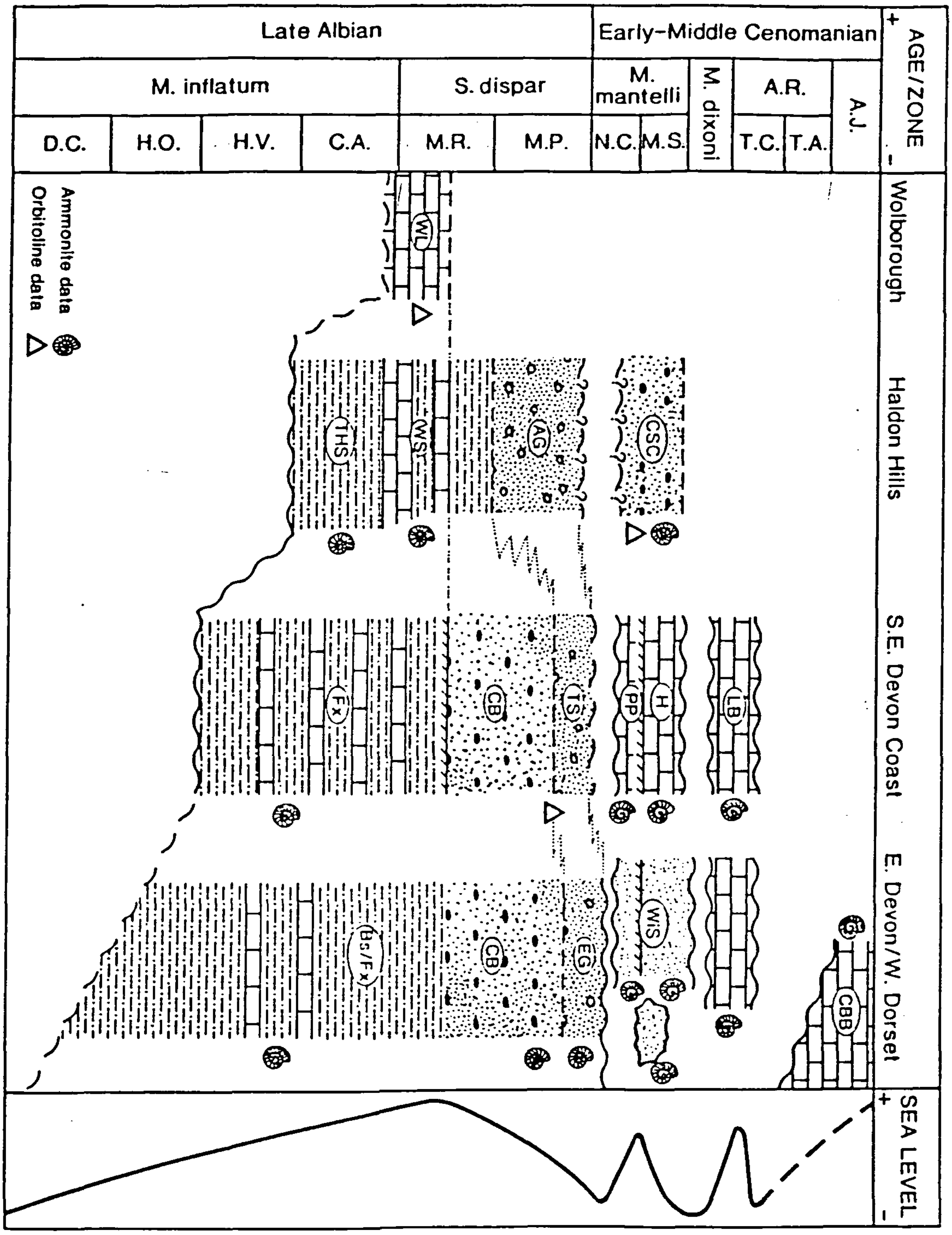


FIG. 5.19: CHRONOSTRATIGRAPHIC CHART OF THE SELBORNE GROUP , S.W. ENGLAND.

Copse population. These relative age assignments support the correlations shown in Figure 5.19.

5.7 Palaeobiogeographic Significance of Orbitolinid Occurrences

Hart *et al.* (1979a) discussed the possible colonisation pathway of *Orbitolina* and came to the conclusion that the orbitoline occurrences in South-West England had probably arrived by way of the Paris Basin. They pointed out that orbitolines recorded from the English Channel Basin and the South-West Approaches Basin (Andrieff *et al.*, 1975; Curry *et al.*, 1970) have been assigned an Early Cenomanian or Albian-Cenomanian age and "that it is difficult to see how this accepted 'Tethyan' genus could appear in the U.K. earlier than in these more southern localities". However, the age of these orbitolinids from the English Channel Basin and the South-West Approaches is quite generalised, and as shown above, it is likely that both Late Albian and Early Cenomanian orbitolinids occur in South-West England.

The occurrence of Late Albian *O. sefini* in both Portugal (Rey *et al.*, 1977) and South-West England suggests that there may have been a migration pathway from the Iberian Penisular via the South-West Approaches to South-West England. Such a pathway can be supported by the palaeogeography proposed by Lott *et al.* (1980) using borehole evidence from offshore South-West England.

CHAPTER 6 SEQUENCE STRATIGRAPHY AND SEA-LEVEL CHANGES

6.1 Introduction

This chapter contains a description of the techniques used in sequence stratigraphy and employs them to integrate all the available information into a basin history in relation to sea-level changes. A sea-level curve, for S.W. England during the Albian/Cenomanian, is presented and compared with other published curves.

Much of the work in this chapter forms the substance of a paper submitted to the Ussher Society and read at their annual conference in January 1991 (Simmons, M.D., Williams, C.L. and Hart, M.B. (in Press)).

6.2 What is Sequence Stratigraphy?

In the 1970's stratigraphers at EXXON developed a new way of looking at sedimentary successions. Initially using relationships seen in seismic sections, but later also using outcrop and well data, the method divides a rock succession up into packages or "sequences". The basic premise of this technique is that sea-levels have fluctuated throughout geologic time, either due to glaciations or through volumetric changes caused by plate movements and variations in sea-floor spreading rates. Cycles of sea-level change occur at several orders of magnitude. Short-term fluctuations lead to the development of sequences, the fundamental unit within the EXXON method. A sequence is a genetically related package of rock bounded by unconformities or their correlative conformities (Van Wagoner *et al.*, 1988). A sequence can be further subdivided into systems tracts. These show the distribution of facies across the shelf and basin during given periods of the sea-level (eustatic) cycle. Each systems tract is characterised by particular sedimentary and seismic geometries, facies relationships and fossil biota. Three main systems tracts can be recognised within a given sequence: a lowstand systems tract developed during a eustatic fall in sea-level; a transgressive systems tract developed during sea-level rise; and a highstand systems tract developed at, and directly after, sea-level has risen to it's maximum in that cycle. This represents the time of maximum transgression. It is often represented by condensed sedimentation.

Despite certain reservations about the methodology and global applicability of sea-level change, "Sequence Stratigraphy" became widely publicised following publication of AAPG Memoir 26 (Payton, 1977), and the technique was widely accepted and utilised in the oil industry. The technique is an exciting one for two main reasons: (i) it draws all the different types of data on a sedimentary succession (seismic, sedimentology, biostratigraphy, etc.) together, and allows a lucid picture of basin history to be drawn and (ii) it is a highly predictive technique which allows facies outside the area of study to be predicted by reference to the systems tract to which they will belong.

As noted above, one of the fundamental tenets of sequence stratigraphy is that sea-levels have fluctuated in a given manner, world-wide, through geological time. A number of "sea-level curves" have been produced documenting this, with the most recent work being that of Haq *et al.* (1987). This shows a global pattern of synchronous sea-level changes and thus a myriad of systems tracts which theoretically should be recognisable world-wide, assuming no local tectonic controls and suitable marine successions in a passive margin setting. Hancock (1989) has produced a sea-level curve specifically for the Cretaceous of the British region, and there are several others, some of which are referred to below. A problem with the Haq *et al.* (1987) curve is that it is often based on observations made on basinal successions. It is better to document sea-level changes from marginal areas where even small fluctuations in sea-level are likely to result in major facies changes. During the Albian - Cenomanian period, south west England was such a marginal area. It therefore provides an ideal opportunity to develop a sea-level curve to compare against those already published for this time period. However, it should be noted that any local sea-level curve is a function of the combination of subsidence, sediment supply and eustatic sea-level change. Each of these factors will be of varying significance, although in this particular instance most significance is placed on the eustatic variation. It is also interesting to re-examine the Albian - Cenomanian succession of south west England within the context of sequence stratigraphy. This may shed some light on the depositional environment and correlation of these problematic deposits.

6.3 Recognition of Sequences and Sea-Level Change in Outcrop

The recognition of sequence boundaries, systems tracts and sea-level changes in outcrop has been the subject of some debate in recent years (eg Wilgus *et al.*, 1988; Hancock, 1989). Sequences, as defined by Van Wagoner *et al.*(1988) (following Mitcham, 1977), are bounded by unconformities (caused by a downward shift in coastal onlap) or their correlative conformities. It therefore follows that the occurrence of missing biozones and marked facies changes allows sequence boundaries to be recognised.

The recognition of sea-level changes (and hence systems tracts) is more complex. Hancock (1989) has suggested the use of hardgrounds to recognise periods of maximum transgression (following Juignet, 1980; Francis, 1984). The subject of why and how hardgrounds form is a complex one (eg see discussions by Fischer and Garrison, 1967; Kennedy and Garrison, 1975; Bromley, 1978; Garrison *et al.*, 1987) which will not be discussed in this work. However, whilst accepting Hancock's premise that hardgrounds form in response to an interruption in sedimentation, this may not always relate to regression. They could form (as noted by Hancock, 1989) in response to winnowing by local bottom currents. These could occur in almost any environmental setting and not be a function of eustatic change. Hardgrounds may also develop during periods of transgression. Indeed, Hancock (1989, p. 577) notes that courses of phosphatic nodules in the Gault may form in response to "... a transgression that carries the shoreline further from the basin. Deposition of sediment was also moved further from the basinal region which was then starved of clay". In a marginal setting, such as that represented by the Late Albian - Cenomanian sediments of S.W. England, an increase in water depth caused by a transgression may cause a marked drop in sedimentation and the formation of a hardground. In terms of sequence stratigraphy, condensed deposition is associated with the maximum flooding surface, or height of transgression (Van Wagoner *et al.*, 1988; Loutit *et al.*, 1988).

Thus at the peak of transgression a hardground may develop, particularly on the shelf, with biozones being condensed or apparently missing. In contrast to Hancock (1989), the present work argues that this condensed sequence will not always overlie the regressive hardground (although it may sometimes, perhaps in the case of the Beer Head Limestone Formation hardgrounds which are multiple (Jarvis and Woodroof, 1984)). Rather it will overlie the lowstand and lower transgressive systems tracts which onlap onto the shelf. Thus, some hardgrounds are associated with regression and unconformity (eg at the top of the Top Sandstones Member) but some are a function of condensation during maximum transgression (eg that at the top of the Foxmould Sands Member).

In the Late Albian - Cenomanian succession of S.W. England this study recognises transgressions and eustatic sea-level rises by periods of maximum onlap (see Fig. 6.1). Also considered are the distribution of facies variations, the diachroneity of facies and the presence of hardgrounds and unconformities.

6.4 Sequence Stratigraphy of the Selborne Group in S.W. England

As shown by Fig. 6.1 there is a gradual east to west onlap of the Selborne Group during the late Albian. The basal Foxmould Sands Member is at least as old as Cristatum Subzone in west Dorset; in south east Devon it is of Varicosum Subzone (see chapters 2, 3, and 5 for the discussion of, and relevant references for all age

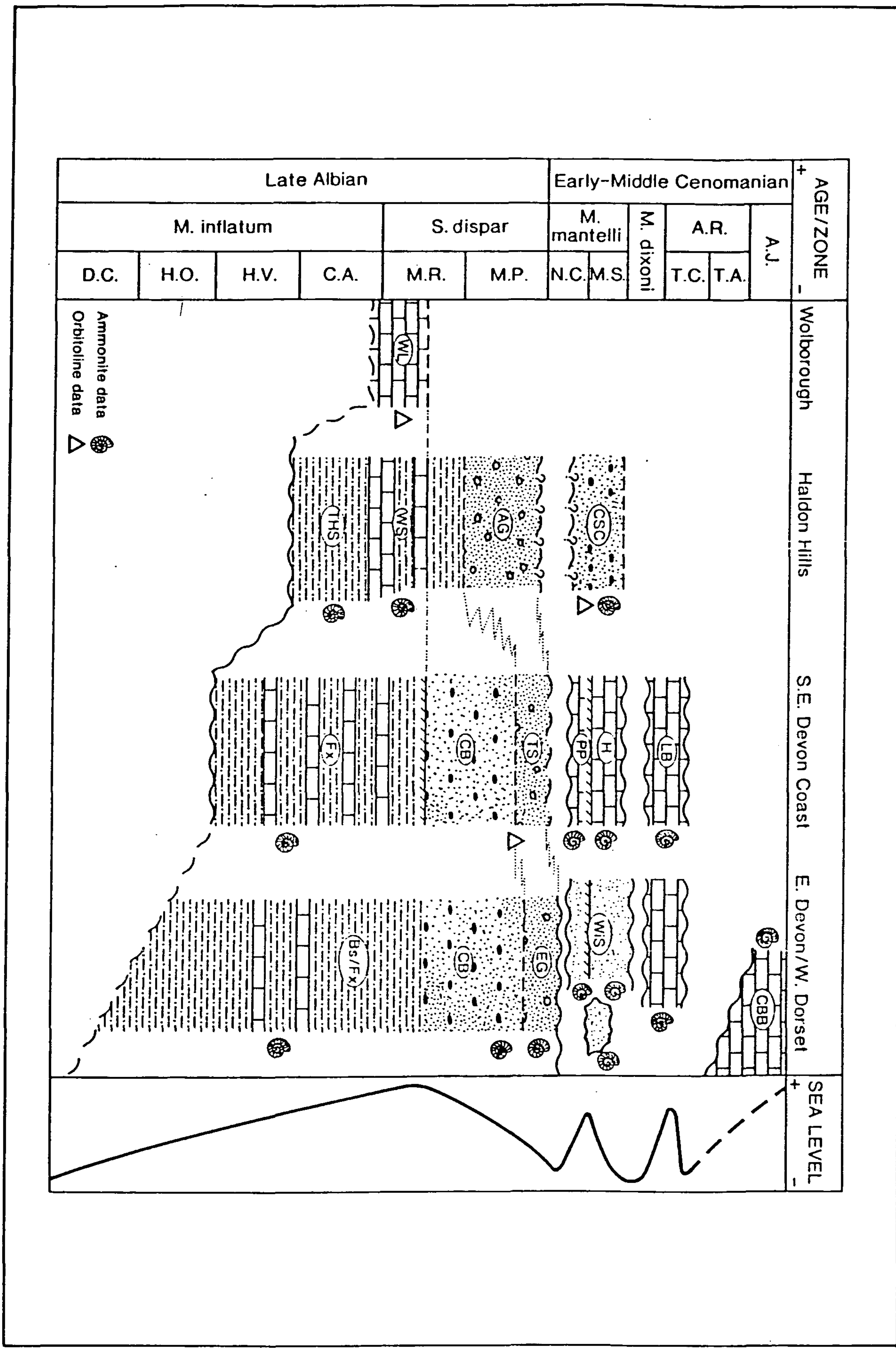


FIG. 6.1: CHRONOSTRATIGRAPHIC CHART OF THE SELBORNE GROUP , S.W. ENGLAND.

determinations given in this section). The base of the Haldon Sands Formation is Auritus Subzone, but the period of maximum transgression is indicated by the Wolborough Limestones Member which is thought to be Rostratum Subzone age. Within the Varicosum - Auritus succession in S.W. England there are no major facies changes or depositional breaks to indicate a cessation of the transgression. Thus sea-level was rising throughout the Inflatum Zone and the time of maximum eustatic rise was in the lower part of the Rostratum Subzone (Dispar Zone). Interestingly, this sea-level rise led to the establishment of a carbonate shelf with orbitoline-rich limestones in the inner shelf, with local coral bioherms basinwards of this (the Haldon Coral Bed, Woodlands Sands Member). The limestones in the Foxmould Sands Member have an outer shelf fauna (see chapter 5). The hardground at the top of the Foxmould Sands Member corresponds to condensation at the time of maximum transgression.

There then followed a gradual regression throughout the remainder of the Dispar Zone. This is indicated by the shallowing of facies throughout the Chert Beds Member and Top Sandstones Member (Tresise, 1960; Williams, 1986; chapter 3 of this work). The Ashcombe Gravels Member, Top Sandstones Member and Eggardon Grit represent a diachronous, regressive, coarse, shallow water facies which becomes progressively younger eastwards. The maximum regression occurs in the basal Cenomanian in the lower part of the Carcitanensis Subzone, as evidenced by the unconformity and hardground at the top of the Top Sandstones Member and Eggardon Grit. However, this apparent regression may, in part , be due to increased sediment supply, although this itself often occurs during a eustatic sea-level fall (highstand systems tract).

Using the above synthesis it is possible to identify the various components of the sequence as follows:

(i) The trangressive systems tract is represented by the Foxmould Sands Member, the lower part of the Telegraph Hill Sands Member and the lower part of the Wolborough Limestones Member.

(ii) The maximum flooding surface lies within the Wolborough Limestones Member and, to the east, within the Woodlands Sands Member. Further to the east it is represented by the hardground at the top of the Foxmould Sands Member.

(iii) The highstand systems tract is represented by (probably) the top of the Wolborough Limestones Member and Woodlands Sands Member and the whole of the Ashcombe Gravels Member at Haldon and the Chert Beds Member and Top Sandstones Member in S.E. Devon and by the Eggardon Grit further to the east.

Rapid eustatic rise and transgression occurred in the upper part of the Carcitanensis Subzone as evidenced by the onlap of the lowermost Cenomanian Limestone (Pounds Pool Member, Beer Head Limestone Formation) and equivalents (lower Wilmington Sands and Cullum Sands-with-Cherts Member) across south Devon. Garrison *et al.* (1987) also recognise an increase in water depth at this time. As with the Late Albian transgression, this leads to the establishment of a carbonate shelf and orbitoline-rich inner shelf limestone (Cullum Sands-with-Cherts Member). The hardground at the top of the Pounds Pool Member (basal Saxbii Subzone) is probably the result of condensation associated with transgression. A shallowing-up trend in the Hooken member overlying the hardground at the top of the Pounds Pool Member, and also within the upper Wilmington Sands indicates a regression and eustatic sea-level fall taking place throughout the majority of the Saxbii Subzone. This culminates in the unconformity seen at the top of the Hooken Member and Wilmington Sands, the latter being within the Dixoni Zone.

The succession of facies within the Little Beach Member indicates a relatively rapid transgressive/regressive cycle. A eustatic sea-level high occurred during the lower part of the Costatus Subzone, and a regression in the upper part of this Subzone. A gradual recovery of sea-level is indicated in the Acutus Subzone and continues into the Jukesbrownei Zone as indicated by the gradual westerly onlap of the Chalk Basement Beds. This transgression may have continued throughout the Late Cenomanian, culminating in the deposition of the Pinnacles Member of S.E. Devon. This is the lateral equivalent of the Plenus Marls of S.E. England (Carter and Hart, 1977; Jarvis *et al.*, 1988), which is associated with a eustatic sea-level high (Hancock, 1989).

It is interesting to note that in a marginal area such as that discussed above it may be possible to estimate the depth of water at any geographical point during the period of maximum transgression. This is only possible if there is a fairly complete sedimentary succession from the maximum flooding surface through the highstand systems tract; the top of which should show evidence of sub-aerial exposure (or at least very shallow water conditions). In essence this means that the sediment pile represents the infilling of the basin to the same depth that the water column covered it at the maximum flooding surface. This would, of course, only be an approximation as such factors as compaction and ongoing basin subsidence are unknowns (although these can also be estimated). But at least a minimum water depth can be calculated. For example, the Selbourne Group deposits at Branscombe indicate that at maximum transgression the water depth in the area was at least 22 metres.

6.5 Comparison with Other Sea-Level Curves

The sea-level curve developed during this study for the Late Albian - Middle Cenomanian of S.W. England is compared in Fig. 6.2 with the global curve of Haq *et al.* (1987) and the more localised curve developed for the British region by Hancock (1989).

There are some similarities between this study's curve and that of Haq *et al.* (1987). Sea-levels are both shown to be rising throughout the Inflatum Zone. As noted by Hancock (1989) this in fact corresponds to the global onset of the major "Cenomanian Transgression" of Suess (1906). Haq *et al.* (1987) have a eustatic high at the Auritus - Rostratum Subzonal boundary whereas this study's curve is slightly higher, in the lower part of the Rostratum Subzone, but perhaps within the range of error for both methods. A subsequent sharp eustatic fall is indicated by Haq *et al.* (1987). This may have initiated and correspond to the onset of a fall in this authors curve but unlike Haq *et al.* this shows sea-level to be falling throughout the Dispar Zone. As noted by Morner (1980), such a dramatic sea-level fall as that indicated by Haq *et al.* (1987) within the lower Rostratum Subzone is difficult to explain. Haq *et al.* (1987) have a recovery of sea-level

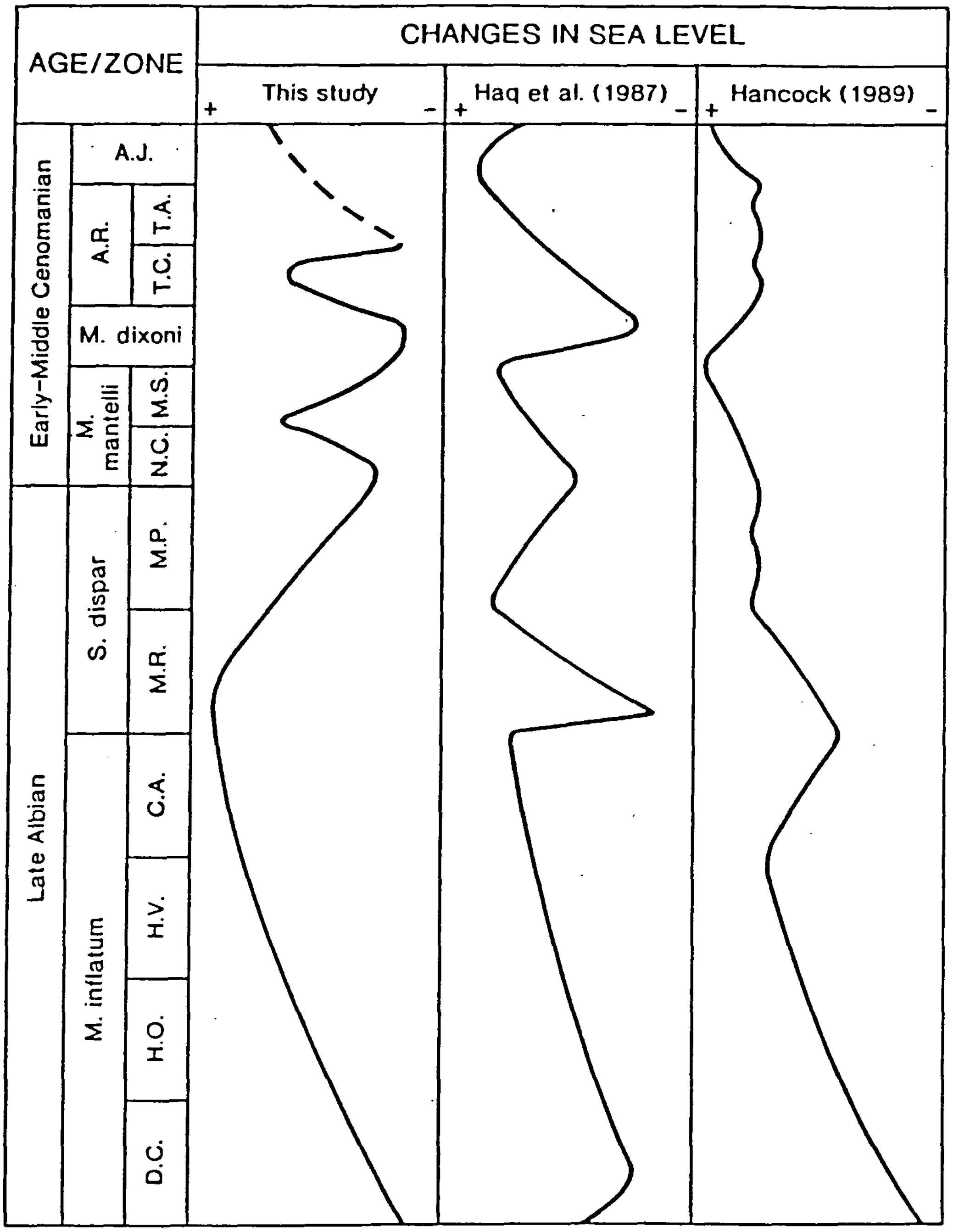


FIG. 6.2: A COMPARISON OF THE SEA LEVEL CURVE DEVELOPED DURING THIS STUDY WITH THE CURVES OF HAQ *et al.* (1987) AND HANCOCK (1989).

during most of the Rostratum Subzone and a fall during the Perinflatum Subzone. This culminates in a regressive trough during the basal part of the Carcitanensis Subzone, which is in agreement with this study. Haq *et al.* (1987) show the subsequent eustatic rise culminating at the top of the Saxbii Subzone; this study shows it to culminate slightly lower. Once again there is agreement with the following regressive trough: it lies within the Dixoni Subzone. Haq *et al.* (1987) then have a eustatic rise taking place through to within the Jukesbrownei Zone. They do not recognise the cycle within the Costatus Subzone.

