THE UNIVERSITY OF HULL

Middle and Upper Jurassic Foraminifera and Radiolaria of Scotland: An Integrated Biostratigraphical and Palaeoenvironmental Approach

being a Thesis submitted for the Degree of

Doctor of Philosophy

in the University of Hull

by

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April, 1995

ABSTRACT

This study is an integrated biostratigraphical and palaeoenvironmental analysis of foraminiferal and radiolarian distribution from all the major Middle and Upper Jurassic marine deposits of Scotland. These sampled sites are divided between two basins with Staffin Bay and Bearreraig Bay within the Inner Hebrides Basin, North West Scotland; and Brora, Balintore, Helmsdale and Eathie Haven representing the Inner Moray Firth Basin, North East Scotland.

A detailed taxonomic section is presented, which provides the means of comparison of microfaunal events between sites. A combined total of 212 species are described, of which 183 are foraminifera and 29 radiolaria; this includes a total of 23 species not previously recorded, comprising 16 foraminiferal and 7 radiolarian taxa.

A Callovian to Lower Kimmeridgian biozonal scheme, the first detailed attempted for the onshore UK, is constructed primarily using the Staffin Bay succession as the type section. It is based upon an integration of distinct foraminiferal and radiolarian taxa and events. This microbiostratigraphy is implicitly tied to the Boreal type ammonite scheme and comprises a total of 9 biozones and 12 sub-biozones. The new biozones are then correlated and compared with the other Scottish sites as well as other world-wide schemes.

A sequential palaeoenvironmental analysis is outlined, firstly by pinpointing microfaunal assemblages that are based upon a combination of the distribution of the major suborders, the species diversity and faunal abundances, as well as integrating the facies types and probable prevalent substrate conditions. These assemblages are then used to define palaeoenvironmental models for each recorded succession, and are related to prevailing substrate and sea water conditions and distance from the 'palaeoshoreline'. As the assemblages are shown to reflect particular conditions this allows a generalised basin development model to be assessed, related to sea-level changes (transgressions and regressions). All the sites are subsequently correlated palaeoenvironmentally.

The relevance of facies dependant distribution is also examined, particularly for benthic foraminiferids. The main conclusion reached is that facies dependence restricts the occurrences of taxa. However, this is not a constant feature as some specific taxa show the ability to colonise several facies types. It is this factor that permits a biostratigraphy to be constructed. Overall, assemblages appear to be related directly to a particular facies, which permits palaeoenvironmental changes to be assessed.

Finally the extensive Middle and Upper Jurassic literature is examined and a generalised world wide biogeography constructed. Four provinces are defined based on characteristic foraminiferal and radiolarian assemblages.

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ACKNOWLEDGEMENTS

Although the concept and logistics of this doctoral research programme were self conceived, it could never have been completed without the help provided by the following people and organisations, whom I wish to acknowledge:-

I am especially indebted to Dr. Phil Copestake (IEDS Ltd; formerly of Britoil and BP) who provided the initial encouragement and arranged the initial financial involvement of Britoil plc (now sadly no more) to fund the extensive field sessions and partial session funding.

Hull University have always been very accommodating in allowing me to follow my project, initially within the Geology Department (also, now sadly defunct) and especially within the School of Geography, who provided facilities including computing (particular thanks to Paul McSherry and Chris Chew). The University allowed me to lecture and demonstrate extensively within the School of Geography to supplement the commercial sponsorships gained. The librarians of the Inter Library Loans Section provided access to some of the more obscure literature.

I would also like to thank the various people who offered me the opportunity to consult to provide funds for this project, including Chris Ebdon (Amoco UK Exploration; formerly BP Exploration) and Robin Dyer (Geostrat Ltd; formerly BP Exploration).

I am especially grateful to Nicol Morton who collected additional samples from the Bearreraig Bay Section after my initial reconnaissance collection. I am indebted to Stefano Cresta (Italian Geological Survey, Rome) and Gulio Pavia (Milan University) who, with financial help from the Geology Department of Hull made it possible to present a paper at the Bajocian Working Group meeting in Piobbico, Italy.

Shell UK (Drs. Sikkema, Sissingh, Wakefield & Cordey) provided sponsorship in order to complete the latter part of the study and also kindly offered support to present papers and attend meetings which have helped shape my views.

John Whittaker kindly allowed access to the British Museum (Natural History) type slide collections for comparative study and also access to extensive literature collections.

Other funding and sponsorship gratefully received was provided by; the British Micropalaeontological Society, NATO ASI, The Systematics Association, The University of Hull (Geology Department), Joseph A. Cushman Award for Student Foraminiferal Research (The Cushman Foundation) and the University of Oslo.

However, without the understanding and support of Martyn Pedley (Hull University; School of Geography), who agreed to become my supervisor and helped ease my transition after departmental closure, completion of this thesis would not have been possible.

Jill Paterson is particularly thanked for her support and help in completing this thesis, as are the many friends who have offered succour and solace.

Finally, a word of thanks to my family who offered their moral support without question.

CHAPTER 1
INTRODUCTION

1.1. Introduction

Research on Jurassic benthic foraminifera has a long history, particularly in the British Isles and Europe, with a general emphasis on the Lower Jurassic. Work in the UK on Middle and Upper Jurassic foraminifera from the latter part of the nineteenth century to the 1950's concentrated on English Sub-Boreal sites and usually covered reconnaissance and related taxonomic research. The Upper Jurassic (Oxfordian-Kimmeridgian) appears to have been more extensively covered than the Middle Jurassic (Aalenian-Callovian). More recently there has been an upsurge in published output, possibly related to the discovery in the early 1970's of North Sea, Jurassic hydrocarbon source and reservoir rocks. However, the extensive Jurassic outcrops in Scotland were still ignored, despite the fact that these deposits provide a possible window through which similar offshore deposits could be compared.

Radiolarian investigation has concentrated on Cenozoic and Recent forms which are generally well preserved and have easily delineated evolutionary sequences. Pioneer workers in the last century were convinced by the earlier theses of Ehrenberg (1854) and Haeckel (1881, 1862, 1887) that radiolaria were not particularly useful in showing evolutionary change. This was due to a lack of understanding of their taxonomy and evolution and resulted in Mesozoic forms being neglected.

Modern, world-wide interest in Jurassic radiolaria has been mainly stimulated by the work of three groups of authors in areas of extensive siliceous deposition. These groups are covered in detail in Chapter 2. The foremost group comprises Pessagno and his co-authors who have since the 1970's dealt with Jurassic and Cretaceous Boreal and Sub-Boreal radiolarian biostratigraphy from Californian deposits. Similar studies have been carried out since the 1980's in Japan by a second group of authors. The final main group consists of de Wever and Baumgartner and their colleagues, working on the Tethyan faunas of Mediterranean Europe.

Onshore UK records of Jurassic radiolaria exist only from two Upper Jurassic Boreal deposits in Scotland, with both sites occurring within the Inner Moray Firth (see Fig. 1.1 for locations); at Eathie Haven, Cromarty (Waterston, 1951) and at Helmsdale, Sutherlandshire (Gregory, 1986). The value of British Jurassic and Cretaceous radiolaria is only now being assessed. Indications of their worth in biostratigraphical zonations are given by Dyer & Copestake (1989) and Partington ***et al.*** (1993a, b) for the Upper Jurassic and Lower Cretaceous of the North Sea, drawing on some initial research by Gregory (1986). In Chapter 2, the extent and distribution of previous work on Jurassic foraminifera and radiolaria is reviewed.

The initial aim of this doctoral research was to systematically collect samples from

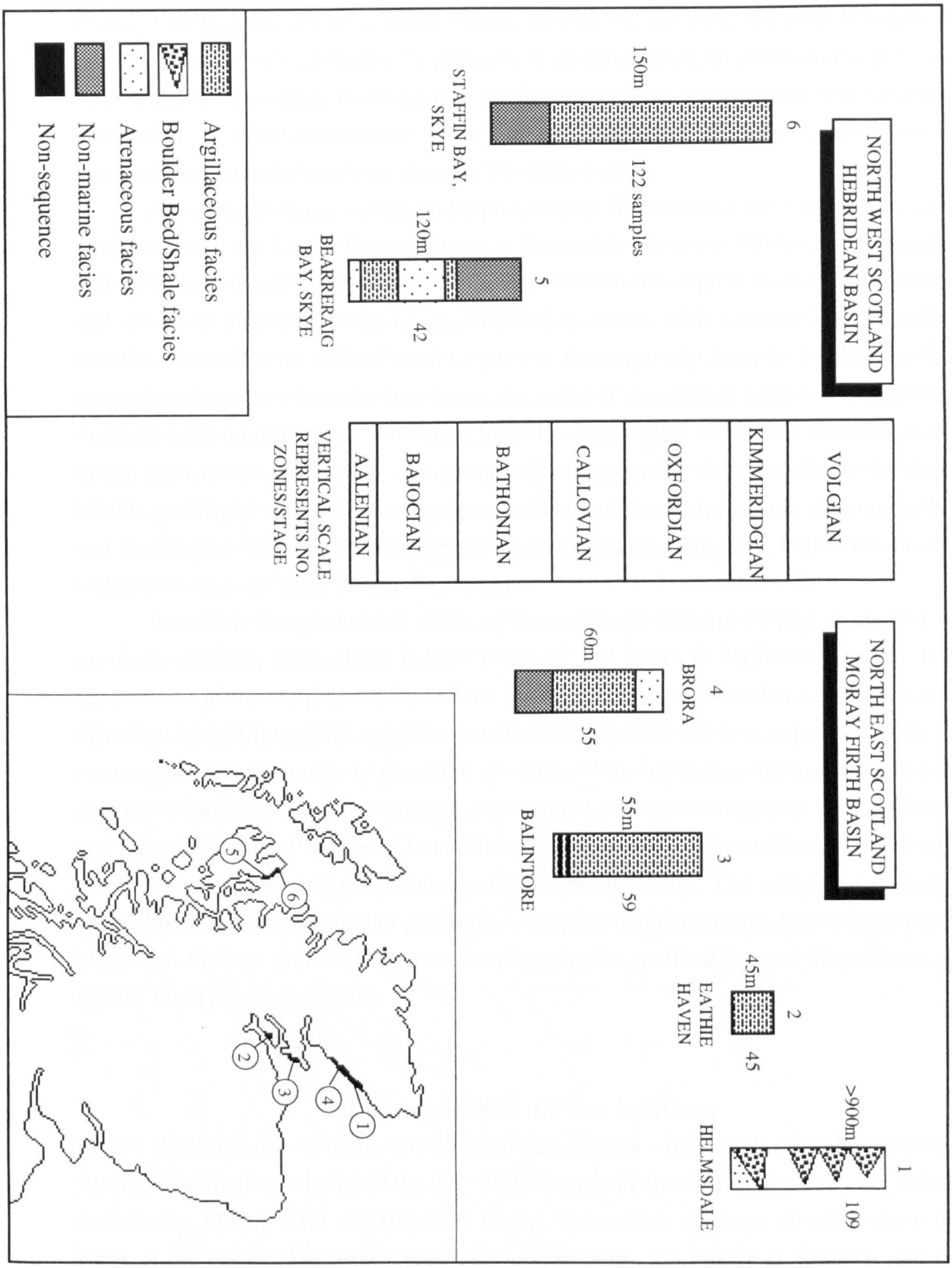


Figure 1.1. Summary of locations and broad lithological divisions, with Jurassic outcrop marked on the map in black

the entire Jurassic Stage of the onshore sections in Scotland which represents the Boreal Province. These sites range in age and area from the Lower Lias through to the Portlandian/Volgian of two separate basins, namely the Inner Moray Firth (Chapter 4) and the Inner Hebrides (Chapter 5), primarily from Skye, Mull, Morvern and Raasay. As no published data exists covering this whole interval, the examination was arranged essentially as a reconnaissance survey to test the actual presence and extent of foraminifera and radiolaria from these poorly studied areas.

An unusually large sample set (approximately 700 samples) was collected because a pilot study of the Lower Kimmeridgian at Helmsdale (Gregory, 1986) had ascertained that microfaunal distribution could be quite poor from this region. It was soon realised that too much information was being generated, however, with most sections providing excellent foraminiferal and radiolarian recovery. Consequently, in order to complete this research and within a feasible time frame, the scope of the original project was redefined to concentrate on the Middle and Upper Jurassic of the region. Figure 1.1 summarises the extent and locations of the sites and sections chosen for study, which include all the major Middle and Upper Jurassic outcrop present in Scotland. Localities include Bearreraig Bay and Staffin Bay from the Inner Hebrides Basin and Brora, Balintore, Eathie Haven and Helmsdale from the Inner Moray Firth Basin.

Excellent documentation exists of the ammonite biostratigraphy as erected by previous workers, particularly Sykes (1975a-b) and Sykes & Callomon (1979). This scheme acts as the template against which foraminiferal and radiolarian distribution, and therefore, biostratigraphical and palaeoenvironmental events can be compared. Figure 1.2 summarises the ammonite biozonation scheme and its correlation between the sites of interest. This study is the first attempt at erecting a microbiostratigraphy for the Middle and Upper Jurassic of Scotland. In addition, very few workers have chosen to deal with both biostratigraphy and palaeoenvironmental interpretation. The integrated approach applied here has the potential of providing a defining template for predictive exploration plays and models such as Sequence Stratigraphy, as outlined by van Wagoner ***et al.*** (1988) and Haq ***et al.*** (1988).

1.2. Introduction to the locations

Figure 1.3 illustrates the important Jurassic depocentres within basins developed during Mesozoic tectonic evolution of the UK. Major areas of extensive sedimentary deposition include the Moray Firth and Hebrides Basins, the surface outcrops of which form the basis of this study. The areas chosen for investigation are briefly as follows, and are discussed in detail under the relevant chapter sections (Chapters 4 and 5):-

1.2.1. Hebrides Basin (Fig. 1.4)

The area encompassing the Hebrides Basin was a major depocentre of Jurassic sediments, which owe their present day existence to the protection given by a later

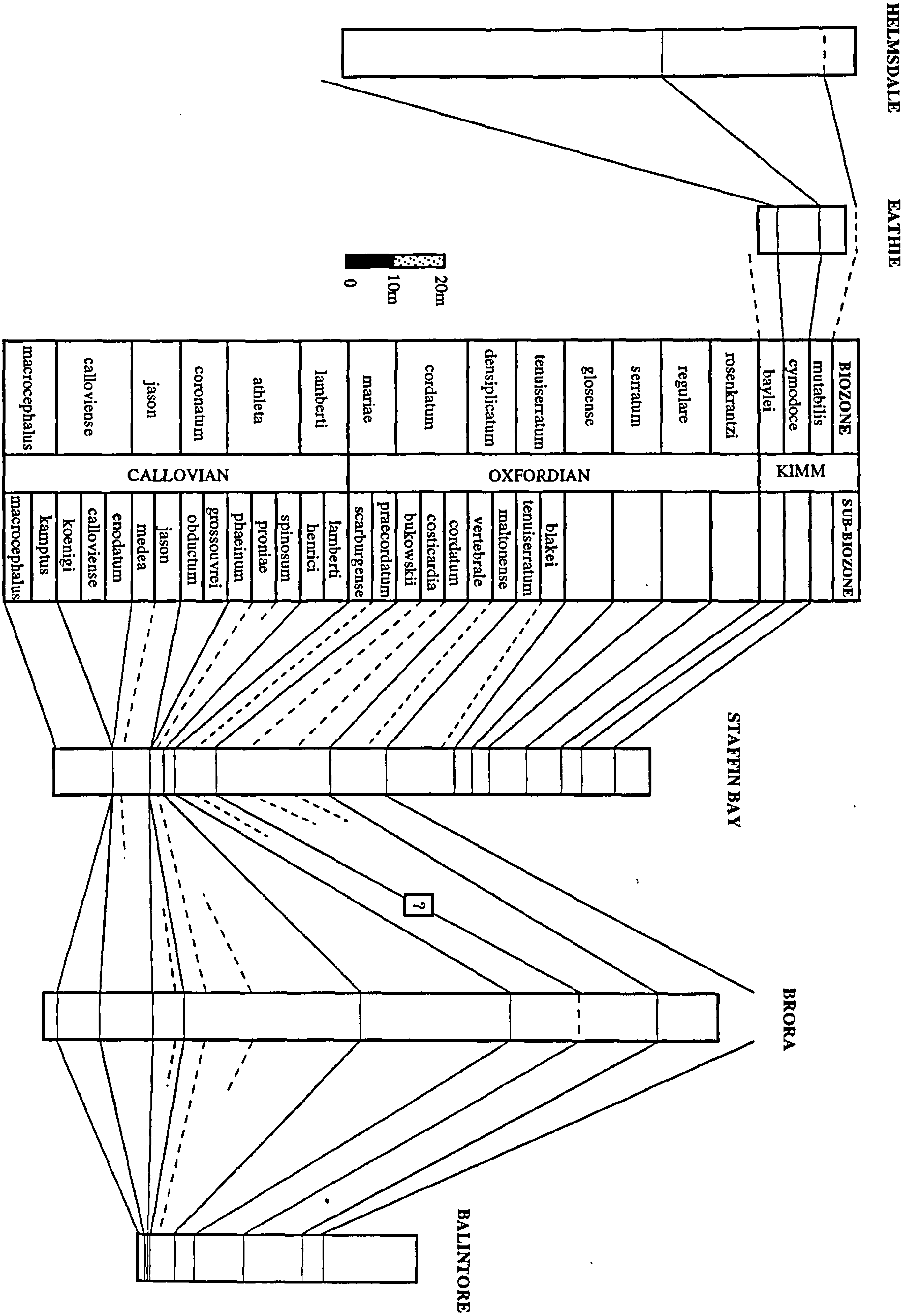


Figure 1.2. Correlation of the standard Boreal ammonite biozones between the studied Scottish sites

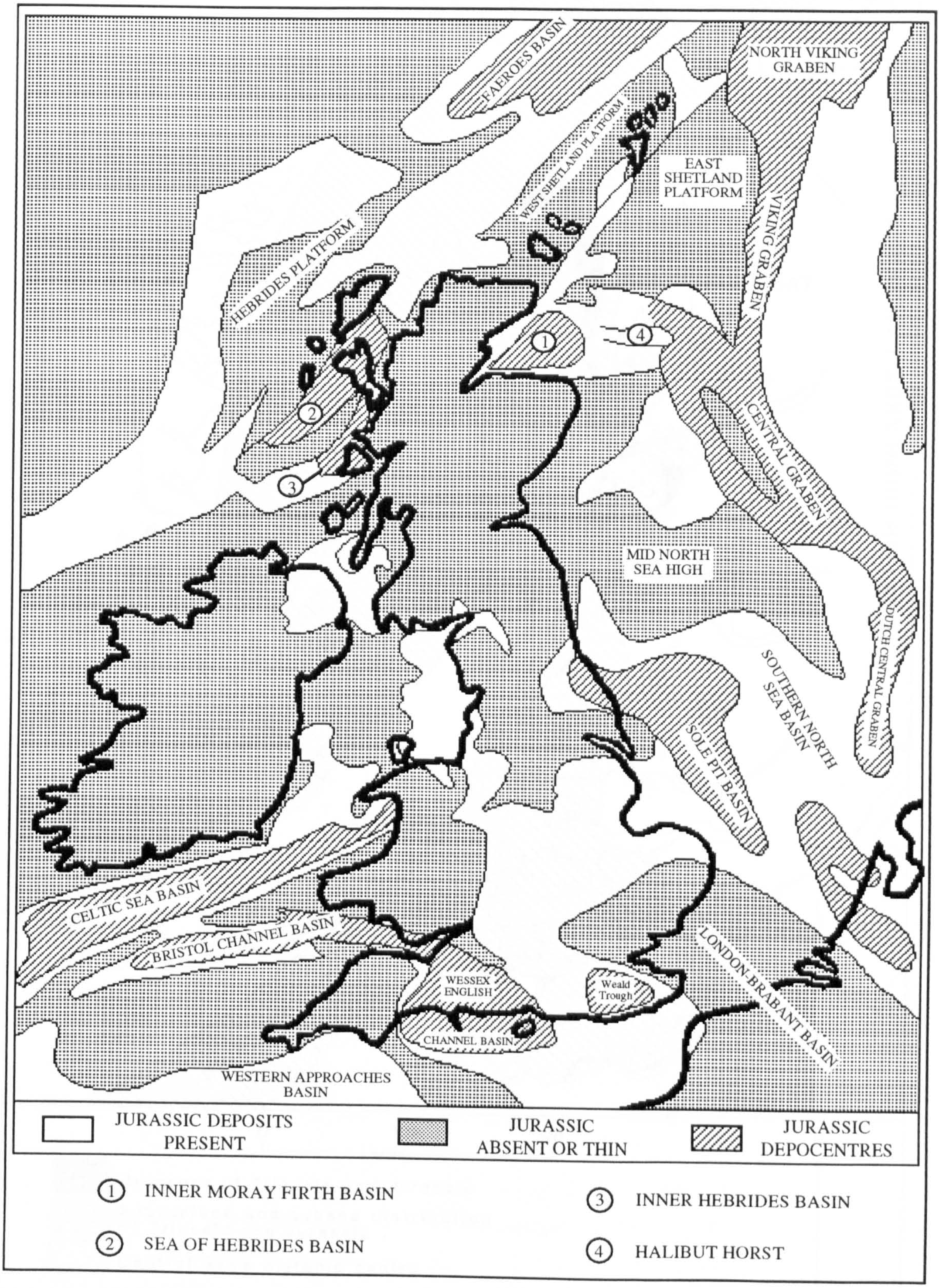


Figure 1.3. Distribution of Jurassic rocks and depocentres in relation to the UK tectonic elements (adapted from Copestake, 1989)

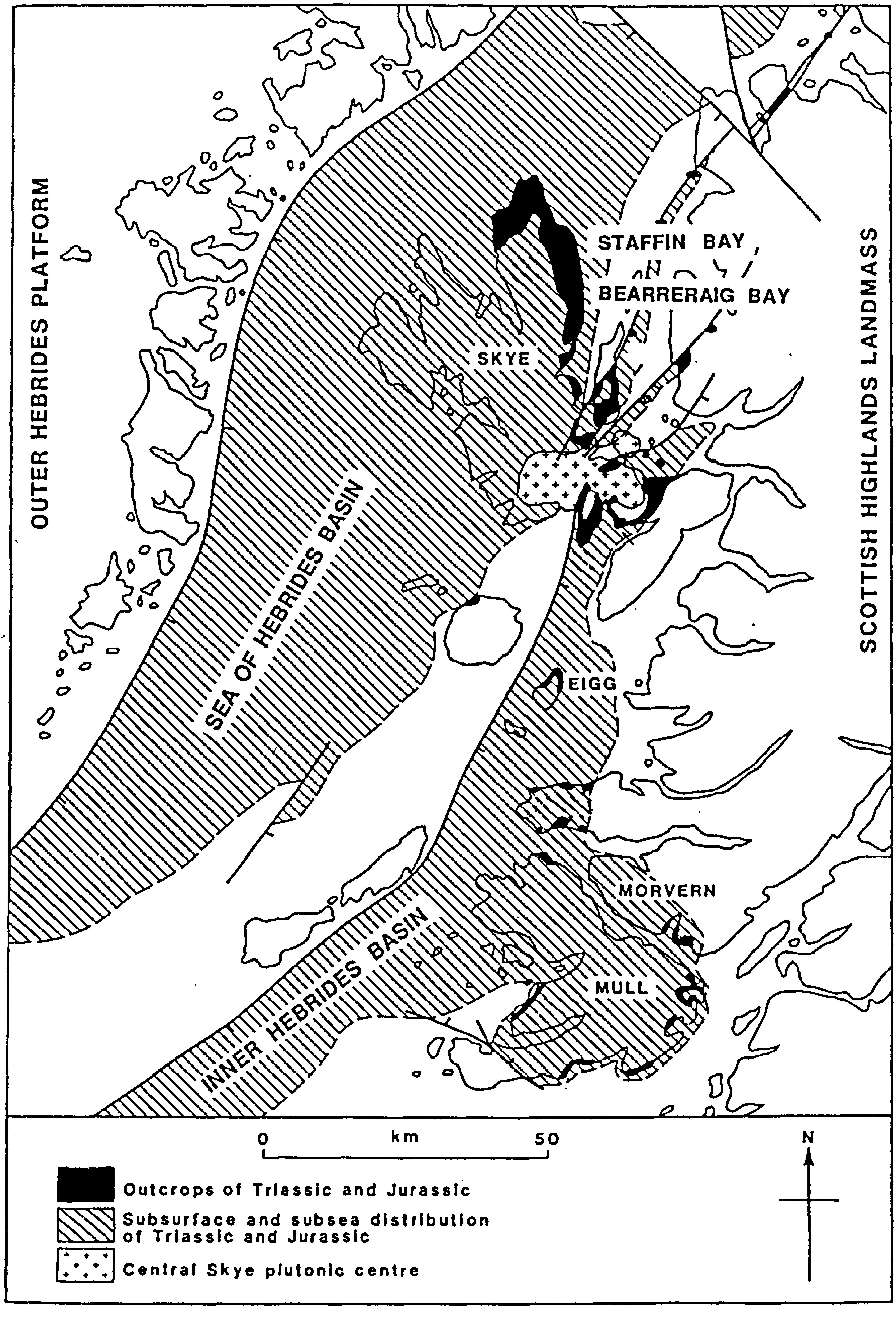


Figure 1.4. Structural elements of the Inner Hebrides Basin (adapted from Morton, 1989)

capping of Tertiary volcanic lavas.

Two main sites were investigated, both occurring on the Isle of Skye;

i). Bearreraig Bay, Skye:- Aalenian-Bajocian. This site was selected to compare foraminiferal distribution with the ammonite biostratigraphy across this stage boundary in an attempt to investigate the validity of its nomination by Morton (1984, 1990a, 1991) as a Global Boundary Stratotype Section and Point (GSSP) for the basal Bajocian.

ii). Staffin Bay, Skye:- Lower Callovian-Lower Kimmeridgian. This locality provided the opportunity to integrate biostratigraphy and palaeoenvironmental analysis. The main points of investigation were;

a). to ascertain foraminiferal/radiolarian distribution.

b). to erect a biostratigraphical template. As Staffin Bay provides the most complete section, it was chosen to select biostratigraphically important forms. This biozonation was assessed against similarly aged deposits in the Inner Moray Firth (i.e. Balintore, Brora, Eathie Haven and Helmsdale).

c). to investigate facies limitations on the distribution of benthic foraminifera and planktonic radiolaria.

d). to test whether basin development can be ascertained by gross assemblage and hence palaeoenvironmental changes.

1.2.2. Inner Moray Firth (Fig. 1.5)

The Jurassic is represented in onshore outcrop as a thin mantle surrounding the Inner Moray Firth and, as such, is a window through which similarly aged deposits in offshore sequences can be studied. The main sites are at;

i). Brora:- Lower Callovian-Lower Oxfordian. This section provides some of the thickest sequences of Callovian strata in the onshore UK and represents nearshore deposition which may be tied directly into deeper water environments at Balintore.

ii). Balintore:- Lower Callovian-Middle Oxfordian. This is a condensed section and the offshore equivalent to the section at Brora, allowing the possibility of testing correlations and faunal changes through time as well as the affects of lateral environmental changes.

iii). Helmsdale:- Lower Kimmeridgian-Volgian. The lower part (***cymodoce*** to ***eudoxus*** ammonite Biozones) of this nearshore, syndepositionally fault controlled area of the basin has already been investigated (Gregory, 1986), but was re-examined in this study in the light of radiolarian recoveries at Eathie Haven; it was also used as the justification for collecting from the overlying younger sequences at Helmsdale.

iv). Eathie Haven:- Lower Kimmeridgian. This is a possible deep water equivalent to the

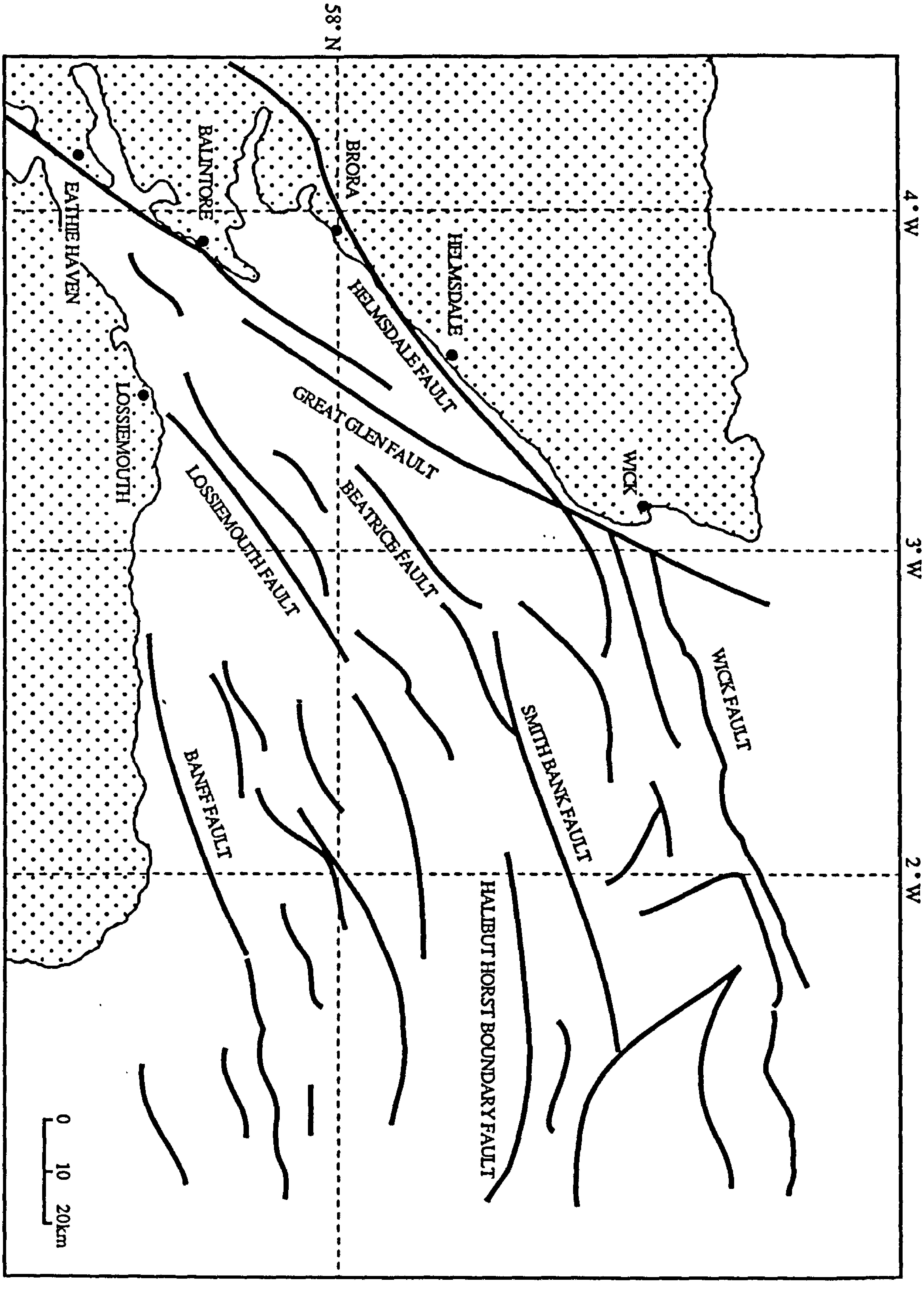


Figure 1.5. Structural elements of the Inner Moray Firth Basin

sequence at Helmsdale covering the Lower Kimmeridgian, which provides the opportunity to test the basinward changes in relationships between foraminifera and radiolaria.

1.3. Regional Setting

Structurally, the Moray Firth and Hebrides Basins are somewhat similar (Figs. 1.3-1.5) as both are controlled in their extent and area by extensional or transtensional tectonics. The Hebrides Basin (Fig. 1.4) comprises a complex half graben created during the early rifting phases of the North Atlantic Ocean (Binns *et al.*, 1975; Ziegler, 1988; O'Neill & England, 1994). Thick Triassic and Jurassic sediments occur in two fault block created basins, separated by a basement ridge. These two basins, the Sea of the Hebrides and the Inner Hebrides Basin (Binns *et al.*, 1975), have similar facies types developed (Fig. 1.4). Only Middle and Upper Jurassic strata from the Sea of the Hebrides will be covered here.

The Moray Firth Basin (Fig. 1.5) forms the western arm of the North Sea Basin trilete system and lies to the east of the Sutherlandshire coast. It is fault controlled and structurally well defined to the west by the Helmsdale and Great Glen Faults and to the north by the Wick Fault. Internally, the basin is subdivided into a series of interlinked grabens and half-grabens. McQuillin *et al.* (1982) suggested a kinematic strike-slip model for basin development, opening as a result of 8km of dextral displacement along the Great Glen Fault during the Jurassic-Early Cretaceous. This view is also supported by the work of Barr (1985), Bird *et al.* (1987) and Roberts *et al.* (1990). Recent detailed seismic interpretation by Underhill (1991a-b), however, throws this model into some doubt, with the Great Glen Fault being dormant in the Jurassic with basin development occurring under an extensional and not strike-slip regime.

What is in no doubt is that the Helmsdale and Wick Faults were particularly active during the Upper Jurassic. In particular, the Helmsdale Fault was associated with syn-sedimentary deposition of the Helmsdale and Kintradwell Boulder Beds (Pickering, 1984; Roberts, 1990; Roberts *et al.*, 1990).

Sykes (1975b) hypothesized that subsequent post-Jurassic movement along the Great Glen Fault, associated with the relative present day location of outcrop, allows depositionally paired sequences representing nearshore and deeper water facies to be tied together. These juxtaposed, paired nearshore/deeper water sections include the Lower Kimmeridgian present at Helmsdale and Eathie Haven and the Callovian-Oxfordian sections at Brora and Balintore. This tectonic view has been thrown into some doubt by the work of Underhill (*op. cit.*), although his hypothesis is that these paired sections still represent shallow/deep facies, as their modern day position is nearly original. Underhill (*pers. comm.*, 1991) indicates that even with post-Jurassic movement, less than 10km of dextral motion is likely to have occurred.

Therefore, it may be possible to correlate transgressions and regressions and the effect sea-level change events have had on the microfaunas from these particular sites.

1.4. Previous Micropalaeontological Research

Previous research from onshore Scottish sections has been limited and mainly confined to examining a small part of a section to compare with other sites, usually within England. Various service and oil companies have attempted to cover the Jurassic of the onshore Scottish sections, but generally little effort has been spent on working the material up to its potential. Robertson's Research (now Simon-Robertson) produced the most comprehensive of these studies, but the data remains unpublished (Robertson's Report, 1974).

Major foraminiferal coverage has been restricted to two taxonomic publications, the first by Cordey (1962) on the Callovian of the Dunans Clay Member of Staffin Bay, Skye. Gordon (1967) looked at a similarly aged section in Brora at the Brora Brick Pit which was filled in 1975. Both established the presence of diverse Middle Jurassic microfaunas.

The earliest published material was by Waterston (1951) who included a brief list of the foraminifera and radiolaria that he recovered in his appraisal of the Lower Kimmeridgian ammonite and bivalve distribution at Eathie Haven, Cromarty. Several authors have collected a few samples for direct comparison with other sections. These include Weir (1943) who sampled the Middle/Upper Jurassic of Skye (6 samples) and Brouwer (1969) who collected Lower Jurassic samples from Portree, also on Skye (3 samples).

More recently published work forming the basis of several sections covered in this thesis include; the palaeoenvironmental analysis of Lower Kimmeridgian foraminifera and radiolaria at Helmsdale (Gregory, 1989); the establishment of a microfaunal radiation that pre-dates the inception of the ammonite marker for the basal Bajocian at Bearreraig Bay, Skye (Gregory, 1990, 1991); the nomination of a biostratigraphically restricted foraminiferid that occurs in many Lower Kimmeridgian sites within the UK (Gregory, 1992); and palaeoenvironmental analysis of basin development using foraminiferal assemblages for the Middle and Upper Jurassic at Staffin Bay, Skye (Gregory, in prep.).

Ostracods have also received little attention with only the unpublished work of Whatley (1965) covering Middle and Upper Jurassic sequences on Skye and at Brora and Balintore. Samples collected in this study from the Aalenian/Bajocian of Bearreraig Bay are currently being processed for ostracoda (Lord; University College, London). Results of this work were to be presented at the Aalenian/Bajocian Working Group Meeting held in Morocco, 1994.

Nannofossils have been scantily covered and studies remain confined to the Middle and Upper Jurassic of Staffin Bay (Hamilton 1978) and the Middle Jurassic of Bearreraig Bay (Medd in Penn *et al.* 1980). Recently completed work includes the examination of the author's samples from Bearreraig Bay by Bown (1991).

Palynological investigations have, on the whole, been more numerous, perhaps reflecting oil company dependence on palynological biozonation for offshore exploration.

Early work carried out by Gitmez (1970) and Gitmez & Sarjeant (1972) covered the Kimmeridgian of Europe and included Scotland; this initial reconnaissance has been updated by more refined sampling.

The Helmsdale Outlier has attracted a large amount of attention since the initial work of Lam & Porter (1977) on dinoflagellates from the Lias-Kimmeridgian. This sequence was updated by Porter (1988) for the Oxfordian. Riley (1981) dated the upper part of the Helmsdale Boulder Beds as Portlandian based on four samples. Barron (1989) provided detailed biostratigraphical resolution of the various Kimmeridgian to Volgian ammonite zones using dinoflagellates. MacLennan & Trewin (1989) covered the Upper Bathonian-Middle Callovian section of the Inner Moray Firth, working with integrated palynofacies. They compared their results with various offshore well data from the Beatrice Field.

The Hebridean Basin has been ignored until recently with the publications of Riding (1982, 1984, 1992) and Riding ***et al.*** (1991) concentrating mainly on the dinoflagellate biostratigraphy of the Middle and Upper Jurassic of Strathaird, Staffin Bay and Bearreraig Bay. His schemes appear to correlate well with similar biozonations for the North Sea (Riley ***et al.***, 1990) and England (Woollam & Riding, 1983).

1.5. Preparation Techniques

The various aspects of sample collection, preparation, picking and microfossil identification are introduced here.

1.5.1. Sample Collection

Poor exposure of the inter-tidal collecting sites covering the Middle and Upper Jurassic of Scotland has possibly discouraged previous large scale studies. Prior to logging and collection all sites were cleared of debris including seaweed, sand and boulders. Additionally, most of these areas have also been affected by tectonic folding of the strata. Hence, all dips were measured during logging so that true thicknesses could be calculated as accurately as possible.

The sections were logged in detail and sample collections were made from 10-20cm deep transects cut into unweathered sediments. Samples were taken at metre reconnaissance intervals, from a 'vertical' thickness of no more than 2cm in order to reduce the effects of faunal mixing.

1.5.2. Sample Preparation

Various preparation techniques were examined in order to decide which would prove to be least damaging to the different microfaunal groups present within samples. The Hydrogen peroxide method outlined by Then & Dougherty (1983) was not used as the associated oxidation can affect iron pyrite. Since foraminifera and radiolaria can be replaced by this material during diagenesis, it was felt that the benefits of this quicker method were outweighed by its more destructive effects.

Radiolaria are normally recovered from siliceous cherts or radiolarites and are therefore extracted using the Hydrofluoric acid method (see Pessagno & Newport, 1972 for details), which involves some etching with Hydrochloric acid. However, this method was rejected here as all samples collected from the Scottish basins could eventually be broken down by the disaggregation technique outlined below and also because a common replacement mineral for the original opaline silica of radiolaria is calcite.

The paraffin technique was therefore deemed to be the least destructive; this procedure is outlined below:-

1). Wash sample to remove all possible contamination.
2). Break sample into small pieces.
3). Dry in an oven at medium temperature overnight.
4). Soak the sample in paraffin for several hours.
5). Remove paraffin and filter to reuse.
6). Replace sample in a metal container, add water and a defloculant, eg. Sodium bicarbonate, and boil gently until the sample is disaggregated, which can take several hours.
7). Wet sieve the disaggregated sample through a 63μm sieve to retain a residue.
8). Remove the residue onto filter paper and dry in an oven.
9). Dry sieve into fractions suitable for picking.

1.5.3. Sample Picking and Identification

Consistency in picking was considered paramount to enable the relative comparison of samples for palaeoecological studies. The residue was size sorted into two fractions; between 63μm and 125μm, and greater than 125μm.

Many oil and service companies apparently use only the greater than 125μm fraction and indeed this is commonplace in Cretaceous studies. The smaller size fraction was used here because many species of Jurassic radiolaria, and some foraminiferal forms, are much smaller than 125μm.

For picking, the residue was spread thinly onto a gridded metal picking tray. Equal tray amounts were scanned for each residue fraction, with all the picked residue being retained and weighed to allow the relative number of foraminiferids per gram to be calculated. Approximately 250 individuals were picked per sample, as studies have shown this to be the minimum necessary to be representative of the total population (Magurran, 1988; Pielou, 1979). Samples were classified as barren if they yielded no microfauna after 1 hour of scanning.

Identification was carried out with an optical binocular microscope, with additional study and photography using S3600 and S600 Cambridge Scanning Electron Microscopes (S.E.M.). Radiolarian identification was enhanced by the use of the S.E.M., which aided detection of characteristic features.

Specimen identification involved the use of literature as covered in Chapter 2

(Previous Research) and Chapter 6 (Taxonomy). The Ellis & Messina Foraminiferal Catalogue of the School of Geography and Earth Resources at Hull University provided a useful resource. Type collections housed at the British Museum (Natural History) and at Hull University (prior to departmental closure) were also examined for comparative purposes.

1.6. Summarised Aims and Objectives

Briefly, the aims and objectives of this work were;

1). To carry out a reconnaissance survey of Middle and Upper Jurassic foraminifera and radiolaria from the Aalenian/Bajocian and Lower Callovian-Volgian of all the major onshore outcrops present in the Inner Moray Firth and Inner Hebrides.

The Bathonian is represented in the Boreal Province by estuarinal non-marine sediments with minor marine horizons and was therefore not investigated. However, foraminiferids have been reported in the Duntulm Formation of the Upper Bathonian on Skye in thin marine incursions which were interpreted as lagoonal by Andrews & Walton (1990; Andrews ***pers. comm.***, 1991).

2). To investigate the taxonomy of the foraminifera and radiolaria recovered, with synonymies and previous distribution for biostratigraphical and palaeoecological comparison.

An important feature is the use of comprehensive species descriptions. These are included to alleviate any misconceptions. Probable new species are indicated by open nomenclature and described fully, but not named, as a doctoral thesis is not the correct vehicle for such practice as defined by the Rules of Zoological Nomenclature (Ride, 1975).

3). To review the extensive world-wide previously published literature to ascertain foraminiferal and radiolarian distribution for biostratigraphical and palaeoenvironmental comparisons and to determine the biogeographical distribution of major groups during the Middle and Upper Jurassic.

4). To tie foraminiferal/radiolarian events into the precise biozonal and sub-biozonal Boreal ammonite zonation available for the Scottish sections.

5). To attempt to erect a novel foraminiferal biozonation for the Middle and Upper Jurassic of Scotland and to compare and assess these with other published biozonations.

6). To assess the biostratigraphical potential of radiolaria.

7). To correlate foraminiferal and radiolarian events within and between the Inner Moray Firth and Inner Hebrides Basins.

8). To investigate the palaeoenvironmental distribution of foraminifera and radiolaria and the value of these groups in palaeoenvironmental analysis, particularly in relation to basin development. Of particular interest is assessing the value of foraminiferal/radiolarian assemblages in defining transgressive/regressive cycles. The most notable example in the study area is the Callovian transgression which can be traced both at intra and inter basinal levels in the Moray Firth and Hebrides Basins. The integrated study of benthic foraminifera and planktonic radiolaria distribution was also investigated to assess basin development in terms of changes of relative sea-level /water column thickness.

9). To examine the extent of facies type control on the distribution of benthic foraminiferal taxa and the impact this often cited limitation has on the potential use in biostratigraphy and palaeoenvironmental interpretation.

CHAPTER 2
PREVIOUS RESEARCH

2.1. Introduction

In this chapter, Middle and Upper Jurassic foraminiferal and radiolarian published articles are reviewed to assess the extent and coverage of previous research. This data has been plotted onto regional maps which cover the UK, Germany, Europe and the rest of the world. These texts have been referred to in the main body of the thesis, within the taxonomy section, or have provided reference that aided taxon identification and delimited biostratigraphical extent. The most relevant articles are additionally discussed in some detail, either here or within the relevant sections of Chapters 1, 4, 5, 6 and 7. A separate section (7.4), which draws from these sources, is also included in an attempt to evaluate the biogeographical and provincial distribution of foraminifera and radiolaria in the Middle and Upper Jurassic.

It is immediately apparent that whilst foraminifera and radiolaria have been studied for about the same period of time, from the mid nineteenth century, there are three times as many published foraminiferal studies. Also, texts dealing with an integrated biostratigraphy and palaeoenvironmental analysis are very rare and even rarer still are accounts dealing with a combination of foraminifera and radiolaria. These features are discussed below.

2.2. Foraminifera

Middle and Upper Jurassic sites throughout the world have been widely studied for their foraminiferal faunas from the latter part of the nineteenth century to the present day. In order to portray this distributional data, these records have been grouped into several regions; the UK (Fig. 2.1), Germany (Fig. 2.2), the rest of Europe (Fig. 2.3) and the rest of the world (Fig. 2.4). The geographical distribution and abundance of published articles may, in some way, represent the historical progression of research from initial reconnaissance through a rigid taxonomic approach to a more considered and integrated palaeoecological analysis. Additionally, analysis of these articles can aid differentiation of broad world-wide faunal provinces, which may have developed during the Jurassic.

2.2.1. United Kingdom

The literature available for the Middle and Upper Jurassic of the British Isles (Fig. 2.1) is extensive and there appear to have been three main periods of foraminiferal research, which can be roughly characterised by philosophy and approach. It is obvious that the classic Jurassic sections in Dorset and the Midlands have been the most closely studied for foraminiferal faunas. Specific previous micropalaeontological research of the

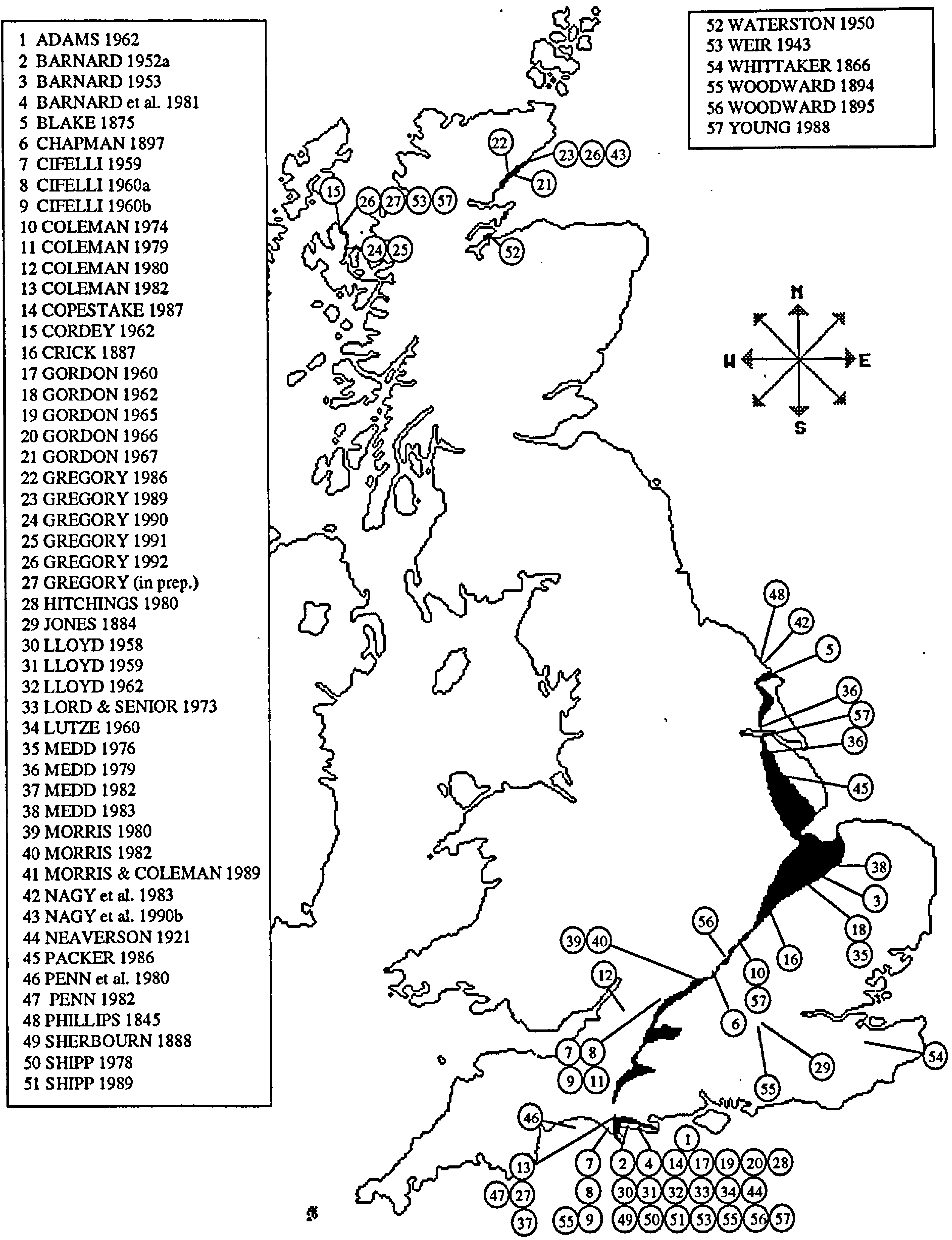


Figure 2.1. Distribution of published research on Middle and Upper Jurassic foraminifera (outcrop marked in black) from the British Isles. Both Shipp (1989, number 51) and Morris & Coleman (1989, number 41) covered the major Jurassic sections, and so are not indicated on the map

Scottish basins is somewhat limited. This has already been discussed in Chapter 1 and will be covered more extensively within the relevant sections of Chapters 4 and 5.