There is only slight agreement between the curve developed during this study and that of Hancock (1989) despite the fact that the latter is more directly relevant to this study. Both curves show a eustatic rise during the early part of the Inflatum Zone; but Hancock shows the eustatic peak to be at the base of the Auritus Subzone. This cannot be reconciled with the clear evidence for continued onlap during the Auritus Subzone at Haldon and Wolborough. Following a regression during the Auritus Subzone, Hancock shows sea-level to be rising or in a state of still-stand during the Dispar Zone. This contradicts the evidence he cites, that there was a Late Albian shallowing of the sea in Devon. However, the possibility of increased supply must be taken into account, although this is most likely to occur during a eustatic sea-level fall (highstand systems tract). Within the Early-Middle Cenomanian Hancock shows a rise culminating at the top of the Saxbii Subzone, followed by slight regression, still-stand and then transgression during the Jukesbrownei Zone. This is quite different to the curve developed for this study (although the eustatic peak at the top of the Saxbii Subzone almost corresponds and is in agreement with the curve of Haq *et al.* (1987)). Perhaps one problem of comparing the curves is that Hancock (1989) uses zonal boundaries as datums for placing his minima and maxima of sea-level change, whilst this study tried to place them within zones where appropriate.

Other sea-level curves may be compared in a general way with the results of this study. Morner (1980) and Matsumato (1980) both show a regression culminating very near the Albian - Cenomanian boundary for a number of localities world-wide, and Juignet (1980) has similar results from the Paris Basin and the Armorican Massif. These agree with this study. Juignet (1980) recorded sea-level highs during the Inflatum Zone, the Saxbii Subzone and the Jukesbrownei Zone. Again agreeing with this study. Cooper (1977) indicated that the Late Albian transgression began during Orbignyi Subzone times. Somewhat later than proposed by the present study. Cooper also noted that the strata across the Albian - Cenomanian boundary are typically represented by regressive deposits world-wide. He mentioned that the Dispar Zone is regressive in the Western Interior of North America, in Brazil, Peru and around Africa. This supports the present work. Cooper's discussion of transgressive peaks in the Cenomanian shows similarities to this study and using the results of Hart and Tarling's (1974) study of Cenomanian palaeogeography he recognises a sea-level rise during the Costatus Subzone. This also is in agreement with the present work.

Differences between the curve developed during this study and those of other workers could be ascribed to local tectonic and isostatic controls on sedimentation (Hart, 1990). That there were mid-Cretaceous tectonic movements in S.W. England has been suggested by a number of workers (eg Smith, 1957; Drummond, 1970; Hart, 1971). To what degree tectonic/isostatic controls overprint eustatic controls in this area (if indeed at all) remains a subject for further investigation.

CHAPTER 7 CONCLUSIONS AND FURTHER WORK

7.1 Introduction

In this chapter the conclusions drawn from this study are presented as a series of 'bullet points' (1-29). These are followed, where appropriate, by a series of points (a-e) which suggest further work which may be usefully undertaken.

7.2 Lithostratigraphy

1) A review is presented of the literature dealing with the lithostratigraphy of the Selborne Group.

2) A new lithostratigraphic scheme is proposed for those deposits formerly known as the Upper Greensand. In the south and south-west of England the proposed Selborne Group is made up of the proposed Wessex Greensand Formation and Gault Clay Formation as well as the existing Haldon Sands Formation.

3) The Wolborough Limestone Member is proposed as part of the existing Haldon Sands Formation. This proposed new member is described in detail and a type section is designated.

4) The Foxmould Sands Member is proposed as the basal member of the proposed Wessex Greensand Formation. It is described in detail and a

type section is designated in the Branscombe to Beer Head section, S.E. Devon.

5) The Chert Beds Member is proposed as part of the proposed Wessex Greensand Formation. It is described in detail and a type section is designated in the Branscombe to Beer Head section, S.E, Devon.

6) The Top Sandstones Member is proposed as the topmost member of the Wessex Greensand Formation. It is described in detail and a type section is designated at Dunscombe, S.E. Devon.

Further Work

a) The integration into the lithostratigraphic scheme of other deposits, of a similar age, to the east of the study area.

7.3 Sedimentology and Facies

7) A review is presented of the available literature dealing with the sedimentology of the Selborne Group of S.W. England.

8) Lithological logs are presented for sections at Branscombe/Beer Head (Type Section for the Foxmould Sands Member and the Chert Beds Member); Kempstone Rocks, Dunscombe, S.E. Devon (Type Section for the Top Sandstones Member); Whitecliff, Seaton, S.E. Devon; and a small quarry at Dunscombe, S.E. Devon.

9) The sediments found in these sections are divided up into 15 facies.

10) Each facies is described in detail including local variations and associations with other facies. An environmental interpretation is suggested for each facies.

11) The Foxmould Sands Member is interpreted as a relatively deep water unit with clay-sized sediments deposited from suspension during normal weather conditions. Rare storm events resulted in the laying down of sands and impure limestones when storm wave base touched bottom and/or storm induced, offshore flowing, bottom currents transported sand out into the basin.

12) The facies in the Chert Beds Member are interpreted as reflecting higher energy events/and shallower water upwards. Deposits reflecting storm events of varying intensity are described and the normal fairweather depositional environment is thought to have been tidally dominated.

13) The Top Sandstones Member is interpreted as being a shallow water tidally dominated deposit.

Further Work

b) It is intended to carry out further investigation to the east of the present study area. Particularly in the region of the mid-Dorset Swell including the Eggardon Grit and Exogyra Rock.

7.4 Diagenesis

14) A review is presented of previous work on the diagenesis of the Selborne Group including chert formation hypotheses.

15) Secondary silica in the Foxmould Sands Member is described. it occurs as chalcedony passively infilling voids and occasionally as a fine quartz cement in the clean quartz sands.

16) A series of events leading to the formation of chert within the Chert Beds Member is proposed. The gradual replacement of calcite and glauconite combined with void-fill chalcedony and microquartz rim cements are shown to result in a ghost fabric.

7.5 Biostratigraphy

17) A review is presented of previous work on the fauna of the Selborne Group including publications dealing with ammonites and foraminifera and zonations based on these groups.

18) A new ammonite occurrence is reported from the Foxmould Sands Member at Branscombe. Identified as *Prohystoceras (Goodhallites) delabechei* it suggests a varicosum Subzone age for the lower part of the Foxmould Sands Member.

19) 23 genera and 32 species of Foraminifera are described, together with information on their geographic and stratigraphic ranges and the palaeoenvironments in which they are found.

20) The smaller Foraminifera suggest that the upper part of the Foxmould Sands Member may be as young as dispar Zone but do not allow any further refinement of the age of the Chert Beds Member.

21) An in depth examination of the occurrence of the large benthonic Foraminiferan *Orbitolina* in S.W. England allowed the following conclusions to be drawn:

i) Orbitolines from the Wolborough Limestone Member (Haldon Sands Fm.) belong to the species *Orbitolina sefini* and embryonic apparatus dimensions suggest a Late Albian age.

ii) Orbitolines from the Cullum Sands-with-Cherts Member (Haldon Sands Fm.) are assigned to *Orbitolina* sp. cf. *concava* and suggest an Early Cenomanian age.

iii) Orbitolines from Dunscombe have been identified as belonging to the *O. sefini* - *O. concava* plexus but precise determinations were not possible.

iv) 'Orbitolina' occurrences from Wilmington in east Devon are, in fact, shown to belong to the sponge genus *Porosphaera.*

22) Using the evidence gathered during this study of Orbitoline occurrences the correlation of various outcrops of Selborne Group deposits in S.W. England was found to be in broad agreement with that put forward by Hamblin and Wood (1976). Some differences remain to be resolved about the details of correlation between the upper part of

the Haldon Sands Formation and the Wessex Greensand Formation of S.E. Devon.

23) The occurrence of both *O. sefini* and *O.*sp. cf. *concava* in S.W. England has allowed the proposal of a colonisation pathway for the Orbitolines from the Iberian Peninsular via the S.W. Approaches to S.W. England rather than by way of the Paris Basin.

24) A reconnaissance study of nannofossils was carried out which, while not allowing any firm conclusions, reported the occurrence of this fossil group from both the Foxmould Sands Member and the Chert Beds Member.

Further Work

c) To search for and examine further occurrences of Orbitolina (especially those reported to occur in S.E. Devon) in order to attempt both further resolution of the correlation from the Haldon Hills to S.E. Devon and correlation to outcrops further east.

d) To carry out more refined analysis on the nannofossils from various sections of the Selborne Group in S.W. England.

7.6 Sequence Stratigraphy and Sea-level Changes

25) Using the techniques of sequence stratigraphy a basin history is presented for S.W. England during Albian/Cenomanian times.

26) The Foxmould Sands Member, the lower part of the Telegraph Hill Sands Member and the lower part of the Wolborough Limestone Member are suggested to be part of a transgressive systems tract.

27) The maximum flooding surface of the same cycle is suggested to be within the Wolborough Limestone Member, within the Woodlands Sands Member and be represented by the hardground at the top of the Foxmould Sands Member.

28) It is suggested that the high stand systems tract is represented by the top of the Wolborough Limestone Member and Woodlands Sands Member, the whole of the Ashcombe Gravels Member and the Chert Beds Member and Top Sandstones Member.

29) A sea-level curve for Albian/Cenomanian times in S.W. England is presented and compared with the published curves of Haq *et al.* (1987) and Hancock (1989).

Further Work

e) To extend the sequence stratigraphy model into S.E. England.

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PLATES

PLATE 1

1. *Tritaxia pyramidata* Reuss, 1844. (x 70). Lateral View. Sample B11/6, Branscombe. Albian and Cenomanian.
2. *Arenobulimina* sp. cf. *A. advena* Cushman, 1936. (X 100). Lateral View. Sample BB8, Branscombe. Very latest Albian.
3. *Eggerellina mariae* ten Dam, 1950. (X 80). Lateral View. Sample BC14, Branscombe. Auritus Subzone - Early Turonian.
4. *Ataxophragmium depressum* Perner, 1892. (X 100). Lateral View. Sample B11/6, Branscombe. Cenomanian.
5. *Nodosaria* sp. (indet.) (X 48). Lateral View. Sample BB6, Branscombe.
6. *Astacolus* sp. (indet.) (X 75). Lateral View. Sample BB10, Branscombe.
7. *Astacolus* sp. (indet.) (X 36). Lateral View. Sample BB14, Branscombe.
8. *Citharina d'orbignyi* Marie, 1938. (X 36). Lateral View. Sample BB7, Branscombe. Early or mid Albian.
9. *Citharinella* sp. (indet.) (X 36). Lateral View. Sample BB13, Branscombe.
10. *Dentalinoides* sp. (indet.) (X 48). Lateral View. Sample BB8, Branscombe.

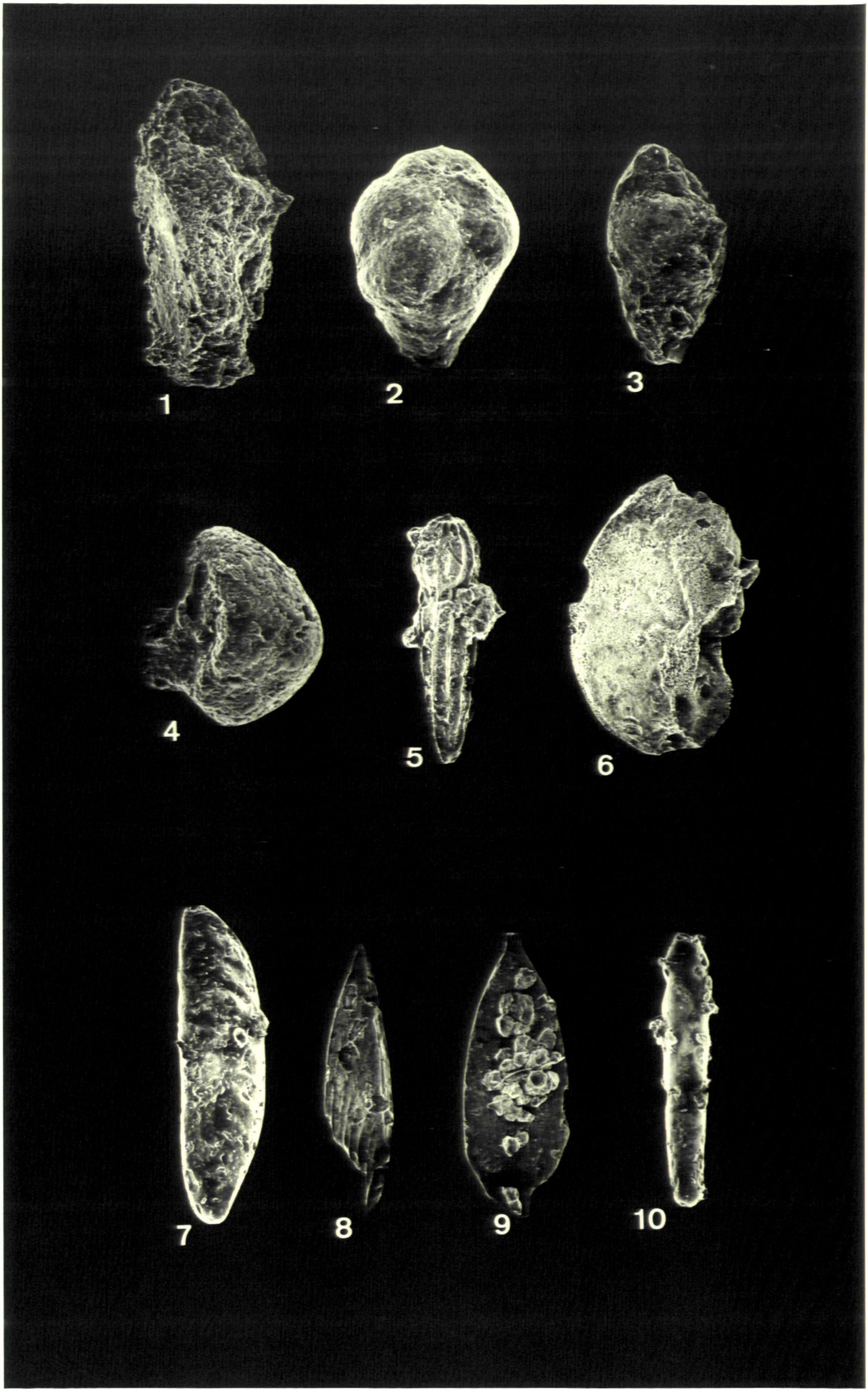
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PLATE 2

1. *Frondicularia filocenta* Reuss, 1862. (X 24). Lateral View. Sample BB8, Branscombe. Mid and Late Albian.
2. *Lenticulina rotulata* var. A. (X 70). Lateral View. Sample BA1, Branscombe.
3. *Lenticulina rotulata* var. B. (X 48). Lateral View. Sample BA1, Branscombe.
4. *Lenticulina rotulata* var. C. (X 70). Lateral View. Sample BA1, Branscombe.
5. *Lenticulina* sp. A. (X 80). Lateral View. Sample BA7, Branscombe.
6. *Lenticulina* sp. B. (X 75). Lateral View. Sample BC4/2, Branscombe.
7. *Neoflabellina* sp. (indet.) (X 36). Lateral View. Sample BB3, Branscombe.
8. *Neoflabellina* sp. (indet.) (X 17). Lateral View. Sample BB8, Branscombe.
9. *Vaginulina kochii* Roemer, 1841. (X 70). Lateral View. Sample BA7, Branscombe.
10. *Tobolia* sp. (indet.) (X 70). Lateral View. Sample BA7, Branscombe.

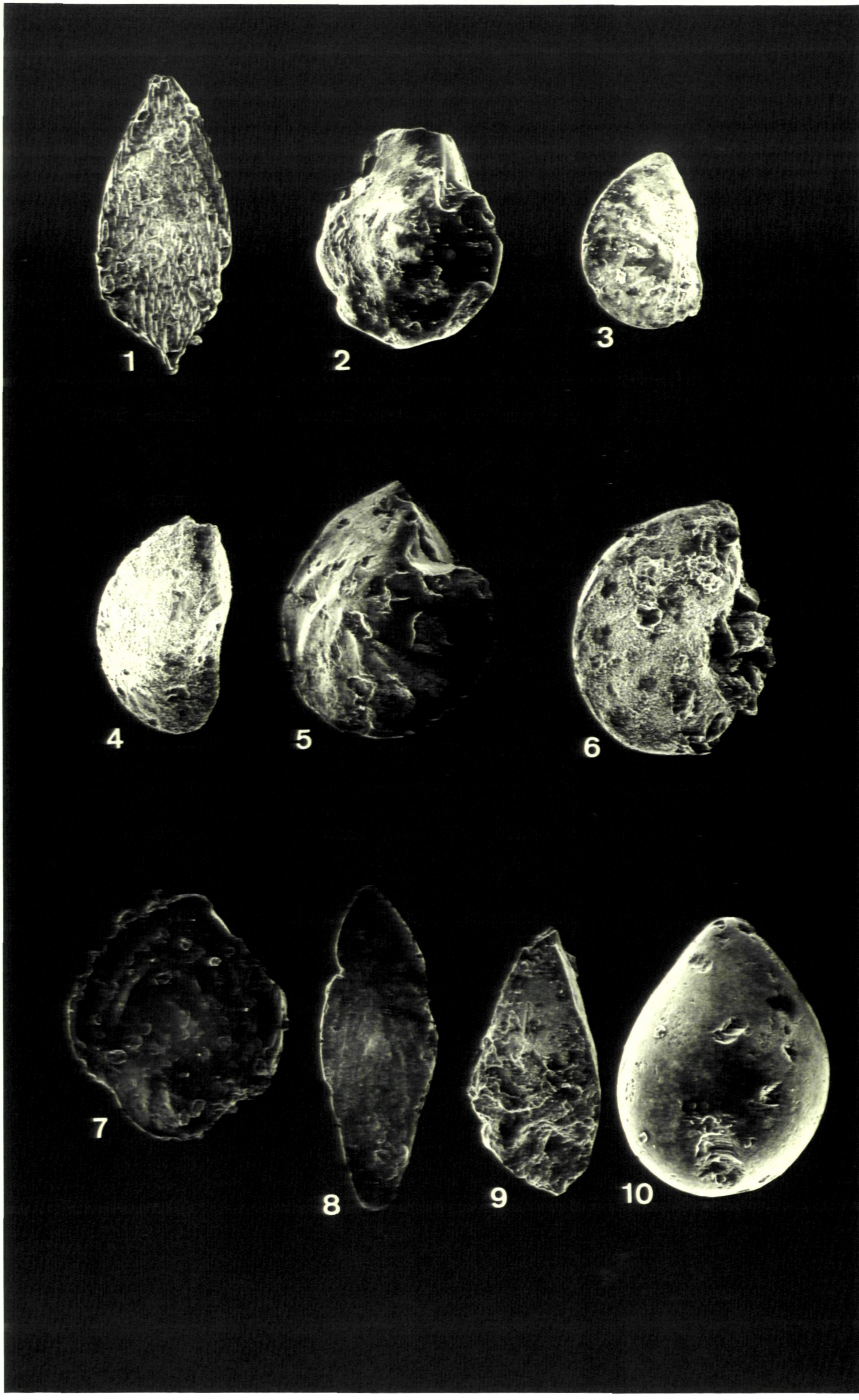
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PLATE 3

1. *Tristix excavatum* Reuss, 1862. (X 100). Lateral View. Sample BB7, Branscombe. Mid to Late Albian.
2. *Patellina* sp. (indet.) (X 100). Lateral View. Sample BB3, Branscombe.
3. *Patellina* sp. (indet.) (X 100). Spiral View. Sample BB3, Branscombe.
4. *Heterohelix moremani* Cushman, 1938. (X 230). Lateral View. Sample BC1/1, Branscombe. Dispar Zone - Late Cenomanian.
5. *Globigerinelloides bentonensis* Morrow, 1934. (X 175). Lateral View. Sample B15/2, Cenomanian Limestone, Branscombe. Rostratus Subzone.
6. *Pleurostomella* sp. (indet.) (X 24). Lateral View. Sample BC2/1, Branscombe.
7. *Gyroidinoides parva* (Khan). (X 175). Umbilical View. Sample BA4, Branscombe. Albian.
8. *Gyroidinoides parva* (Khan). (X 175). Lateral View. Sample BA4, Branscombe. Albian.
9. *Gavelinella cenomanica* Brotzen, 1942. (X 100). Spiral View. Sample BB14, Branscombe. Very topmost Albian - Cenomanian.
10. *Gavelinella intermedia* (Berthelin). (X 100). Umbilical View. Sample BB14, Branscombe. Albian and Cenomanian.
11. *Lingulogavelinella* sp. (indet.) (X 100). Spiral View. Sample B15/2, Cenomanian Limestone, Branscombe.
12. *Lingulogavelinella jarzevae* Vasilenko, 1954. (X 100). Umbilical View. Sample B12/1, Cenomanian Limestone, Branscombe. Dispar Zone and Early Cenomanian.