Historically, the initial burst of research occurred between 1845 and 1897 and is represented by nine publications. These articles provide a first pass reconnaissance of foraminiferal distribution, undertaken by a few professional people involved in the naturalist pursuits that characterised the latter part of the nineteenth century.

Phillips (1845) provided one of the earliest description of foraminifera from the Middle and Upper Jurassic of the UK, with a brief account on the 'microscopic shells' recovered from the Lias and Kimmeridgian of the Yorkshire coast. Work from the latter part of the nineteenth century was either of a rudimentary taxonomic nature or was comprised almost wholly of species lists of taxa similar to those described from equivalent aged continental deposits by authors such as Terquem and Schwager (see Fig. 2.3 for references). Examples of such listings include the surveys by Chapman (1897) from Hartwell and by Woodward (1894, 1895) who concentrated on a lithostratigraphical description of Middle and Upper Jurassic of England and the macrofossils and microfossils contained within these sediments.

Slightly more detailed studies include reports by Jones (1884) of foraminifera recovered from deep water well borings that penetrated the Jurassic. Whittaker (1866) recovered ***Lenticulina*** from the Oxford Clay of several boreholes in Kent and Crick (1887) briefly described five genera from the Oxford Clay of Keyston. Cherbourg (1888) studied samples from the Upper Jurassic of Dorset and remarked on the adherent foraminifera ***Bullopora*** and its apparent attached mode of life.

The early and middle part of the twentieth century was notable for the sparsity of published material. Exceptions include Neaverson (1921) who re-described faunas recovered by Crick (1887) from the Upper Jurassic of the now classic Dorset section. An important piece of work was published by Weir (1943), who studied a wide range of samples from Lower to Upper Jurassic sections of Scotland and England. He applied a rigid taxonomic regime, with descriptions of many apparently new taxa which were missed by later workers. Some of these taxa now appear, in certain circumstances, to take taxonomic priority over some well established forms (Chapter 6, Taxonomy).

The period after the second world war was represented by 17 articles, beginning in the 1950's and culminating in the late 1960's. These established the emergence of a more precise and mature taxonomic approach for Middle and Upper Jurassic foraminifera. In addition, there were first attempts at population studies and biostratigraphy; the work generally concentrated upon the now 'classic' sections of England in Dorset and the Midlands. These investigations were carried out by several authors, initiated primarily by Barnard (1952a, 1953) working on Upper Oxford Clay sections (***lamberti-cordatum*** Biozones) from Dorset and Huntingdonshire. It appears that only a proportion of the total fauna was recorded within these publications (Copestake ***pers. comm.***, 1987). Lloyd (1959, 1962) furnished detailed taxonomic and distributional data for the Upper Jurassic agglutinated, miliolid, robertinid and polymorphinid taxa of the Dorset coast, but did not publish the more diverse and abundant lagenid population recovered (Lloyd, 1958; unpublished PhD thesis; partly covered by Shipp, 1989). Gordon was also prolific in this period, working on faunas from the Ampthill Clay of Cambridgeshire (Gordon, 1960, 1962) and the Corallian (Oxfordian) of Dorset (Gordon, 1965), illustrating his papers with ***camera lucida*** drawings and morphotypic variation within certain lagenid and agglutinated taxa. He followed this with detailed morphotypic variations and biometrical analysis of the more numerically important lagenid taxa, such as ***Lenticulina muensteri*** and ***L. tricarinella***, from the Middle and Upper Jurassic (Gordon, 1966), establishing and grouping a series of intraspecific forms whose end members had been previously split into different taxa. Cifelli (1959, 1960a, b) produced a wide ranging study of Middle Jurassic (Bathonian) sediments of the Cotswolds and erected a faunal zonation based on details of facies dependent assemblages. Lutze (1960), who primarily worked on German sections, included some comparative material from Dorset for his monographic work on Callovian and Oxfordian foraminifera.

The third period extends from 1973 to the present day and is represented by 29 articles which cover both outcrop and subcrop areas. The latter type of study was undertaken under the auspices of the British Geological Survey (formerly the Institute of Geological Services) as part of their borehole programme examining the Middle and Upper Jurassic. Generally, this work consisted of listing foraminiferal distribution and occasionally illustrating some of the stratigraphically important forms. The Milton Keynes borehole was examined by Coleman (1974) who covered the Oxford Clay and Kellaways Beds. Medd (1979) looked at two boreholes from Worlaby in Humberside and listed the Upper Jurassic foraminifera. The Bajocian of Lyme Bay and the Bathonian Fullers Earth of Horescombe Vale were examined by Penn ***et al.*** (1980) and Coleman (1980) respectively. Medd (1982) and Coleman (1982) in association with Penn ***et al.*** (1980) examined the foraminifera from the Middle and Upper Jurassic of the Winterbourne Kingston borehole. Additionally, as a consequence of the BGS programme, Medd (1983) studied samples from the Callovian of Peterborough, constructing a biostratigraphical zonation of this small part of the Upper Jurassic and discussing the fauna in terms of gross faunal turnovers and facies development.

An unusual life mode was discovered by Hitchings (1980) for a lenticulinid foraminiferid which inhabited vacant pores in corals and sponges, adapting its test shape to enable invasion.

Of importance for comparative purposes are later works which developed palaeoecological considerations (e.g. Barnard ***et al.***, 1981) or biostratigraphical ranges of common taxa (e.g. Morris & Coleman, 1989; Shipp, 1989). The latter group of authors tackled the Bathonian to Callovian and Oxfordian to Kimmeridgian respectively, indicating and illustrating stratigraphically important taxa. Some palaeoecological generalisations were also presented, with assignation of preferred palaeoenvironments of several foraminiferal groups based on facies analysis. Barnard ***et al.*** (1981) investigated in some detail the Oxford Clay (mid Callovian-Lower Oxfordian) of southern England in terms of a broad foraminiferid faunal composition related to test wall composition. This led to an interpretation of depth, salinity and sedimentation rate as applied to palaeogeographical maps for England (Dorset to Yorkshire) during the Oxford Clay deposition. Copestake (1987) recollected and listed foraminifera from many of the classic sections, however, there were no illustrations but only brief lists and a few stratigraphical comments on the Bathonian to Portlandian.

Nagy *et al.* (1983) hypothesised that a marginal marine situation existed for the majority of the Bajocian of the Yorkshire coast, based upon the facies and a foraminiferal association with a predominance of agglutinated taxa.

There have also been several doctoral theses containing particularly important data, but unfortunately they have remained largely unpublished. Examples include the work of Lloyd (1958), Shipp (1978), Morris (1980) and Young (1987).

Articles concerning the offshore regions of the UK and Eire (as illustrated on Fig. 2.3) have only been published in any significant numbers since the 1980's - a consequence of the oil industry exploring these areas. However, it is apparent that despite the economic importance of North Sea (including the Norwegian Shelf) and Irish Sea Jurassic source and reservoir rocks, relatively little has been published, with many papers merely mentioning any foraminifera that occurred. This is probably a direct consequence of the commercial sensitivity of the data; additionally there is a reliance on palynological driven zonations. Important initial papers are those by Nagy (1985a, b) who studied the Statfjord field which included Early Bajocian sediments. He characterised various deltaic environments of the Brent Formation by the changes in the sometimes extensive agglutinated dominated assemblages present.

Morris & Coleman (1989) and Morris & Dyer (1990) described predominantly agglutinated dominated faunas from the Tarbert, Heather and Kimmeridge Clay Formations of Middle to Upper Jurassic sequences from the North Viking Graben. They indicated the usefulness of agglutinated foraminifera in regional and field correlation. It must be noted that regional in this case may be applied only to the most northerly part of the Boreal Realm.

Nagy & Johansen (1989) investigated the preservational and distributional factors affecting a single species, ***Reophax metensis,*** from the Lower and Middle Jurassic of the Statfjord Field, inferring that its dominance in certain locations was indicative of prodeltaic conditions. Nagy *et al.* (1990b) analysed faunas from the Statfjord area, the Yorkshire Coast and Northern Scotland, relating distribution of assemblages to facies with a predominance of agglutinated taxa correlated to organic rich sediments. Toarcian to Bajocian agglutinated dominated taxa from the Statfjord region were further analysed quantitatively by Nagy & Johansen (1991) who established environmental conditions and interpretation on the basis of these. Nagy (1992) developed this theme further and attempted to support his hypotheses with complex statistical analysis of foraminiferal faunas from the North Sea region.

Recent articles by Partington *et al.* (1993a, b) are probably the most important biostratigraphical studies published to date and represent a synthesis of commercial data held by British Petroleum and its partners (including some published and unpublished data from this thesis). This extensive database covers the Middle and Upper Jurassic of the Northern North Sea, Viking and Central Grabens with a biostratigraphical zonation based primarily on acme tops and final appearances of specific radiolarian and foraminiferal taxa. Richards *et al.* (1993), in their lithostratigraphical nomenclature of the UK North Sea Sector, use some of the data of Partington *et al.* (*op cit.*), but in less detail. In conclusion, these authors noted that assemblages recovered from the Middle and Upper Jurassic of the North Sea are notable for the predominance of agglutinated faunas, with calcareous taxa being poorly represented.

The Celtic Sea, south west offshore Ireland, which has also been the site of commercial activity, was investigated by Colin *et al.* (1981) who recorded the presence of Upper Jurassic and Cretaceous microfaunas. This was followed by several articles by Ainsworth & Horton (1986) and Ainsworth *et al.* (1987, 1989) which erected a very broad biostratigraphy related to events (tops), associations of lagenid dominated microfaunas (foraminifera and ostracods) and palynology for the Lower to Upper Jurassic sequences. The Middle and Upper Jurassic microfaunas appear to be somewhat impoverished compared to the Lower Jurassic.

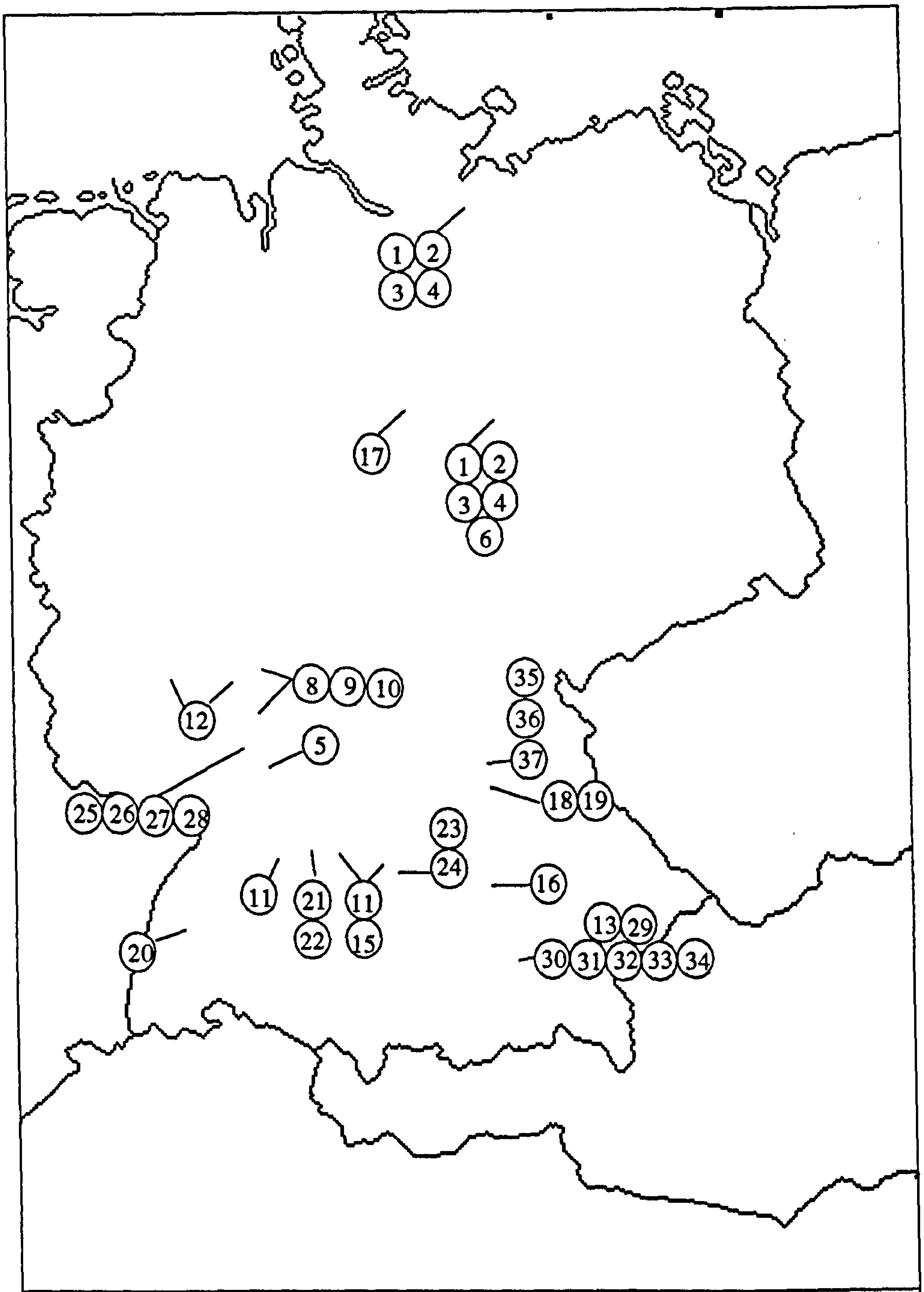
2.2.2. Germany (Fig. 2.2)

The majority of early German research was carried out on the Lower Jurassic with little being published on the Middle and Upper Jurassic until the 1930's. Exceptions include the pioneering taxonomic work of Gümbel (1862) and Schwager (1865) who worked on Bathonian to Oxfordian faunas, illustrating taxa with fine hand drawings. Many of the species nominated in these early works are still valid today.

The period from the late nineteenth century to the late 1930's was not particularly productive. Exceptions include Paalzow (1917, 1922) who devoted much of his time to a taxonomic approach of Middle Jurassic foraminifera. Unfortunately his hand drawn illustrations are hard to interpret. Berz (1931) observed in detail the adherent growth patterns of nubecularid taxa attached to the outer surfaces of ooides from the Middle Jurassic.

Later German work from 1937 to the early 1970's, although more prevalent, is difficult to assess, as the majority of texts are devoted to small sections and are often difficult to interpret or synthesise geologically (e.g. Kuhn, 1938; Neth, 1953; Schindelwolf, 1955). The obvious exceptions are briefly described below.

Bartenstein & Brand (1937) were the first authors to establish a major role for foraminifera in terms of biostratigraphy for the Bajocian to Lower Callovian of north west Germany. Their various lithostratigraphical divisions, corresponding to ammonite biozones, were characterised by biostratigraphically restricted forms along with typical faunal elements. They also established the existence of foraminiferal facies dependent



1 BARTENSTEIN 1948a
2 BARTENSTEIN 1948b
3 BARTENSTEIN 1952
4 BARTENSTEIN & BRAND 1937
5 BERZ 1931
6 BRAND 1939
7 BRAND & FAHRION 1962
8 FRENTZEN 1941
9 FRENTZEN 1942
10 FRENTZEN 1944
11 GROISS 1966
12 GROISS 1970
13 GÜMBEL 1862
14 KLINGER et al. 1962
15 KUHN 1938
16 LINDENBERG 1967
17 LUTZE 1960
18 MUNK 1978
19 MUNK 1980
20 NETH 1953
21 OHMERT 1988
22 OHMERT et al. 1991
23 PAALZOW 1917
24 PAALZOW 1922
25 RIEGRAF 1987a
26 RIEGRAF 1987b
27 RIEGRAF 1987c
28 RIEGRAF 1988
29 SCHINDELWOLF 1955
30 SCHWAGER 1865
31 SEIBOLD & SEIBOLD 1953
32 SEIBOLD & SEIBOLD 1955
33 SEIBOLD & SEIBOLD 1956
34 SEIBOLD & SEIBOLD 1960 a, b
35 WICHER 1938
36 WINTER 1970
37 ZIEGLER, 1959

Figure 2.2. Distribution of published research on Middle and Upper Jurassic foraminifera of Germany (Klinger *et al.*, 1962 and Brand & Fahrion 1962 reviewed all German sites)

distribution, noting the abundance of agglutinated foraminiferids with 'black' shales.

Frentzen (1941, 1942, 1944) concentrated his studies in the region of Baden and built up a substantial database of the whole Jurassic with special attention being paid to the agglutinated taxa present. Unfortunately, his illustrations are poor and the stratigraphical data is difficult to extract.

Detailed taxonomy of various groups, including agglutinated taxa such as ***Ammobaculites*** and lagenid taxa such as ***Lenticulina,*** were covered by Bartenstein (1948a, b, 1952).

Seibold & Seibold (1955, 1956) revised the taxonomy of Schwager (1865) and Gümbel (1862), illustrating some of the taxa by light microphotography. They also investigated distributional and palaeoecological patterns of foraminifera from the Middle/Upper Jurassic (Seibold & Seibold, 1953) and from sponge rich deposits (Seibold & Seibold, 1960a, b), relating distribution to facies.

Ziegler (1959) studied numerous boreholes covering the Aalenian to Callovian, concentrating primarily on the Bajocian and Bathonian. He characterised each ammonite biozone by listing the foraminifera present.

Lutze (1960) provided excellent illustrations and a well defined taxonomic approach to Callovian-Oxfordian taxa from north west Germany, recording distribution as well as some biometric data for selected forms. He also highlighted the foraminiferal response to a transgression within the Callovian.

Winter (1970) was one of the first authors to attempt to identify a palaeoecological distribution for the Lower Kimmeridgian foraminifera of south west Germany. His work took the form of proportional pie charts representing the major foraminiferal suborders, which were then related to biofacies. However, the majority of the text concentrated on detailed taxonomy and biometric analysis of selected foraminiferid taxa.

Subsequently, from the late 1970's, research in Germany became more palaeoecologically oriented. Of importance were two articles by Munk (1978, 1980). The first dealt with Bajocian-Callovian palaeogeography, biostratigraphy and broad palaeoecological distribution based on detailed graphical representation of foraminiferal suborders. She related faunal changes to sediment type and facies. A similar approach and technique was used in analysis of the Lower Kimmeridgian of Germany (Munk, 1980).

Riegraf (1987a-c, 1988) used new processing techniques and sampled phosphatic nodules, establishing the presence of Callovian and Oxfordian planktonic foraminiferids (Riegraf 1987b, c) and Callovian-Kimmeridgian agglutinated foraminifera (1987a, 1988) which were apparently missing or were not originally present within the surrounding shales. Riegraf (1987a) retrieved microfaunas similar to those recovered by Seibold & Seibold (1960a, b) from sponge bioherms. Particularly detailed is an account by Riegraf (1987c) on the distribution of the planktonic Globuligerinidae from the Callovian, which also covers their world-wide distribution. The conclusion reached is that these forms were initially present in the Callovian of the Tethys region and were then established in other regions as a consequence of maximum flooding related to the Callovian transgression.

2.2.3. Europe

Europe also has a long history of foraminiferal research and the data is summarised into the respective areas below (Fig. 2.3).

(i). France.

The majority of French work appears to be restricted to small sections dealing with distribution and taxonomy. However, some of the earlier texts are the detailed monographic works undertaken by Terquem (1868, 1870a, b, 1874, 1883, 1886) on the taxonomy of Jurassic foraminifera from the Moselle region in a series of monographs covering the Middle and Upper Jurassic (Oolithique series). His output was prodigious but he appears to have been a taxonomic splitter and described many new taxa that now appear to belong to single biological species. Additionally, his illustrations are somewhat difficult to interpret. Some authors have attempted to address this problem by restudying his work, but at present this has been restricted to his better known Lower Jurassic material (e.g. Ruget. 1976). Deeke (1884, 1886) listed foraminifera from the Alsace region as a comparison with foraminifera recovered by his contemporaries.

Only French articles that have been used extensively will be covered below, however, many of the minor articles (as illustrated on Fig. 2.3) have been used in determining the regional and distributional extent of taxa recovered from Scottish sites.

Aalenian to Callovian sediments from the southern area of the Jura mountains were studied by Wernli (1971), Wernli & Septfontaine (1971) and Wernli (1972), covering the taxonomy and distribution of a lagenid dominated population recovered from shales and calcarenites. Ruget (1979) and Delance & Ruget (1989) also investigated Bajocian/Bathonian stratigraphically important taxa from Nivernais, principally the sculptured lenticulinids, providing comparison with Portuguese sections (Ruget, 1973).

Barnard & Shipp (1981) applied assemblage distributional pattern change techniques similar to those they employed in the Oxford Clay of Southern England (Barnard *et al.*, 1981) to a small Upper Kimmeridgian section in the Boulonnais. They found an agglutinated rich fauna and related its presence to palaeoenvironmental conditions.

(ii). Switzerland.

Research from Switzerland, particularly from the Jura mountains, was initiated by Kübler & Zwingli (1866, 1870) who described, illustrated and introduced many taxa still in use today. Another important worker was Haeusler (see offset box on Fig. 2.3. for details) who, in a series of numerous, widely scattered but short papers, illustrated foraminiferal populations in some detail from a limited stratigraphical extent. The importance of his studies related to morphotypic variation in miliolid, lagenid and agglutinated foraminiferid taxa (e.g. Haeusler, 1882a-c, 1883a, b, 1887). In a useful

1 AINSWORTH & HORTON 1986
2 AINSWORTH et al. 1987
3 AINSWORTH et al. 1989
4 BANG 1968
5 BANG 1971
6 BANG 1972
7 BARBIERI 1964
8 BARNARD & SHIPP 1981
9 BEAUDOIN 1968
10 BENHARD 1986
11 BIELECKA 1960
12 BIELECKA 1965
13 BIELECKA 1988
14 BIELECKA & POZARYSKI 1954
15 BIELECKA & STYK 1963
16 BIELECKA & STYK 1966
17 BIELECKA & STYK 1967a
18 BIELECKA & STYK 1967b
19 BIELECKA & STYK 1968
20 BIELECKA & STYK 1969
21 BIELECKA & STYK 1981
22 BIELECKA et al. 1988
23 BIGNOT & GUYADER 1966
24 BIZON 1958
25 BOURROUILH & MOULLADE 1963
26 COLIN et al. 1981
27 CUSHMAN 1930
28 CUSHMAN & GLAZEWSKI 1949
29 DAM & REINHOLD 1942
30 DEEKE 1884
31 DEEKE 1886
32 DELANCE & RUGET 1989
33 DIENI 1985
34 DIENI & MASSARI 1985
35 ENAY 1963
36 ENAY et al. 1982
37 FERNET 1960
38 FISCHER 1965
39 FOURCADE 1963
40 FUCHS 1973
41 FUGANTI & MOSNA 1966
42 GARBOWSKA 1970
43 GIOVAGNOLI &
SCHIAVINOTTO 1991
44 GUSIC 1969
45 GUY-OHLSON & NORLING 1988
46 GUYADER 1960
47 HANZLIKOVA 1965
48 HOTTINGER 1971
49 JENDRYKA-FUGLEWICZ 1975
50 JONES 1873
50A KOECHLIN 1941
51 KOPIK 1960
52 KOPIK 1969
53 KÜBLER & ZWINGLI 1866
54 KÜBLER & ZWINGLI 1870
55 LØFALDLI & NAGY 1980
56 LØFALDLI & NAGY 1983
57 LUTERBACHER 1961
58 MAGNE 1966
59 MALECKI 1954
60 MIHAILOVA & TRIFINOVA 1968
61 MORRIS & COLEMAN 1989
62 MORRIS & DYER 1990
63 NAGY 1985 a-b
63A NAGY 1992
64 NAGY & JOHANSEN 1989
65 NAGY & JOHANSEN 1991
66 NAGY & LØFALDLI 1981
67 NAGY et al. 1988
68 NAGY et al. 1990a
69 NAGY et al. 1990b
70 NORLING 1972
70A NORLING et al. 1993
70B OESTERLE 1968
71 PAALZOW 1932
71A PARTINGTON et al. 1993b
72 PAZDROWA 1957
73 PAZDROWA 1958a
74 PAZDROWA 1958b
75 PAZDROWA 1959
76 PAZDROWA 1960
77 PAZDROWA 1967
78 PAZDROWA 1969
79 PAZDROWA 1972
80 PFENDER 1933
81 RADOICIC 1969
82 RAMALHO 1969
83 RICHARDS et al. 1993
84 RUGET 1973
85 RUGET 1979
86 SEPTFONTAINE 1977
87 SIDO 1966
88 STAM 1986
89 TRIFONOVA 1968
90 TRIFONOVA 1985
91 WERNLI 1971
92 WERNLI 1972
93 WERNLI & SEPTFONTAINE 1971
94 WILLIAMSON & STAM 1988
95 WISNIOWSKI 1890, 1891

T. TERQUEM
(1866a, b, 1868, 1870a-b, 1874,
1883, 1886).
H. HAEUSLER
(1881a, b, 1882a-c, 1883a-b,
1886, 1887, 1890, 1893a, b).

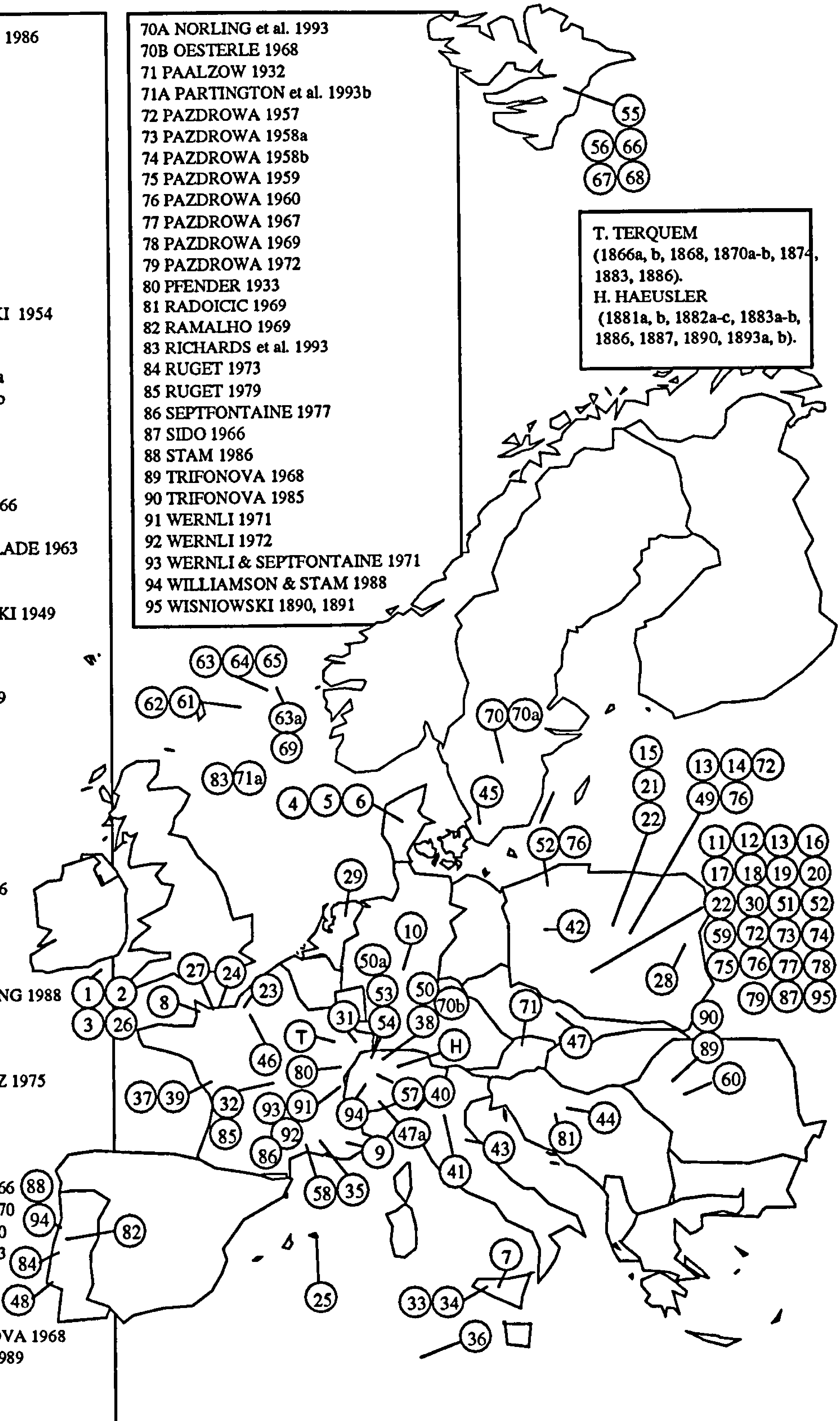


Figure 2.3. Published research on Middle and Upper Jurassic foraminifera of Europe (Partington et al., 1993 and Richards et al., 1993 cover the UK North Sea sector)

revision, Oesterle (1968) re-described and re-illustrated many of the taxa erected by Haeusler (*op. cit.*) and Kübler & Zwingli (*op. cit.*). Little additional work has since been published, although exceptions include Koechlin (1941), Luterbacher (1961) and Fischer (1965) who provided data on Bathonian to Kimmeridgian foraminifera. A more detailed and integrated account was published by Wernli & Septfontaine (1971) who compared Middle Jurassic faunas from France and Switzerland, noting a relatively similar Boreal fauna with discrepancies accounted for by faunal changes progressing across a developing basin. Some Tethyan influences were noted by Hottinger (1971) who retrieved small, but complex walled agglutinated taxa.

(iii). Poland.

The Polish lowlands have been the focus of much attention by a small team of workers since the 1950's. The initial presence of Jurassic faunas was established by Wisniowski (1890, 1891) who investigated the Callovian and established the presence of a miliolid dominated fauna, however, there was little published material until the 1950's. The impetus was provided by Bielecka & Pozaryski (1954) who looked in detail at predominately Middle Jurassic calcareous dominated faunas. They proposed a basic zonation based on facies dependence and also described in detail the taxonomy of the faunas. Bielecka & Styk (1963, 1966, 1967a, b, 1968, 1969, 1981) generally covered the Callovian to Oxfordian, listing sometimes in great detail the foraminiferal faunas recovered with stratigraphical ranges. Unfortunately, relatively few of the taxa were illustrated. Kopik (1960, 1969) looked at the Middle Jurassic, covering lagenid foraminifera which were used to indicate a maximum extent of transgression during the Bajocian/Bathonian.

Pazdrowa (1957, 1958a, b, 1959, 1960, 1967, 1969, 1972) worked almost exclusively on faunas from the Middle Jurassic, establishing a rigid but apparently robust taxonomy concentrated upon the miliolids and based on biometric principles and population studies. The most detailed of her studies were on the genera ***Palaeomiliolina*** and ***Ophthalmidium*** (Pazdrowa, 1959, 1972). A similar biometric study was carried out by Garbowska (1970) who zoned the Upper Oxfordian and Lower Kimmeridgian outcrops on dominant components of the assemblages recovered. Fuchs (1973) established the presence of planktonic foraminifera from the Callovian/Oxfordian of Poland.

Some of the criticisms which could have been levelled at the Polish articles regarding the lack of good illustrations have been addressed by recent publication of Middle to Upper Jurassic atlases produced by Bielecka (1988) and Bielecka ***et al.*** (1988) which are well illustrated.

(iv). Scandinavia.

Scandinavian studies are limited due to the paucity of Jurassic outcrop. The earliest accounts are from Denmark and relate to lists of foraminifera from boreholes that have penetrated Jurassic strata (Bang, 1968, 1971, 1972). The Swedish region is notable for articles by Norling (1972), Guy-Ohlsen & Norling (1988) and Norling ***et al.*** (1993). Initial research (Norling, 1972) established the presence of foraminifera from borehole material and a broad biozonation was developed. This was subsequently extended to outcrop material (Norling ***et al.***, 1993).

Svalbard represents one of the most extensive northerly outcrops of Jurassic strata in the Scandinavian region and has been studied in some detail by a team comprising the University of Oslo and Norwegian oil companies (Løfaldli & Nagy, 1980, 1983; Nagy & Løfaldli, 1981; Nagy ***et al.***, 1988, 1990a). They established the presence of an agglutinated dominated foraminiferid fauna within the Upper Jurassic and Early Cretaceous (Callovian-Berriasian). These authors also remarked on apparent palaeoecological distribution of the faunas, relating agglutinated dominated assemblages to organic content. They also erected broad biostratigraphical schemes for the region, comparing their faunas with limited data from the North Sea (Nagy, 1985a, b), and established the importance of previously ignored Russian publications (Nagy ***et al.*** 1990a, b).

(v). Italy and the Mediterranean area.

Due to the presence of hard Jurassic limestones in Italy and Sicily, there have been few records of Middle and Upper Jurassic foraminiferid faunas. Those that are available often feature poorly preserved faunas of larger, complex walled agglutinates present from thin argillaceous units (e.g. Fuganti & Mosna, 1966). Giovagnoli & Schiavinotto (1991) established the presence of a planktonic foraminiferid fauna from central Italy, to which they applied a biometric and population analysis.

Sediments from Croatia (Gusic, 1969) also yielded larger complex walled agglutinated foraminiferids such as ***Pfenderina*** and ***Kurnubia,*** whilst Radoicic (1969) recorded new species of ***Involutina.*** Such assemblages are typically retrieved from Tethyan carbonate sediments and are similar to faunas recovered by Bourrouilh & Moullade (1963) from Minorca. Interestingly, Enay ***et al.*** (1982) proved the presence of Oxfordian/Kimmeridgian lagenid dominated assemblages from dredged samples from offshore Malta and there appears to be good correlation with thin argillaceous deposits from sites in Sicily (Dieni, 1985; Dieni & Massari, 1985).

(vi). Portugal.

Portugal, which represents the most westerly exposure of European Jurassic strata, within the Lusitanian Basin, has a relatively recent history of research. Ruget (1973) established the presence of a lagenid dominated Bathonian assemblage. Stam (1986) and Williamson & Stam (1988) have used Portuguese Middle and Upper Jurassic sections for comparative purposes with similarly aged sediments present in the Canadian offshore. Stam (1986) additionally utilised Q and R mode cluster statistical techniques to analyse assemblages and related these to palaeoenvironmental factors. Hottinger (1971) recovered sparse faunas from the Upper Jurassic carbonate dominated facies of south west Portugal which, by the presence of larger, complex walled agglutinates, indicated the presence of the Tethys in this part of the Mediterranean.

2.2.4. The Rest of the World

Records of foraminifera are grouped into their geographical respective areas (Fig. 2.4).

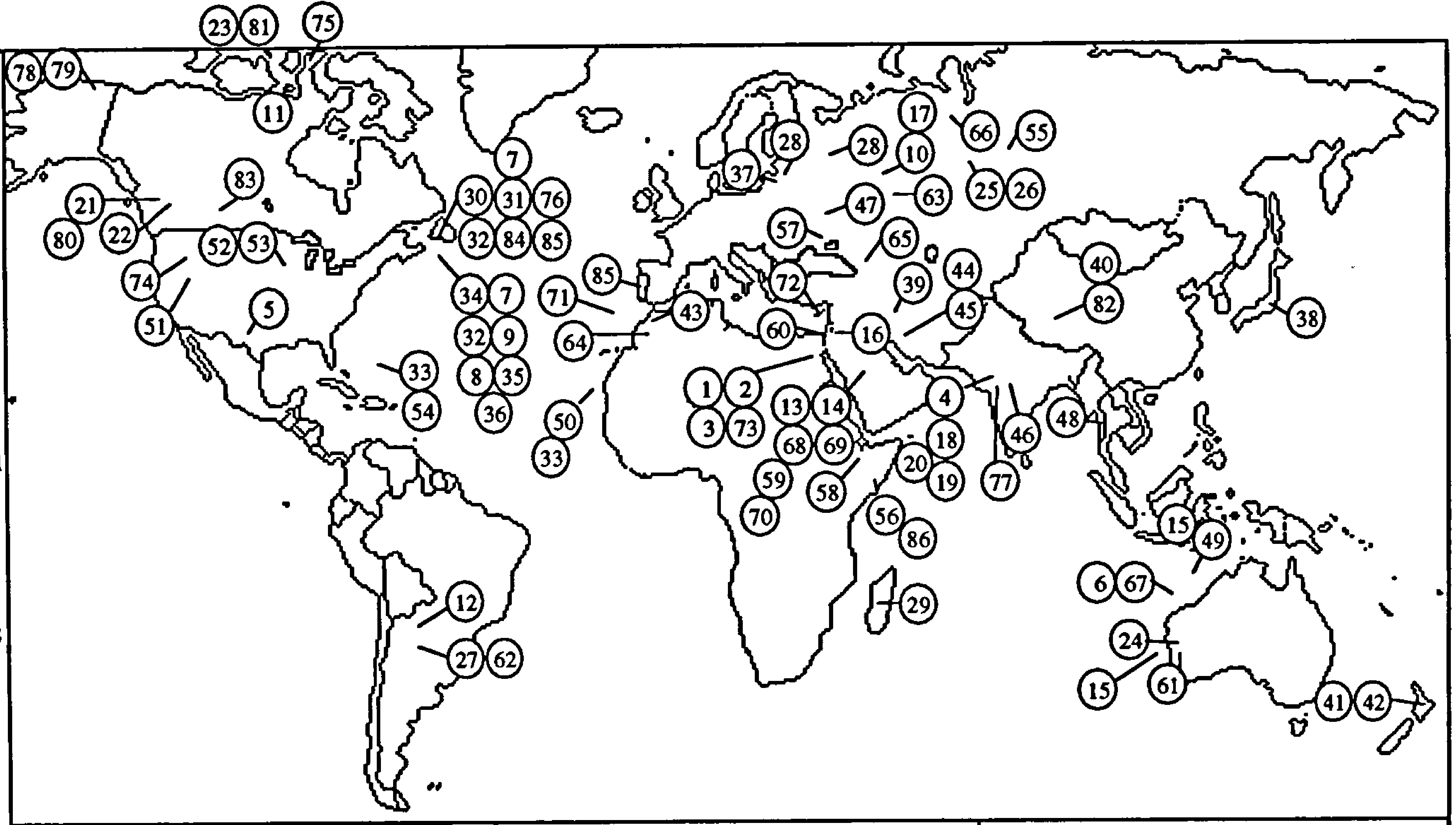
(i). North America.

The North American region has substantial Jurassic deposits and this is reflected in the large number of articles published, particularly since the 1950's. The United States of America and Canada have a somewhat similar pattern of study. Initial research was mainly carried out in the early part of the twentieth century, but the reports are difficult to synthesise into a modern biozonal scheme due to their brevity and as a consequence of poor ammonite control and provinciality. This initial burst included work in the USA by Albritton (1937), Lalicker (1950) and Sandridge (1933), who looked at the Bathonian to Oxfordian in Montana. All authors described a predominantly calcareous benthic dominated fauna, similar to records from Europe. The Jurassic of Canada was similarly covered by Wickenden (1933). These authors generally nominated every species they encountered as new, although subsequently the majority of these taxa can be seen to be synonymous with faunas previously described from Europe.

The 1950's in the USA and Alaska marked a burst of important work by Tappan (1951, 1955) and Loeblich & Tappan (1950a, b) on the descriptive micropalaeontology of material from outcrop and boreholes. Probably the most important study was by Tappan (1955) who worked on several boreholes and outcrop material from the Alaskan Arctic coastal plains. She established the presence of a diverse and abundant agglutinated dominated fauna from the Upper Jurassic, with subordinated lagenids, and additionally erected many new taxa, listing briefly their vertical distribution. Many of these taxa now appear to be synonymous with earlier European records, especially within the calcareous taxa which were established only on the basis of minor size differences. Such examples are particularly evident in Loeblich & Tappan's (1950a, b) studies of Oxfordian and Callovian faunas from central regions of the USA.

As a consequence of Deep Sea Drilling Project (DSDP) drilling of several legs along the American eastern seaboard, Luterbacher (1972) and Gradstein (1983) retrieved Middle and Upper Jurassic faunas, ranging from mixed calcareous dominated 'neritic' to agglutinated dominated 'abyssal' faunas.

The Canadian region is notable for a large number of published articles from the 1970's to the present day, with the majority being directly related to the DSDP which penetrated Late Jurassic/Cretaceous sediments offshore Newfoundland and the Grand Banks. Reports include those by Ascoli (1976, 1984), Gradstein (1976, 1978, 1979, 1986), Gradstein *et al.* (1975) and Ascoli *et al.* (1984) who all attempted to biostratigraphically divide and correlate between well sections. As a direct consequence



1 ABDELMALIK 1981
2 ABDEL SHAFY & IBRAHIM 1990
3 ABDOU & MARZOUK 1969
4 AGRAWAL & SINGH 1961
5 ALBRITTON 1937
6 APTHORPE & HEATH 1981
7 ASCOLI 1976
8 ASCOLI 1984
9 ASCOLI et al. 1984
10 AZBEL 1987
11 BALKWILL et al. 1977
12 BALLENT 1984
13 BANNER & WHITTAKER 1991
14 BANNER et al. 1991
15 BARTENSTEIN 1974
16 BASHA 1983
17 BASOV et al. 1973
18 BHALLA & ABBAS 1975
19 BHALLA & ABBAS 1976, 1978
20 BHALLA & TALIB 1980
21 BROOKE & BRAUN 1972
22 BROOKE & BRAUN 1981
23 CHAMNEY 1971
24 CHAPMAN 1904
25 DAIN 1948
26 DAIN 1972
27 DELLAPE et al. 1978
28 EFIMOVA & MESEZHNIKOV 1991
29 ESPITALIE & SIGAL 1963
30 GRADSTEIN 1976
31 GRADSTEIN 1978
32 GRADSTEIN 1979
33 GRADSTEIN 1983
34 GRADSTEIN 1986
35 GRADSTEIN et al. 1975
36 GRADSTEIN et al. 1985
37 GRIGELIS 1958
38 HANZAWA 1939
39 HENSON 1947
40 HE YANG 1982
41 HORNIBROOK 1953
42 HORNIBROOK et al. 1989
43 HOTTINGER 1971
44 KALANTARI 1969
45 KALANTARI 1982
46 KALIA & CHOWDHURY 1983
47 KAPTARENKO 1959
48 KEMPER 1976
49 KUZNETSOVA 1974
50 KUZNETSOVA & SIEBOLD 1978
51 LALICKER 1950
52 LOEBLICH & TAPPAN 1950a
53 LOEBLICH & TAPPAN 1950b
54 LUTERBACHER 1972
55 LUTOVA 1981
56 MACFADYEN 1935
57 MAMONTOVA 1959
58 MANSOUR 1975
59 MANIVIT et al. 1990
60MAYNC 1966
61 MOORE 1870
62 MUSSACCHIO 1979
63 MYATLIUK 1939
64 PEYBERNÉS et al. 1987
65 POROSHINA 1986
66 PUTRYA 1970
67 QUILTY 1990
68 REDMOND 1964a
69 REDMOND 1964b
70 REDMOND 1965
71 RIEGRAF et al. 1984
72 RENZ & REICHEL 1948
73 SAID & BARAKAT 1958
74 SANDRIDGE 1933
75 SOUYA 1976
76 STAM 1986
77 SUBBOTINA et al. 1960
78 TAPPAN 1951
79 TAPPAN 1955
80 WALL 1960
81 WALL 1983a, b, c
82 WANG YI-GANG 1988
83 WICKENDEN 1933
84 WILLIAMSON 1987
85 WILLIAMSON & STAM 1988
86 WYNN-JONES 1993

Figure 2.4. Global distribution of published research on Middle and Upper Jurassic Foraminifera (excludes the UK, Fig 2.1; Germany, Fig. 2.2; and Europe, Fig. 2.3)

of Canadian offshore drilling within the Newfoundland and Grand Banks Basin, Gradstein *et al.* (1985) and Williamson (1987) developed various statistical methods of defining and refining distributional patterns. These techniques were used to produce correlative biostratigraphical schemes based on final appearances and to characterise palaeoecological groupings. This type of technique was principally utilised within the Early Cretaceous and Latest Jurassic.

Other Canadian areas under study include the extensive Middle and Upper Jurassic sediments from Saskatchewan and British Columbia by Brooke & Braun (1972, 1981) who established a foraminiferal biostratigraphy based on agglutinated dominated faunas refined from an earlier regional study by Wall (1960). They also recognised a Boreal correlation of their material but noticed two provinces characterised by different assemblages. Their more northerly and agglutinated dominated faunas appeared to correlate with a wide range of northern areas from Arctic regions including Alaska, Sverdrup Basin and western and northern Siberia from the Callovian to Portlandian. The second group recovered from the western interior compared with European Boreal elements.

The Arctic Archipelago has attracted interest due to the presence of exploitable oil and gas reserves. The first account was provided by Chamney (1971) and detailed the presence of agglutinated dominated faunas. This was followed by a comprehensive coverage from the Triassic to Lower Cretaceous by Souaya (1976) who erected a broad biostratigraphical zonal scheme and noted the presence of an agglutinated dominated fauna majority for the Jurassic. In a series of papers, Balkwill *et al.* (1977) and Wall (1983a, b, c) also recorded an extensive agglutinated dominated fauna from the eastern Sverdrup Basin from the Middle to Upper Jurassic and Early Cretaceous. Wall *(op. cit.)* broadly zoned these deposits and correlated them with similar deposits in British Columbia, Svalbard and Siberia.

Williamson & Stam (1988) investigated the taxonomy and palaeoecology of the genus ***Epistomina*** in detail, from Canadian sites in particular and world-wide generally. They attempted to correlate the predominance of this genus to the availability of suitable clay/shale facies. The deposition of more $CaCo_3$ rich sediments proved to be more conducive to epistominid survival.

(ii). South America.

Records are poor from the South American region which is somewhat surprising considering the number of papers covering ammonite bearing Jurassic strata (e.g. Westermann, 1981; Riccardi & Westermann, 1984). The papers that have been produced are principally from Argentina by Dellape *et al.* (1978), Musacchio (1979) and Ballent (1984) who recovered a lagenid dominated fauna from the Middle and Upper Jurassic which shows many affinities with European Sub-Boreal assemblages.

(iii). Antipodes and the Far East.

Relatively little work has been carried out in the Antipodean region. This is directly related to the paucity of Middle and Upper Jurassic outcrop. Moore (1870) and Chapman (1904) covered faunas from Geraldton (western Australia), but in little detail. Kuznetsova (1974) and Bartenstein (1974) were involved in Deep Sea Drilling legs off western and north west Australia, recovering predominantly primitive agglutinated foraminifera from Upper Oxfordian to Valanginian sediments. The faunas were dominated by single or two chambered taxa and these were related to a deep water flysch deposition below the Calcium Carbonate Compensation Depth (CCCD). Samples dredged from the Exmouth Plateau, offshore north west Australia, were recorded by Quilty (1990) and Apthorpe & Heath (1981). Quilty (*op. cit.*) recovered calcareous benthic dominated and cosmopolitan faunas from these dredged samples, with the majority of the deposits being Triassic or Lower Jurassic in character and the youngest possibly being Callovian/Oxfordian in age. Hornibrook (1953) was the first person to record a Jurassic foraminiferal fauna from New Zealand and further developed this work (Hornibrook ***et al.***, 1989). The faunas are poorly known, but appear to be dominated by lagenids.

Reports from the Jurassic of the Far East are very scarce and this is probably related to the predominance of deep water radiolarites. An encrusting foraminiferid was reported by Hanzawa (1939) from a Japanese algal rich limestone. Kemper (1976) reported larger complex walled agglutinated forms, such as ***Kurnubia*** and ***Orbitopsella*** from limestones in the Middle and Upper Jurassic of Thailand. These faunas showed strong affinities with Tethyan faunas recovered in carbonates from Mediterranean sites such as Israel, the Balearic Islands and Turkey.

Chinese studies are restricted to the Tibetan region (Wang Yi Gang, 1988; He Yang, 1982). Within the Middle Jurassic the faunas are apparently Tethyan in character with larger complex agglutinated taxa. The data is, however, preliminary and comprises merely a listing of the dominant forms.

(iv). Middle East.

The Middle East region, although marked by very large Middle and Upper Jurassic oil fields, has a relatively poor history of research. Redmond (1964a, b, 1965) reported a selection of larger agglutinated foraminiferids from the Middle and Upper Jurassic of Saudi Arabia, primarily from a taxonomic approach. Banner & Whittaker (1991) and Banner ***et al.*** (1991) re-examined Redmond's (*op cit.*) material, describing new agglutinated genera. Manivit ***et al.*** (1990) listed the common taxa recovered from Saudi Arabia. The majority of the Middle and Upper Jurassic sediments were dominated by ***Trocholina*** species (initially noted by Henson, 1947) and large complex walled agglutinated taxa including ***Kurnubia*** and canaliculate taxa such as ***Riyadhella*** spp., ***Redmondoides*** spp and ***Pseudomarssonella*** spp. These papers deal with either biostratigraphy or phylogeny, with little detail on palaeoenvironments. However, Manivit *et al.* (1990) included sedimentary facies, suggesting shallow, warm, well oxygenated, clear waters. Kalantari (1969, 1982) recorded a range of smaller and larger agglutinated foraminifera/***Trocholina*** dominated faunas from several areas of Iraq.