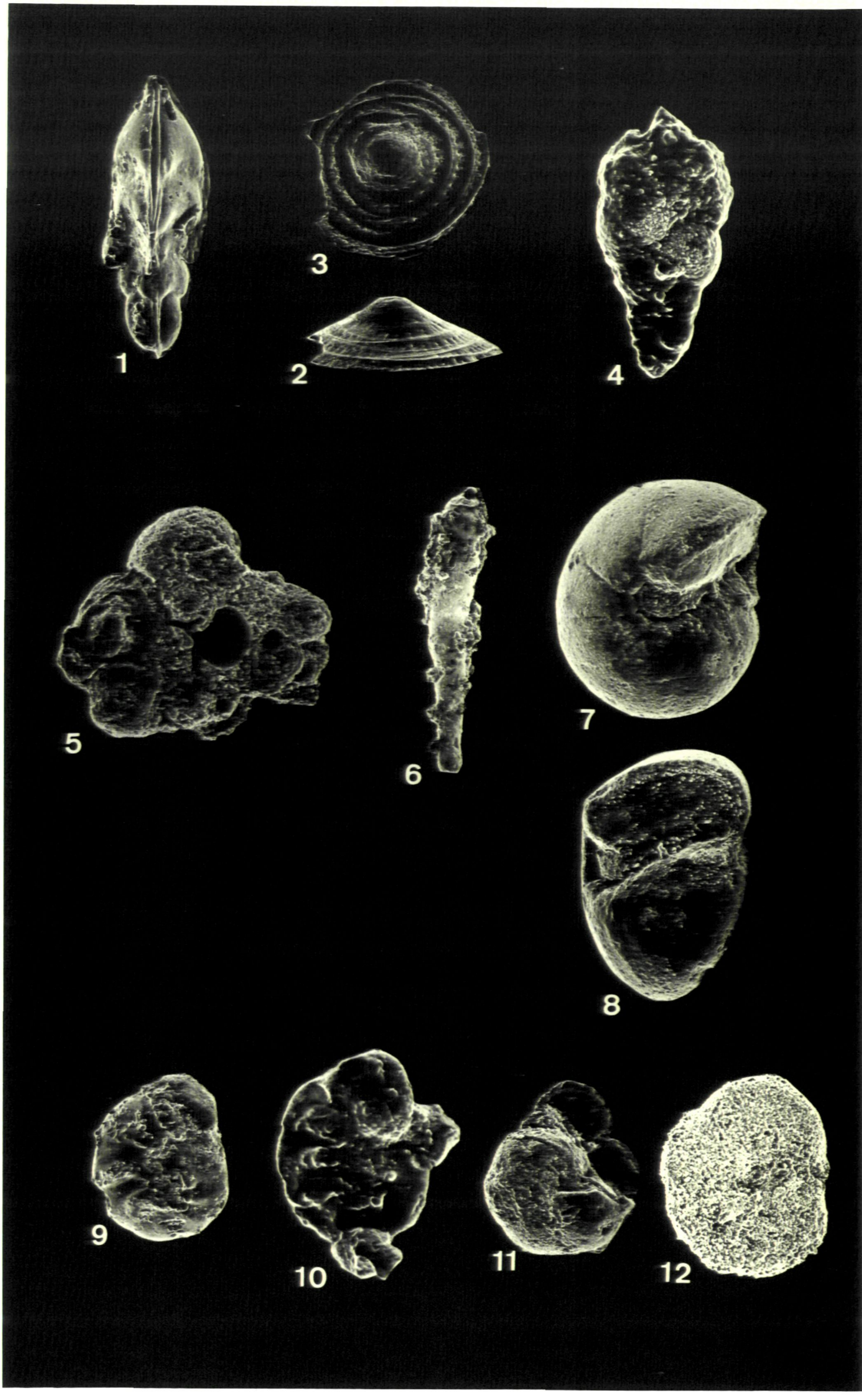
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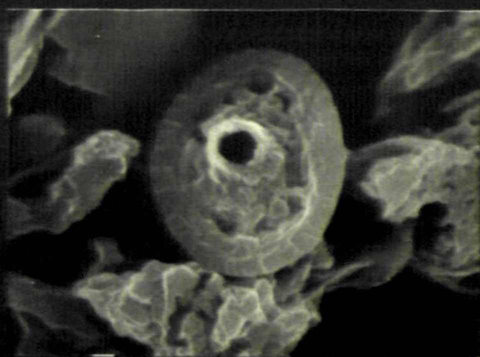
PLATE 4

1. *Parhabdolithus asper* (X 4800). Sample C4/5, Branscombe. Ryazanian - Cenomanian.
2. *Zygodiscus erectus* (X 9600). Sample C4/5, Branscombe. Sinemurian - Cenomanian.
3. *Zygodiscus* sp. (indet.) (X 9600). Sample C4/5, Branscombe.
4. *Ellipsagelosphaera* sp. (indet.) (X 4800). Sample C4/5, Branscombe.
5. *Zygodiscus compactus* (X 4800). Sample B8/2, Branscombe. Barremian - Campanian.
6. *Parhabdolithus achylostaurion*. (X 5000). Sample B8/2, Branscombe. Late Aptian - Turonian.



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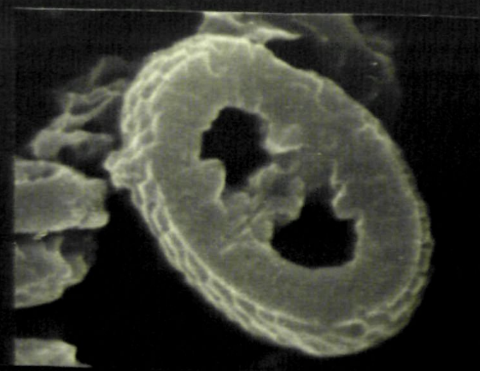

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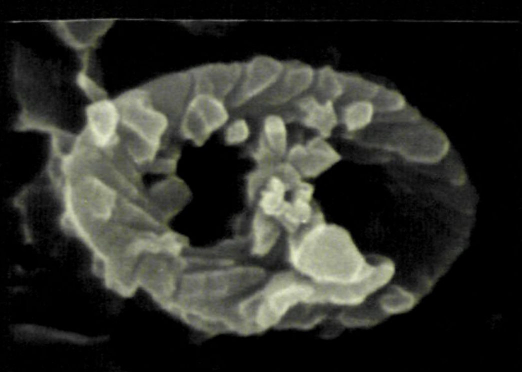

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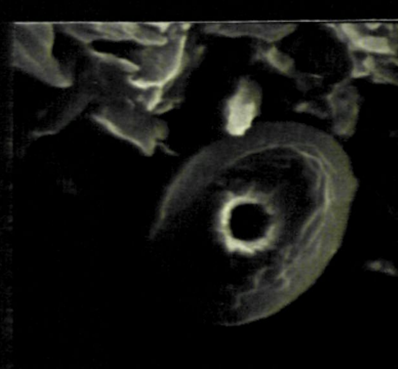

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APPENDIX

Short Communication

A Note on the Occurrence of *Orbitolina (Orbitolina) sefini* Henson, 1948 (Foraminiferida) in the Upper Greensand of S. W. England

1. Introduction

The discovery of fossiliferous Upper Greensand at Wolborough (Figure 1) during the I.G.S. Exeter University re-mapping (1966–69) of the 1:50 000 Newton Abbot (339) Geological Map was fully documented by Carter and Hart (1977). In 1974 a trench [GR.855700] was dug 400 m S of Wolborough Church and exposed a succession comprising 8.5 m of gravels, glauconitic clayey sands and glauconitic quartziferous limestones resting on Devonian shales (Manley and Weaver, 1979; Selwood *et al.*, 1984, p.122 and fig. 21). The succession, reproduced in Figure 1, contains a fossiliferous limestone bed from which abundant orbitolines have been recovered. Similar fossiliferous greensands including a bed of calcareous sandstone with sparse orbitolines were uncovered during the construction of the A.380 Newton Abbot By Pass [GR.877739], preserved in a solution hollow in Devonian limestones (Selwood *et al.*, ibid., p.121). Rare orbitolines were also found in patchily cemented shelly lenses ('*Rutitrigonia* Bed') at a presumed equivalent level near the base of the Greensand succession at Babcombe Copse [GR.869766] (Selwood *et al.*, ibid., fig. 21). Hamblin and Wood (1976) assigned all these orbitoline-bearing greensands to the Woodlands Sands Member of the Haldon Hills Upper Greensand succession (Haldon Sands Formation), and placed them in the Upper Albian (*Stoliczkaia dispar* Zone) on the basis of two ammonites which probably had their provenance in this member. The Late Albian age of the Woodlands Sands is substantiated by the discovery of an indigenous *dispar* Zone ammonite assemblage in the east Devon equivalent of the overlying Ashcombe Gravels Member. In addition to these proven Upper Albian occurrences, orbitolines are common at Babcombe Copse and Smallacombe Goyle [GR.922768] in cherts of the Cullum Sands with Cherts Member, a unit which is partially or wholly of Cenomanian age.

A recent revision of the orbitolines belonging to the *concava–sefini* group (Schroeder, 1985 *a, b*) has allowed a further, more detailed, consideration of the orbitolines from the greensands of South Devon.

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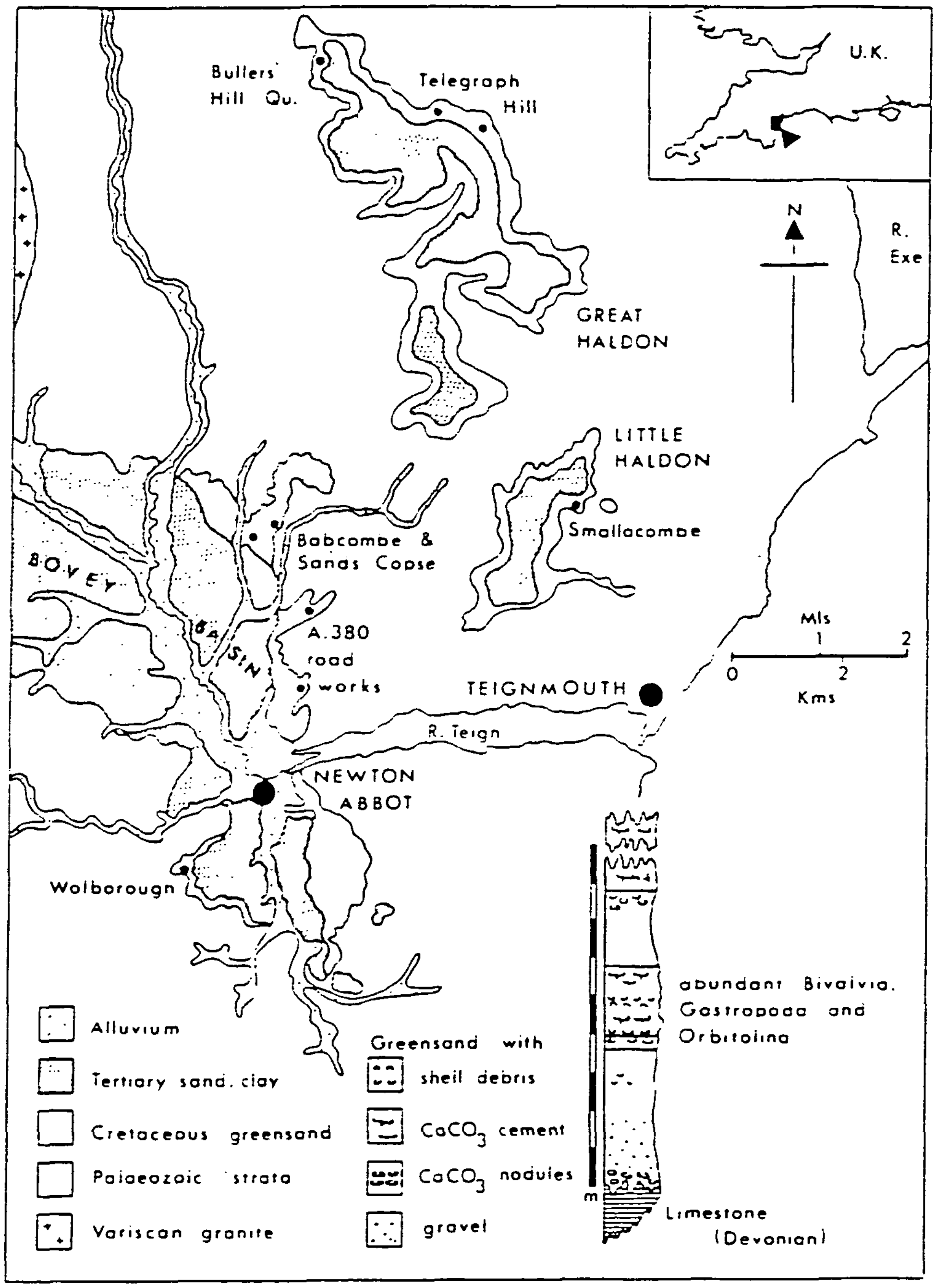


Figure 1. Locality map of the Haldon Hills with details of the Upper Greensand succession at Wolborough. Small black circles indicate past and present greensand exposures.

2. Systematic palaeontology

Family: Orbitolinidae Martin, 1889
Genus: *Orbitolina* d'Orbigny, 1850
Subgenus: *Orbitolina* d'Orbigny, 1850
Orbitolina (Orbitolina) sefini Henson, 1948

1948 *Orbitolina concava* (Lamarck) var. *sefini* Henson, 64–65, pl.5, figs 1–2 (*non* figs 3–4 (= *Orbitolina* (*Conicorbitolina*) *conica*)).
1977 *Orbitolina (Orbitolina) concava* (Lamarck): Rey, Bilotte and Peybernès, 378, pl.2, figs 11–12.
1978 *Orbitolina* (*Orbitolina*) cf. *concava qatarica* Berthou and Schroeder, p.76, pl.4, figs 8–12.
1985b *Orbitolina* (*Orbitolina*) *sefini* Henson: Schroeder, 66–67, pl.30, figs 1–8.

This species has recently been revised by Schroeder (1985 *b*), using the type material of Henson, which is stored in the British Museum (Natural History), London.

The *Orbitolina* fauna from the glauconitic, calcarous, sandstones of the Woodlands Sands Member is composed nearly exclusively of megalospheric specimens. Only one section can be attributed to the microspheric generation.

The *megalospheric forms* (Figure 2(a)–(d) and (f)–(g)) have a diameter of 4–5 mm and a height of 1–1.3 mm. The dorsal surface of the slightly conical specimens is generally more or less convex or sometimes nearly planar; the ventral surface of young forms is also convex (Figure 2(b)), but adult specimens show a clear central depression on this side (Figure 2(a), (c)).

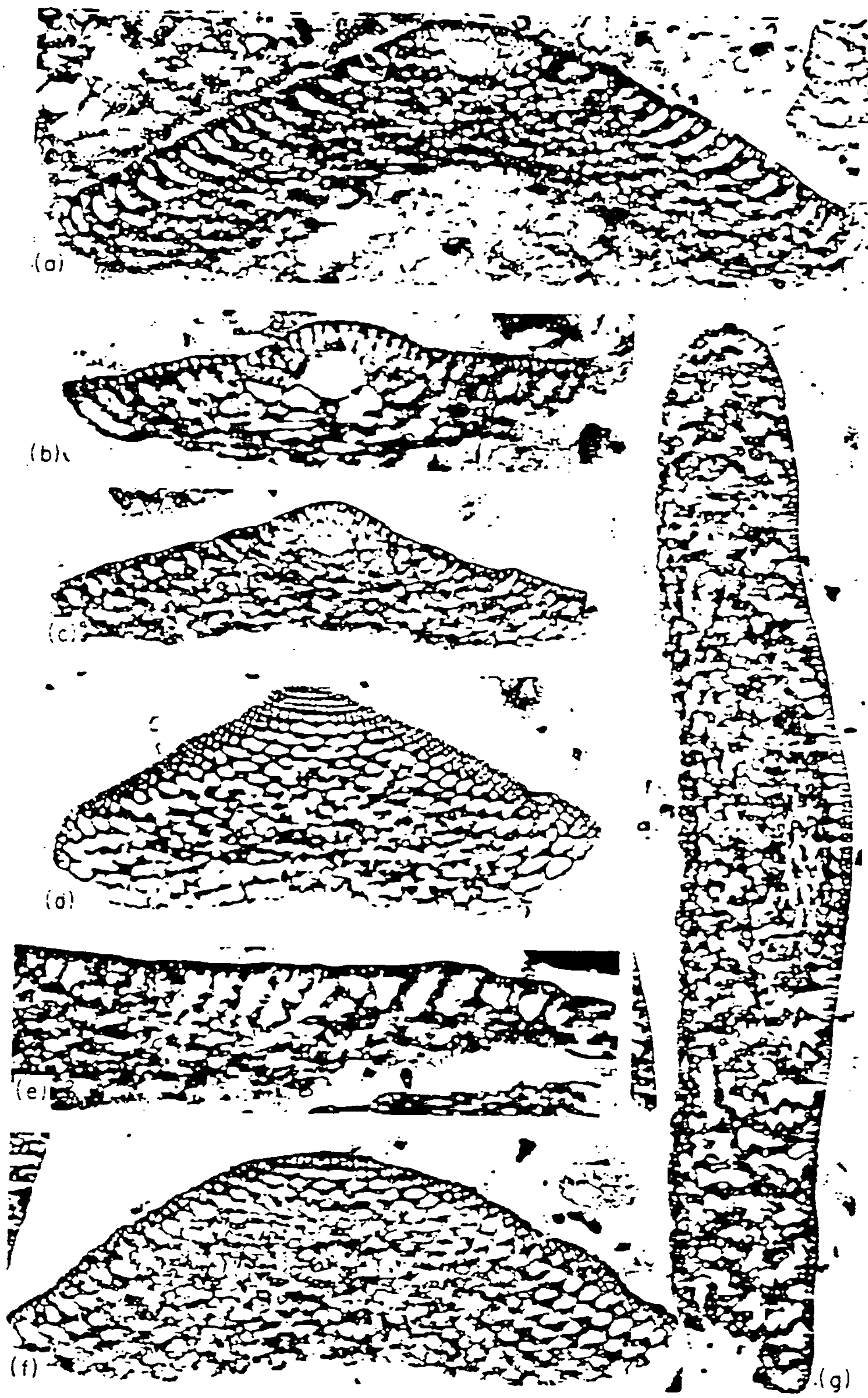
The *megalospheric embryonic apparatus* (diameter 0.6–0.72 mm), situated at the apex of the test (Figure 2(a)–(c)), consists of an ellipsoidal protoconch (diameter 0.2–0.24 mm), a well-developed and subdivided deuteroconch and a considerably thinner but relatively large subembryonic zone.

The following *post-embryonic chamber layers*, averaging 14–15 per last millimetre of the test surface, are first of all disc-shaped; later they become annular (Figure 2(a),(c)).

Within the *marginal zone* of the chamber layers, the outer part of each marginal chamberlet is subdivided by 3–4 vertical and 2–3 horizontal subepidermal plates forming a relatively regular network immediately below the test surface (Figure 2(d), (g)).

The well-developed outer part of the central zone (= radial zone) is clearly visible in axial sections (Figure 2(a)). The shape of the radial partitions and chamber passages, alternating in position from one chamber layer to the next, is triangular in tangential sections (Figure 2(d), (f)). The inner part of the central zone contains so much foreign material (detrital quartz, calcareous grains, microscopic fossil debris) that its structures cannot be determined.

The only specimen of the *microspheric generation* seen in thin section (Figure 2(e)) is represented by a subaxial section. The test is disc-shaped (height 0.6 mm), showing a slightly convex dorsal surface and a nearly plane base. Externally, this specimen is distinguished from the megalospheric forms by its large diameter of more than 8 mm. The increased size of this


(a)
(b)
(c)
(d)
(e)
(f)
(g)

generation is the result of the rapid increase in thickness of the chamber layers, averaging 6 in the last millimetre of the test. The presence of 5–7 horizontal sub-epidermal plates per marginal chamber of the tardontogenetic stage (Figure 2(e)) indicates a well-developed alveolar layer.

3. Remarks

Schroeder (1985 *a*, p. 65) has indicated that the majority of the orbitolines described from the late Albian and early Cenomanian of Western Europe, described (or cited) as *Orbitolina concava* (Lamarck), belong in *O.* (*O.*) *sefini* Henson. A re-assessment of the type material of "*Orbitolina concava* (Lamark) var. *sefini*" has shown that the "ideotypes" of this taxon (Henson, 1948, pl.5, figs 3–4) from Israel belong in *Orbitolina* (*Conicorbitolina*) *conica* (d'Archiac, 1837); see Schroeder (1962). The syntypes (Henson, 1948, pl.5, figs 1–2) however, from Sefin Dagh (Iraq) are microspheric forms which are found in the same thin sections (B.M.N.H. slides P35902 and P35903) together with numerous megalospheric specimens belonging to the subgenus *Orbitolina* (*Orbitolina*). These other individuals were never described or figured.

The original material ("syntypes") of *O.* (*O.*) *sefini* is, therefore, represented by two generations, from which the megalospheric specimens are characterised by exclusively triangular cross-sections of the radial partitions and the chamber passages within the radial zone of the chamber layers. The specimens from Devon, figured here, show absolutely identical structures. In the A-forms of *O.* (*O.*) *concava* (Lamarck) the chamber passages show sub-rectangular cross-sections and are separated by small, radial partitions (Schroeder, 1962, p.187; 1975, p.119, text-fig. 2C; 1985a, p.65, pl.29, figs 7–8).

4. Stratigraphic implications

Henson (1948, p.65) first described this species from "Cenomanian limestone with small oysters suggesting *Exogyra flabellata* (Goldfuss)". In Northern Spain *O.* (*O.*) *sefini* ranges from late Albian to early Cenomanian (Schroeder, 1985 b, p.67). It occurs with *Planomalina buxtorfi* (Gandolfi) in the "Vraconian" of the Sierra de Aulet (Hofker, 1963, p.194; Schroeder, 1973, p.147; Peybernès, 1976, p.362). It is also recorded with *Stoliczkaia* aff. *dispar* and *S.* aff. *rhamnota* in the "Vraconian" of Astobiza (Rat, 1958, p.322). It occurs together with *O.* (*Mesorbitolina*) *aperta* (Erman) and *Graysonites* sp. in the earliest Cenomanian of Nava de Ordunte (Schroeder,

Figure 2. *Orbitolina* (*Orbitolina*) *sefini* Henson, 1948. All specimens from the glauconitic calcareous sandstones of Wolborough, South Devon: (a) axial section of a megalospheric form 170 5 (× 30); (b) axial section of a young megalospheric form 170 1 (× 47.5); (c) axial section of a megalospheric form 170 7 (× 30); (d) oblique vertical section of a megalospheric form 170 6 (× 30); (e) vertical section through the last chambers of a microspheric form 170.5 (× 30); (f) oblique vertical section of a megalospheric form 170.2 (× 30); (g) oblique horizontal section of a megalospheric form 170 7 (× 30).

1962, p.172) and in the early Cenomanian of Baranda with *Mantelliceras* ex. gr. *cantianum* Spath (Schroeder, 1962, p.172).

In South Devon Hamblin and Wood (1976) equated the Woodlands Sands Member with the Chert Beds of the Devon Coast, with the inevitable conclusion that they were referable to the *S. dispar* Zone. In the same paper Hamblin and Wood placed the Cullum Sands in the Cenomanian and cherts from this stratigraphic unit also contain orbitolines. Unfortunately the preservation of these individuals is so poor that accurate determination is impossible.

Carter and Hart (1977) came to a different conclusion on the basis of a rather primitive analysis of the *Orbitolina* fauna and the other associated microfauna. Hart, Manley and Weaver (1979) extended this analysis of the *Orbitolina* fauna and by comparison with other faunas in N.W. Europe suggested that the orbitolines from the Woodlands Sands Member could be either latest Albian or earliest Cenomanian in age. However if the Woodlands Sands (with *O.* (*O.*) *sefini*) are latest Albian and the Cullum Cherts could be confirmed as earliest Cenomanian this would confirm the range of *O.* (*O.*) *sefini* in S.W. England as the same as that cited for Spain.

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6

The cherts of the Upper Greensand (Cretaceous) of south-east Devon

C.L. WILLIAMS

An aerial view of south-east Devon reveals a pattern of wooded hills standing out from rolling pastureland with incising river valleys. The coast displays high sea cliffs of chalk in the east gradually flattening westwards to cliffs of Upper Greensand with characteristic, highly vegetated, slumps and slips. Further west are seen the coastal cliffs of red Permo–Triassic muds and sands and the large estuary of the river Exe.

Introduction

During the mid-Cretaceous a shallow sea covered the south-east Devon area at least as far west as the Haldon Hills (Fig.6.1). This lime-rich, marine, environment at first deposited the Upper Greensand and later the Chalk. Subsequent erosion in the west removed most of these deposits, decalcifying the Chalk and leaving local deposits of loose flint on top of the silicified 'Blackdown Facies' of the Upper Greensand. Further east thicker deposits have not yet eroded sufficiently to completely remove the Chalk from the Upper Greensand which remains in its normal calcareous facies, consisting of calc-arenites with cherts, limestones and silts.

The material examined was taken from two localities within the 'Normal Facies' at Branscombe and Whitecliff, just to the west of Seaton (Fig.6.2). The Cretaceous sediments rest unconformably on red mudstones of Triassic age, although this lower boundary is rarely seen, and are superseded unconformably by Cenomanian limestones. Traditionally the Upper Greensand in this area is divided into the (basal) Foxmould Sands, the Chert Beds and the Top Sandstones (Jukes-Browne & Hill, 1900) and this nomenclature has been retained here, although it is misleading, and under revision. The Upper Greensand is generally regarded as being of Albian age although it may, in part, be Cenomanian.

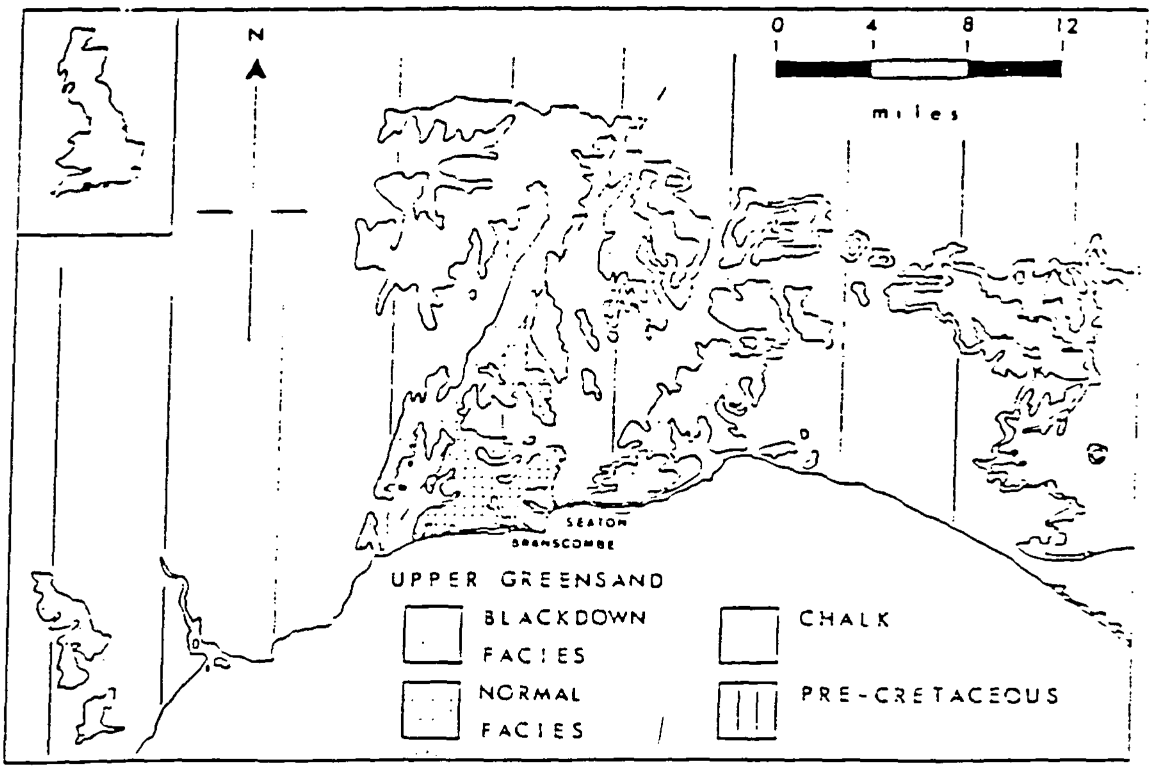

Fig.6.1. Geological map of south-east Devon.

The Foxmould Sands consist of some 25 m of glauconite sands, calc-arenites and silts with hard limestone bands. The bulk of the Foxmould is made up of highly bioturbated mud and silt-rich sands and calc-arenites, which locally contain abundant *Exogyra obliquata* (Pulteney) and the serpulid *Rotularia convava* (J. Sowerby). These muddy sediments also contain Ostracoda and benthonic Foraminifera, together with terrestrial plant debris. Mud-free bands of limestone and calc-arenite occur frequently and often exhibit sedimentary structures such as parallel laminae and wave rippled tops that indicate that the deposits were laid down at water depths between normal wave base and storm wave base. A hiatus occurs at the top of the Foxmould with a shell rich horizon.

The Chert Beds consist of about 20 m of mud-free calc-arenites. Sedimentary structures are rare in this unit and bioturbation is difficult to see, with the exception of large burrows, probably formed by decapod crustaceans. This unit is made up of calc-arenite with shell fragments and relatively little quartz. Occasional storm deposits show erosive bases and some cross-bedding, and these usually have a higher quartz content. Nodular horizons of partially chertified calc-arenites are distinct and irregular courses of glauconite 'stringers' are locally common in the upper part of the Chert Beds and in the Top Sandstone. The cherts occur in various morphologies, from irregular nodules to laterally impersistent horizons which vary in thickness (up to about 30 cm). The Top Sandstone consists of about 2 m of calc-arenite, often with very little quartz, and should be regarded as a loosely cemented limestone.

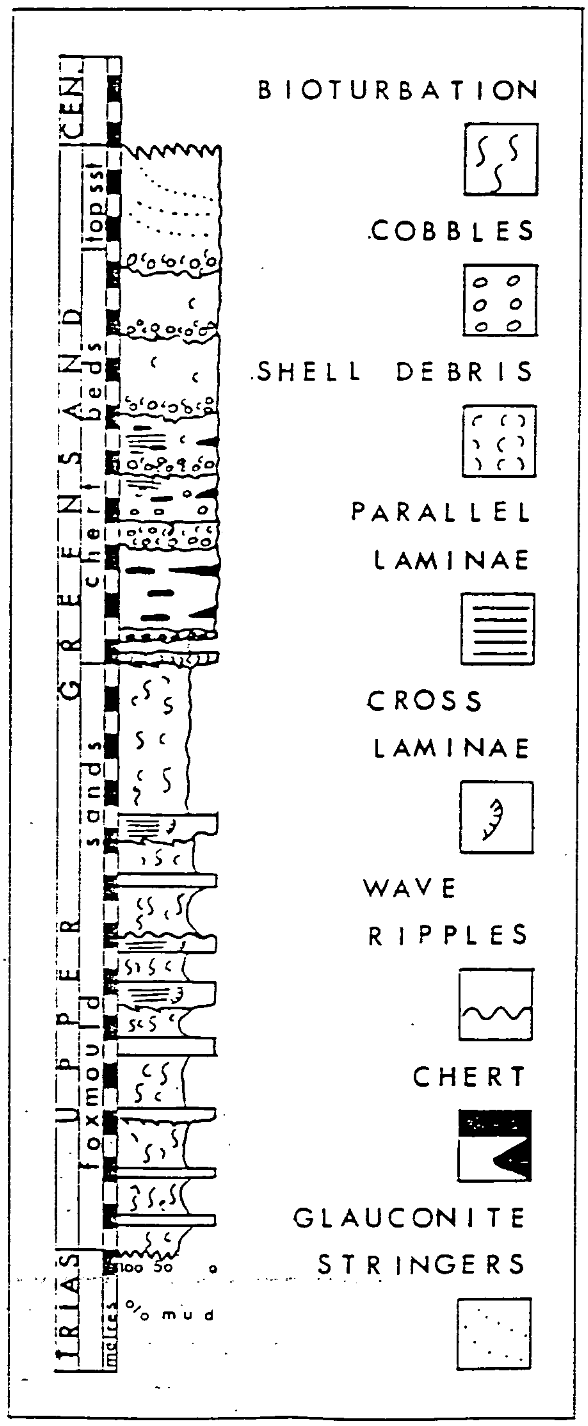

Fig.6.2. Lithological succession of the Upper Greensand in south-east Devon.

Sedimentary structures within the chert

The medium grained calc-arenites, which make up the bulk of the Chert Beds, exhibit few sedimentary structures. Occasional coarse grained storm deposits, about 1 m thick, display cross-bedding, wave reworked tops and erosive bases. These deposits make up only a small percentage of the sediments of the Chert Beds and elucidation of the depositional environment for the majority of the unit is difficult. In some instances, however, this problem is partially solved by the preservation of sedimentary structures within chert nodules and bands.

The percentage of quartz detritals varies widely in the calc-arenites of the Chert Beds. Some cherts contain large numbers of quartz detritals, often unaltered in appearance and with sedimentary structures remaining intact, thus reflecting the nature of their deposition. These well-preserved structures suggest a secondary and replacive origin for the chert.

A block of chert which is sectioned and polished appears translucent, allowing a three dimensional view of sedimentary structures when their form is picked out by quartz detritals. An example of the usefulness of this preservation is shown in Fig.6.3, which illustrates a polished block of chert, taken from Seaton Hole. The cross-bedding is picked out by the quartz detritals and silicified shell fragments. In this instance the cross-sets are bimodal and suggest an environment influenced by tidal currents. A detailed examination (Fig.6.4) reveals the presence of burrows which disturb the laminae. In this sample U-shaped burrows predominate in the upper set, suggesting that the organism was able to cope with the sediment deposition rate by altering the depth of its burrow.

The preservation of these sedimentary structures, in contrast with the surrounding calc-arenites, suggests either a very rapid deposition rate or a very early chert forming diagenetic event. A deposition rate sufficient to preclude the destruction of sedimentary structures, by placing them

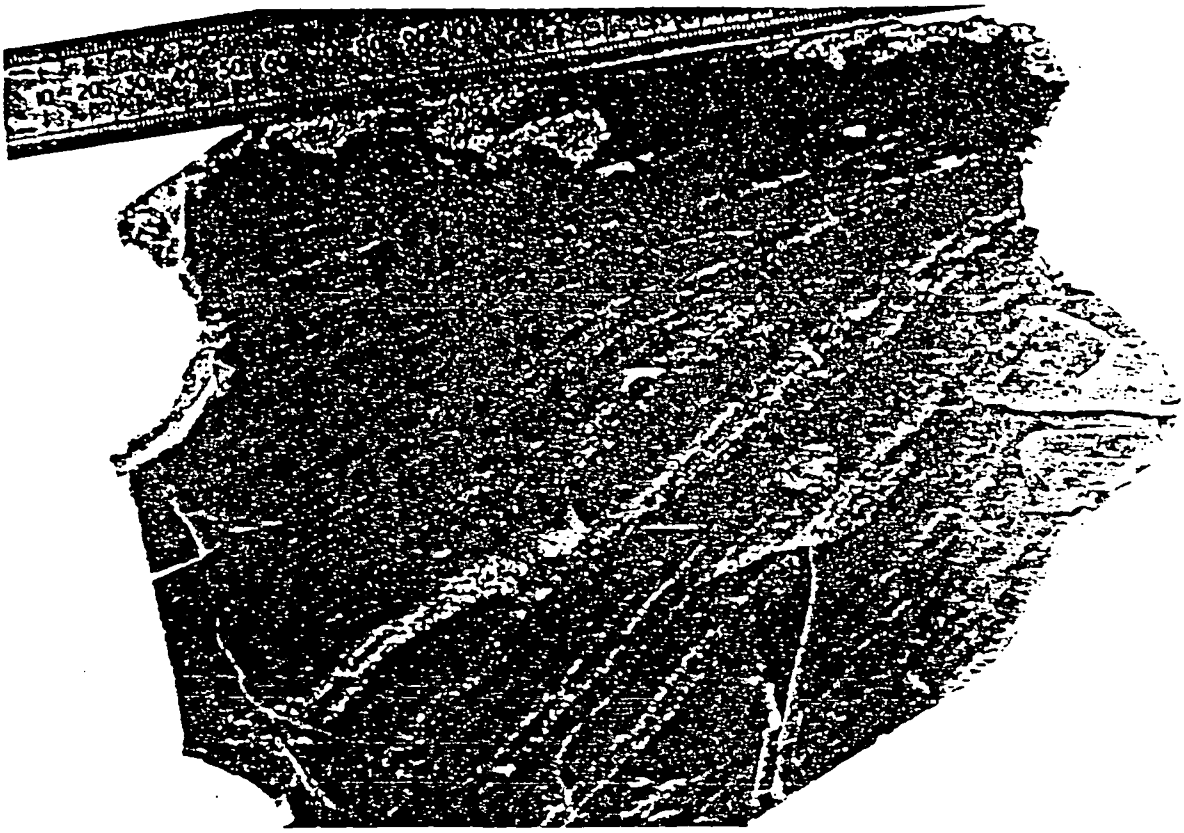

Fig.6.3. A polished section of chert showing the preservation of bimodal cross-sets.

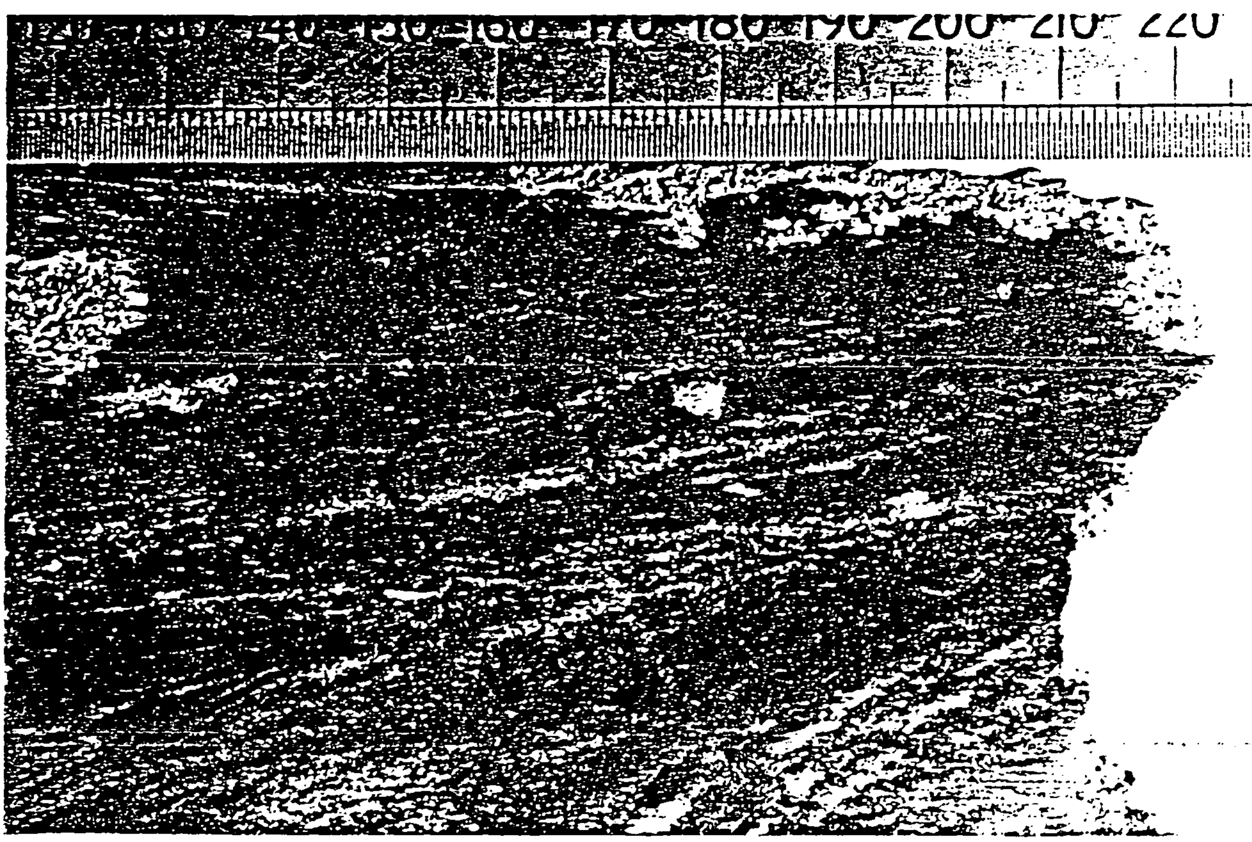

Fig.6.4. Detail of cross-sets showing U-shaped burrows.

too deep, too quickly for infaunal organisms to reach would seem to be contra-indicated by the presence of U-shaped burrows. The organism forming these structures would have maintained its burrow so that the top of the 'U' was open to the water/sediment interface.

Secondary silica in the Foxmould Sands

In the Foxmould Sands secondary silica is almost entirely confined to the relatively mud-free, storm sorted calc-arenite horizons. These storm deposits consist of medium grained quartz detritals and organically derived carbonate grains. They display a larger grain size than the silt and mud deposits that make up the bulk of the Foxmould and lack the extensive bioturbation which characterises the finer deposits.

Bivalve shells and fragments are common as are the coiled calcareous tubes of the serpulid *Rotularia concava*. The latter are abundant in some horizons and are often welded together to form discontinuous limestone bands. Voids tend to occur within these serpulids and it is these spaces which are frequently infilled with secondary silica (Fig.6.5).

Chalcedony, a cryptocrystalline, fibrous type of silica, is the form which the secondary void-fill silica takes and very little evidence is seen of microquartz replacement of calcite. This passive filling of voids appears to be the limit of secondary silica development and no true cherts are found in the Foxmould Sands. That the secondary silica occurs within the mud-free storm deposits is probably a reflection of the increased permeability, allowing easier movement of silica rich interstitial fluids.

Secondary silica in the Chert Beds

Sections of cherts typically display a siliceous envelope reaching into the surrounding calc-arenite (Fig.6.6). Moving outwards from the chert this envelope has a progressively lower silica content. The thickness of this zone varies considerably but is generally measured in centimetres. If the zone around the cherts represents an area adjacent to the maximum development of secondary silica, in which silicification becomes progressively reduced, then an examination of the incidence of secondary silica inwards from the edge of the envelope should reflect the replacive growth of chert within the calc-arenite. This process did not always proceed to completion and abundant nodules of partially silicified calc–arenite are found in the Chert Beds.

A series of thin sections taken across the transition zone reveals the nature of the silica replacement of the calc-arenite and will now be described. Despite their name, the Chert Beds consist largely of calc-arenites of varying grain size, which reflect the different energy levels obtaining during deposition. The same mineral species occur throughout the calc–arenites but they differ in size, habit and concentration. Quartz detritals may be present in a

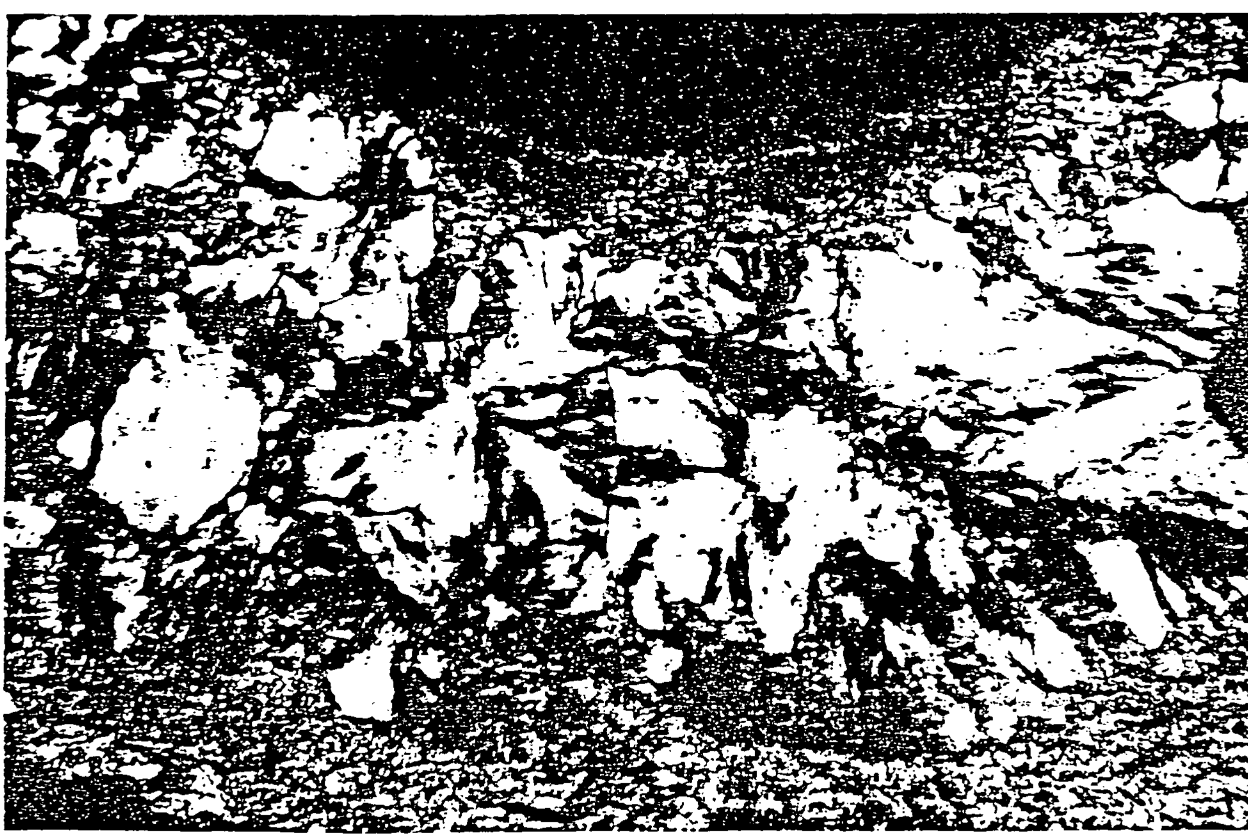

Fig.6.5. Chalcedonic infill of voids within serpulid worm tubes, Foxmould Sands (fov = 1.2 mm).

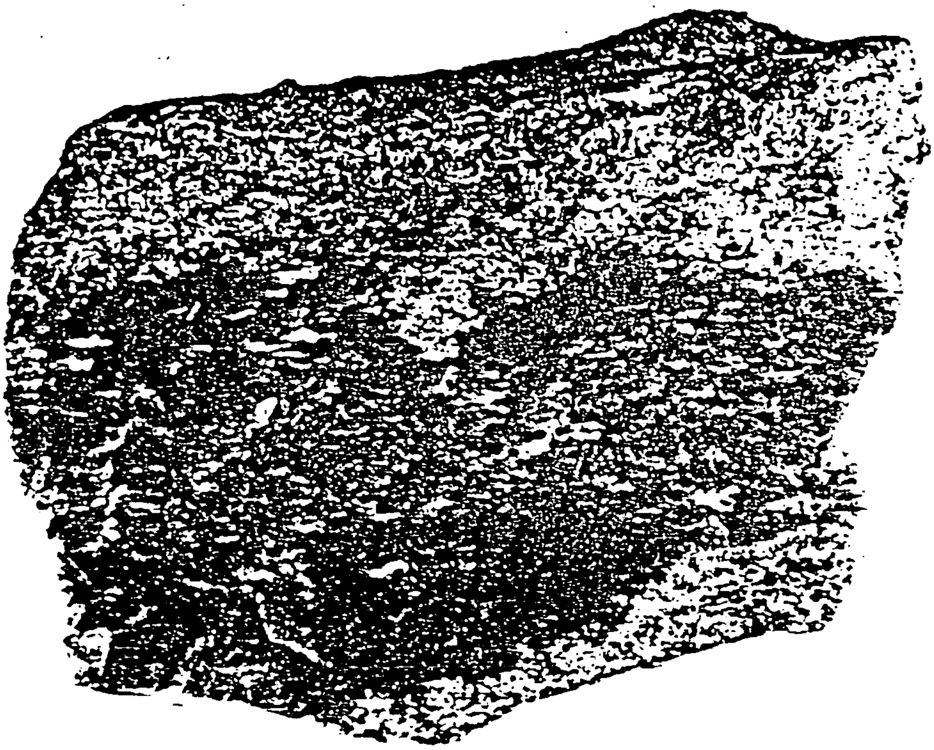

Fig.6.6. Section of chert showing siliceous envelope.

sample in varying percentages, grain sizes and morphologies. Grain sizes vary from fine to very coarse, the latter normally being well rounded and the former sub-angular. The percentage of quartz present varies from 70% to as little as 5%, when the rock is technically a loosely cemented limestone.

Calcite is the other major component and varies from 30% to 95% of the rock. The calcite is made up of organically derived fragments, some of which are recognisable but most of which are comminuted. The organic debris consists of fragments of molluscs, echinoids, Bryozoa and sponges, together with rare Foraminifera.

The only accessory mineral of note is glauconite and this normally makes up less than 10% of the rock. A typical thin section taken from the calc-arenite within the Chert Beds but not directly associated with chert is shown in Fig.6.7. Voids occur within the rock especially in the proximity of calcite organic fragments. As the chert is approached these are silica infilled. The silica is in the form of radiating chalcedony fibres similar to those infilling voids in the Foxmould Sands. This passive silica infill of voids is here augmented by the replacement of calcite by microquartz around the edges of the void. This replacement of whole calcite grains with microquartz grains becomes increasingly common near the edge of the chert. Some grains are observed to be completely unaltered, while others are completely replaced by microquartz. In addition, the amount of chalcedony increases suggesting either a higher incidence of primary voids or the complete dissolution of some calcite grains (Fig.6.8). Eventually, glauconite grains are seen to have undergone the same process.

Sections taken on the edge of the chert exhibit secondary quartz crystals larger than the replacive microquartz. These crystals form an envelope around quartz detritals and replaced calcite and glauconite grains (Fig.6.9). Within the chert, thin sections reveal microquartz grains and occasional quartz detritals, often enveloped in larger secondary quartz crystals. The whole is welded together by chalcedonic quartz (Fig.6.10).

Thus the chert is an imperfect ghost of the original fabric of the calc-arenite. Microquartz grains represent former calcite and glauconite grains, while larger secondary quartz crystals occur on the periphery of these microquartz grains and outline original quartz detritals. The voids, both original and those left after the dissolution of carbonate material, are filled with chalcedony.

Cherts vary considerably in their quartz detrital content, some having none, some showing partially dissolved grains and others being packed with quartz grains. This variation is probably a reflection of the varied quartz detrital content found within the calc-arenites of the Chert Beds.

Conclusions

It has been observed that calc-arenites within the Chert Beds become progressively more siliceous as they approach a chert band. It is suggested that this increasing silicification may reflect the sequence of events leading to the formation

Fig.6.7. Calc-arencte of the Chert Beds showing large rounded quartz grains, calcite and voids (fov = 3.1 mm).