The earliest record from Egypt was provided by Said & Barakat's (1958) account of the Bajocian to Kimmeridgian of the Sinai region. They recovered a lagenid dominated fauna from the argillaceous sediments, with many species in common with earlier European studies. However, it appears that the majority of the sections were not analysed due to the indurated nature of the strata. Very rare larger, complex walled agglutinated foraminifera were also noted. Similar lagenid dominated faunas were also recorded by Abdelmalik (1981), Abdel- Shafy & Ibrahim (1990) and Abdou & Marzouk (1969).

(v). Africa.

Jurassic faunas from east Africa are poorly known, with the best known account by Macfadyen (1935) of the Jurassic of Somalia. His work was reviewed by Wynn-Jones (1993) who dated the strata as Oxfordian. The faunas also appear to be typically Boreal with a predominance of lagenids. Epistalié & Sigal (1963) produced a very detailed taxonomic account of Callovian to Hauterivian foraminifera from Madagascar and again noted lagenid dominated faunas. Mansour (1975) recorded the Tethyan agglutinated foraminiferid ***Pfenderina*** from Ethiopia. Other African studies are limited to Deep Sea Drilling Project legs which penetrated Jurassic sediments from offshore western Africa (Kuznetsova & Seibold, 1978; Gradstein, 1983) where a spirillinid and lagenid dominated fauna was recovered. Offshore Morocco was covered by Riegraf *et al.* (1984) who indicated that the Middle Jurassic was a regressive phase as shown by impoverished faunas, whilst the Late Jurassic transgression was dominated by lagenids and spirillinids. All authors reported poorly preserved faunas. Hottinger (1971) recovered sparse Tethyan faunas characterised by complex walled agglutinates from onshore eastern Morocco; similar faunas were recorded by Peybernés *et al.* (1987).

(vi). India.

Studies from the Indian Subcontinent have centred around the oil and gas potential of the Kutch district on the western coast of India, with the majority of authors (Subbotina *et al.* 1960; Agrawal & Singh, 1961) covering taxonomy and rudimentary distributional patterns of the lagenid dominated faunas. The stratigraphical interval generally covers the Middle to Upper Jurassic and further reports by Bhalla & Abbas (1975, 1976, 1978) and Bhalla & Talib (1980) have noted the presence of diverse lagenid and simple agglutinated faunas with no complex larger agglutinated taxa present, which led them to propose a sub-province of the Tethys. Kalia & Chowdhury (1983) showed the similarity of Callovian sediments in India with Boreal areas whilst the Bathonian showed some Tethyan faunas characterised by rare complex larger agglutinated taxa.

(vii). CIS.

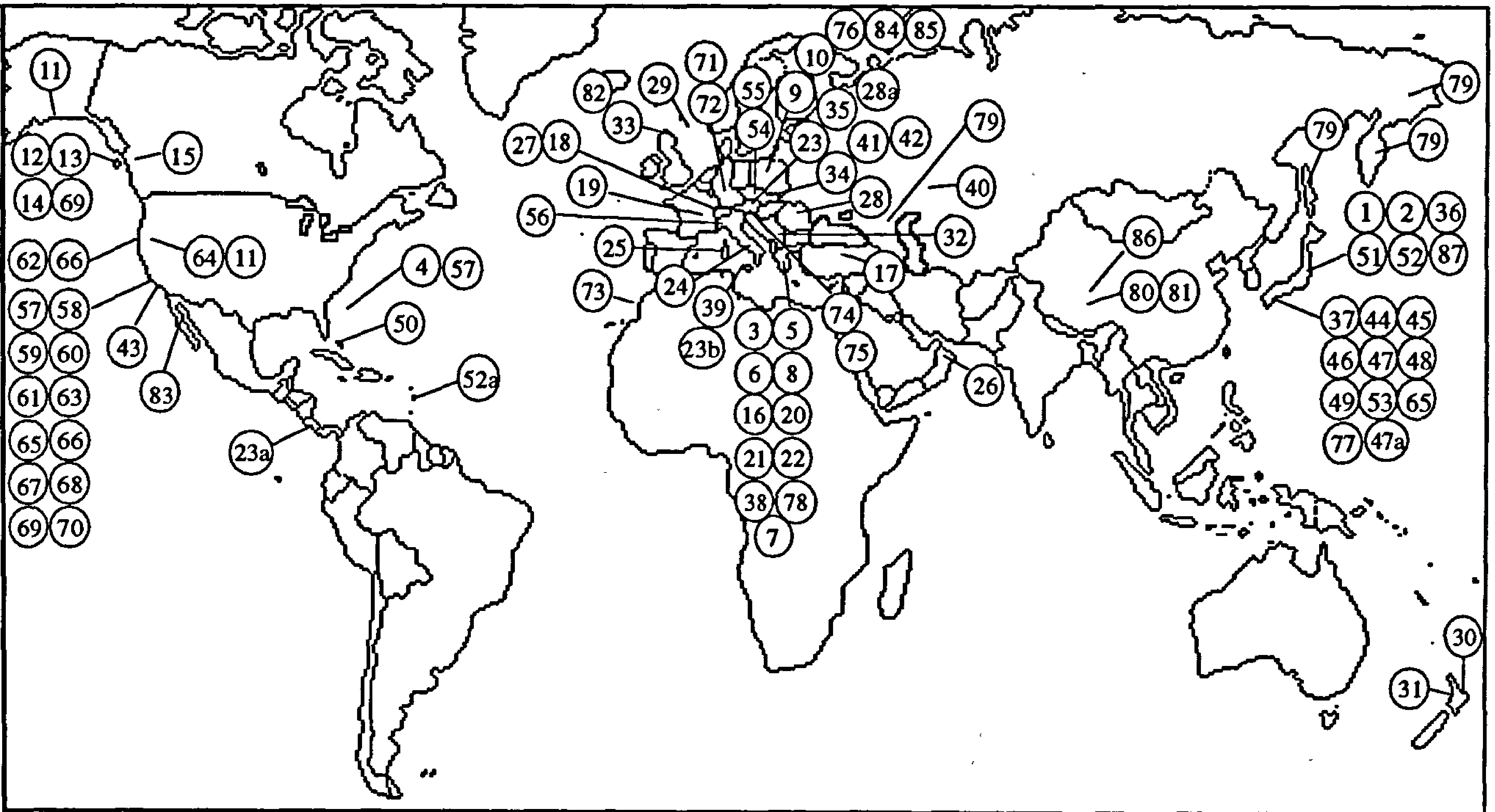
One region not extensively included in this survey is the former Soviet Union which, however, has a long and detailed history of foraminiferal research. The problem lies in obtaining published material and in the translation of Cyrillic script. In order to avoid mistakes over areas and foraminiferal distributions, only those papers which have been translated have been inserted in this regional study. The most useful text was produced by Dain (1972) who studied extensive outcrop and borehole material from eastern Russian and Siberia, documenting the Middle and Upper Jurassic. He erected many new taxa, particularly agglutinated forms, which are only now being accepted by western workers. More recently a Mesozoic Atlas edited by Efimova & Mesezhnikov (1991) illustrated, by line drawings, foraminiferal faunas grouped in ammonite delineated sections.

2.3. Radiolaria

The study of Jurassic radiolaria has only recently been attracting attention and this is reflected in the relatively small database of published articles (Fig. 2.5). Out of 92 papers examined relating to the Middle and Upper Jurassic, only 10 were published prior to 1977. Geographically, radiolaria initially appear to be limited to fairly deep oceanic conditions where there is good circulation, which is reflected in the concentration of research on radiolarian cherts from the Californian Ranges, Japan and the originally deeper water Mediterranean areas. However, other faunas from British Columbia and the Boreal deposits of Northern UK are also coming to light.

Previous research on Jurassic radiolaria is distinguished by a notable absence or scarcity of work prior to the late 1970's. Initial studies were carried out by Rüst (1885, 1889), working on the German and Swiss Jurassic sediments, and Parona (1890), who looked at Jurassic radiolaria from the Apennines in Italy. Their pioneering work was taxonomic in nature and they established many of the radiolarian taxa in use today. They based their taxonomy on the work of their contemporary Ehrenberg (1873, 1875), who had erected the first meaningful classification of extant and fossil radiolaria.

Due to the belief that radiolaria were a very slowly evolving group, as suggested by Ehrenberg (*op cit.*), and to difficulties in their extraction, later research was very limited. Heitzer (1930) studied radiolarian faunas from the Middle Jurassic of Austria. Waterston (1951) indicated radiolarians that were present in Lower Kimmeridgian sediments from his ammonite and bivalve biostratigraphical study at Eathie Haven, providing the first record of radiolarians from the UK. One of the most detailed taxonomic accounts of this period was by Dumitrica (1970) on Mesozoic nassellarians from Romania, which covered in some detail the Callovian-Oxfordian. Kozlova (1971) published the earliest radiolarian account from the former Soviet Union. Working on Lower Kimmeridgian sediments from the Timan-Ural region of the CIS, he produced rough sketches of several 'new' species. Sido (1966) included thin section photomicrographs of radiolarian rich sediments from the Bathonian of Poland.



1 AITA 1982
2 AITA & OKADA 1986
3 BAUMGARTNER 1980
4 BAUMGARTNER 1983
5 BAUMGARTNER 1984, 1987
6 BAUMGARTNER & BERNOULLI 1976
7 BAUMGARTNER et al. 1980
8 BAUMGARTNER et al. 1981
9 BIELECKA et al. 1988
10 BIELECKA 1988
11 BLOME 1984
12 CARTER 1988
13 CARTER & JAKOBS 1991
14 CARTER et al. 1988
15 CORDEY et al. 1987
16 DANELIAN et al. 1986
17 DE WEVER 1982
18 DE WEVER & CABY 1981
19 DE WEVER & CORDEY 1986
20 DE WEVER & DERCOURT 1985
21 DE WEVER & DEVOS 1982
22 DE WEVER & THIÉBAULT 1981
23 DE WEVER et al. 1985a
23a DE WEVER et al. 1985b
23b DE WEVER et al. 1986
24 DE WEVER et al. 1987a
25 DE WEVER et al. 1987b
26 DE WEVER et al. 1990
27 DONOFRIO & MÖSTLER 1978
28 DUMITRICA 1970
28a DUMITRICA & DE WEVER 1991
29 DYER & COPESTAKE 1989
30 FEARY & PESSAGNO 1980
31 FOLEY et al. 1986
32 GORICAN 1987
33 GREGORY 1986
34 GRILL & KOZUR 1986
35 HEITZER 1930
36 HORI & OTSUKA 1989
37 ISHIDA 1983
38 KARAKITSIOS et al. 1988
39 KITO et al. 1990

40 KOZLOVA 1971
41 KOZUR 1985
42 KOZUR & MÖSTLER 1981
43 McLAUGHLIN & PESSAGNO 1979
44 MATSUOKA 1983
45 MATSUOKA 1984
46 MATSUOKA 1986a
47 MATSUOKA 1986b
47a MATSUOKA 1993
48 MATSUOKA & YAO 1985
49 MATSUOKA & YAO 1986
50 MATTSON & PESSAGNO 1979
51 MITZUTANI & KIDO 1983
52 MITZUTANI et al. 1984
52a MONTGOMERY et al. 1992
53 NAKASEKO & NISHIMURA 1981

54 OZVOLDOVA 1975
55 OZVOLDOVA 1979
56 PARONA 1890
57 PESSAGNO 1971
58 PESSAGNO 1977c
59 PESSAGNO 1979
60 PESSAGNO 1991a
61 PESSAGNO 1991b
62 PESSAGNO & BLOME 1980
63 PESSAGNO & BLOME 1982
64 PESSAGNO & BLOME 1990
65 PESSAGNO & MITZUTANI 1991
66 PESSAGNO & WHALEN 1982
67 PESSAGNO et al. 1984
68 PESSAGNO et al. 1986
69 PESSAGNO et al. 1987

70 PESSAGNO et al. 1989
71 RIEGRAF 1986
72 RIEGRAF 1987b
73 RIEGRAF et al. 1984
74 RÜST 1885
75 RÜST 1889
76 SIDO 1966
77 TAKEMURA & NAKASEKO 1982
78 THIÉBAULT et al. 1980
79 VISHNEVSKAYA 1993
80 WANG YI GANG 1988
81 WANG YU & JIN ZHANG 1982
82 WATERSTON 1951
83 WHALEN & PESSAGNO 1984
84 WIDZ 1991
85 WIDZ & DE WEVER 1993
86 WU 1993
87 YAO et al. 1980

Figure 2.5. Global distribution of published research on Middle and Upper Jurassic radiolaria

The impetus for the burst of modern research on Jurassic radiolaria which marks the 1970's onwards, were the new extractive techniques developed primarily by Pessagno (1971) and Pessagno & Newport (1972) for Jurassic and Cretaceous radiolaria. Additionally, there was a realisation that radiolarian faunas evolved very rapidly, allowing the zonation of the Cretaceous and Tertiary with a high degree of resolution.

Output on Middle and Upper Jurassic radiolarians has focused on regions where siliceous cherts have developed as a consequence of biogenic deposition in deep water oceanic environments affected by nutrient upwelling. These cherts have a distinct geographical distribution and are particularly prevalent along the western Seaboard of North America and Canada, the Mediterranean outcrops of Greece, Turkey, Corsica, Sicily and the radiolarian cherts that comprise the Islands of Japan (see Fig. 7.9 for a palaeogeographical summary). These areas have been studied by several groups of workers (see Fig. 2.5) who appear to have had differing primary aims.

i). Californian Coastal Regions.

Pessagno and his colleagues worked on the radiolarian chert terraines of the Middle and Upper Jurassic of the Californian coastal regions. This region is part of the western area of the Cordilleran Region of North America which is characterised by a collage of derived geological terraines displaced tectonically from lower to higher latitudes. This group of authors has consistently attempted to erect biozonations based primarily on radiolaria and foraminifera, as the ammonite recovery from these sites was very poor. In detail, the first coverage of this area was by Pessagno (1971) who compared a limited hagiastrid fauna from the Blake-Bahama Basin and the California Coast Ranges. Subsequent to this was the most important modern publication by Pessagno (1977c) on the Upper Jurassic (Upper Kimmeridgian-Berriasian) of the California Coast Ranges, which paved the way for modern Jurassic studies culminating in the erection of a fairly detailed radiolarian biostratigraphy of this complex and tectonically disturbed region associated with the Franciscan ophiolite complex (Pessagno *et al.*, 1984, 1986, 1987; Pessagno, 1991a). This group have also erected many of the taxa which have subsequently been recovered from a wide range of areas, particularly in the Boreal and Tethyan provinces (e.g. Pessagno 1977c, 1979; Pessagno *et al.*, 1986, 1989; Pessagno & Blome, 1982). The Upper Triassic to Early Callovian of the region was covered by Pessagno & Blome (1980, 1982). The major problem with this region is the absence of good ammonite biostratigraphical control to act as a primary zonal template for comparative purposes.

The Middle Jurassic of Alaska, Oregon and British Columbia, which is also an area of complex structures, was studied by Pessagno & Whalen (1982) and Blome (1984) who recovered extremely diverse radiolarian faunas primarily from the Hettangian to Lower Callovian and Lower to Middle Callovian respectively. These authors discussed the faunas in terms of phylogenetic relationships and detailed taxonomy, erecting many new species. Similar diverse faunas were recovered from the Middle Jurassic by Cordey *et al.* (1987) from the ribbon radiolarite deposits of British Columbia. A more detailed taxonomic treatment of faunas from Queen Charlotte Island was undertaken by Carter *et al.* (1988) and Carter (1988), who established the presence of an abundant Late Pliensbachian-Bajocian fauna and also concentrated on the Aalenian radiolarian fauna (Carter & Jakobs, 1991).

Isolated records of radiolaria have also been reported from Mexico (Whalen & Pessagno, 1984) and Costa Rica (De Wever *et al.*, 1985b) proving the extent of the siliceous cherts and limestones that characterise the western areas of the North and Central Americas. The Caribbean and eastern Seaboard of America have also provided radiolarian bearing deposits (Mattson & Pessagno, 1979; Baumgartner, 1983). Montgomery *et al.* (1992) indicated that there appeared to be a Tethyan/Boreal mixing of faunas from sediments analysed from the Lesser Antilles.

ii). Alpine-Mediterranean Region.

Most workers have generally been concerned with a taxonomic approach allied to biostratigraphical dating of patch work and complex sequences, primarily within the Greek region. Baumgartner & Bernoulli (1976) were the first to date radiolarian mudstones from the Greek ophiolite complex as Late Jurassic and Early Cretaceous. Biostratigraphic zonation of this region was undertaken by Baumgartner *et al.* (1980) who correlated radiolarian faunas from Greece (Argolis Peninsula and the Pindos Zone) with the Romanian Carpathians, Italian Alps and Sicily and erected biochronologic intervals based upon unitary association statistical techniques which broadly correlated to Jurassic stages. These unitary associations were subsequently updated by Baumgartner (1983, 1984, 1987) and Baumgartner *et al.* (1981).

De Wever, in a number of collaborative efforts, placed emphasis on biostratigraphical dating (Bajocian to Tithonian) of small isolated areas within the complex tectonic regions of Greece in the Pindos-Olonos Radiolarite Zone (e.g. De Wever & Thiébault, 1981; De Wever & Dercourt, 1985; De Wever & Cordey, 1986; Danelian *et al.*, 1986; Karakitsios *et al.*, 1988).

Other Mediterranean sites have yielded radiolarians: De Wever *et al.* (1986) established the presence of Oxfordian-Valanginian faunas in their integrated macro and micro study of the Sicilian area; Kito *et al.* (1990) undertook an additional biostratigraphical study of Middle and Upper Jurassic sections of Sicily and compared zonations erected by Pessagno *et al.* (1984, 1986, 1989), Baumgartner (1984, 1987) and Carter (1988), indicating differences in their ranges established; De Wever *et al.* (1987b) dated Callovian to Lower Kimmeridgian sediments of Corsica using the radiolarian assemblages recovered.

Gorican (1987) proved a direct correlation between the Greek radiolarites of the Pindos Zone and material that was recovered from the Upper Bathonian to Lower Kimmeridgian of the former Yugoslavia.

Widz (1991) and Widz & De Wever (1993) covered, in some detail, the abundant and well preserved radiolarian faunas from the Oxfordian to Kimmeridgian of the Pieniny Klippen Belt in the Polish Carpathians. They compared ranges with those designated from similarly aged deposits of Greece by Baumgartner (1984, 1987). Jurassic sediments from northern Hungary were covered by Kozur & Möstler (1981), Kozur (1985) and Grill & Kozur (1986) who established a Bajocian age based upon comparative analysis with the ammonites recovered. De Wever & Caby (1981) retrieved Oxfordian/Kimmeridgian radiolarians from within manganese carbonate layers in the French Alps.

iii). Japan/Far East.

The third major crustal area of radiolarite development is in Japan, where the Jurassic radiolarian faunas have been studied in some detail. However, an intrinsic problem with the Japanese material has been that the majority of the sections are exposed only as small blocks within a complex tectonic regime which also lack a good independent macrofaunal biozonation. This has inevitably led to an absence of overall constant synthesis and therefore a poorly applied correlation. In summary, Yao ***et al.*** (1980), Matsuoka (1983, 1984, 1986a, b), Mitzutani & Kido (1983) and Matsuoka & Yao (1985) have proposed several Jurassic assemblages and zones reflecting evolutionary lineages primarily based on nassellarian taxa. It appears that only a small proportion of the taxa present have been described and had their ranges ascertained. The majority of these studies relate to the Late-Latest Jurassic. Recently, attempts have been made to address this lack of correlation between provinces, with moderate success, particularly across the Pacific basin (Pessagno & Mitzutani, 1991). The Russian equivalents to the Japanese strata were studied by Vishnevskaya (1993), including the Kamchatka region and Sakhalin Island, which appear to be similar to the Japanese sections in that ammonite data was poor or totally absent.

iv). Other Regions.

Isolated studies also show that radiolaria can be retrieved from relatively shallower water epi-continental seas and areas where a siliceous dominated depositional regime was not immediately evident. Examples include the Scottish onshore sections at Brora, Balintore, Helmsdale and Staffin Bay (Gregory, this work, 1986), the North Sea (Dyer & Copestake, 1989; Partington ***et al.***, 1993a, b) and the Middle Jurassic of Germany where radiolaria were recovered from phosphatic nodules (Riegraf, 1986, 1987b). Other isolated areas of research include the Middle and Upper Jurassic of New Zealand which established the presence of radiolaria (Foley ***et al.***, 1986; Feary & Pessagno, 1980). Wang Yu & Jin Zhang (1982) and Wang Yi Gang (1988) indicated the presence of radiolaria in Middle Jurassic sediments of the Xiang Province of China. Jurassic radiolarian biostratigraphy was briefly covered within Permian to Cretaceous sequences from the Oman Mountains by De Wever ***et al.*** (1990).

Radiolaria have, therefore, been retrieved from normal micropalaeontological preparations of argillaceous sediments and the absence of published accounts may be a consequence of several factors. Firstly, radiolaria were often not the primary object of micropalaeontological study and were therefore were not collected or reported. This point can be illustrated by many primarily foraminiferal texts where radiolaria merit a brief mention, for example from the Middle and Upper Jurassic of the Polish Lowlands (Bielecka, 1960, 1988; Bielecka *et al.*, 1988). It does not seem unreasonable to suggest that some authors may not have recorded radiolaria, even if present. As an additional interesting aside, Upper Jurassic radiolaria have occasionally been incorrectly described as other microfauna, as illustrated by Dumitrica & De Wever's (1991) re-examination of two species described as foraminifera by Karrer (1867) from the Oxfordian of Austria.

Secondly, the presence or absence of radiolaria may be due to preservational factors. Silica is a notoriously difficult mineral to preserve in the geological record, being extremely soluble with respect to sea water which is usually under saturated in silica. So, preservation requires special circumstances of silica enrichment of sea water, for instance by nutrient upwelling or by volcanic activity liberating silica. Rapid burial also probably increases the chance of preservation, if not by primary silica, but by several other minerals, the most commonly reported being calcite or pyrite, followed by glauconite.

In conclusion, it is apparent that the majority of the discussed texts deal with taxonomy and/or biostratigraphy, with little emphasis placed on the palaeoecology or palaeoenvironmental interpretation other than a discussion of the planktonic mode of life. Pessagno (1991b) has attempted to redress this imbalance by providing a discussion of the biogeographical provinciality of high and low latitude faunas. This point is included in the integrated palaeobiogeography in Chapter 7.

Even within the Cretaceous, where the faunas are better preserved, few authors have tackled this subject. An exception is Koutsoukos & Hart (1990b) who produced broad distributional patterns related to relative depth of the continental shelf of radiolarians from the Siegipe Basin in Brazil.

CHAPTER 3
RATIONALE AND APPROACH

3.1. Introduction

This chapter serves as a general introduction to the techniques and philosophy of the biostratigraphical and palaeoecological approaches covered in this study of foraminifera and radiolaria from the Middle and Upper Jurassic of Scotland.

There appears to have been a polarisation of species differentiation in terms of taxonomic approaches, with a division into those authors who split taxa based upon minute test differences and those who group or lump forms using less rigid criteria. As a generalisation, it appears that 'taxonomic splitters' tend to be biostratigraphers, who are looking for subtle morphological change that may have been chronostratigraphically limited. On the other hand, many palaeoecologists appear to be 'lumpers', as it is apparently easier to pick out palaeoenvironmental trends in the geological record if there is some grouping of forms which are indicative of particular niches.

The approach chosen here has been to attempt to combine and integrate these two, apparently irreconcilable, attitudes in order to maximise information. Firstly, in terms of splitting, subspecies are used. There has been criticism of subspecific nomination (or plexus as discussed by Barnard, 1963), which is based upon the premise that true subspecies represent populations which are geographically separate but can interbreed, whilst certain groups labelled as subspecies may in fact be allopatric species not able to interbreed (Mayr, 1969). As it is almost impossible to interpret the differences in these opposing views from the fossil record, a subspecies is defined pragmatically here as being chronogeologically derived; therefore this subdivision is utilised in a biostratigraphical context. The external test features of certain foraminiferal taxa appear to evolve in such a way as to produce minor differences in specific characteristics which may be useful for delineating biozones. This has been shown, for example, in the ***Lingulina tenera*** plexus of the Lower Jurassic (Barnard, 1956; Nørvang, 1957; Copestake & Johnson, 1981, 1984, 1989).

Secondly, for palaeoecological and palaeoenvironmental interpretations, a more generalised, or lumping, approach is used, whereby taxa are grouped initially into genera and then into their respective family groups, based on test wall structure. The relative changes of these groupings can then be analysed, in conjunction with specific foraminiferal and radiolarian distribution, facies type and macrofaunal distribution, to ascertain the effect of environmental changes induced by transgression and regression. This then allows a crude basin development to be interpreted.