Fig.6.8. Thin section from the edge of the siliceous envelope showing calcite (light), quartz detritals (clear), microquartz grains (speckled) and fibrous chalcedony (fov = 1.2 mm).

Fig.6.9. Detail from Fig.6.8 showing an envelope of secondary quartz around quartz detritals (fov = 0.6 mm).

Fig.6.10. Thin section taken from within the chert showing the ghost fabric of the calc-arenite; microquartz grains are picked out by the secondary quartz rims and chalcedony fills all the voids (fov = 0.6 mm).

of chert. The first appearance of secondary silica is in the form of chalcedonic infill of voids, particularly within calcite shell fragments, which in turn act as nuclei for the microquartz replacement of calcite around the edges of the voids. The progressive replacement of calcite by microquartz continues simultaneously with the replacement of glauconite and the deposition of secondary quartz crystals around quartz detritals and replaced calcite. Chalcedonic infill of voids continues throughout and the chert shows an imperfect ghost of the former calc-arenite fabric. The original fabric is picked out by the secondary quartz growth around the edges of quartz detritals and microquartz grains.

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Foraminifera and correlation of the Upper Greensand, Branscombe, south-east Devon

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The problems of dating and correlation of the Upper Greensand in south-west England have been discussed by Hamblin and Wood (1976), Selwood *et al.* (1984), Hart (1971, 1973), Carter and Hart (1977), Hart *et al.* (1979) and Schroeder *et al.* (1986).

Hamblin and Wood (1976) erected a formal lithostratigraphy for the Upper Greensand of the Haldon Hills and subsequently attempted a series of lithostratigraphic correlations with the east Devon coast (Selwood *et al.* 1984), (Fig. 1). They concluded that the basal Telegraph Hill Sands Member at Haldon was the equivalent of the Foxmould Sands of south-east Devon and was thought to be Albian (*varicosum* or *auritus* subzone) in age. The Woodlands Sands Member was correlated with the greater part of the Chert Beds in east Devon and the Wolborough Greensand. These units were also considered to be Albian in age. The Ashcombe Gravels Member and the Top Sandstones of the Upper Greensand in SE Devon were thought to be late Albian (*dispar* Zone) in age on the basis of a lithologic correlation with Shapwick Grange Quarry near Lyme Regis. Finally the topmost lithostratigraphic division of the Haldon Hills, the Cullum Sands-with-Cherts Member, was correlated with either the non-sequence between the Top Sandstones and Bed A1 or with some other part of the Cenomanian Limestone. These units were considered to be early Cenomanian in age.

Hart (1971, 1973) suggested that the species *Orbitolina concava* (Lamarck) was of early Cenomanian age and that this inferred that much of the Upper Greensand Chert Beds of SW England in which this species occurred was also of this age. Carter and Hart (1977) concluded that the populations of *O. lenticularis* found in SW England belonged to the same "faunal community" as those found in the type Lower Cenomanian and that this indicated an early Cenomanian (*Mantelliceras mantelli* Zone) age for the Upper Greensand in which they occurred. Hart, Manley and Weaver (1979) reported a biometric analysis of the orbitoline fauna at Wolborough together with material from the type Lower Cenomanian at Ballon, Albian material from Portugal and cherts found at Bullers Hill Quarry. They concluded that the Wolborough fauna indicated a Late Albian - Early Cenomanian age and that the fauna from Bullers Hill Quarry suggested an early Cenomanian age.

Schroeder *et al.* (1986) presented the revised nomenclature for the orbitolines found in SW England. Most of these orbitolines had been attributed in the past to the sub-species *Orbitolina (Orbitolina) concava qatarica* but were now considered to belong to the species *Orbitolina (Orbitolina)* sefini Henson 1948, with a stratigraphic range from latest Albian to earliest Cenomanian. Schroeder *et al.* were able to identify the orbitolines from Wolborough as belonging to the species *O. (O.) sefini* but because

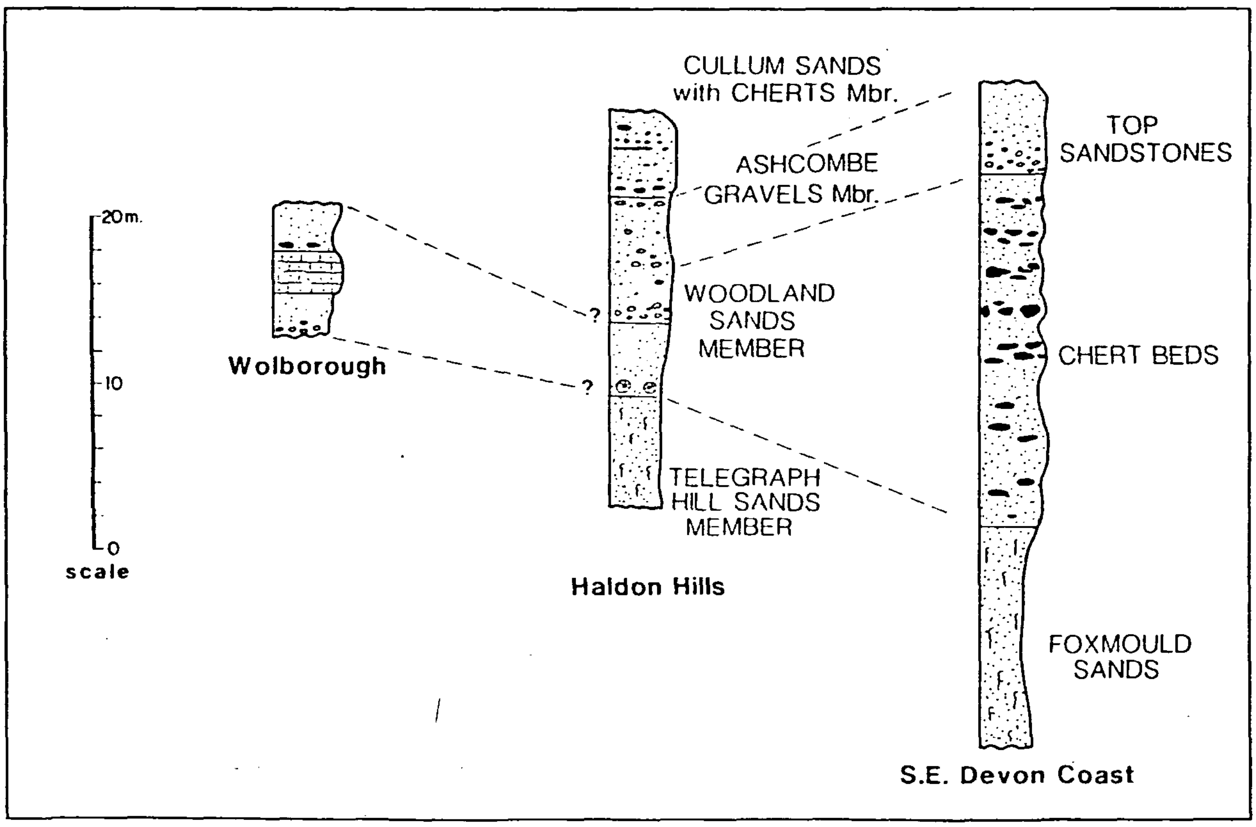

Figure 1. Correlation between sections of the Upper Greensand in south and east Devon (after Hamblin and Wood 1976).

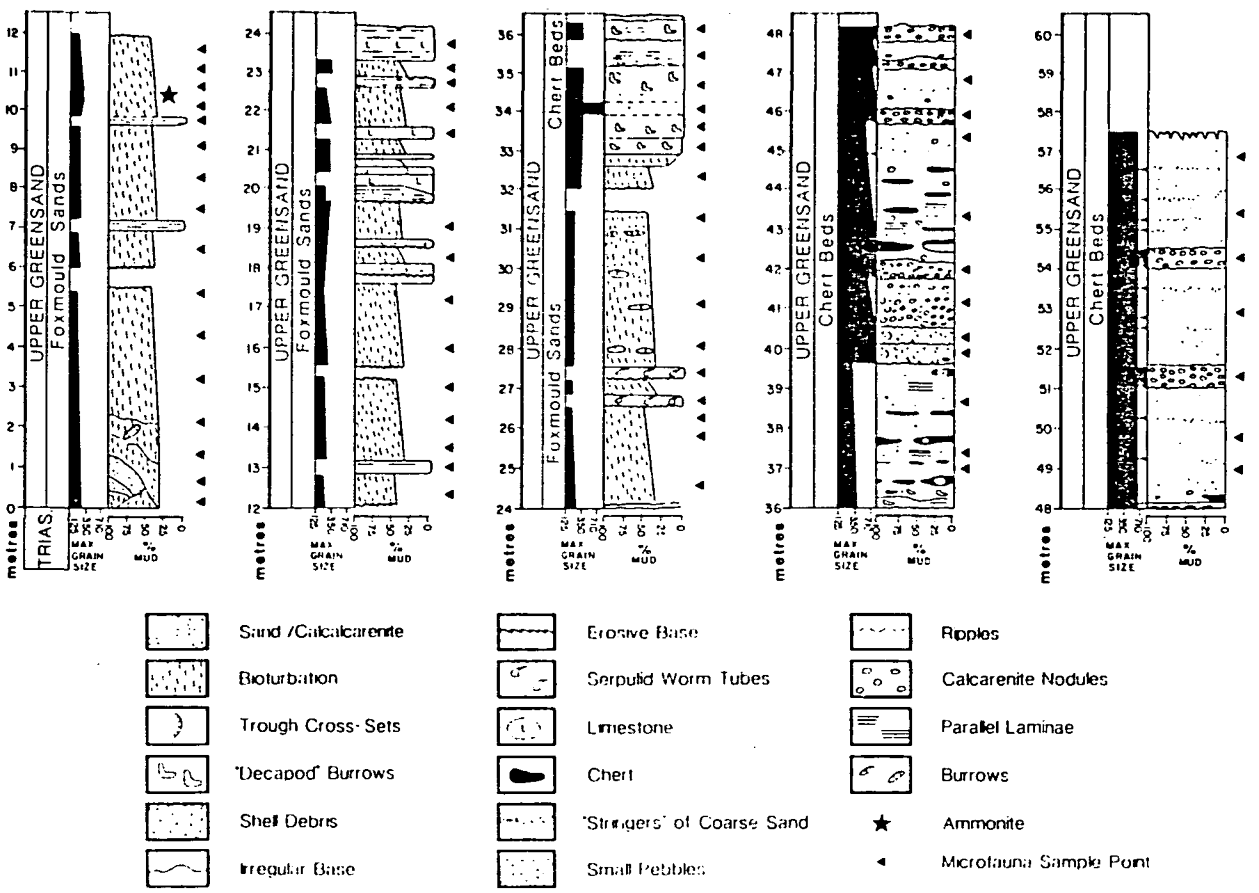

Figure 2. Sedimentary succession of the Upper Greensand at Branscombe.

of poor preservation it was not possible to confirm identifications at other localities in SW England.

In an attempt to clarify the problems of dating and correlation of the Upper Greensand in SW England the present work examined the microfauna to be found in the section at Branscombe, concentrating on the Foraminifera. The only new ammonite to be found was identified by Owen (pers comm.) as *Prohysteroceras (Goodhallites) delabechei* Spath which suggests a confirmation of *varicosum* subzone age for the lower part of the Foxmould Sands.

A sedimentary log of the section was drawn-up (Fig. 2) and samples taken to be processed for microfauna. Most of the samples were barren and those that did have a foraminiferal content had a poor fauna in terms of both numbers and species diversity. Preservation was generally poor and it was not always possible to identify below generic level. Those samples which did yield *Foraminifera* were almost entirely confined to the Foxmould Sands (Fig. 3). The stratigraphically useful species observed were: *Arenobulimina* cf *advena* - very latest Albian (*dispar* to Cenomanian), *Citharina d'orbignyi* - Lower to Middle Albian, *Heterohelix moremani* - *dispar* in southern England, *Praeglobotruncana delrioensis* - *dispar* to Mid-Cenomanian and *Gavelinella cenomanica* - *dispar* to Cenomanian. These suggest that the upper part of the Foxmould, at least, may be dispar zone in age. This casts some doubt on the lithostratigraphic correlation proposed by Hamblin and Wood (1976) between the Haldon Hills and SE Devon with regard to the lateral equivalents of the Foxmould Sands but does not, at present, enable any further correlation of the Chert Beds.

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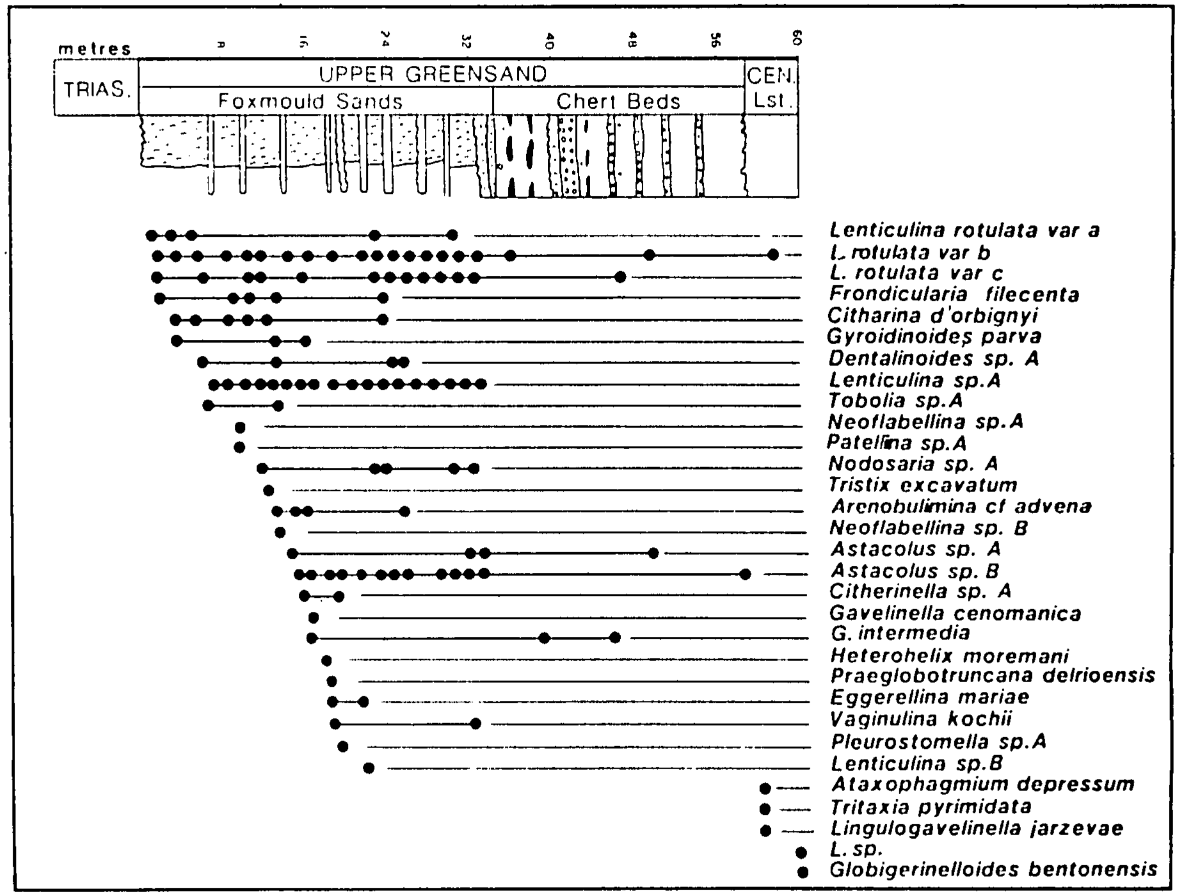

Figure 3. Occurrences of Foraminifera in the Upper Greensand, Branscombe, SE Devon.

Cretaceous Orbitolinidae (Foraminifera) from Onshore and Offshore South-West England

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ABSTRACT - The occurrence of orbitolinids in onshore and offshore South-West England is fully documented for the first time. Palorbitolina lenticularis is known from the Early Aptian - Late Barremian sediments of the offshore Fastnet Basin, and may also occur in the Aptian Farringdon Greensand. Late Albian Orbitolina sefini occurs in the Wolborough Limestone of Devon, whilst at Haldon, Devon, the orbitoline faunas are of Early Cenomanian age and referable to Orbitolina cf. concava. The orbitolinids from the Upper Greensand of the South-East Devon coast and the Fastnet Basin cannot be precisely identified, but belong to the Late Albian - Early Cenomanian O. sefini - O. concava plexus. Previous records of Orbitolina from the Upper Greensand at Wilmington are shown to be mistaken. These records are in fact referable to the sponge Porosphaera. The precise identification of some of the orbitolinids from South-West England supports the ages of the Wolborough Limestone and Haldon Sands suggested by Hamblin and Wood (1976). It is thought that orbitolinids migrated from Iberia to South-West England via the South-West Approaches during the Late Albian.

INTRODUCTION

The Orbitolinidae are a family of complex agglutinating larger Foraminifera, typical of the Tethyan Realm. Although known from Jurassic and Palaeogene sediments, they are most typical of, and most diverse, during Early and mid-Cretaceous times. The occurrence of orbitolinids in the Early and mid-Cretaceous sediments of onshore and offshore South-West England represents some of the the most northerly records of this foraminiferal group.

Orbitolinids are known from Early Cretaceous sediments of the Fastnet Basin in the offshore area (and more rarely the Lower Greensand of the onshore area) and from the mid-Cretaceous Upper Greensand and equivalents in both the onshore and offshore areas. In all cases the occurrence of orbitolinids provides valuable chronostratigraphic information, since orbitolinid species have relatively restricted stratigraphic ranges. This is important, since the formations in which the orbitolinids occur are usually poorly dated by macrofossils and other microfossil groups.

In this paper, previous and new records of Orbitolinidae from South-West England are redescribed in terms of the current taxonomic nomenclature. The local and regional stratigraphic significance of the faunas is discussed, as are the palaeobiogeographic implications.

PREVIOUS WORK

The position of the locations mentioned in the text below are shown on Figure 1.

The first records of orbitolinids from anywhere in the United Kingdom can be traced back to Godwin-Austen (1842) who stated "The Orbitolites [in this sense, a junior synonym of Orbitolina] which occur sparingly on Haldon, are exceedingly numerous in beds below Lindridge Hill...". Both these localities are in South-East Devon. Parker and Jones (1860) were aware of the occurrence of Orbitolina in the mid-Cretaceous sediments of Devon. They referred these occurrences to the species Orbitolina concava Lamarck. However, some of their records of Orbitolina (eg. from the chalk and chalk marl) are in fact misidentifications of the sponge Porosphaera as first pointed out by Hinde (1904). Sporadic records then occur in studies made during the later part of the nineteenth century and the first half of this century on the Upper Greensand of South-West England (e.g. Meyer, 1874; Jukes-Browne and Hill, 1900). More recently Hamblin and Wood (1976), Edwards (1979) and Selwood et al. (1984) have documented the occurrence of orbitolinids in the Upper Greensand equivalents of the Haldon Hills and Wolborough areas of Devon.

It was not until the work of Hart, published in a series of papers (Hart, 1971, 1973, 1982; Hart and Tarling, 1974; Carter and Hart; 1977; Hart et al., 1979a; Hart and Williams, 1990) that the orbitolinids of South-West England were considered in any detail, and their applications for stratigraphic correlation realised. Hart and his colleagues recorded Orbitolina from Wolborough, the Haldon Hills, the South-East Devon coast and Warminster. Their occurrence was used to suggest that the upper part of the Upper Greensand was Early Cenomanian in age. On the basis of a preliminary analysis of external dimensions of the orbitolinids from the Upper Greensand and its equivalents, Hart et al. (1979a) suggested that the Wolborough faunas were older than those of the Haldon Hills. The Wolborough faunas compared well with those from Late Albian sediments in Portugal, whilst the Haldon Hill faunas compared well with those from the Early Cenomanian of Ballon, France.

Schroeder et al. (1986) revised the taxonomy of the Wolborough orbitolinids. They were placed in the species Orbitolina sefini Henson on the basis of internal structures, notably size and shape of embryonic apparatus and chamberlets.

Williams _et_ _al_. (1988) discussed the occurrence of other benthonic foraminifera from the Upper Greensand of South-West England. This work indicated that the lower part of the Upper Greensand (that below the _Orbitolina_ occurrences) was Late Albian.

Hume (1897) recorded _Orbitolina_ from the Hibernian Greensand of Northern Ireland, and this interesting northerly record has been repeated by Hancock (1961) and Reid (1971). However, Carter and Hart (1977) and Reid (pers. comm., 1984) note that actual specimens to confirm this record are lacking. McGugan (1953) in his review of Upper Cretaceous foraminifera from Northern Ireland does not mention _Orbitolina_.

Ainsworth _et_ _al_. (1985, 1987) and Ainsworth and Horton (1986) documented the occurrence of orbitolinids from Wealden/Lower Greensand and Upper Greensand equivalents of the Fastnet Basin. Curry _et_ _al_. (1970) and Andreieff _et_ _al_. (1975) have recorded orbitolinids from mid-Cretaceous sediments of the Western Approaches to the English Channel.

ORBITOLINID TAXONOMY

As discussed by Schroeder (e.g. 1962, 1963, 1975) and Hofker (1963, 1966), the internal structure of orbitolinids is the most critical feature for taxonomic separation. Within the subfamily Orbitolininae (_Orbitolina_ _sensu_ _lato_), the most important feature is the macrospheric embryonic apparatus (see Figure 2). The structure and size of this delimits genera and species, and allows for the construction of phylogenetic lineages. Hofker (1963, 1966) considered there to be only one phylogenetic lineage within the Orbitolininae, and that this could be grouped under one species name - _Orbitolina_ _lenticularis_ (Blumenbach). However Schroeder (e.g. 1975) has shown this to be incorrect. A number of phylogenetic lineages exist within the Orbitolininae which allow for separation into distinct genera and short ranging and transitional species. This taxonomy is now widely accepted as being correct.

For further details of the morphological terminology used in describing the orbitolinids see Schroeder (1975) and Arnaud-Vanneau (1980).

PALORBITOLINA OCCURRENCES

Orbitolinids have been reported from the Early Aptian - Late Barremian (Wealden - Lower Greensand equivalents) of the Fastnet Basin by Ainsworth *et al*. (1985). These occurred in the Cities Service exploration well 63/10-1. Examination of specimens kindly supplied by Dr. Ainsworth, revealed them to belong to the species *Palorbitolina lenticularis* (Blumenbach) (Plate 1a-b).

The monotypic genus *Palorbitolina* is distinguished by a relatively simple embryonic apparatus (Schroeder, 1963; 1975). This consists of an apically situated spherical embryonic chamber (a combined proloculus and deuteroconch), and in advanced specimens, peri-embryonic chamberlets (Plate 1b). The deuteroconch and peri-embryonic chamberlets typically show a surface division by septa. The lack of a subembryonic zone distinguishes this species from the more complex Albian - Cenomanian genus *Orbitolina* which is also found in the Fastnet Basin.

Gušić (1981) and Simmons and Hart (1987) suggested that progressive increases in the size and complexity of the embryonic apparatus could be used to distinguish different stages with the evolution of *P. lenticularis*. These in turn, could enable a subdivision of the Late Barremian - Early Aptian time-span. However, large populations are needed to undertake this with confidence and the limited material available to us in this study is thus unsuitable.

Orbitolinids are known to occur in the Farringdon Greensand (Lower Greensand equivalent) (Natural History Museum, London, Curry Collection). Some of these specimens have been examined in thin-section, but unfortunately a diagnostic embryonic apparatus was not found. However, the Aptian age of the sediments suggests that these orbitolinids are likely to be P. lenticularis. The specimens are associated with Choffatella decipiens Schlumberger (Hart, pers. comm., 1990) a foraminifera with which P. lenticularis often occurs.

P.lenticularis has a known stratigraphic range of Late Barremian - Early Aptian (Schroeder, 1975; Simmons, 1990). This compares favourably with the associated microfauna and microflora recorded by Ainsworth et al. (1985, 1987).

The validity of the genus Palorbitolina has been established by Schroeder and Simmons, 1988, 1989; ICZN, 1990).

ORBITOLINA OCCURRENCES

As noted above, there are relatively numerous records of orbitolinids from the mid-Cretaceous Upper Greensand and equivalents of onshore and offshore South-West England. There are also more questionable records from Northern Ireland.