3.2. Biostratigraphy

The Middle and Upper Jurassic of Scotland, along with the rest of the UK has, until now, had no foraminiferal or radiolarian biostratigraphical scheme erected. The Lower Callovian to Lower Kimmeridgian section at Staffin Bay on the Isle of Skye has been chosen as the stratotype for the combined foraminiferal and radiolarian biozonation (Chapter 4; fig. 4.23), as it is the most complete and well documented part of the area studied. The microfaunal indices selected were easy to identify, occurred in reasonable numbers and had a relatively constant stratigraphical range when compared to other published sections and composite schemes (Chapter 7). Other sections in this study also allow comparison of the various parts of the Staffin Bay stratotype; Eathie Haven and Kintradwell cover the Lower Kimmeridgian, whilst Balintore and Brora provide comparison for the Lower Callovian to Lower/Middle Oxfordian.

A major requirement of any biozonal form is that it should be independent of facies control. Unfortunately, when dealing with benthic microfossils, the palaeoenvironment has a bearing on biostratigraphy. Many forms are facies controlled in their distribution and this lessens the usefulness of some taxa as biozonal indices. This is a known limitation with benthic organisms, but to a certain extent must also affect radiolaria, which inhabit various depths in the water column and so can be limited by the actual water column thickness. Planktonic Jurassic foraminifera, which have a Jurassic world-wide record (e.g. Stam, 1986, 1987b, c; Chapter 7), were recovered in this study for the first time in the UK, from the Upper Oxfordian of Staffin Bay. They did not occur in sufficient numbers to be of any specific palaeoecological/biostratigraphical use, except to give a very rough indication of correlation with similar deposits in Europe and Russia (Yakoleva ***pers. comm.***, 1992).

In defining a biozonation scheme for the foraminifera recovered here, only forms that appeared to colonise several facies types have been chosen as the biozonal fossils. Fortunately, certain benthic forms, particularly the lagenids in the Jurassic, appeared able to exploit several facies types relatively successfully. These forms have been selected wherever possible in preference to those taxa that were obviously affected by facies, such as the miliolids.

Ammonites presently serve as the highest resolution biostratigraphical tool for the Jurassic. The scheme used for the Middle and Upper Jurassic of Scotland (Fig. 1.2) is broadly based on the work of Sykes (1975a, b), Sykes & Surlyk (1976), Sykes & Callomon (1979) and Wright (1973, 1989). This forms the basis of a template against which the microbiostratigraphy can be tied and correlated. Once established, this second order correlation then provides the means to date, with reasonable accuracy, areas where ammonites cannot be retrieved, as is common in oil exploration drilling. Microbiostratigraphical datums are not always exactly coincident with the ammonite biozonal boundaries. Also, even when dealing with the high resolution of ammonite data, secondarily derived microbiostratigraphical or palynological schemes, when correlated, will be diachronous to some extent due to the relative differences in the evolution rates and subsequent migration of the various taxa.

A further consideration is that the Middle and Upper Oxfordian was marked by a degree of provinciality of ammonite genera, leading to three regions with different, but correlatable biozonal forms. Figure 3.1 summarises the various biozonal schemes and stage nomenclature that have been erected for this interval. The Staffin Bay section also provides the type reference section for the Middle and Upper Oxfordian Boreal ammonite province (see section 4.3.3).

The generally accepted definition of high resolution ammonite biozones in well established sections is by the first appearance of the biozonal form. Thus, the top of any biozone is defined by the base of the succeeding biozone. This contrasts with micropalaeontological and palynological biostratigraphical techniques which are more varied in approach and which often utilise a combination of first and final appearances (tops) of forms and even acmes for localised correlations. The use of final appearances is a necessary approach in commercial well drilling to minimise the effects of caving which mask evolutionary inceptions. Theoretically, problems could occur when using tops for regional correlation, because it is difficult to envisage a cause (other than sea-level fluctuations affecting basin-wide distribution) that would prompt a synchronous extinction of a single species over a large area. First appearances are probably more reliable because, if suitable migration routes were available (which can also be affected by relative sea-level changes) and the taxa were not facies dependent, this type of event would appear to be more geologically synchronous.

3.2.1. Biozone Types

Following the International Stratigraphic Guide (Hedberg, 1976) and the recommendations of Whittaker *et al.* (1991), zones defined by fossil indicators are nominated biozones. There are several types of biozone and these can be grouped into two sets; Range Biozones and a miscellaneous group.

Range Biozones are defined by an index species' stratigraphical range and there are several types, as illustrated in Figure 3.2 and described below:

i). Total Range Biozone, which is based on the total stratigraphical and geographical range of the index fossil and is defined by its first and final appearances.

ii). Concurrent Range Biozone (or Overlap Zone of Johnson, 1979), which can be determined by two or multiple taxon indices that overlap in their ranges (see Fig. 3.2).

iii). Interval Range Biozone, which is defined as the stratigraphical interval between two species events.

The other group, miscellaneous biozones (Fig. 3.3), includes the Assemblage Biozone, which is typified by a series, or assemblage of forms that can be determined to be unique in time. Assemblage Biozone boundaries are notoriously difficult to define as facies controlled distribution can adversely affect the faunal elements within an assemblage.

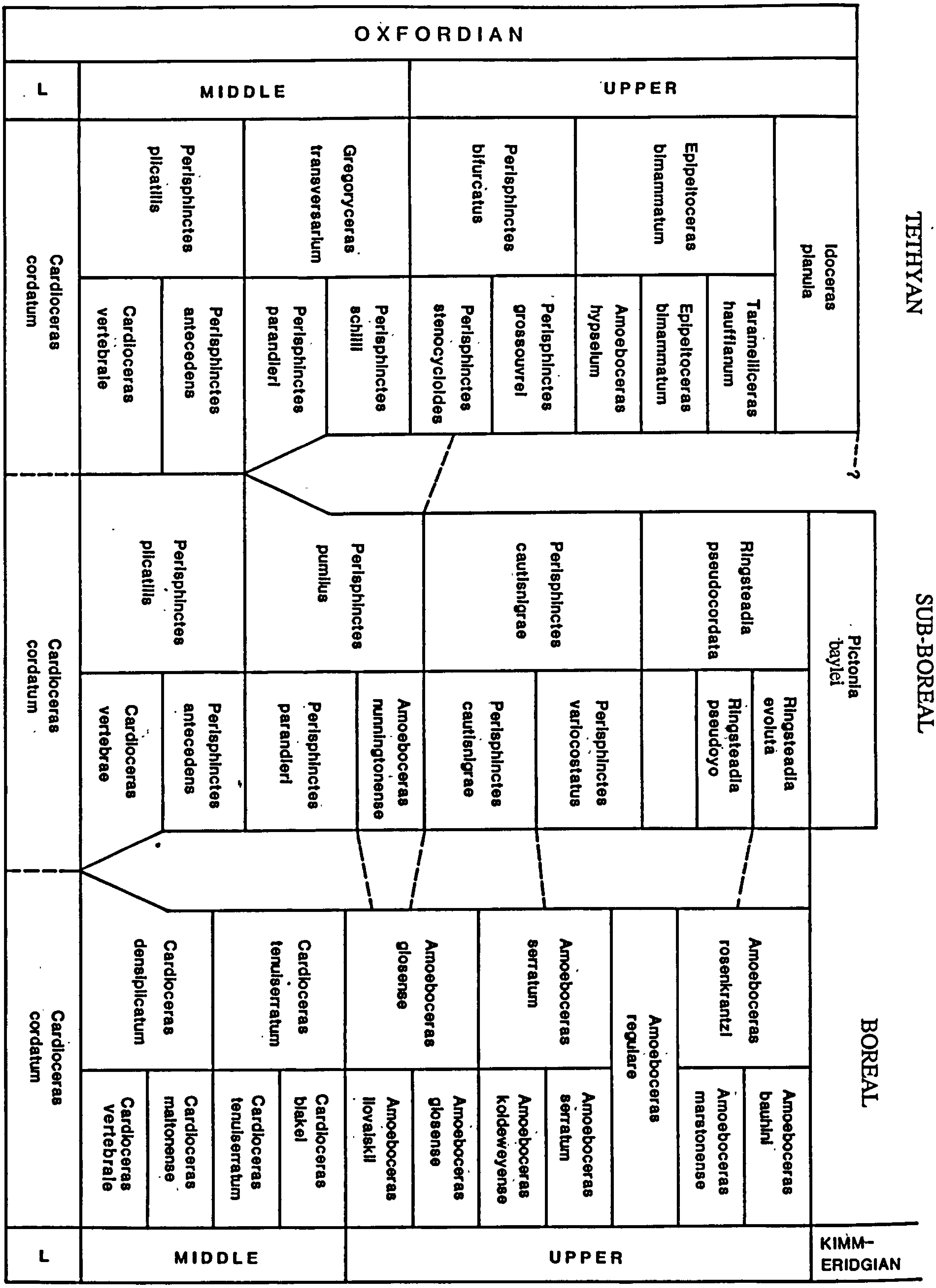


Figure 3.1. Ammonite biozonation for the Middle and Upper Oxfordian with correlation between the Tethyan, Sub-Boreal and Boreal Provinces (adapted from Sykes & Callomon, 1979)

Also affected by environmental factors are Acme Biozones, which are delineated by the maximum abundance of a particular form in time. Problems with this type of biozone are twofold. Firstly, the total extent of the maximum abundances defining the boundaries is hard to define. Secondly, many taxa nominated as acme biozonal indicators occur in abundance due to the prevalence of certain favourable environmental conditions, which may not have been sustained either for a consistent period of time or over a large geographical area.

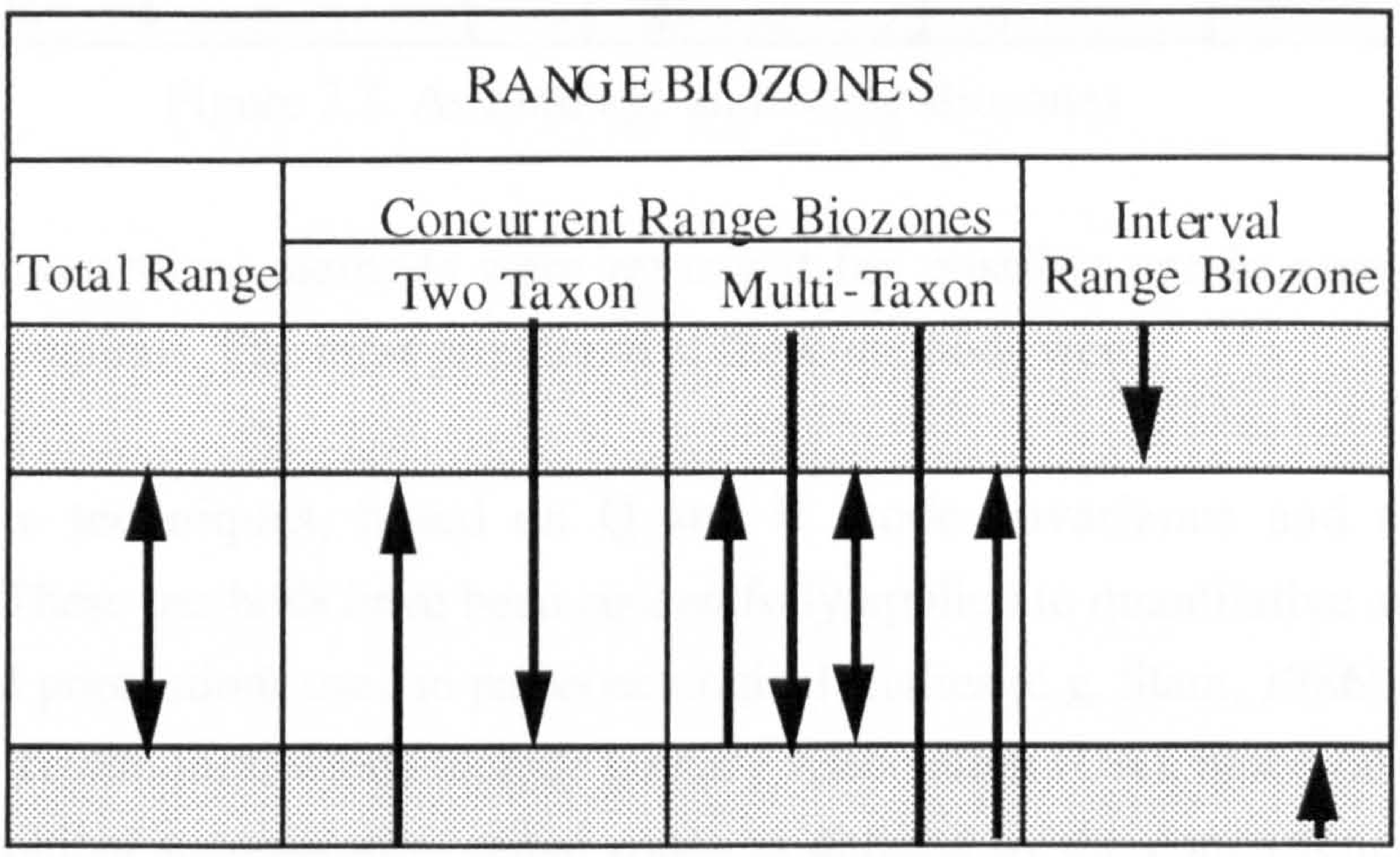


Figure 3.2. Range Biozones divided into main types;
a). Total Range Biozone
b). Concurrent Range Biozone
c). Interval Range Biozone

Therefore, in establishing a biozonation, there is a definite order of preference in use of the various biozone types. Range Biozones are the most useful, as first and final appearances can be theoretically correlated over large regional areas. The total range of a form may, however, be controlled by the final appearance, which may not be consistent or as synchronous as the evolutionary appearance and subsequent migration. Concurrent Range Biozones are therefore the ideal type of biozone to be delineated. Assemblage and Acme Biozones are less useful due to the unpredictable effects of both biotic and abiotic environmental factors which may have an impact on microfaunal distribution (Section 3.3).

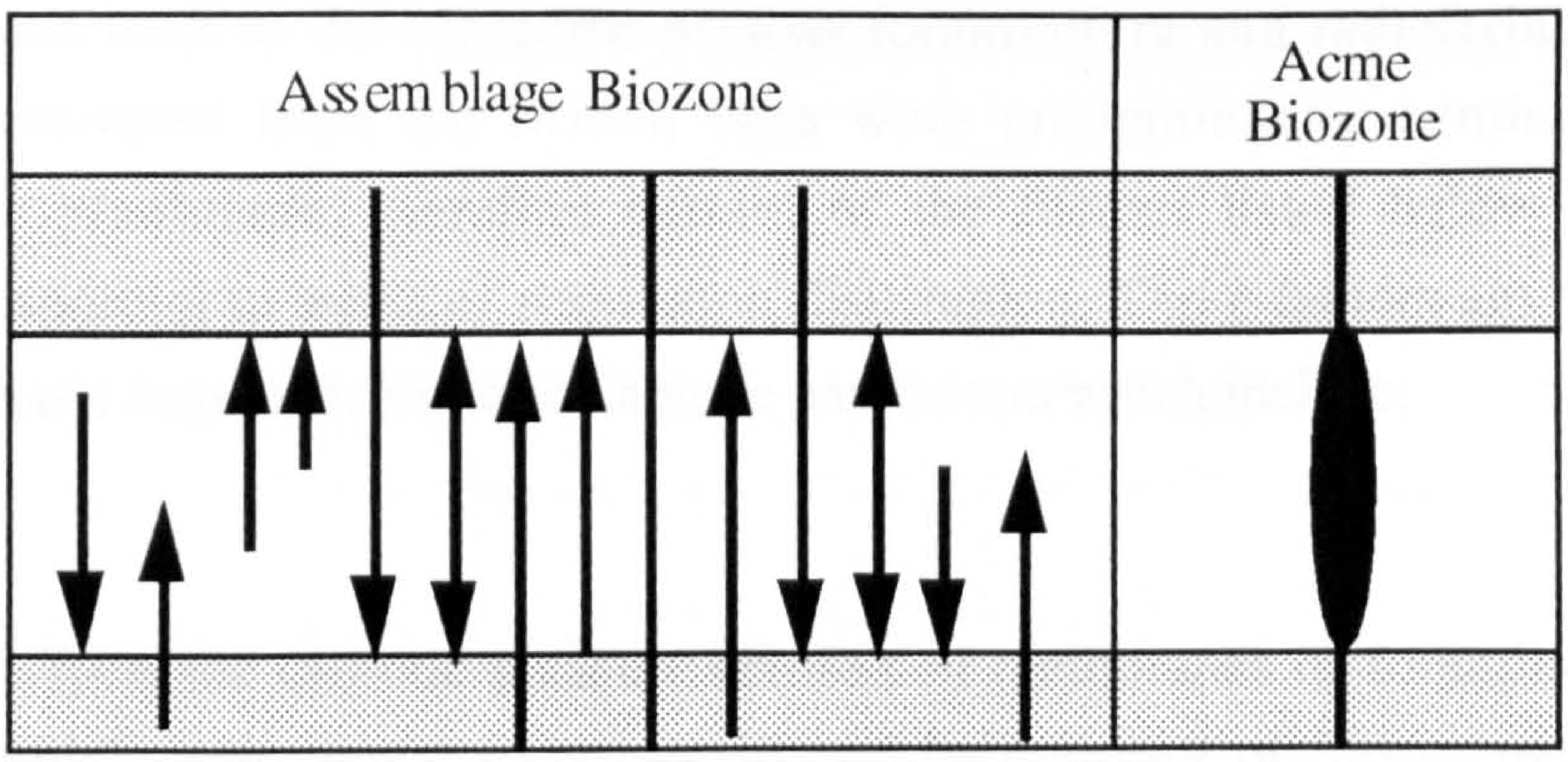


Figure 3.3. Assemblage and Acme Biozones

Various statistical methods were reviewed for possible use in assessing and correlating biozonations. The most prominent of these methods were:

1). Multivariate techniques, based on Q and R mode covariance and clustering techniques. These methods have been successfully applied to quantitative analysis of foraminiferal populations used in palaeoecological studies (e.g. Stam, 1986).
2). Sequencing Techniques, which include Unitary Association (UA), based on assessing the stratigraphical succession of range zones as defined by the concurrence of taxa, and Ranking and Scaling Techniques (RASC) as used by Gradstein ***et al.*** 1985.

These statistical approaches were not used in this study as large data sets and access to relevant computer software are required. To be viable RASC and UA both require at least 10 stratigraphical sections (Gradstein ***et al.***, 1985). Thus, the number of samples and sections covered from Scotland was too small to be considered for processing in such a manner. RASC and UA are very useful for establishing a working biostratigraphy for correlation of well sections where there is a high incidence of cave in and contamination caused by drilling. These methods can indicate the likelihood of correlation cross-overs being caused by such mixing. This type of error was not considered relevant for the Scottish material as all the sections were from outcrop and samples were collected and processed in such a way as to limit contamination.

3.3. Palaeoecological Considerations

This section is included to summarise the main ecological, biotic and abiotic factors which may influence the distribution of foraminifera and radiolaria. These factors have been observed in modern faunas, so the relevance of such factors in palaeoenvironmental interpretation is also briefly discussed. Additionally, some comments are offered concerning assumptions and the problems inherent in interpreting fossil assemblages based upon a uniformitarian approach.

3.3.1. Introduction

A series of physical and biological factors influence the abundance and distribution of marine organisms such as the sarcodine protists foraminifera and radiolaria. Jurassic foraminifera recovered from the British Isles were predominantly benthic, whilst radiolaria were planktonic, therefore certain of the factors listed below must be differentially important in terms of population distribution. These factors are generally simplified into basic important biotic and abiotic parameters which include:

1). Salinity.

This factor affects the osmotic pressure across cell membranes of foraminifera and radiolaria, which both appear to be sensitive. The majority of forms, particularly radiolaria, are stenohaline in their requirements. Salinity appears to be most variable in surface waters and is controlled by evaporation and by terrestrial runoff. Some foraminifera from the Jurassic may equate with modern taxa, for example miliolids may predominate in areas of increased salinity, whilst agglutinated taxa may have been more tolerant to salinity fluctuations, including brackish waters.

2). Illumination.

Light can be important for modern day faunal distribution patterns, but its influence is difficult to assess and is probably more easily related as a light gradient attenuating with slope and distance from shore. Availability of light also has an important bearing on taxa that utilise symbionts, limiting distribution to the photic zone. It seems reasonable to assume that Jurassic radiolaria had the same symbiotic requirements and relationships with dinoflagellates as are exhibited by all modern extant polycystine taxa. Dinoflagellates provide both symbionts and prey (Anderson, 1983; Anderson *et al.* 1989c). Radiolaria and dinoflagellates co-exist today and probably did so in the Jurassic. Gregory (1986) attempted to show a positive correlation between the distributional patterns of radiolaria and dinoflagellate cysts in terms of predation or symbiosis. For foraminiferal taxa, certain generalisations may be valid for Jurassic taxa, namely that groups whose wall structure precludes sufficient light from penetrating the test would not likely possess symbionts. Such forms probably include agglutinated foraminifera, miliolids and possibly robertinids. On the other hand, lagenid wall structure would allow sufficient light penetration, but unequivocal evidence is lacking from the geological record of symbiotic relationships and modern day records are not conclusive as lagenids now appear to inhabit deeper water environments. Modern spirillinids utilise symbionts (Myers, 1935, 1936; Brasier, 1975), but again direct fossil evidence of symbiosis is lacking. The abundance of fossil spirillinids in predominantly shallow water environments (e.g. Helmsdale, Section 5.4) may, however, reflect a reliance on symbionts.

3). Temperature.

Severe temperature fluctuations affect foraminiferal and radiolarian distribution by inducing death, whilst moderate fluctuations can limit reproduction and hence competition. Bradshaw (1961), in a series of laboratory experiments, observed the detrimental effects of temperature on foraminiferal physiology. Anderson (1983) and

Anderson ***et al.*** (1989b) formed similar conclusions regarding radiolarian distribution.

For Jurassic environments the overall ambient sea water temperature appears to have been relatively temperate, as shown by clay mineralogy analyses of Hallam ***et al.*** (1991) and Hurst (1982, 1985), thereby possibly negating extremes. However, it must be stressed that these analyses were conducted from limited geographical datapoints.

4). Skeletal mineral availability.

As both foraminifera and radiolaria produce a skeletal test, the availability of calcium carbonate and silica respectively can produce restrictions on colonisation of environments. Normal marine water is generally saturated or supersaturated with respect to calcium carbonate and the concentration of the CO_3^{2-} ion is dependent on pH and the concentration of CO_2. The CO_3^{2-} ion is affected by temperature (Griener, 1970 1974), making foraminiferal test secretion in colder waters more difficult (Corliss, 1985).

For radiolaria the situation is somewhat different, as their siliceous skeletal mineralogy depends on the availability of silica in sea water. It has been shown (McGowan, 1971; Friedman ***et al.***, 1976; Johnson, 1976; Rützler & Macintyre, 1978) that sea water is generally undersaturated with respect to silica, therefore secretion under normal circumstances is an energy consuming process. Silica enrichment is a good source of material and this generally occurs at sites of upwelling or as a consequence of volcanic activity.

5). Oxygen availability and pH.

Levels of dissolved oxygen, which are important for foraminiferal and radiolarian respiratory and physiological processes, generally decline with depth and temperature. Therefore, benthic foraminifera which are restricted to the substrate are dependent upon this factor. Oxygen levels can be reduced by abundant levels of organic matter, promoting rapid oxygen consumption and giving rise to a reducing environment. Low values of substrate pH, induced by the deposition of organic carbon and lowered levels of oxygen availability, may also exclude calcareous forms by ***in situ*** decalcification.

Oxygen availability is related to four biofacies as defined by Tyson & Pearson (1991);

a). Aerobic which is a normal marine habitat supporting a wide range of benthic faunal elements and relates to oxic levels of 8-2ml O_2.

b). Dysaerobic biofacies which possesses a limited benthic fauna and relates to dysoxic levels of between 2 and 0.2 ml O_2.

c). Quasianaerobic biofacies (defined by Koutsoukos ***et al.,*** 1990) relates to laminated sediments without a benthic macrofauna and with no bioturbation, but which have a limited ***in situ*** benthic microfauna. This facies type is therefore not truly anaerobic and appears to relate to suboxic levels between 0.2 and 0.01 ml O_2.

d). Anaerobic which is completely free of organisms with metabolisms dependent upon the availability of oxygen and relates to anoxic levels of oxygen, i.e. 0 ml O_2.

6). Depth.