We have examined material from Wolborough, the Haldon Hills, Wilmington, and the South-East Devon coast. We have also studied material from the mid-Cretaceous sediments of the Fastnet Basin.

The most abundant faunas of orbitolinids from onshore South-West England occur in Upper Greensand equivalent sediments at Wolborough, near Newton

Abbot, South Devon (Figure 1). Schroeder et al. (1986) demonstrated that these occurrences could be referred to the species Orbitolina sefini. O. sefini has a complex embryonic apparatus, which in our specimens has a typical diameter of between 0.5 and 0.72mm (see Figure 3), with an ellipsoidal protoconch (diameter 0.18 - 0.24mm) surrounded by a subdivided deuteroconch and a considerably thinner, but relatively large, subembryonic zone (Plate 1c). The species is distinguished by exclusively triangular cross-sections of the radial partitions and the chamber passages within the radial zone of the chamber layers (Schroeder, 1985a, pl. 30, fig. 1; Schroeder et al., 1986, Fig. 2d, f and Plate 1d). In Orbitolina concava the chamber passages show sub-rectangular cross-sections and are separated by small, radial partitions (e.g. Schroeder 1985b, pl. 29, figs. 7-8). O. sefini can also be distinguished from O. concava by its smaller embryonic apparatus diameter (in O. concava typically 0.7 - 0.9mm) (Schroeder, 1985b, see also Figure 3).

According to Schroeder (1985a) O. sefini has a range from intra-Late Albian to intra-Early Cenomanian. The Wolborough limestones in which O. sefini occurs have been correlated with the Woodlands Sands Member of Haldon Hill (Hamblin and Wood, 1976). The Woodland Sands Member was thought by Hamblin and Wood (1976) to be Late Albian on the basis of a debatable correlation to the Chert Beds of South-East Devon, and the presence of two poorly preserved ammonites thought to have their provenance in the Woodland Sands Member. However, the molluscan fauna found within the Woodlands Sands Member was said to have a Cenomanian aspect. As shown in Figure 3, the embryonic apparatus diameters for O. sefini from Wolborough are close to those recorded for Late Albian (Dispar Zone) O.

sefini from Portugal. This tends to confirm a Late Albian age for the Wolborough occurrences.

We have also noted the occurrence of O. sefini in samples from the Wolborough Limestone equivalent or Woodlands Sands Member equivalent in the road cutting of the Newton Abbot by-pass just north of Newton Abbot (Plate 1d–e).

Orbitolinids are also common at a stratigraphically higher level than at Wolborough in the Upper Greensand and Cenomanian Limestone equivalents of the Haldon Hills (see Figure 1). These occurrences are in the Cullum Sands with Chert Member of the Haldon Sands Formation (Hamblin and Wood, 1976). Hamblin and Wood (1976) suggests that this unit correlates with either the non-sequence between the Upper Greensand and Cenomanian, and/or the lower part of the Cenomanian Limestone (Bed A1) (= Beer Head Limestone Formation, Pounds Pool and Hooken Members of Jarvis and Woodroof, 1984). This correlation indicates an Early Cenomanian age for the Cullum Sands with Chert Member, an age substantiated by the occurrence of Early Cenomanian ammonites in the Haldon section which are thought to have been derived from the Cullum Sands.

The orbitolinids are poorly preserved and are often silicified (Plate 1f and Plate 2a). However, they can be seen to posses a complex embryonic apparatus divisible into a lenticular protoconch surrounded by a subdivided deuteroconch and a thin subembryonic zone. This indicates these occurrences can be referred to the genus Orbitolina. Of note is the diameter of the embryonic apparatus. It is greater than that of the O. sefini specimens from Wolborough having an average value of 0.95mm (see Figure 3). This suggests that these specimens are not referable to O. sefini and have a closer affinity to O. concava. Indeed, the diameter of the embryonic apparatus of the Haldon Hills specimens is slightly greater than that of topotypic specimens of O. concava from Ballon, France (see Figure 3 and Plate 2b). Unfortunately the poor preservation of the specimens from the Haldon Hills does not allow for recognition of the characteristic sub-rectangular cross-sections of chamber passages O. concava. Thus these specimens are referred to Orbitolina sp. cf. O. concava.

Orbitolina concava has a well defined stratigraphic range in which it is restricted to the Early Cenomanian. The likely recognition of this species confirms the results of Hart et al. (1979a) who suggested the Cullum Sands orbitolinids had a close affinity with O. concava from the Early Cenomanian of Ballon, whilst the Wolborough orbitolinids had a closer affinity with Late Albian Orbitolina from Portugal. This work was based a comparison on external dimensions of the orbitolinids, a criteria that is not usually considered valid for speciation of orbitolines.

A limited number of orbitolines have been examined from the Upper Greensand of the South-East Devon coast. These are specimens collected by Dr. Graham Elliott from a level in the uppermost Chert Beds or lowermost Top Sandstones at Dunscombe and referred to by Hofker (1963) and Carter and Hart (1977). They are housed in the Natural History Museum, London (registration numbers P45079 and P43429). Despite extensive searches by the current authors, the level with Orbitolina could not be located on the South-East Devon Coast. A few of the Dunscombe specimens were thin-sectioned. Although poorly preserved, the embryonic apparatus of these specimens clearly places them in the O. sefini - O. concava plexus (Plate 2c). Their embryonic apparatus dimensions plot midway between those of O. sefini and those of O. concava (see Figure 3). The marginal zone of these specimens shows a close similarity to O. sefini from Wolborough (Plate 2d). However, it must be stressed that the precise identity of these orbitolinids remains uncertain.

Similarly it has not proved possible to provide a precise identification of the orbitolinids found in the glauconitic sands of the Fastnet Basin (Upper Greensand equivalent) and first mentioned by Ainsworth et al. (1985). Loose specimens provided by Dr. Ainsworth from the BP well 56/10-1 were thin-sectioned, but only poorly preserved embryonic apparatuses were observed. However, these and the nature of the chamber layers suggests that these specimens belong in the O. sefini - O. concava plexus. Using a variety of microfossil groups, Ainsworth et al. (1987) suggested that the sediments containing these orbitolinids were of Early Cenomanian age.

It has not been possible to examine orbitolinid specimens from the Warminster Greensand (Carter and Hart, 1977), or the Hibernian Greensand of Northern Ireland. However, the Early Cenomanian age of the sediments these orbitolinids are recorded from suggests they are likely to be within the O. sefini - O. concava plexus.

"ORBITOLINA" FROM THE UPPER GREENSAND AT WILMINGTON

Of interest is the record of Orbitolina from the Upper Greensand exposed beneath the Wilmington Sands (Beer Head Limestone Formation equivalent) at Wilmington, East Devon (see Figures 1 and 4) (eg. Carter and Hart, 1977; Hart, 1982, 1983). We have been able to examine specimens from White Hart Pit, Wilmington collected by Prof. Hart, Prof. Murray and Dr. Curry (the later held in the Natural History Museum, London). Whilst these specimens resemble orbitolinid foraminifera externally, thin-sections of the specimens reveal them to have a completely different structure which is non-foraminiferal (Plate 2e). Comparison with material from other fossil groups in the Natural History Museum, London, shows that these specimens can be referred to the sponge genus Porosphaera. Jukes-Brown and Hill (1900) recorded Porosphaera urceolata from the uppermost Upper Greensand at Warminster. It is likely that the fossil found by Jukes-Brown and Hill is the same as that found at Wilmington. However, assignment to the species P. urceolata (a junior synonym of P. pileolus according to Hinde (1904)) is doubtful because this species is typical of the chalk and is somewhat larger and some spherical than the Wilmington specimens.

This is not the first time that Porosphaera and Orbitolina have been confused. According to Hinde (1904), Parker and Jones (1860) records of Orbitolina are in fact of Porosphaera. This is not strictly true. Parker and Jones (1860) mix records of both true Orbitolina (eg. from the Haldon Hills) with those of Porosphaera (eg. from the Chalk). It is uncertain if the mention of Orbitolina from the Warminster Sands by Parker and Jones (1860) refers to true Orbitolina or to Porosphaera.

STRATIGRAPHIC SIGNIFICANCE

The Upper Greensand of South-East Devon is currently subdivided into three informal units; the Foxmould Sands, the Chert Beds, and the Top Sandstones (see Figure 4). A paper introducing a formal lithostratigraphy is in preparation. Further west, in the Haldon Hills area, a formal stratigraphy has been proposed by Hamblin and Wood (1976) (see Figure 4). It is further described by Selwood et al. (1984).

However, problems exist with the lithological correlation of the Haldon Hills succession to that of the South-East Devon coast. Furthermore there has been disagreement over the chronostratigraphic correlation of the sections. Hart (1971) suggested that the majority of the Chert Beds and the Top Sandstones of the coastal sections were of Early Cenomanian age, based on the foraminiferal fauna (including Orbitolina). By correlation to the Haldon Hills (see Carter and Hart, 1977, Fig. 46) much of the Haldon Hills section is therefore also Early Cenomanian. Hamblin and Wood (1976) whilst agreeing that the upper part of the Haldon Hills section was Cenomanian, considered the majority of the coastal section to be Late Albian. Their argument was based on lithostratigraphic correlation and the occurrence of a Dispar Zone (Late Albian) ammonite fauna in the upper Chert Beds of Shapwick Grange Quarry (Figure 1).

The critical Dispar Zone ammonite fauna from Shapwick Grange quarry is an important line of evidence for suggesting that the majority of the Upper Greensand is of Late Albian age. Although neither Hart et al. (1979b) or Jarvis et al. (1987) could confirm a Late Albian age for the ammonite bearing horizon at Shapwick Grange using a variety of microfossil groups, Owen (pers. comm. 1990) confirms that the ammonite fauna is of latest Albian age (uppermost dispar zone) and that it is not a remane deposit similar to those known from East Dorset (Carter and Hart, 1977).

Whilst the Shapwick Grange Quarry ammonite fauna indicates that the Chert Beds must be Late Albian (contrary to the view of Hart 1971, et seq.) it does not rule out the possibility that the Top Sandstones are Early Cenomanian. This was suggested by Kennedy (1970) who provided ammonite evidence that the Eggerdon Grit was, at least in part, Early Cenomanian. The Top Sandstones is the lateral equivalent of the Eggerdon Grit (see Figure 4), although note that this coarse sandy facies at the top of the Upper Greensand is likely to be diachronous.

The orbitolinids found in the Upper Greensand of South-West England give some useful indications about correlation of this marginal facies between localities. The Wolborough orbitolinids can be assigned to O. sefini which suggests an intra Late Albian - intra Early Cenomanian age. In fact, the embryonic apparatus measurements plot very close to those for Late Albian O. sefini from Portugal (see Figure 3). This tends to support the Late Albian age ascribed to these sediments by Hamblin and Wood (1976) and their tentative correlation to the Late Albian Woodlands Sands Member of the Haldon Sands Formation of Haldon Hill. It is clear that the orbitolinids from the Cullum Sands with Chert Member of Haldon Hill belong to a separate, younger population (O. cf. concava), most likely Early Cenomanian. Again, this confirms the age ascribed to this unit by Hamblin and Wood (1976).

However, the critical question of correlation of the Haldon Hills section to that of the South-East Devon coast still remains essentially unanswered. The simplistic correlation of the orbitolinid rich Cullum Sands with Chert to the orbitolinid bearing Top Sandstones/Uppermost Chert Beds at Dunscombe on the South-East Devon coast is thought unlikely, and in any case, the orbitolinids studied from Dunscombe cannot be precisely identified at present. Rather, the definite Early Cenomanian age suggested for the Cullum Sands with Cherts indicates a correlation with the lower part of the Beer Head Limestone to be likely. We suggest that lithologically, the Ashcombe Gravels Member correlates with the Top Sandstones and upper Chert Beds (Figure 4). These correlations are in broad agreement with some of the suggestions of Hamblin and Wood (1976).

It is known that embryonic apparatus size in orbitolinids increases with time within a phylogenetic lineage (eg. Schroeder, 1975; Gusic, 1981), thus within the O. sefini - O. concava plexus we can assume that greater embryonic apparatus size indicates a younger age. Therefore Figure 3 suggests that three distinct populations of Orbitolina occur in the Upper Greensand: the Wolborough Late Albian population, which is older than the Dunscombe population, which in turn is older than the Early Cenomanian Babcombe Copse population. These relative age assignments support the correlations shown in Figure 4.

PALAEOBIOGEOGRAPHIC SIGNIFICANCE

Hart et al. (1979a) discussed the possible colonisation pathway of Orbitolina and came to the conclusion that the orbitoline occurrences in South-West England had probably arrived by way of the Paris Basin. They pointed out that orbitolines recorded from the English Channel Basin and the South-West Approaches Basin (Andreieff et al., 1975; Curry et al., 1970) have been assigned an Early Cenomanian or Albian - Cenomanian age and "that is difficult to see how this accepted 'Tethyan' genus could appear in the U.K. earlier than in these more southern localities". However the age of these orbitolinids from the English Channel Basin and the South-West Approaches is quite generalized, and as shown above, it is likely that both Late Albian and Early Cenomanian orbitolinids occur in South-West England.

The occurrence of Late Albian O. sefini in both Portugal (Rey et al., 1977) and South-West England suggests that there may have been a migration pathway from the Iberian Peninsula via the South-West Approaches to South-West England. Such a pathway can be supported by the palaeogeography proposed by Lott et al. (1980) using borehole evidence from offshore South-West England.

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We are indebted to Prof. Malcolm Hart (Polytechnic Southwest) for his assistance during the course of this study. We wish to thank the technical staff of Polytechnic Southwest and Richard Hodgkinson (Natural History Museum) for their assistance in preparing specimens. For their advice and help in providing specimens for study we thank Pete Manley (Polytechnic Southwest), Kelvin Boot (Exeter Museum), Dr. Graham Elliott, Dr. Geoff Adams and Dr. John Whittaker (all Natural History Museum), and also Dr. Nigel Ainsworth (Paleo Services) and Prof. John Murray (Southampton University). Dr. Paul Taylor (Natural History Museum) resolved the identity of the Wilmington Sands specimens. This paper is published with permission kindly granted by BP Research.

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FIGURE CAPTIONS

Figure 1: Location map showing orbitolinid occurrences in the onshore and offshore British Isles area, and locations mentioned in the text (in part after Hamblin and Wood, 1976).

Figure 2: Orbitolinid internal structure (after Schroeder, 1975).

Figure 3: Graphical plot of embryonic apparatus measurements for Orbitolina from Dunscombe, Wolborough, Babcombe Copse (Haldon Hills), Portugal and Ballon, France.

Figure 4: Chronostratigraphic Summary Chart for the Late Albian - Middle Cenomanian of South-West England. Ammonite zonation follows Owen (1984), Wright et al. (1984) and Hancock (1989). A.J = A. jukesbrownei, T.A = T. acutus, T.C = T. costatus, A.R = A. rhotomagense, M.S = M. saxbii, N.C = N. carcitanensis, M.P = M. perinflatum, M.R = M. rostratum, C.A = C. auritus, H.V = H. varicosum, H.O = H. orbignyi, D.C = D. cristatum. Lithostratigraphy abbreviations are as follows: WL = Wolborough Limestone, THS = Telegraph Hills Sands Member, WS = Woodlands Sands Member, AG = Ashcombe Gravels Member, CSC = Cullum Sands with Cherts Member, Fx = Foxmould Sands, CB = Chert Beds, TS = Top Srandstones, PP = Pounds Pool Member, H = Hooken Member, LB = Little Beach Member, BS = Blackdown Sands, EG = Eggerdon Grit, WiS = Wilmington Sands, CBB = Chalk Basement Beds. Sea-level curve shows relative change of coastal onlap. For further discussion of this figure see Simmons et al. (in press).

Explanation of Plate 1:

Figures a-b: Palorbitolina lenticularis (x100), Barremian - Aptian, Fastnet Basin, Cities Services well 63/10-1. Detail of embryonic apparatus. Figure b shows a form with peri-embryonic chamberlets.

Figure c: Orbitolina sefini (x40), Late Albian, Wolborough Limestone, Wolborough, Devon.

Figure d: O. sefini (x40), Late Albian, Wolborough Limestone, Newton Abbot By-pass, Devon. Note triangular shape of radial partitions and chamber passages.

Figure e: O. sefini (x100), Late Albian, Wolborough Limestone, Newton Abbot By-pass, Devon. Detail of embryonic apparatus.

Figure f: Orbitolina cf. concava (x100), Early Cenomanian, Cullum Sands with Cherts Member, Babcombe Copse, Haldon, Devon. Detail of embryonic apparatus.

Explanation of Plate 2:

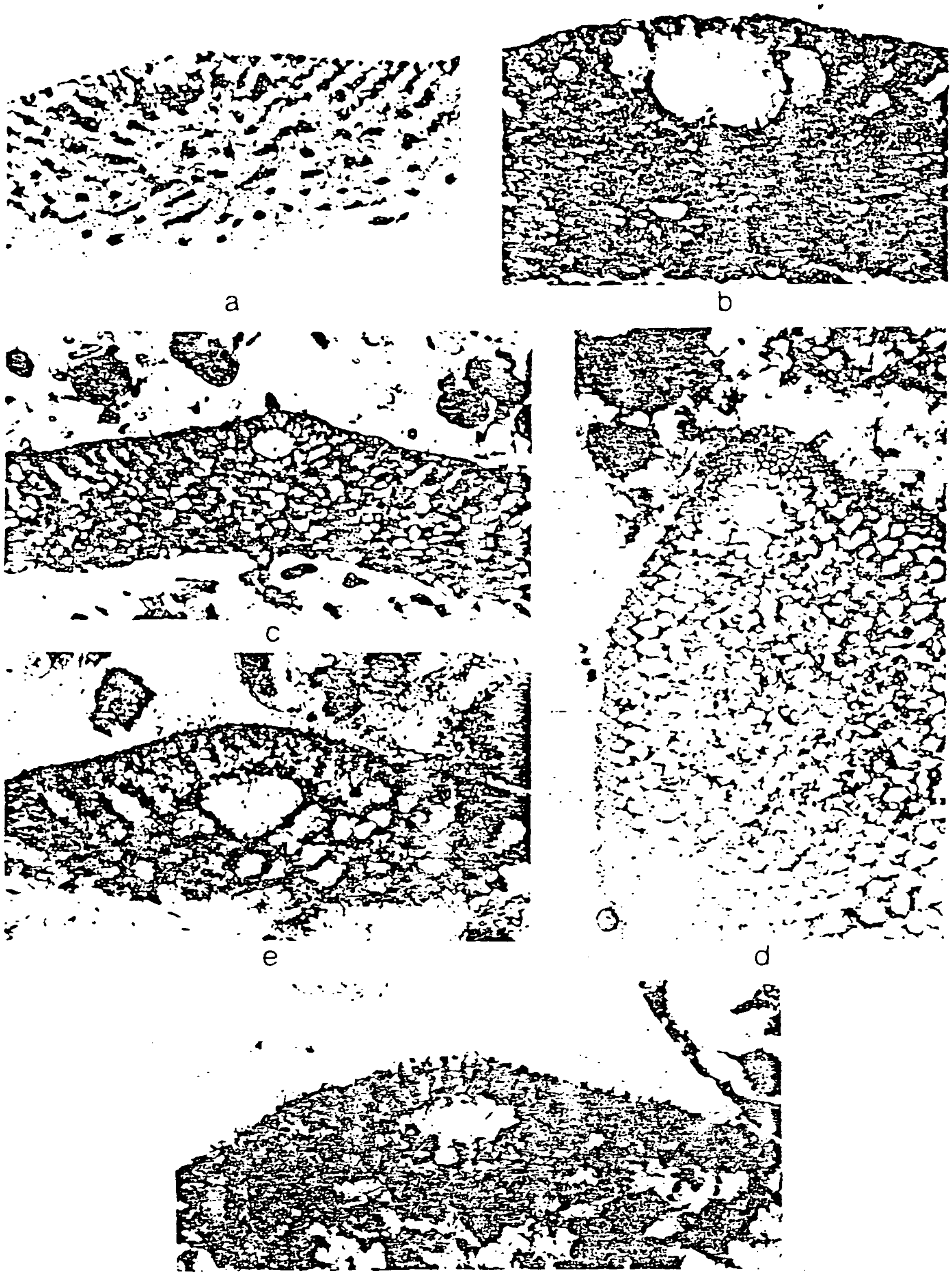
Figure a: Orbitolina cf. concava (x40), Early Cenomanian, Cullum Sands with Cherts Member, Babcombe Copse, Haldon, Devon.

Figure b: Orbitolina concava (x40), topotype material, Early Cenomanian, Ballon, Sarthe, France.

Figure c: O. sefini - O. concava (x100), close to Albian/Cenomanian boundary, upper Chert Beds/Top Sandstones, Dunscombe Quarry, South-East Devon. Detail of embryonic apparatus. Natural History Museum specimen P. 45079.

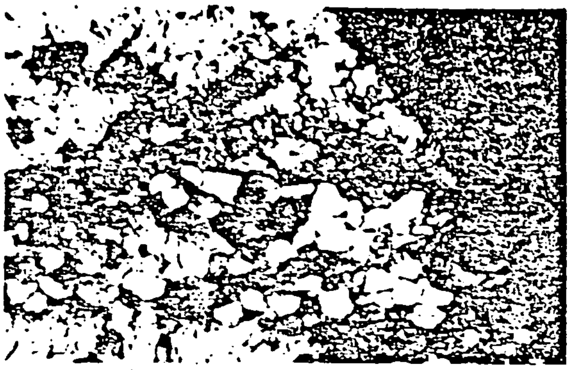
Figure d: O. sefini - O. concava (x40), close to Albian/Cenomanian boundary, upper Chert Beds/Top Sandstones, Dunscombe Quarry, South-East Devon. Detail of marginal zone. Compare this to that for O. sefini figured by Schroeder et al. (1986), Figure 2e. Natural History Museum Specimen P.43429.

Figure e: Porosphaera sp. (x20), Early Cenomanian?, Upper Greensand, White Hart Pit, Wilmington, Devon.