The majority of the factors outlined above vary in some fashion with slope depth and related water mass depth, the strongest relationships being with hydrostatic pressure, light, temperature and salinity. Therefore, it is difficult to ascertain whether there is a direct correlation between depth and distribution for benthic foraminifera and planktonic radiolaria. Even within modern studies where all the biological and physical parameters could be measured it is still difficult to be specific with regard to a depth distribution due to microfacial differences (e.g. Corliss, 1985). Funnell (1967) cautioned against absolute interpretation of depth from fossil assemblages due to the fact that several factors are influenced by depth. Furthermore, Murray (1991) pointed out that there is too much reliance on attempts to pinpoint an absolute depth from foraminiferal faunas. At present, particularly in the fossil record, depth should be a purely qualitative measure, deduced as much from the facies and integrated fossil groups as from a reliance singly on the microfaunal population.

3.3.2. Techniques

For this study, several parameters were defined in order to compare and assess any palaeoecological and, therefore, palaeoenvironmental changes that occurred. These techniques are outlined below:

1). Absolute abundance of individual taxa, plotted on range charts as utilised in the biostratigraphical sections (Chapter 4, Chapter 7).

2). Distribution of selected dominant taxa from each sample as a percentage of the total number of individuals.

3). Relative percentage distribution of the major generic groupings, arranged within the major hierarchical groups.

4). Relative percentage distribution of the major hierarchical groups based on wall structure and hence taxonomic position, defined here as Agglutinated Foraminiferids, Lagenids, Robertinids, Miliolids and Spirillinids.

5). Number of specimens per gram of residue picked.

6). The diversity index α.

Species diversity has become an important ecological and, to some extent, palaeoecological tool. Diversity is a central ecological theme to spatial and temporal variation and consists of two components; variety and relative abundance. The various indices available are discussed and assessed below.

At the most elementary level, diversity is restricted to a straightforward species count. This method is not generally used as no community or population has a constant species of equal abundance, the normal range usually comprises a majority of rare forms, a number of common forms and a few forms which are abundant (Magurran, 1988).

Therefore, diversity indices are normally divided into two types. The first is a measure of species richness, the most commonly used of which is Sanders' (1968) Rarefaction method which allows unequal sample sizes to be compared. These indices suffer from a loss of information as the calculation produces the expected number of species per sample.

The second type of index measures species abundance and tends to utilise all the community information. It can be expressed either as a log Normal distribution, as a geometric series, or as a logarithmic series. The earliest and still most widely used method in micropalaeontology and to a certain extent in modern ecological studies (Taylor, 1978; Magurran, 1988), is Fisher's Logarithmic model (Fisher ***et al.***, 1943) or α index. This describes mathematically the relationship between the number of species and the number of individuals in those species. Williams (1964) provided a nomograph in order to read α values directly. Murray (1968, 1973, 1991) and Murray & Wright (1974) tested and used Fisher's α index to analyse Tertiary and Recent foraminiferid faunas.

The α index is a log series value and is expressed as:

$$\alpha=\frac{N(1-x)}{x}$$

x is estimated from

$$\frac{S}{N}=\frac{(1-x)}{x(\ln(1-x)}.$$

Where S= the number of species
N=the total number of individuals

7). Ternary diagrams, which were initially utilised by Murray (1973) for foraminifera suborders, have been adapted as in Figure 3.4, plotting the relative percentages of foraminiferids, spumellarian and nassellarian radiolarians. This produces a visual representation which may have some use in elucidating palaeoenvironmental changes over time. However, this technique was only applied to the relatively abundant, and therefore statistically viable, radiolarian faunas of the Lower Kimmeridgian of Eathie Haven and Helmsdale (see Sections 5.4 and 5.5 respectively for details and Chapter 7 for results). This method could be used to replace the planktonic/benthic ratios used in defining relative distance from shore used for Cretaceous to Recent sediments.

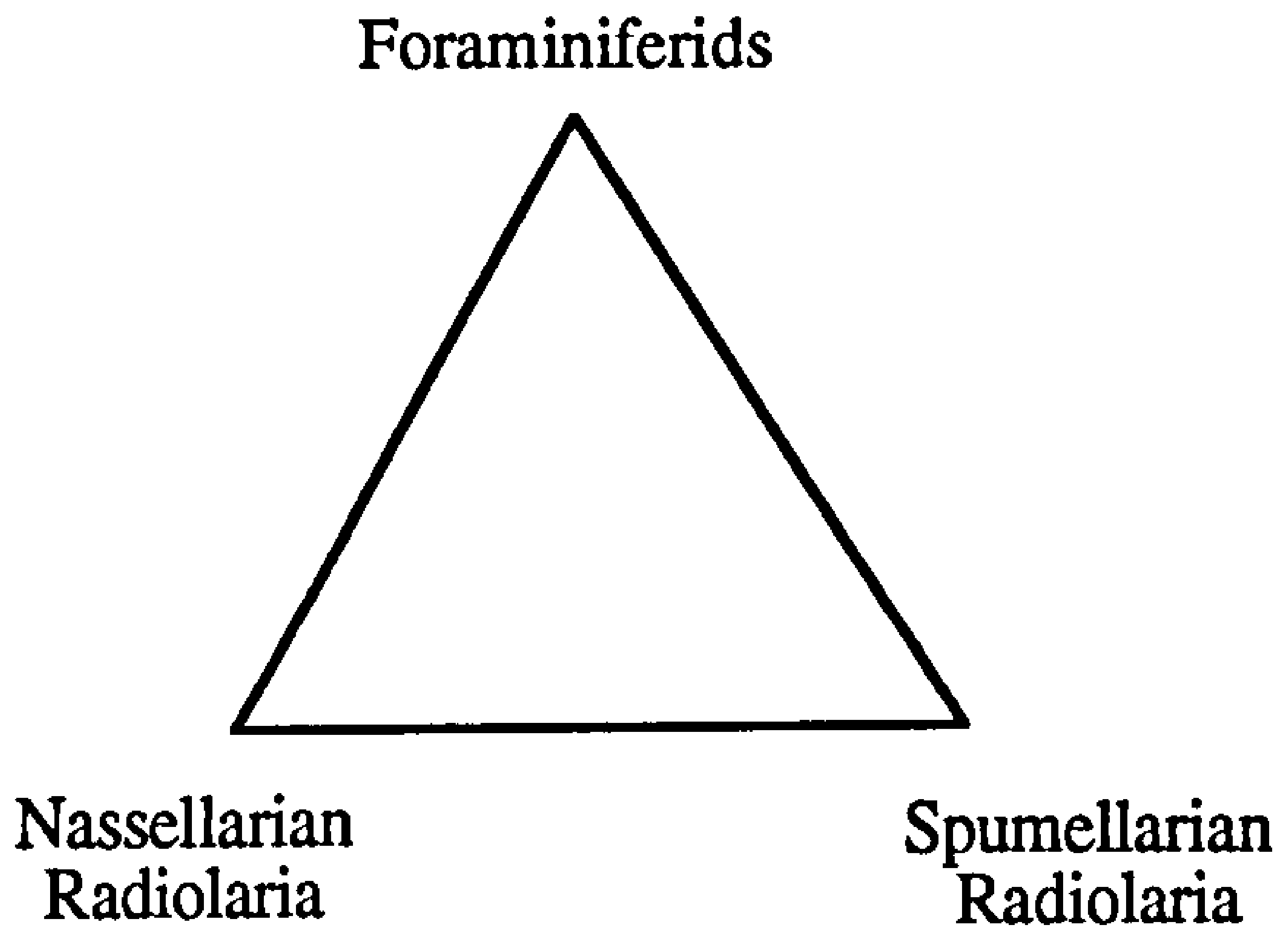


Figure 3.4. Ternary Diagram of percentage foraminiferal and radiolarian distribution

3.3.3. Conclusions

When interpreting the results from this study, a series of assumptions were made which should be taken into account. In some cases the questions which arise from applying such assumptions can not be addressed with the present extent of knowledge and require a much more in depth analysis of the modern day biology and physiology of foraminifera and radiolaria. The main issues can be raised as a series of questions:

1). Do Jurassic microfaunal assemblages compare with modern faunas and their distributional patterns?

A major problem with understanding the palaeoecology and niches of the majority of Jurassic foraminifera is that uniformitarianism does not appear to be of direct use in deducing the palaeoenvironment. Comparison with modern analogues is fraught with difficulties as the composition of foraminiferal assemblages has changed dramatically since the Jurassic. Within most normal marine Jurassic shelf environments, lagenids tended to dominate in terms of either total abundance or diversity (Gordon, 1970; Scheibnerova 1972; Haynes, 1981). From the Cretaceous to the modern day there has been an evolutionary trend whereby lagenids have been ousted from their initially favourable niches by competition and rapid evolution of rotaliid foraminifera with their multiperforate test structure (Haynes, 1981; see Murray, 1991 for a list of the environmental parameters of modern foraminifera). Lagenids now occur as subsidiary components, or dominate in deeper water environments where competitive selection or pressure is not as rigorous as in the shallower shelf environments. Hence, results from extensive modern studies, which used some of the statistical methods outlined, to deduce and characterise particular modern environments, cannot provide direct comparisons between recent assemblages and those from the Jurassic. This becomes especially apparent in terms of Fishers α diversity index, as there is little direct comparison between the ecological ranges and environments derived from comprehensive modern studies (e.g. such as synthesised by Murray, 1973, 1991) and from the Jurassic. This is due to the vast differences in the faunal composition of modern day environments and those in the Jurassic. Overall, this thesis shows that α index values from the Jurassic are much lower than in modern environments. This must be as a consequence of proliferation of recent taxa. However, these differences do not detract from using such indices for comparing facies within the Jurassic because, despite the lack of direct comparison with recent data, relevant information is still generated. This data can then be used in combination with facies types to attempt to define gross environmental changes that occurred through time and also laterally across basinal environments. However, some groups such as the spirillinids and miliolids which colonise specific modern, shallow water niches appear, because of their wall structure and/or ecological requirements, to have remained almost constant or restricted in their niche ranges. Hence, direct comparison may have more validity for these groups.

It is probably justifiable to apply a uniformitarian approach to radiolarian distribution patterns since their physiological requirements appear to be more restrictive or easily defined than those of benthic foraminifera. However, in terms of their total distribution in the Jurassic (as seen in the Scottish basins and from the previous research review, Section 2.3) there may be a case for believing that radiolaria were able to exploit relatively shallower environments than at the present day. Competition within the water mass, particularly from siliceous diatoms and planktonic foraminifera is of more importance in modern environments than it was in the Jurassic. Although planktonic foraminifera were present in the Jurassic they were not numerically important. Additionally, siliceous diatoms are an important component of modern marine sediments, but the present evidence is that testate diatoms only emerged from the Early and Middle Cretaceous (Burckle, 1978) with poor records from the Jurassic.

The majority of research on radiolaria has been on Recent material in which they are certainly the most diverse of holoplanktonic groups (McGowan, 1971) with an estimated 400-500 extant species. Most studies relate to tropical ocean radiolarian oozes with Haeckel (1887) being the first to study radiolaria in the water column. Until the 1970's there were few palaeoecological studies of radiolaria and the major conclusions were that as a group they are exclusively marine and planktonic; Haeckel (1887), however, noted an ability to attach and use pseudopodia to crawl. The vertical distribution in the modern water column is still not fully understood. Bjørklund (1974) stated that there was a seasonal occurrence and depth zonation and that some forms can be introduced by influxes of ocean current activity. Casey *et al.* (1979) compared the ecological niches of radiolarian and planktonic foraminifera, concluding that there are as many polycystine radiolaria as there are niches that they inhabit, whilst overall planktonic foraminiferids occupy far fewer. Polycystine radiolarian populations in the Gulf of Mexico are best developed in boundary current areas and are fewer in the open ocean areas. The densest populations in the shallow water are developed with boundary currents and are poorly represented in neritic waters except during periods of open ocean intrusion (Casey, 1977; Casey *et al.*, 1979, 1981, 1982). This latter effect is probably applicable to the Jurassic epi-continental North Sea.

In recent years there have been experimental studies on the physiological ecology of radiolaria, carried out in particular by Anderson (1983) and Anderson ***et al.*** (1989a, b, c) who have primarily cultured ***Spongaster tetras tetras***. They observed growth patterns related to seasonal patterns, predation, the co-existence of two species in the same niche related to differing nutrient requirements and symbiont activity. They also tested extremes of temperature, salinity and light intensity (Anderson ***et al.*** 1989c) on ***S. tetras tetras*** and confirmed that it is restricted to warmer temperature masses. Anderson ***et al.*** (1990) investigated the extremes in survival of the radiolarian ***Didyocytrtis tetrathalamus tetrathalamus*** which, although restricted to warmer water masses, appeared to be able to survive at lower temperatures and lower light levels. Their major conclusion was that other environmental factors can have an effect on the restriction of distribution. Uncertainty over absolute controls is evident and much more work is required on the physiology of radiolaria, as well as foraminifera. Conclusions generated in this study must be viewed in this light.

2). Does the fossil assemblage represent the original biological population?

There has been much debate on what a fossil population constitutes in terms of the original biological community. Murray (1973, 1976, 1991) outlined population studies of modern benthic foraminiferids in terms of living, dead and total (living plus dead) populations. The living assemblage represents the live population at an instant in time and is generally assumed to be in equilibrium with the environment (see Murray 1973 for the mathematical analysis of this point), whilst the dead population consists of an accumulation of the living population and may or may not be truly representative of the living population. The total assemblage represents the living plus dead populations.

Scott & Medioli (1980) discussed the reliability and usefulness of using only total populations in palaeoecology and ecology with regard to the living surface and total (living plus dead) populations and concluded that both palaeoecologists and ecologists should only look at the total population.

Murray (1982) argued with the conclusions of Scott & Medioli (*op. cit.*) as they did not record the dead populations. He reasonably objects to their statement that "paleoenvironmentalists have no choice but to examine buried total populations; therefore it is indeed fortunate that their only modern analogue is also best" on the grounds that truly ecological studies can only be carried out on living assemblages over a period of time.

Both of the approaches, as outlined by Murray (*op. cit.*) and Scott & Medioli (1980), have their merits. Murray's methods are seen to be essential in determining the true ecology of the living population within modern benthic assemblages which can give pointers to the fossil record. However, the dead assemblage (or fossil assemblage, assuming a favourable taphonomic process) is all that palaeontologists have left to study and, as such, can be seen as a result of a time averaging effect. The result is that any palaeoecology and palaeoenvironmental changes identified by such studies must be viewed in a generalised context, i.e. in terms of a geological time frame rather than as a snapshot of the true living population at one moment in time.

Post-mortem changes are an important factor on the outcome of the final microfaunal assemblage composition. In terms of taphonomy or the study of burial conditions, dissolution of microfauna is the most destructive of these and all samples have to be assessed for the possible effects of this factor. Foraminiferal deposition beneath the Calcium Carbonate Compensation Depth (CCCD) was not an important factor during the Jurassic of the Hebrides and Inner Moray Firth areas, as both these basins were part of relatively shallow epi-continental seas. Water depths were estimated by Brown (1984) to be no deeper than 200 metres. Thus, any post-deposition dissolution will have been as a result of other factors, such as the pH and redox potential of the substrate. If these factors were extreme anyway, actual secretion of a calcareous test would be very difficult, and forms requiring little calcite, e.g. agglutinated taxa, may dominate. There would also appear to be a scale of survivability for post-depositional dissolution, with agglutinated taxa most likely to survive, then lagenids, miliolids and spirillinids all probably having roughly the same chances. Robertinids, composed of aragonite, appear to have the least chance of preservation, unless there is a diagenetic alteration to the more stable form of calcite, as the relative ease of dissolution of bivalves has shown. Within the calcareous foraminiferal groups there is probably a further scale of survivability with robust forms having a better chance, for example thick shelled lenticulinids over thin shelled nodosariids.

Therefore, when assessing the ecological potential of samples, specimens and residues were examined for evidence of etching, particularly of robertinids, and also the presence of internal pyritised moulds which may indicate relatively rapid dissolution after burial in a reducing type environment. The macrofaunal elements were also examined for evidence of dissolution, such as etching of bivalve fragments.

The presence or absence of particular calcareous forms may have other explanations. For example planktonic globigerinids, although not as widespread as in the Cretaceous, do have a rather specific Jurassic geographical distribution as indicated by Riegraf (1987b, c) and Stam (1986). This appears to be related to the extent of the Callovian Tethyan transgressions. However, until this study, no specimens were reported from the UK; those recovered here were not well preserved, in contrast to the associated microfaunas. This may indicate a relatively large amount of transport, with associated degradation pointing to transport from deeper water environments which could sustain the hydrographic preferences of these planktonic forms.

Pre and post-depositional dissolution of radiolaria has often been noted as

Adapted from Nagy (1992)							Jones & Charnock (1985)		Koutsoukos & Hart (1990a)	
MORPHO-GROUP AND SUBGROUP		MORPHO-TYPE	CHAMBERS	SUPPOSED FEEDING HABIT	LIFE POSITION	EXAMPLES	MORPHO-GROUP	SUB-GROUP	MORPHO-GROUP	SUB-GROUP
1	1-a	Tubular / branching	Unilocular	Primary suspension-feeder	Epifaunal elevated	Bathysiphon Jaculella	A	A	AG	C
2	2-a	Globular	Unilocular	Passive deposit-feeder	Surficial/ epifaunal	Saccammina Psammosphaera	B	B1	AG	B4
	2-b	Planoconvex-trochospiral, Planoconvex-streptospiral	Multilocular	Active herbivore, detritivore, ommnivore	Surficial/ epifaunal	Recurvoides Trochammina		B3	AG ?AG	B2 ?A
3	3-a	Rounded-planispiral	Multilocular	Active detritivore, bacterivore, herbivore	Infaunal to surficial	Haplophragmoides	C	C1		
	3-b	Subcylindrical, Tapered	Multilocular	Detritivore, bacterial scavenger	Infaunal	Reophax Verneuilinoides Ammobaculites			AG	A
4	4-a	Flattened-planispiral, irregular	Bilocular	Active to passive herbivore, detritivore	Epifaunal to phytal	Ammodiscus Glomospira	B	B2	AG	B3
		Flattened-trochospiral	Multiloc.			Trochammina	D	D	AG	B1
	4-b	Irregular-attached	Unilocular	Passive herbivore	Epifaunal to phytal	Ammovertella	B	B4	?AG	?C

Figure 3.5. Summary of agglutinated foraminiferal morphotypes related to habitat/life styles (summarised from proposals by Nagy, 1992; Jones & Charnock, 1985; Koutsoukos & Hart, 1990a)

extensive. Johnson (1976) indicated that there can be a major dissolution of radiolaria over a matter of hours to weeks, especially in silica deficient areas. This effect is also probably destructively selective with respect to thinner tests. Boltouskoy ***et al.*** (1993) suggested from their study of sedimentary input in the Atlantic that up to 95% of radiolarian test could be lost to the fossil record. Additionally, they noted the preferential survival of spumellarian test which appear to be thicker in construction over nassellarians. Dissolution was noted to be more prevalent in areas of low organic production and low phosphate levels. Goll & Bjørklund (1974) projected a somewhat imperfect relationship between opal silica skeleton survival and a high phosphorous/phosphate level. The actual distribution of radiolaria is related to oceanic phosphorous divergences and radiolarian abundances may be a crude measure of upwelling. This relationship is regarded as imperfectly understood due to the problems of test dissolution and dilution or concentration of original faunas by differing sedimentation rates.

3). Can palaeoenvironments be deduced from morphotype distributional patterns?

Within the ecosystem itself, studies can be focused upon autoecology which covers the individual's physiological response and adaptation to the environment, or synecology which encompasses organisms in context with coexisting communities and their relationships with the environment. Within the literature, true palaeoecological approaches are few. Recently, however, several authors have used foraminiferal morphotypes to deduce palaeoenvironmental significance and to combine a synecological and autoecological approach.

The most comprehensive of these approaches have scrutinised agglutinated foraminiferids. Jones & Charnock (1985) defined four morphotypes and eight subgroups based on an integration of test morphologies and feeding habits for Tertiary agglutinated dominated faunas of the North Sea (Fig. 3.5). They proposed six feeding strategies which involved: uptake of dissolved organic matter, herbivorous, carnivorous, omnivorous, suspension feeding and detrital bacterial scavenging.

Morphogroup A was represented by primary suspension feeders with primitive tubular branching and apertures oriented away from the sediment. This group included ***Bathysiphon*** and ***Jaculella.***

Morphogroup B was represented by surface dwelling herbivores, detritivors and omnivores all of which were epifaunal and include saccamminids, coiled ammodiscids and lenticular/planispiral lituolids with some globular trochamminids also included. These diverse morphotypes appear to be adaptations to an active feeding habit and were further divided into 4 subgroups.

Morphogroup C was represented by sediment dwelling herbivores and detritivors which inhabited an epifaunal type niche and possessed a generally elongate test. This group is further divided into two sub-groups. C1 includes uniserial hormosinids such as ***Reophax***; uncoiling lituolid planispires, such as ***Ammobaculites*** and biserial/uniserial textulariids, trochamminds and verneuilinids, all of which show a later reduction in chambers possibly as a selective pressure acting on infaunal habitat. Most forms appear to be able to take advantage of an interstitial surface life position by attachment. In the modern environment most representatives of C1 dwell in shelf and upper continental slope environments. Buzas (1974) indicated that modern ***Ammobaculites*** have less stringent oxygen requirements. Sub-group C2 includes elongate quinqeloculine morphologies which were not encountered in this study.

Morphogroup D includes herbivores with a low trochospiral morphology, such as some trochamminids, and reflects a high energy environment.

Nagy's (1992) approach was to adapt the morphotype models of Jones & Charnock (*op. cit.*) to the major Jurassic agglutinated foraminiferid groups and to characterise various environmental settings from significant development of the groups and subgroups defined. Four morphogroups were outlined (Fig. 3.5);

Morphogroup 1 was characterised by tubular forms exhibiting a primary aperture. These forms appear to have a preference for deep oceanic settings in the modern environment and are poorly adapted for strong currents.

Morphogroup 2 includes forms that are epifaunal in habitat and live at the sediment-water transition. These can be grouped into two types. Subgroup 2a covers unilocular globular species which are passive deposit feeders. Type 2b covers the multilocular forms which are planoconvex to concavoconvex with a trochospiral coiling mode and low elevated streptospiral taxa. Both forms appear to have the ability to move freely at the surface substrate/water boundary. Nagy ***et al.*** (1988, 1990a, b) hypothesised that this ability allowed taxa to survive in environments with a high organic carbon content. This group includes ***Trochammina*** and ***Recurvoides.***

Morphogroup 3 was characterised by an infaunal lifestyle. Subgroup 3a was dominated by forms which are planispiral, and possess an elongate, rounded periphery such as ***Haplophragmoides kingakensis*** and ***Ammobaculites fontinensis.*** As ***Haplophragmoides*** was often the last genera to disappear in Jurassic black shales (Nagy *et al.*, 1988, 1990a) with increasing organic carbon, it appears reasonable to hypothesise that this group was tolerant to the establishment of dysaerobic conditions. Subgroup 3b contains elongate taxa including ***Verneuilinoides*** and ***Reophax.***

Morphogroup 4 was divided into forms that are flattened trochospires or have irregular coiling and were interpreted as being vagrant to attached epifaunal taxa, and indicative of high energy, marginal marine environments.

Nagy (*op. cit.*) divided his study area in the North Sea into 3 deltaic environments, with the prodelta experiencing normal marine conditions with a low diversity agglutinate population responding to high sedimentation rates dominated by epifaunal group 2b and infaunal group 3b. The lower delta front was hyposaline with only agglutinated taxa and a reduced diversity dominated by group 4a, also indicative of intermittently stagnant bottom waters. The interdistributary bay was hypothesised as brackish, being dominated by group 4a and often characterised by the dominance of a single morphotype, reflecting a restrictive environment.

Koutsoukos & Hart (1990a) also attempted to summarise morphogroup categories for Cretaceous agglutinated and calcareous benthic taxa, relating distribution patterns to a combination of trophic structures, biotic and abiotic factors including distribution on the shelf and slope.

Morphotypes	**Morphogroup/ subgroup**	**Microhabitat**	**Trophic Group**
Plano-convex, trochospiral, lenticular	(CHA1,2)	Epifaunal	Deposit
Inflated biconvex, lenticular, planispiral	(CHA3), (CHA6)	Epifaunal/ Shallow Infaunal	Deposit
Conical, low trochospiral	(CHA4), (CHA7)	Epifaunal	Deposit/passive herbivores
Discoidal/flattened	(CHA8)	Epifaunal	Deposit
Globular, broad palmate, elongate uniserial, planispiral-uniserial	(CHB1-3)	Epifaunal/Infaunal	Deposit
Fusiform, compressed	(CPA)	Epifaunal	Deposit
Elongate to ovate quinqueloculine	(CPB)	Epifaunal/Shallow Infaunal	Deposit

Figure 3.6. Calcareous benthic foraminiferal morphotypes (adapted from Koutsoukos & Hart, 1990a with their morpho and sub-morphogroups included)

This was also related to the functional adaptive morphology of tests. Their agglutinated scheme can be compared (Fig. 3.5), albeit very loosely, to the Jurassic model proposed by Nagy (1992) and the Tertiary by Jones & Charnock (1985). Koutsoukos & Hart's (1990a) selected calcareous forms prove to be difficult to use as abundances and actual genera common to both the Jurassic and Cretaceous do not compare well. However, the broad morphotypes which were related to palaeocommunity strategies, may possibly have some relevance for Jurassic taxa (Fig. 3.6). As the purpose of this thesis is to attempt a broad palaeoenvironmental interpretation, conclusions regarding groupings and feeding strategies are briefly commented upon in the main palaeoenvironmental conclusions drawn in Chapters 4 and 5.