RCS 23961

Plate 1

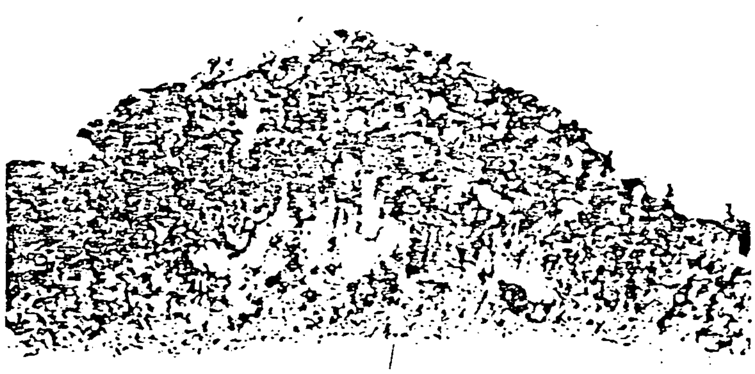


a

b

c

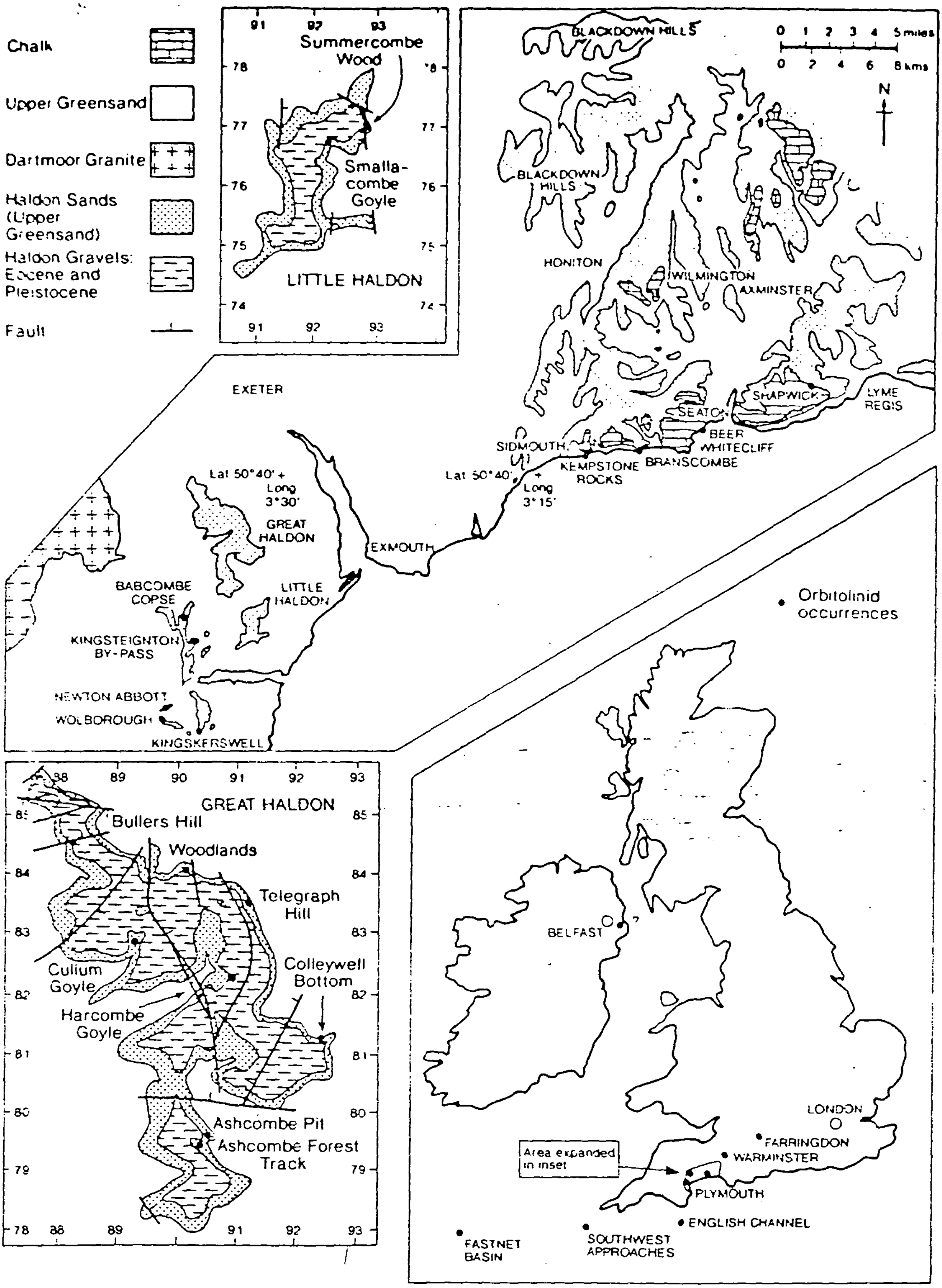
d



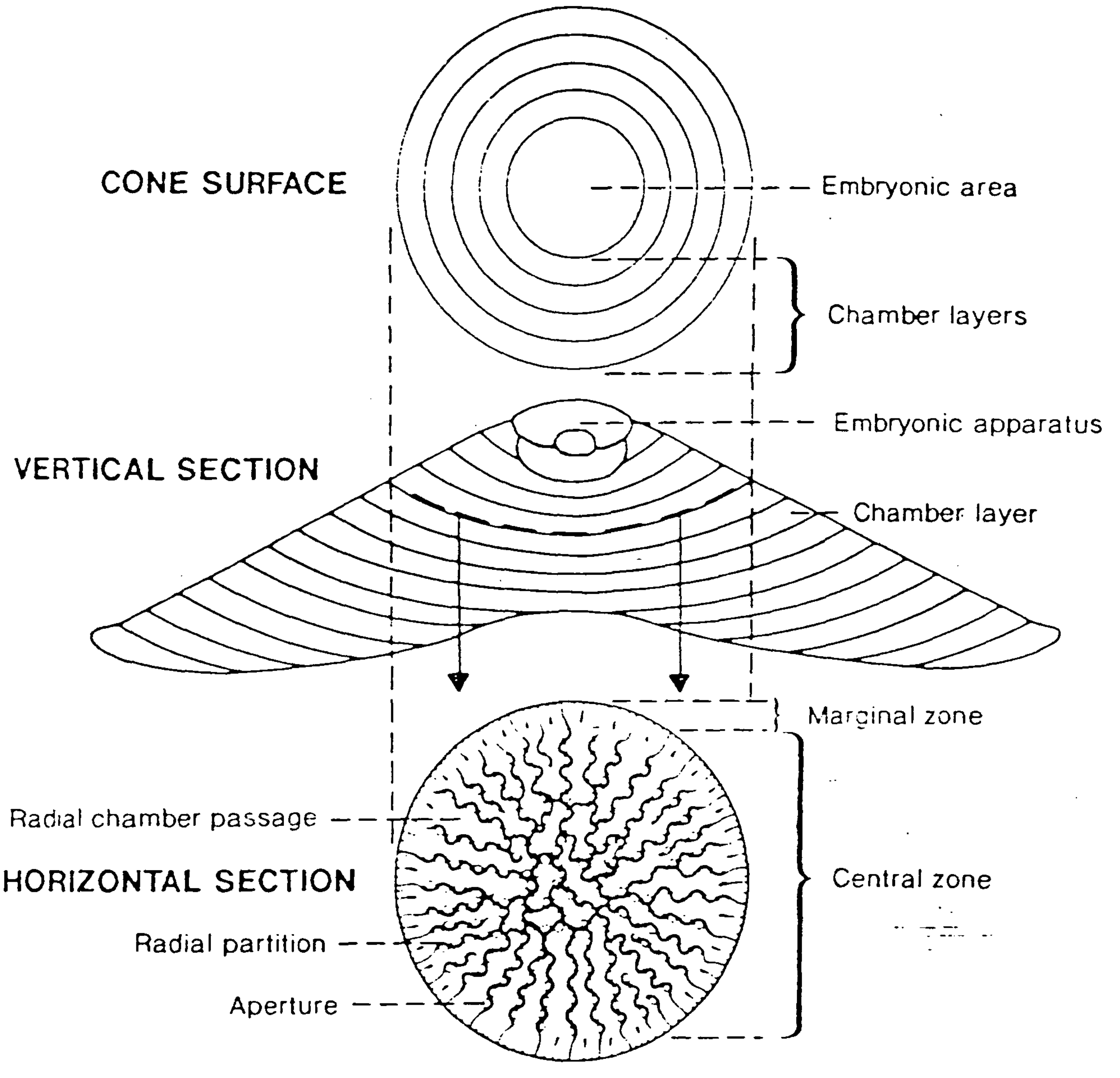
e

RCS 29962

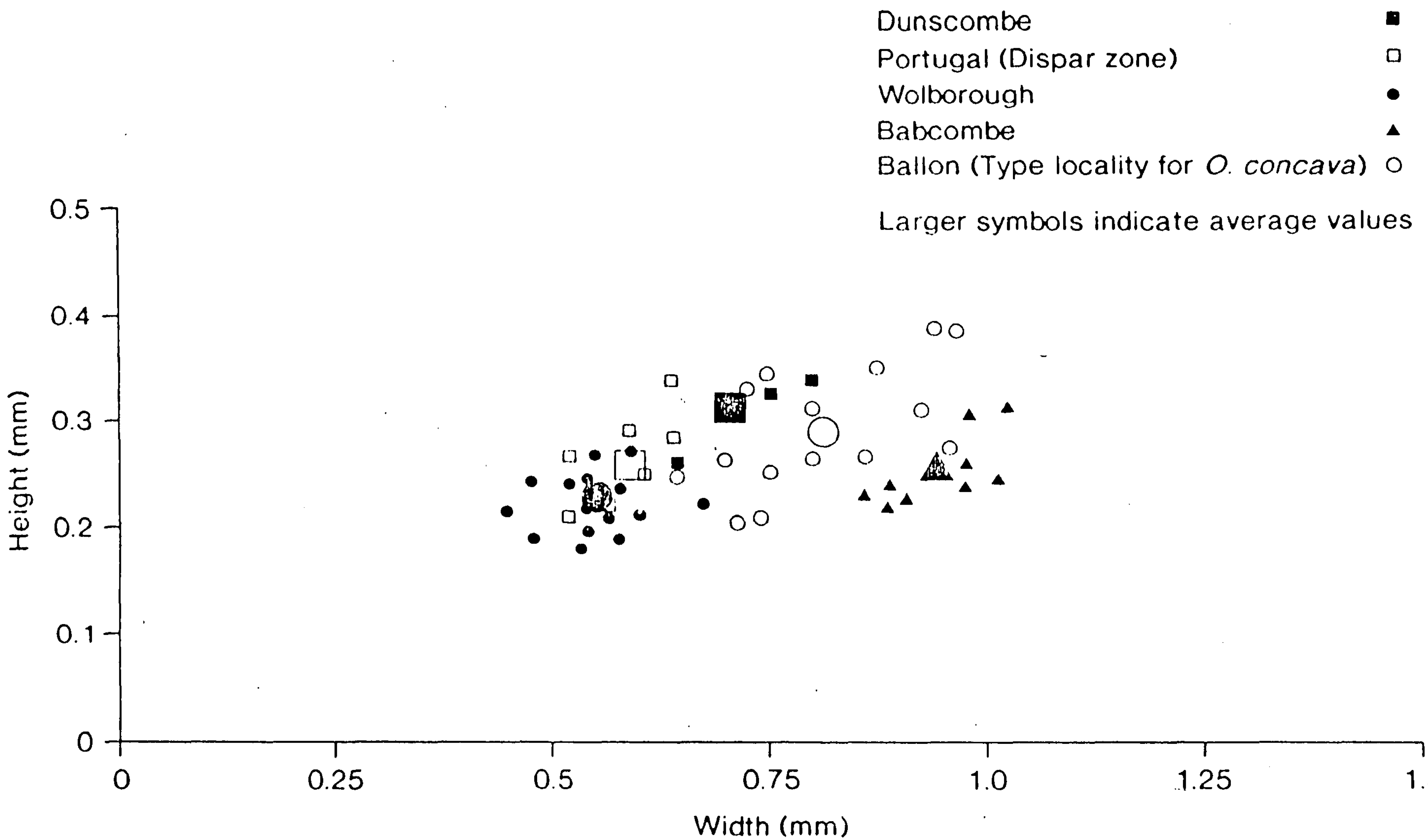
Plate 2


Chalk
Upper Greensand
Dartmoor Granite
Haldon Sands (Upper Greensand)
Haldon Gravels: Eocene and Pleistocene
Fault
Summercombe Wood
Smallacombe Goyle
LITTLE HALDON
BLACKDOWN HILLS
0 1 2 3 4 5 miles
0 2 4 6 8 kms
N
HONITON
WILMINGTON
AXMINSTER
SHAPWICK
LYME REGIS
SEATON
BEER
WHITECLIFF
BRANSCOMBE
SIDMOUTH
KEMPSTONE ROCKS
Lat 50°40'
Long 3°15'
EXETER
Lat 50°40'
Long 3°30'
GREAT HALDON
EXMOUTH
BABCOMBE COPSE
LITTLE HALDON
KINGSTEIGNTON BY-PASS
NEWTON ABBOTT
WOLBOROUGH
KINGSKERSWELL
GREAT HALDON
Bullers Hill
Woodlands
Telegraph Hill
Culium Goyle
Colleywell Bottom
Harcombe Goyle
Ashcombe Pit
Ashcombe Forest Track
Orbitolinid occurrences
BELFAST
LONDON
FARRINGDON
WARMINSTER
Area expanded in inset
PLYMOUTH
ENGLISH CHANNEL
FASTNET BASIN
SOUTHWEST APPROACHES

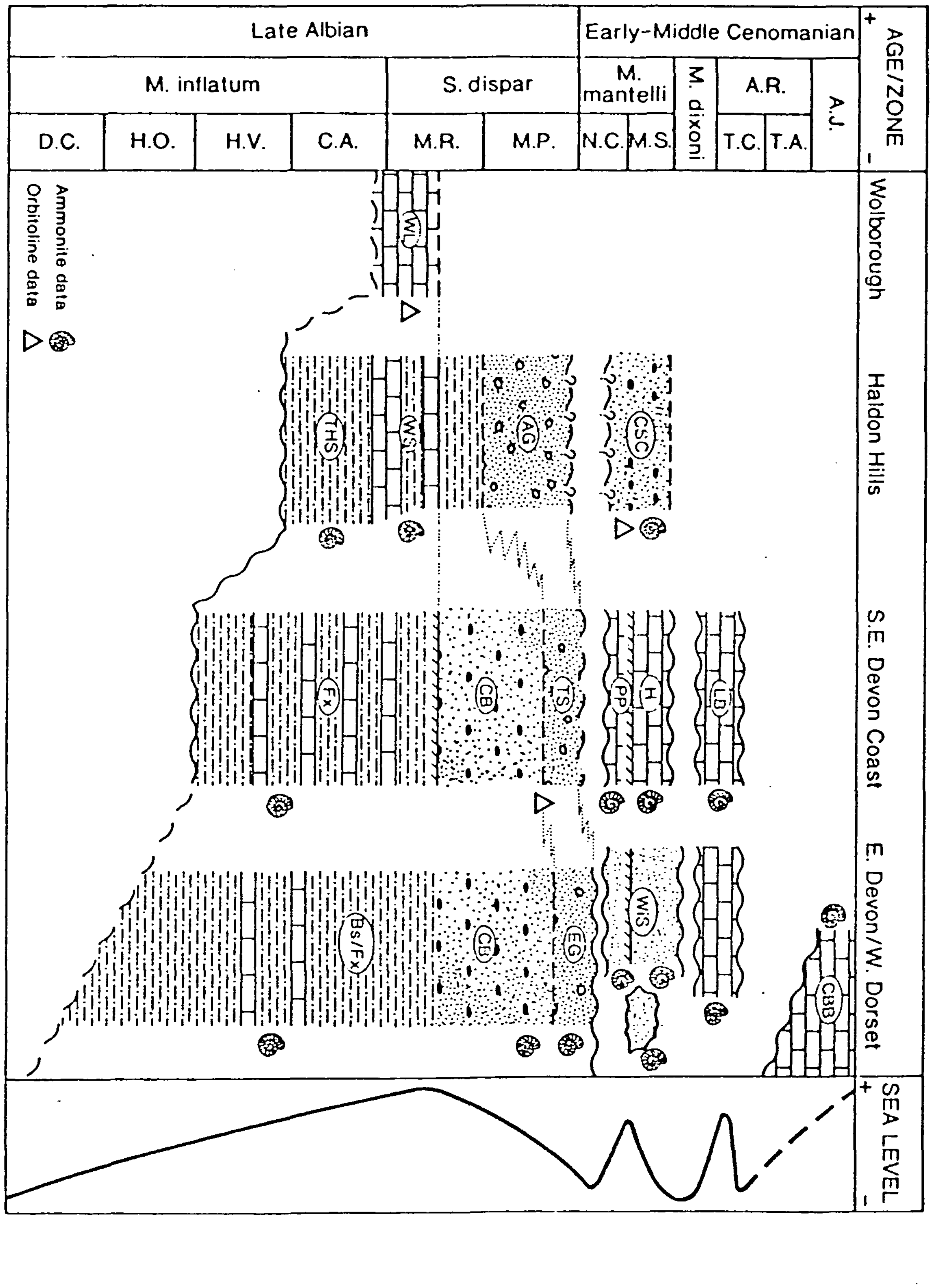
RCS 30009


CONE SURFACE
Embryonic area
Chamber layers
Embryonic apparatus
VERTICAL SECTION
Chamber layer
Marginal zone
Radial chamber passage
HORIZONTAL SECTION
Central zone
Radial partition
Aperture

RCS 30007


Dunscombe
Portugal (Dispar zone)
Wolborough
Babcombe
Ballon (Type locality for *O. concava*)
Larger symbols indicate average values
Height (mm)
0.5
0.4
0.3
0.2
0.1
0
0
0.25
0.5
0.75
1.0
1.25
1.5
Width (mm)

A - 393



Late Albian
Early-Middle Cenomanian
AGE/ZONE
M. inflatum
S. dispar
M. mantelli
M. dixoni
A.R.
A.J.
D.C.
H.O.
H.V.
C.A.
M.R.
M.P.
N.C.
M.S.
T.C.
T.A.
Wolborough
Haldon Hills
S.E. Devon Coast
E. Devon/W. Dorset
SEA LEVEL
WL
THS
WST
AG
CSC
Fx
CB
TS
PP
H
LD
Bs/Fx
EG
WS
CBB
Ammonite data
Orbitoline data

RCS 29710

Read at the Annual Conference of the Ussher Society, January 1991

Sea-level changes across the Albian-Cenomanian boundary in south-west England

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C.L. WILLIAMS

M.B. HART

Simmons, M.D., Williams, C.L. and Hart, M.B. 1991. Sea-level changes across the Albian-Cenomanian boundary in south-west England. *Proceedings of the Ussher Society*, 7, 000-000.

The marginal Albian - Cenomanian sediments of south-west England provide an ideal succession in which to study sea-level changes. The recognition of maximum onlap, facies variations and hardground surfaces, has enabled us to establish a sea-level curve for the Late Albian - Middle Cenomanian of this area. The curve shows an gradual sea-level rise during the Inflatum Zone, reaching a peak in the basal Rostratum Subzone (Dispar Zone). A sea-level fall throughout the majority of the Dispar Zone reaches a trough in the basal Cenomanian (Carcitanensis Subzone). A subsequent rise in sea-level reaches a peak in the lower part of the Saxbii Subzone. Sea-level falls to a low in the Dixoni Zone, and there is a short transgressive - regressive cycle in the Costatus Subzone, after which a general sea-level rise is indicated. This sea-level curve is compared with the global curve of Haq *et al.* (1987) and the more localized curve for Britain by Hancock (1989). Whilst there are some similarities with the Haq *et al.* curve, there is less similarity with that of Hancock. The curve for south-west England compares favourably with the

transgressions and regressions documented in the Paris Basin and Armorican Massif regions by Juignet (1980).

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Introduction

In the 1970's stratigraphers in EXXON developed a new way at looking at sedimentary successions. Initially using relationships seen in seismic sections, but later also using outcrop and well data, the method breaks a rock succession up into packages or "sequences". The basic premise of this technique is that sea-levels have fluctuated throughout geologic time, either due to glaciations or through volumetric changes caused by plate movements and variations in sea-floor spreading rates. Cycles of sea-level change occur at several orders of magnitude. Short-term fluctuations lead to the development of sequences, the fundamental unit within the EXXON method. A sequence is a genetically related package of rock bounded by unconformities or their correlative conformities (Van Wagoner *et al.*, 1988). A sequence can be further subdivided into systems tracts. These show the distribution of facies across the shelf and basin during given periods of the sea-level change (eustatic) cycle. Each systems tract is characterised by particular sedimentary and seismic geometries, facies relationships and fossil biota. Three main systems tracts can be recognised within a given sequence: a lowstand systems tract developed during a eustatic fall in sea-level; a transgressive systems tract developed during sea-level rise; and a highstand systems tract developed at and directly after sea-level has risen to its maximum in that cycle. Also of importance is the maximum flooding surface. This represents the time of maximum transgression. It is often represented by condensed sedimentation.

Not withstanding certain reservations about the methodology and global applicability of sea-level change, "Sequence Stratigraphy" became widely publicized following publication of AAPG Memoir 26 (Payton, 1977), and the technique was widely accepted and utilized in the oil industry. It is fair to say that it has been slower to be employed by academic geologists, perhaps because they do not have access to as complete a seismic dataset as industry geologists. The technique is an exciting one for two main reasons. Firstly, it draws all the different types of data on a sedimentary succession (seismic, sedimentology, biostratigraphy, etc.) together, and allows for a lucid picture of basin history to be drawn. Secondly it is a highly predictive technique. Facies out of the area of study can be predicted by reference to the systems tracts they will fall in.

As noted above, one of the fundamental tenets of sequence stratigraphy is that sea-levels have fluctuated in a given manner world-wide through geological time. A number of so called "sea-level curves" have been produced documenting this, with the most important recent work being that of Haq *et al.* (1987). This shows a global pattern of synchronous sea-level changes and thus a myriad of systems tracts which theoretically should be recognisable world-wide, assuming no local tectonic controls and suitable marine successions in a passive margin setting. Hancock (1989) has produced a sea-level curve specifically for the Cretaceous of British region, and there are several others some of which are referred to below. A problem with the Haq *et al.* (1987) curve is that it is often based on observations made on basinal successions. It is better to document sea-level changes from marginal areas where even small fluctuations in sea-level are likely to result in major facies changes. During the Albian - Cenomanian period, south-west England was such a marginal area. It therefore provides an ideal opportunity to develop a sea-level curve and compare this against those already published for this time period. However, it should be noted that any local sea-level curve is a function of the combination of subsidence, sediment supply and eustatic sea-level change. Each of these factors will be of varying significance, although in this particular instance most significance is placed on the eustatic variation. It is also interesting to re-examine the Albian - Cenomanian succession of south-west England within the context of sequence stratigraphy. This may shed light on the depositional environment and correlation of these problematic deposits.

The south-west England succession

Early studies on the Albian - Cenomanian succession of south-west England (eg. Jukes-Brown and Hill, 1900; 1903) recognised that it was more marginal in nature in comparison with the basinal succession seen in south-east England. This has been confirmed and expanded upon in later, more detailed studies of sedimentology and fossil faunas (eg. Smith, 1957, 1961, 1965; Tresise, 1960; Hancock, 1969; Kennedy, 1970; Hart, 1973, 1982, 1983; Ali, 1975, 1976; Hamblin and Wood, 1976; Carter and Hart, 1977; Jarvis and Woodroof, 1984; Williams, 1986; Garrison *et al.*, 1987; Williams *et al.*, 1988; Hart and Williams, 1990).

In south-west England the Late Albian - Middle Cenomanian is represented by the Upper Greensand and the Cenomanian Limestone and their equivalents (see Fig. 1).

The Upper Greensand of the south-east Devon coast is divided into the Foxmould Sands, Chert Beds and Top Sandstones (Jukes Brown and Hill, 1900; Tresise, 1960) and has recently been described by Williams (1986) Garrison *et al.* (1987) and Williams *et al.* (1988). A new formal lithostratigraphy is in preparation. The Foxmould Sands are burrowed, glauconitic fine sands -

silts with occasional limestone beds. They are separated from the overlying Chert Beds by a hardground. The Chert Beds are mud-free carbonate cemented sandstones with large chert nodules and large burrow systems. Phosphatic pebble beds also occur. The Top Sandstones are a thin, coarse carbonate cemented sandstone or loosely cemented limestone. The age of the Upper Greensand is not well established. Ammonites are scarce, but Late Albian Auritus and Varicosum Subzone faunas are known from the Foxmould Sands (Hancock, 1969; Williams *et al.*, 1988). Micropalaeontological evidence suggests that the Foxmould sands may be as young as Rhotomagense Subzone (Williams et. al., 1988) (see Fig. 1). Suggestions by Hart (1971, 1973) and Carter and Hart (1977) that the Chert Beds are Cenomanian using microfauna have been refuted by the record of a Dispar Zone ammonite fauna near the top of the Chert Beds at Shapwick Grange Quarry, south-west Dorset (Hamblin and Wood, 1976). This fauna is most likely from the higher part of the Dispar Zone (H.G. Owen, personal communication). It is possible, probably likely, that the highest part of the Chert Beds and the Top Sandstones extend into the basal Cenomanian Carcitanensis Subzone. Orbitoline foraminifera from this level provide only equivocal evidence (Simmons and Williams, in press).

The Cenomanian Limestone (Smith, 1957) has been renamed the Beer Head Limestone Formation by Jarvis and Woodroof (1984) and the classic A1, A2, B and C divisions first described by Jukes-Browne and Hill (1903) (but following Meyer, 1874), formally redescribed and renamed the Pounds Pool, Hooken, Little Beach and Pinnacles Members respectively. Each member is bounded by a hardground, and each member also shows marked thickness variations, perhaps related to local tectonic controls (Smith 1957, 1961, 1965; Drummond, 1970; Hart, 1971, 1982; Jarvis and Woodroof, 1984). The Beer Head Limestone Formation has been thoroughly described by Jarvis and Woodroof (1984). It consists of bioclastic detritus-rich limestones and locally intraformational conglomerates and phosphatic pebble beds. The age of the constituent members of the Beer Head Limestone is well established by ammonite faunas (Kennedy, 1970; Juignet and Kennedy, 1976; Wright and Kennedy, 1981; Jarvis and Woodroof, 1984). The Pounds Pool Member can be referred to the higher part of the Carcitanensis Subzone, the Hooken Member to the Saxbii Subzone, and the Little Beach Member to the upper Dixoni Zone and lower Costatus Subzone. The Pinnacles Member contains a fauna indicating a position between the Geslinianum Zone and Judii Zone (uppermost Cenomanian - Gracile Zone of authors). As noted by Carter and Hart (1977) and Hancock (1989) the ammonite faunas of the Beer Head Limestone are often in a phosphatised condition and may be reworked. Carter and Hart (1977) went as far as to question some of the ages suggested by the ammonite faunas, noting that foraminifera are more likely to be indigenous. However, for the purposes of this study we accept the ammonite evidence (largely documented by Kennedy, 1970) which is also supported by other macrofossil data (Kennedy and Hancock, 1976).

To the east and north of the south-east Devon coast the Beer Head Limestone is locally replaced by the Wilmington Sands. Kennedy (1970) has demonstrated that these sands are broadly equivalent to the Pounds Pool and Hooken Members of the Beer Head Limestone. The Wilmington Sands overly an coarse, shelly Upper Greensand similar to the Eggerdon Grit of further east (and thus probably basal Cenomanian). The lower Wilmington Sands probably equate to the Pounds Pool Member and can be referred to the upper Carcitanensis Subzone, whilst the overlying "grizzle" equates to the Hooken Member and contains ammonites suggesting a Saxbii Subzone - lower Dixoni Zone age (Kennedy, 1970). Overlying the Wilmington Sands is a thin limestone equivalent to the Little Beach Member, followed by the latest Cenomanian basal chalk/Pinnacles Member equivalent.

In west Dorset the Upper Greensand can be divided in the Eggerdon Grit (a lateral equivalent of the Top Sandstones), the Chert Beds and Foxmould Sands, the latter passing downward into a Gault facies. In this area the onset of Gault/Upper Greensand is at least as old as Cristatum Subzone, perhaps Lautus Zone (Rawson *et al.*, 1978; Hancock, 1989). The Eggerdon Grit is of upper Dispar Zone - basal Carcitanensis Subzone age (Kennedy, 1970). Often the Eggerdon Grit is overlain directly by the Chalk Basement Beds which are usually of Middle Cenomanian Acutus Subzone or Jukesbrownei Zone age and becomes younger to the west (Kennedy, 1970; Carter and Hart, 1977 - see also Fig. 1). Occasionally, a thin remane deposit or conglomerate is present which may contain ammonites indicating a Saxbii Subzone age (Kennedy, 1970). Unusually, considering the age of the Little Beach Member, Dixoni Zone or Costatus Subzone faunas are absent in this area, perhaps indicating the presence of a local high, although the Hooke Valley Conglomerate may be of this age.

Westerly Upper Greensand outliers occur at the Haldon Hills and at Wolborough near Newton Abbot (Selwood *et al.*, 1984). The Haldon Hills succession has been described by Hamblin and Wood (1976) who introduced the term Haldon Sands Formation with four members: (in ascending order) Telegraph Hill Sands; Woodlands Sands; Ashcombe Gravels; and Cullum Sands with Cherts. The Telegraph Hill Sands Member contained an Auritus Subzone ammonite fauna, whilst the overlying Woodlands Sands Member (including limestones and the Haldon Coral Bed) was dated as Dispar Zone (presumably lower Rostratum Subzone). The Ashcombe Gravels Member contains no age diagnostic fauna but is interpreted as being of Dispar Zone age. The overlying Cullum Sands with Cherts Member contains Early Cenomanian ammonites (Hamblin and Wood, 1976). An Early Cenomanian age is also suggested by the presence of orbitolinids referable to *Orbitolina* cf. *concava* (Simmons and Williams, in press). Hamblin and Wood (1976) suggested that the Cullum Sands with Cherts Member might correlate with the lower part of the Cenomanian Limestone (=Beer Head Limestone Formation). This seems likely given the age of the two units. The Ashcombe Gravels Member has a lithological affinity with the Top Sandstones, although this coarse lithofacies is likely to be diachronous (see Fig. 1). A break in sedimentation is suggested between the Ashcombe Gravels and the Cullum Sands with Cherts Members. This is supported by the marked lithological change between the two units observed in the field and the coarse, kaolinised base of the Cullum Sands with Cherts Member.

The Wolborough Limestones (Edwards, 1979) represents the most westerly onshore outcrop of Upper Greensand equivalents. They have been correlated by Hamblin and Wood (1976) to the the Woodlands Sands Member of Haldon Hill, indicating that they are of Rostratum Subzone age. This Late Albian age is supported by the rich orbitoline fauna they contain (Schroeder *et al.*, 1986) which is most likely of Dispar Zone age (Simmons and Williams, in press).

The recognition of sequences and sea-level change in outcrop

The recognition of sequence boundaries, systems tracts and sea-level changes in outcrop has been the subject of some debate in recent years (eg. Wilgus *et al.*, 1988; Hancock, 1989). Sequences, as defined by Van Wagoner *et al.*, (1988) (following Mitchum, 1977) are bounded by unconformities (caused by a downward shift in coastal onlap) or their correlative conformities. It therefore follows that sequence boundaries will be recognised by missing biozones and marked facies changes.

The recognition of sea-level changes (and hence systems tracts) is more complex. Hancock (1989) has suggested the use of hardgrounds to recognise periods of maximum regression (following Juignet, 1980; Francis, 1984). The subject of why and how hardgrounds form is a complex one (for example, see discussions of Fischer and Garrison, 1967; Kennedy and Garrison, 1975; Bromley, 1978; Garrison *et al.*, 1987) and beyond the scope of this article. However, whilst accepting Hancock's premise that hardgrounds form in response to an interruption in sedimentation, this may not always relate to regression. In chalk facies hardgrounds will form in response to a reduction in nannofossil accumulation. This could simply relate to a shallowing caused by a regressive eustatic event. Alternatively (and as noted by Hancock, 1989), it may relate to winnowing by local bottom currents. These could occur in almost any environmental setting and not be a function of eustatic change. Hancock (1989, p. 569) notes the need to distinguish between hardgrounds which are the result of a general lowering of sea-level and those which are "local accidents of winnowing currents over, say, a diapiric uplift". But hardgrounds may also develop during periods of transgression. Indeed, Hancock (1989, p. 577) notes that courses of phosphatic nodules in the Gault, the equivalent of chalk hardgrounds, may form in response to "...a transgression that carried the shoreline further from the basin. Deposition of sediment was also moved further from the basinal region which was then starved of clay". In a marginal setting, such as that represented by the Late Albian - Cenomanian sediments of south-west England, an increase in water depth caused by a transgression may cause a marked drop in sedimentation and the formation of a hardground. In terms of sequence stratigraphy, condensed deposition is associated with the maximum flooding surface, or height of transgression (Van Wagoner *et al.*, 1988; Loutit *et al.*, 1988). Thus at the peak of transgression, a hardground may develop, particularly on the shelf, with biozones being condensed or apparently missing. In contrast to Hancock (1989), we would argue that this condensed sequence will not always overly the regressive hardground (although it may sometimes, perhaps as in the case of some of the Beer Head Limestone Formation hardgrounds which are multiple (Jarvis and Woodroof, 1984). Rather it will overly the lowstand and lower transgressive systems tracts which will onlap onto the shelf. Thus in conclusion, some hardgrounds are associated with regression and unconformity (eg. that at the top of the Top Sandstones), but some are the function of condensation during maximum transgression (eg. that at the top of the Foxmould Sands).

In the Late Albian - Cenomanian succession in south-west England we recognise transgressions and eustatic sea-level rises by periods of maximum onlap (as documented in Fig. 1). We also consider the distribution of facies variations, the diachroneity of facies and the presence of hardgrounds and unconformities.

Sea-level changes in south-west England

As shown by Fig. 1, there is a gradual east to west onlap of the Upper Greensand and equivalents during the Late Albian. The basal Foxmould Sands are at least as old as Cristatum Subzone in west Dorset, in south-east Devon they are of Varicosum Subzone. The base of the Haldon Sands Formation is Auritus Subzone, but the period of maximum transgression is indicated by the Wolborough Limestones which are thought to be Rostratum Subzone age. Within the Varicosum - Auritus succession in south-west England there are no major facies changes or depositional breaks to indicate a cessation of the transgression. Thus sea-level was rising throughout the Inflatum Zone and the time of maximum eustatic rise was in the lower part of the Rostratum Subzone (Dispar Zone). Interestingly, this sea-level rise led to the establishment of a carbonate shelf with orbitoline-rich limestones in the inner shelf, with local coral bioherms basinward of this (the Haldon Coral Bed, Woodlands Sands Member). The limestones in the Foxmould Sands have an outer shelf fauna. The hardground at the top of the Foxmould Sands corresponds to condensation at the time of maximum transgression.

There then followed a gradual regression throughout the remainder of the Dispar Zone. This is indicated by the shallowing of facies throughout the Chert Beds and Top Sandstones (Tresise, 1960; Williams, 1986). The Ashcombe Gravels, Top Sandstones and Eggerdon Grit represent a diachronous regressive, coarse, shallow water facies which becomes progressively younger eastwards. The maximum regression occurs in the basal Cenomanian in the lower part of the Carcitanensis Subzone, as evidenced by the unconformity and hardground at the top of the Top Sandstones and Eggerdon Grit. However, one should also be aware that this apparent regression may in part be due increased sediment supply, although this itself often occurs during a eustatic sea-level fall (highstand systems tract).

Rapid eustatic rise and transgression occurred in the upper part of the Carcitanensis Subzone as evidenced by the onlap of the lowermost Cenomanian Limestone (Pounds Pool Member, Beer Head Limestone Formation) and equivalents (lower Wilmington Sands and Cullum Sands with Cherts Member) across south Devon. Garrison *et al.* (1987) also recognise an increase in water depth at this time. As with the Late Albian transgression, this leads to the establishment of a carbonate shelf and orbitoline rich inner shelf limestone (Cullum Sands with Cherts Member). The hardground at the top of the Pounds Pool Member (basal Saxbii Subzone) is probably the result of condensation associated with transgression. A shallowing-up trend in the Hooken Member overlying the hardground at the top of the Pounds Pool Member, and also within the upper Wilmington Sands indicates a regression and eustatic sea-level fall taking place throughout the majority of the Saxbii Subzone. This culminates in the unconformity seen at the top of the Hooken Member and Wilmington Sands, the latter being within the Dixoni Zone.

The succession of facies within the Little Beach Member indicates a further relatively rapid transgressive - regressive cycle. A eustatic sea-level high occurred during the lower part of the

Costatus Subzone, and a regression in the upper part of this Subzone. A gradual recovery of sea-level is indicated in the Acutus Subzone and continues into the Jukesbrownei Zone as indicated by the gradual westerly onlap of the Chalk Basement Beds. This transgression may have continued throughout the Late Cenomanian, culminating in the deposition of the Pinnacles Member of south-east Devon. This is the lateral equivalent of the Plenus Marls of south-east England (Carter and Hart, 1977; Jarvis *et al.*, 1988), which is associated with a eustatic sea-level high (Hancock, 1989).

Comparison with other sea-level curves

Fig. 2 compares the sea-level curve we have developed for the Late Albian - Middle Cenomanian of south-west England with the global curve of Haq *et al.* (1987) and more localized curve developed for the British region by Hancock (1989).

There are some similarities between our curve and that of Haq *et al.* (1987). Sea-levels are both shown to be rising throughout most of the Inflatum Zone. As noted by Hancock (1989) this in fact corresponds to the global onset of the major "Cenomanian Transgression" of Suess (1906). Haq *et al.* (1987) have a eustatic high at the Auritus - Rostratum Subzone boundary. Ours is slightly higher, in the lower part of the Rostratum Subzone, but perhaps within the range of error in both methods. A subsequent sharp eustatic fall is indicated by Haq *et al.* (1987). This may have initiated and correspond to the onset of a fall on our curve, but unlike Haq *et al.*, we observe sea-level to be falling throughout the Dispar Zone. As noted by Morner (1980), such a dramatic sea-level fall as that indicated by Haq *et al.* (1987) within the lower Rostratum Subzone is difficult to explain. Haq *et al.* (1987) have a recovery of sea-level during most of the Rostratum Subzone and a fall during the Perinflatum Subzone. This culminates in a regressive trough during the basal part of the Carcitanensis Subzone, which is in agreement with our work. Haq *et al.* (1987) show the subsequent eustatic rise culminating at the top of the Saxbii Subzone; we show it to culminate slightly lower. Once again there is agreement with the following regressive trough: it lies within the Dixoni Subzone. Haq *et al.* (1987) then have a eustatic rise taking place through to within the Jukesbrownei Zone. They do not recognise the cycle which we see within the Costatus Subzone.

Surprisingly, given that it is more directly relevant than the curve of Haq *et al.* (1987), there is only slight agreement between our curve and that of Hancock (1989). They both show a eustatic rise during the early part of the Inflatum Zone. However, Hancock (1989) shows the eustatic peak to be at the base of the Auritus Subzone. This cannot be reconciled with the clear evidence for continued onlap during the Auritus Subzone at Haldon and at Wolborough. Following a regression during the Auritus Subzone, Hancock (1989) shows sea-level to be rising or in a state of still-stand during Dispar Zone times. This contradicts the evidence he himself cites, that there was a Late Albian shallowing of the sea in Devon. However, the possibility of increased sediment supply must be taken into account, although this is most likely to occur during a eustatic sea-level fall (highstand systems tract). Within the Early - Middle Cenomanian Hancock (1989) shows a rise culminating at the top of the Saxbii Subzone, followed by slight regression, still-stand and then transgression during Jukesbrownei Zone times. This is quite different to our curve (although the eustatic peak at the top of the Saxbii Subzone is close to our result, and in agreement with Haq *et al.* (1987)). Perhaps one problem in comparing our curve to that of Hancock (1989) is that he uses zonal boundaries as datums for placing his minima and maxima of sea-level change, whilst we have tried to place ours within zones where appropriate.

Other workers' data on sea-level change is often too generalized to be compared directly to ours. However, a regression culminating at, or very near, the Albian - Cenomanian boundary is indicated by Morner (1980) and Matsumoto (1980) for a number of localities world-wide, and by Juignet (1980) for the Paris Basin and the Armorican Massif. This is in agreement with our work. Juignet (1980) recorded sea-level highs during the Inflatum Zone, the Saxbii Subzone and Jukesbrownei Zone. Again, this agrees with our results. Cooper (1977) indicated that the Late Albian transgression began during Orbignyi Subzone times. This is slightly later than our work. Cooper also noted that the strata across the Albian - Cenomanian boundary are typically represented by regressive deposits worldwide. He mentioned that the Dispar Zone is regressive in the Western Interior of North America, in Brazil, Peru and around Africa. This matches our results. His discussion of transgressive peaks in the Cenomanian shows similarities with our work. Using the results of Hart and Tarling's (1974) study of Cenomanian palaeogeography, he is unusual in that like us, he recognizes a sea-level rise during the Costatus Subzone.

Differences between our curve and those of other workers could be ascribed to local tectonic and isostatic controls on sedimentation (Hart, 1990). That there were mid-Cretaceous tectonic movements in south-west England has been suggested by a number of workers (eg. Smith, 1957; Drummond, 1970; Hart, 1971). To what degree tectonic/isostatic controls overprint eustatic controls in this area (if indeed at all) remains a subject for further investigation.

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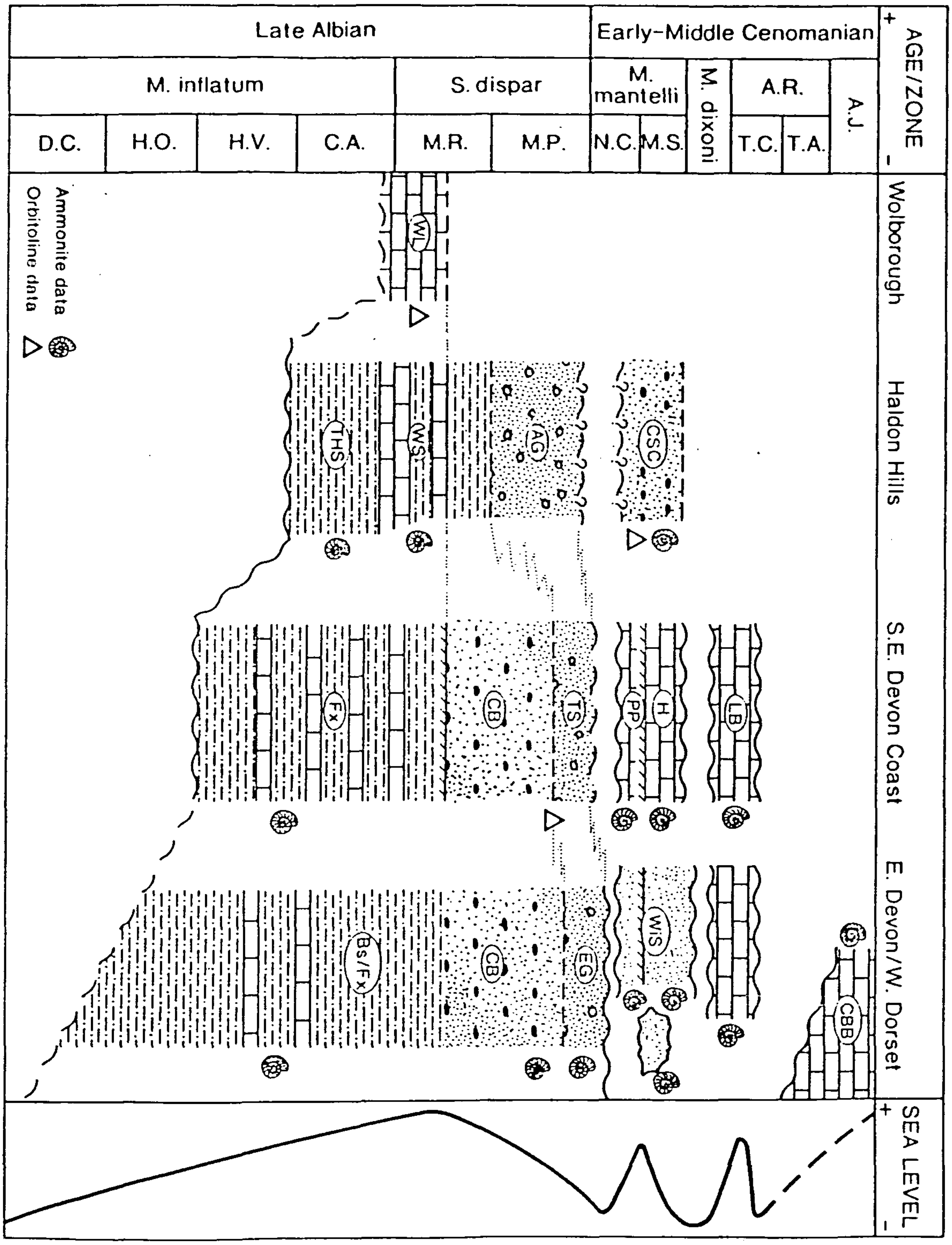
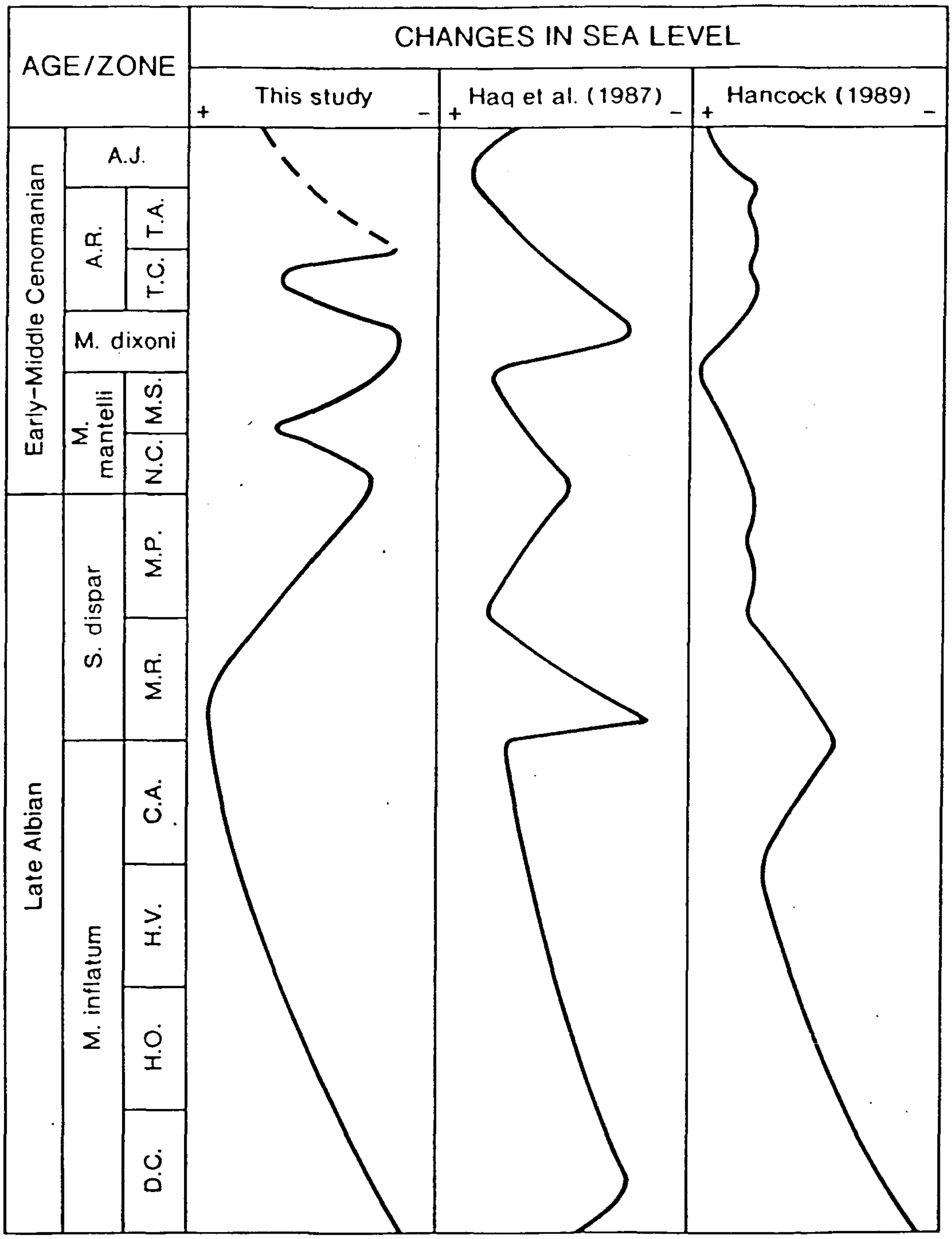
FIGURE CAPTIONS

Figure 1:Chronostratigraphic summary chart for the Late Albian - Middle Cenomanian of south-west England. Ammonite zonation follows Owen (1984), Wright *et al.* (1984) and Hancock (1989). A.J = A. jukesbrownei, T.A = T. acutus, T.C = T. costatus, A.R = A. rhotomagense, M.S = M. saxbii, N.C = N. carcitanensis, M.P = M. perinflatum, M.R = M. rostratum, C.A = C. auritus, H.V = H. varicosum, H.O = H. orbignyi, D.C = D. cristatum. Lithostratigraphy abbreviations are as follows: WL = Wolborough Limestone, THS = Telegraph Hills Sands Member, WS = Woodlands Sands Member, AG = Ashcombe Gravels Member, CSC = Cullum Sands with Cherts Member, FX = Foxmould Sands, CB = Chert Beds, TS = Top Sandstones, PP = Pounds Pool Member, H = Hooken Member, LB = Little Beach Member, BS = Blackdown Sands, EG = Eggerdon Grit, WiS = Wilmington Sands, CBB = Chalk Basement Beds. Sea-level change curve is generalized and shows relative magnitude of onlap.

Figure 2:Comparison of sea-level curves for the Late Albian - Middle Cenomanian. Ammonite zonation as for Figure 1. Sea-level changes shown are relative not absolute.


Late Albian
Early-Middle Cenomanian
AGE/ZONE
M. inflatum
S. dispar
M. mantelli
M. dixoni
A.R.
A.J.
D.C.
H.O.
H.V.
C.A.
M.R.
M.P.
N.C.
M.S.
T.C.
T.A.
Wolborough
Haldon Hills
S.E. Devon Coast
E. Devon/W. Dorset
WL
THS
WS
AG
CSC
Fx
CB
TS
PP
H
LB
Bs/Fx
CB
EG
WIS
CBB
Ammonite data
Orbitoline data
SEA LEVEL


AGE/ZONE
CHANGES IN SEA LEVEL
This study
Haq et al. (1987)
Hancock (1989)
+
-
Early-Middle Cenomanian
Late Albian
A.J.
A.R.
T.A.
T.C.
M. dixoni
M. mantelli
M.S.
N.C.
S. dispar
M.P.
M.R.
M. inflatum
C.A.
H.V.
H.O.
D.C.

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