Some authors have attempted to assess broad palaeoecological patterns. Gordon (1970) synthesised and summarised world-wide data available at the time, producing a broad Jurassic biogeography of assemblages based upon relative abundances of the suborders present. This data was mainly restricted to the northern hemisphere, with three niches typical of Boreal shelf environments erected:

i). Lagenid/Lagenid mixed, which apparently represented a typical shelf sea with sedimentary influx and carbonate deposition.

ii). Assemblages dominated by simple agglutinated taxa, characterising deeper or shallow marine conditions of cooler ambient sea water temperature.

iii). Assemblages with a dominance of other calcareous taxa such as ***Epistomina, Ophthalmidium*** or ***Spirillina,*** of unknown significance other than being related to either shallow or deep water conditions.

The Tethys was divided into two assemblages which were characterised by either a domination of complex walled, larger agglutinated foraminifera or by planktonic foraminifera. Due to the enormous increase in literature since the 1970's (covered in Chapter 2) an up-to-date biogeography for Jurassic foraminifera is included in Chapter 7. When combined with radiolarian data this provides a more refined distinction of the Tethyan and Boreal Provinces. There is also an apparent bipolarity of faunal similarities between the extremes in the present day southern and northern hemispheres.

Stam (1986) utilised direct Q and R mode statistical analysis to cluster foraminiferal distribution. His broad conclusions were related to depth in an absolute manner and he indicated that spirillinids and miliolids dominated shallow water depths (50 metres or less), lagenids dominated between 50m and 150m, whilst epistominids and agglutinated taxa dwelled below 150m.

Very little work has been carried out on the palaeoecological significance of radiolaria from the Jurassic other than general comments about distribution being related to connectivity with open oceanic conditions. Indeed, as an estimated 70% of the total Jurassic radiolarian fauna is still to be discovered and described (Pessagno ***et al.***, 1986), palaeoecological conclusions are obviously scarce. Bioprovincial distribution of radiolarian faunas is still in its infancy. Pessagno (1991b) utilised an integrated macro, microfossil and palaeomagnetic study of the published literature (including Pessagno ***et al.***, 1984, 1986, 1987) to construct a broad Jurassic radiolarian palaeobiogeography based on the Tethyan and Boreal Realms. He divided the Tethyan into two assemblages. The Central Tethyan Province was characterised by a high diversity pantanelliid radiolarian fauna with no ***Parvicingula*** present. The Northern Tethyan Province had a high pantanelliid fauna associated with common specimens of ***Parvicingula.*** The Boreal Realm was subdivided into the Southern Boreal Province, typified by a sharp decline in pantanelliids and by dominant and diverse ***Parvicingula.*** The Northern Boreal Province was marked by a lack of pantanelliids, whilst ***Parvicingula*** was abundant. No palaeoenvironmental factors, other than a direct correlation to latitude, were cited by Pessagno (1991b) for this distribution, which must also relate to hydrographic parameters such as temperature and upwelling. In terms of the general faunas recovered from the Scottish Basins, there are no pantanelliids or specimens of ***Ristola*** but ***Parvicingula*** can be common. Therefore this region, as expected, lies within the Northern Boreal Province of Pessagno (1991b). However, it is concluded here that more work must be carried out on the world wide distribution of other common components of radiolarian faunas, in particular the spumellarians.

Some of the more applicable/comparative pieces of work have been carried out within the Cretaceous and include a study by Koutsoukos & Hart (1990b) who recorded radiolarians from the mid-Cretaceous of the Sergipe Basin of Brazil. Their major conclusions were that spumellarian taxa were dominant in all sections whilst nassellarian taxa appear to thrive in deeper water environments and that the presence of radiolaria is in response to better developed oceanic circulation patterns and silica saturation of the water mass. An interesting feature was the dominance of radiolarian tests within the Cenomanian-Turonian sediments in conjunction with dysaerobic bottom conditions which indicated well oxygenated surface waters associated with bottom waters and substrates enriched in carbon dioxide and a low pH. These conditions appear to have been conducive to post-mortem survival of silica tests.

Empson-Morin (1981, 1984) covered several cores from Campanian DSDP sites within the Mid-Pacific Mountains, attempting to delineate latitude and depth distribution in relation to morphology. She showed a bimodal distribution of nassellarians which were common in shallow and deep water deposits. Shallower water appeared to be dominated by two or three morphotypes, whilst intermediate depths were dominated by a predominance of spumellarians.

CHAPTER 4
THE HEBRIDES BASIN

4.1. Introduction

The Hebrides Basin, on the western coast of Scotland, is constrained by the regional onshore geology, being bounded to the north west by the Minch Fault, to the south west by the Camasunary-Skerryvore Fault and is overstepped to the north by the Torridonian Sandstone Formation. The overall regional tectonic structure of the area was investigated initially by McQuillin & Binns (1973) and Binns ***et al.*** (1975), who considered the Hebrides Basin to be divided into two sub basins which consisted of a series of fault blocks or half grabens (Fig. 1.4). More recently O'Neill & England (1994) established from seismic and gravity data that the half graben geometry is correct, but that only one basin is probably present. They also believe that the entire Jurassic sequence, which thickens towards the Minch Fault, was deposited during thermal subsidence following Triassic rifting.

The two areas of interest both lie on the east coast of the northern tip of Trotternish on the Isle of Skye and include the Aalenian/Bajocian of Bearreraig Bay and the Callovian to Kimmeridgian of Staffin Bay (Fig. 1.1).

4.2. Bearreraig Bay, Isle of Skye

4.2.1. Introduction

The magnificently preserved section along the foreshore and in the burn of Bearreraig Bay, some 10km north of Portree in north east Skye, represents a unique opportunity to study in detail a thick, marine, clastic sequence spanning the Toarcian through to the Upper Bajocian (Figure 4.1 shows the locality and extent of the outcrops). Of particular interest for this doctoral project was the opportunity of investigating foraminiferal distribution and inception from this section, which has been nominated as a Global Boundary Stratotype Section and Point (GSSP) for the Bajocian Stage. Results from an initial reconnaissance (U1-U21) and follow up sampling (M1-M6; MP1-MP11) formed the basis of two papers (Gregory, 1990; 1991) which are now elaborated.

Previous geological research at Bearreraig Bay has been intense, but sporadic. Murchison (1829b) visited the section in the nineteenth century and collected from the extensive Aalenian deposits; this is also the type section for the ammonite genus ***Murchisonae***. This initial survey was followed by others such as Judd (1878) and Lee & Pringle (1932) who described the sediments and listed the macrofauna.

In 1954 a Hydroelectric Power Station was constructed (GR. 51635271), which effectively curtailed the waterfall, thereby allowing access to the steep sided burn. This allowed a more detailed study of the burn section, carried out by Anderson & Dunham (1966) and Morton (1965, 1975, 1976, 1984, 1987, 1988, 1990a, 1991), who

Figure 4.1. Litho and biostratigraphical subdivision of the Bearerraig Bay sucession

concentrated on the ammonite biostratigraphy and lithostratigraphy of the Aalenian and Bajocian.

From Morton's work (*op. cit.*) it has become apparent that it is possible to delineate, with confidence, the first appearance of the ammonite genus ***Hyperlioceras***. Following much discussion, this event was designated as the marker for the basal Bajocian boundary (see Mouterde ***et al.***, 1972; the Bajocian Working Group meetings held in Piobbicco in 1988 (Pavia, 1991) and Bearreraig Bay in 1991 (Morton 1991); and the Jurassic Subcommission meetings held in Erlangen, 1984 and Lisbon, 1987). However, some reservations concerning the provinciality, possible endemism and exact timing relating to the first appearance of ***Hyperlioceras*** have been raised (Pavia 1991).

Bearreraig Bay is one of several nominated stratotypes for the basal stratotype boundary (Morton, 1984, 1990a, 1991). Cabo Mondego in Portugal appears to be the only other serious contender at present (Roche ***et al.***, 1990), but problems exist there concerning the completeness of the section near the actual boundary (***pers. comms.***, Morton, 1989; Ruget, 1991).

A GSSP encompasses chronostratigraphical divisions that are defined in a boundary stratotype and is based on biological or non-biological features and therefore equates to the 'Golden Spike'. The base alone is defined and therefore the top of each unit is 'defined' by the base of the succeeding unit. This has been advocated as a preferable method of stratigraphical delineation (Ager, 1993). Cowie (1986) lists the criteria for selection of a boundary stratotype and the Bearreraig Bay section fulfils almost all of these requirements. The most important are:

1). Continuous sedimentation across the boundary, without erosive events.

2). A thick, marine, monofacies sequence.

3). Abundant macro and microfaunal assemblages which can be used in biostratigraphical correlation.

4). Supplementary work, including magnetostratigraphy. At Bearreraig Bay this is in the preliminary stage (Hailwood ***et al.*** 1991), with much of the section from the Upper Aalenian to Bajocian carrying a reverse polarity magnetism, with a boundary between the underlying normal polarity interval placed between the ***murchisonae*** and ***concavum*** Biozones. This correlates well with palaeomagnetic investigations from other similarly aged sections.

5). Easy access and if possible a conservation protection order to preserve the site, such as SSSI status at Bearreraig Bay.

One minor failing of the section is that ***Hyperlioceras***, although widespread, is not totally cosmopolitan, and does not occur in a few key non-European/African sections, such as South America (Riccardi & Westermann, 1984). However, other supplementary genera (e.g. ***Euhoploceras*** and ***Fontannesia***), which are present at all of these localities could be used to correlate the sites back to the Bearreraig Bay section. These sites would then be designated as Auxiliary Stratotypes for correlative purposes, with Bearreraig Bay serving as GSSP, defining the base of the Bajocian Stage.

4.2.2. Previous Micropalaeontological Research

Work on the microfauna and flora from Bearreraig Bay has been very limited. There is an unpublished, preliminary account on calcareous nannoplankton (Morton ***pers. comm.***, 1988 concerning a PhD thesis by Dockerill, University College, London), but the floras encountered were very poorly preserved, with diagenesis being cited as the main agent of destruction. These initial findings have been confirmed more recently by Bown (1991) who prepared the author's samples from Bearreraig Bay for nannoplankton analysis. The nannofossils recovered were again poorly preserved and showed little change across the samples studied (U1-U21, Fig. 4.1). Stratigraphically, three forms dominate, which also indicates that these assemblages fall within the ***Lotharingius contractus*** Nannofossil Sub-biozone of Bown ***et al.*** (1988), which ranges from the ***murchisonae*** to ***discites*** Biozones.

Medd (in Penn ***et al.***, 1980) listed the spores, pollen and microplankton encountered in 12 samples taken from the Bearreraig Bay Sandstone Formation and compared the material with the Lyme Bay Borehole in Dorset. Further palynological analysis (of the author's samples) has been carried out (Riding, British Geological Survey), but has not yet been published. A diverse palynomorph assemblage was recovered, being dominated by terrestrial floras of gymnospermous pollen and pteridophyte spores. Dinoflagellates were also present, but in low numbers and diversity, being dominated by ***Nannoceratopsis.***

Ostracod analysis, also of the author's samples, is still underway (Lord, University College, London).

4.2.3. Ammonite Biostratigraphy

Ammonite biostratigraphical schemes, where present, are always used as a template against which a foraminiferal zonation is compared and tied. Bearreraig Bay has been the focus of much study by Morton (as summarised by Morton, 1984, 1990a, 1991). The ammonite genus ***Graphoceras*** occurs in the basal 8 metres of the Udairn Shale Member, and is the ancestral form to ***Hyperlioceras***, which defines the base of the Bajocian stage. The first appearance of the latter at Bearreraig Bay occurs approximately 11 metres from the base of the Udairn Shale Member.

The ammonite faunas were well preserved, occurring mainly within nodular beds and concretions in which abundant representatives of Sonniniidae and Stephanoceratidae were also found, along with Graphoceratidae. From biometrical analysis, Morton (1988) considered that each nodule containing ammonites was representative of a fairly complete biological population.

4.2.4. Lithostratigraphy

The entire exposed section at Bearreraig Bay is over 300 metres thick and spans the Toarcian through to the Late Bajocian/Bathonian. Jurassic sediments are preserved as thick, gently north westerly dipping strata which were affected by minor faulting and are capped by thick dolerite sills. Although located relatively close to the Palaeogene Plutonic Centres in the Hebrides, the relevant sequences at Bearreraig Bay are only intruded by minor dykes that have very localised thermal metamorphic affects.

The Aalenian/Bajocian boundary is contained within a thick sequence of fairly uniform, silty shales of the Udairn Shale Member of the Bearreraig Sandstone Formation (Figs. 4.1, 4.2). Lithological variation is limited to the presence of bands, or scattered occurrences, of calcareous nodules. These nodules are initially calcitic in the Aalenian part of the section and gradually change in chemical composition to become sideritic through the Bajocian (Morton, 1990a).

The lithostratigraphical scheme used here follows Morton (1984), which in turn is based upon a combination of the work of Morton & Hudson (1964), Morton (1965) and Anderson & Dunham (1966). Bearreraig Bay is the type section of the Bearreraig Sandstone Formation (originally the Bearreraig Sandstone Series of Morton & Hudson, 1964). The principal members are summarised in Figure 4.1 and in ascending stratigraphical order are:

i). Dunn Caan Shale Member (18m), which spans the Toarcian (***aalensis*** Sub-biozone-***opalinum*** Biozone) and is composed of well indurated, anoxic black shales.

ii). Ollach Sandstone Member (24m), which ranges from the ***murchisonae*** Biozone to the lower ***concavum*** Biozone and is a coarsening upwards series of silty limestones and massive, quartz rich sandstones, interbedded with fairly fine grained, silty sandstones.

iii). Udairn Shale Member (72m), which is a thick sequence covering the Aalenian and Bajocian stages (intra ***concavum*** Biozone-intra ***laeviscula*** Biozone) and is marked by an abrupt lithological change from the underlying member. It is a fairly uniform, silty shale in the lower section, interbedded irregularly with calcareous beds or nodules. The upper part is marked by a gradual overall increase in grain size to siltstones and fine grained sandstones, and also by the presence of cyclical bedding.

iv). Holm Sandstone Member (36m), which ranges from the intra ***laeviscula*** Biozone to the intra ***sauzei*** Biozone and is initially a muddy sandstone, which then grades into a medium grained, well sorted sandstone. Within several of the more massive units of sandstone there are bands of large, calcareous doggers.

v). Rigg Sandstone Member (74m) ranges from the intra ***sauzei*** to ***subfurcatum*** Biozones and is composed of a series of thick, coarse grained, cross-bedded sandstones.

vi). ***Garantiana*** Clay Member (2m). The construction of the dam has obscured this member at Bearreraig Bay. Where visible in other nearby sections (e.g. Rigg Cliff), it is a thin, laterally extensive, dark shale.

The Bearreraig Sandstone Formation is overlain by the Great Estuarine Group, representing the uppermost Bajocian, Bathonian and lowermost Callovian. This group is almost entirely composed of non-marine sediments (Harris & Hudson, 1980) and was consequently not investigated for foraminifera. However, the Duntulm Formation (formerly the Lower Ostrea Beds of Hudson, 1962), which occurs throughout the Inner Hebrides, is a marine, brackish lagoonal complex in which a very limited miliolid fauna occurs

(Andrews & Walton, 1990 (Fig. 3, photomicrograph b) and Andrews ***pers. comm.***, 1991).

Exposure of the Udairn Shale Member, which provides the focus of attention for the Aalenian/Bajocian, is divided between several closely spaced localities which can be correlated with confidence. These sections are:

i). A gully section to the south of Bearreraig Burn (GR. 51865245) which comprises the ***murchisonae*** and lower ***concavum*** Biozones;

ii). A pipeline section (GR. 51705271) located along the north-eastern burn valley side, which also includes the Aalenian/Bajocian boundary; and

iii). The remainder of the Udairn Shale Member and overlying members of the Bearreraig Sandstone Formation, which is exposed in the burn section (GR. 51635271).

The initial sampling frequency was approximately 1 metre (Fig. 4.1; samples U1-U21) which is the normal interval for reconnaissance work. However, definition of the Bajocian Boundary and restudy of the foraminiferal taxa which were recovered in the original sampling (Gregory, 1989) called for a higher resolution sampling. Additional collecting was carried out by Morton (Birkbeck College) in 1990 and involved further excavation and logging of the sites, allowing refined correlation of the various parts of the section (Fig. 4.1; samples MP1-MP11; M1-M6). When combined with the initial sampling, the interval resolution is between 10 and 30 cm (Fig. 4.1).

Morton (1991) placed the actual Bajocian boundary 11.25 metres above the final bed of the Ollach Sandstone Member. Revision of sample locations and figures in Gregory (1990) relocates 2 metres of the sequence previously included within the Udairn Shale Member to the Ollach Sandstone Member (Fig. 4.1; samples U1-U3). Also refined is a stratigraphical gap of 2.7 metres between the 'gully' and 'pipeline' sections which has been breached by further collecting and study of the sections.

Anderson & Dunham (1966) formalised the Udairn Shale Member (Shaly Sandstone of Morton, 1965), but it must be noted that the majority of this member is in fact a fine grained, muddy sandstone or siltstone. It has a sharp contact with the underlying Ollach Sandstone Member, the final bed of which is a prominent, hard, grey calcareous sandstone marker of about 1 metre in thickness. The first 4 metres of the Udairn Shale Member within the ***concavum*** Biozone consists of a series of small 1 metre thick cycles that gradually coarsen upwards from an initially silty shale to an indurated, harder, muddy siltstone/sandstone band. The next part of the sequence, to sample U14 of the ***discites*** Biozone, is a fairly monotonous muddy, micaceous siltstone that gradually coarsens upwards. The Aalenian/Bajocian boundary is contained within this part of the sequence, some 11 metres from the base. Cyclical bedding then dominates the remaining Udairn Shale Member, but tends to be larger scale, in the region of 2-3 metres. There is also an overall, larger scale, coarsening upwards cycle that ends with the deposition of the fine to medium grained sandstones of the Holm Sandstone Member.

The softer shale bands within the Udairn Shale Member are characterised by thin bedding and some localised bioturbation. Small to medium sized calcareous and sideritic

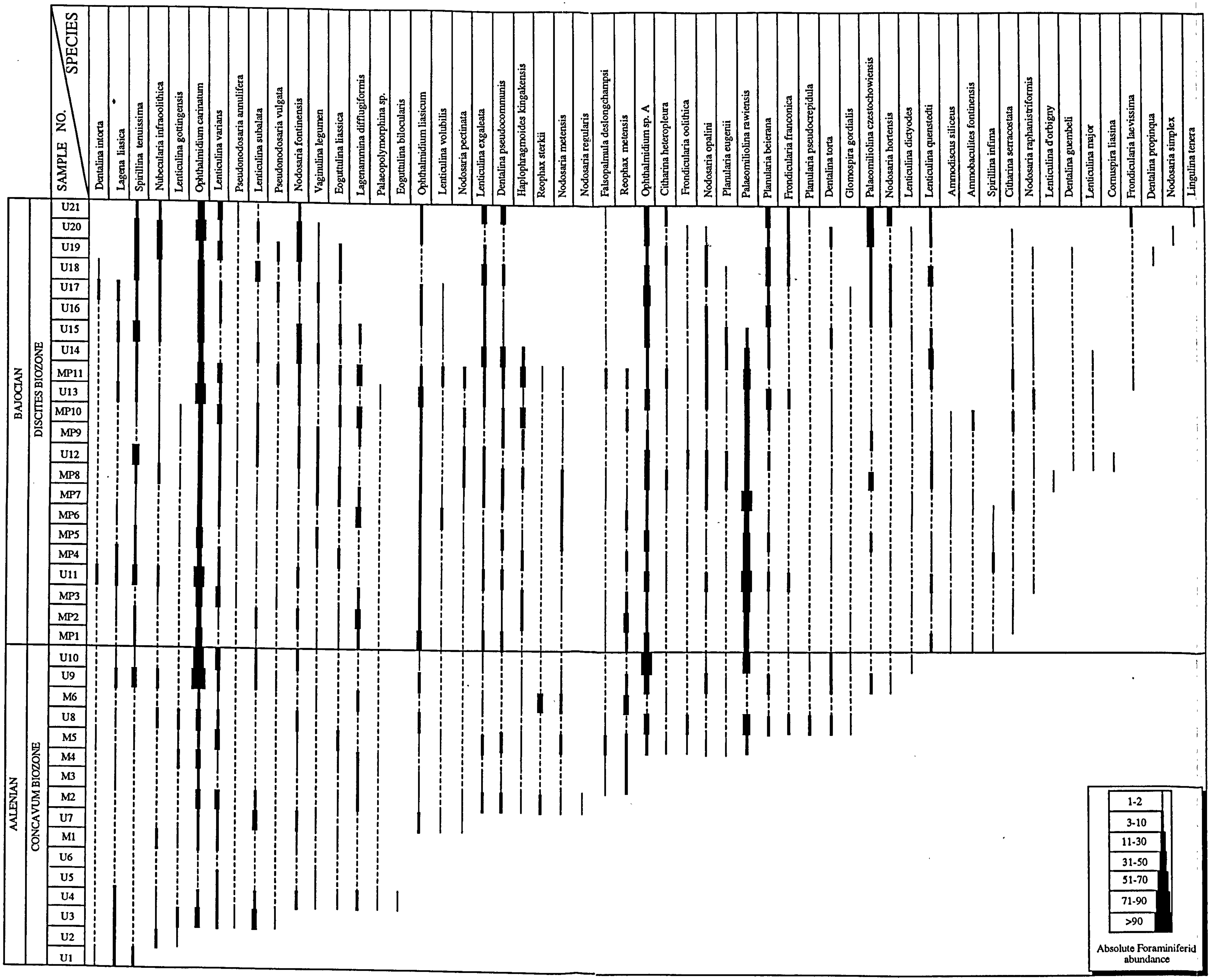


Figure 4.2. Foraminiferal distribution range chart for the Aalenian and Bajocian of Bearreraig Bay

concretions are scattered throughout these cycles. Ammonites and other macrofossil remains often form the nucleus of these concretions, suggesting a post-depositional diagenetic origin. Crinoid fragments are also very common within the upper part of the ***concavum*** Biozone and most of the basal ***discites*** Biozone. These fragments occasionally form thin beds 1-2mm in thickness.

Macrofossils are common and usually occur within the calcareous nodules, but several of the shale horizons proved to be very productive in macrofossil remains. Ammonites are commonly reported, although this may be a result of the intensive collection required to establish a viable biozonation. Morton (1990a) also recorded the bivalve distribution; the ***concavum*** Biozone up to 8.8 metres from the base of the Udairn Shale member is typified by deposit feeders such as ***Bositra***, ***Nuculoma***, ***Grammatodon*** and ***Oxytoma***. From this point up into the ***discites*** Biozone there was a marked decrease in bivalve diversity, with ***Mytiloceramus*** becoming common, and only ***Grammatodon*** of the former group being represented in any numbers. Belemnites and gastropods occur throughout the section, whilst brachiopods are very rare. Terrestrial plant debris such as driftwood is common; Bateman & Morton (in press) record a diverse, land derived flora that is exceptionally well preserved. This must indicate a nearshore source area to allow such flora to be preserved in the fossil record.

4.2.5. Foraminiferal Distribution

Foraminiferal assemblages recovered from across the Aalenian /Bajocian boundary were surprisingly abundant and diverse (Fig. 4.2). It had been assumed, from the lack of published data covering the microfossils of Bearreraig Bay, that this section would not yield many foraminiferids.

In detail, the sampled part of the top of the Ollach Sandstone Member (U1-U3) is characterised by very poor foraminiferal recovery with a total of only 10 species, the most common being ***Ophthalmidium carinatum***, ***Lenticulina varians***, ***L. subalata*** and ***L. gottingensis***, with other lagenids such as ***Eoguttulina liassica*** present. Microfaunal numbers and diversity of foraminifera are also very low here (Fig. 4.4). There is no immediate turnover or change in faunas that corresponds with the initial deposition of the silty shales of the Udairn Shale Member until several metres into the succession (at U7/M2). From this point there is a marked radiation in faunal diversity and abundances. 41 of the total 55 species are introduced immediately prior to the basal Bajocian boundary.

Miliolids dominate the majority of samples in terms of abundance, principally represented by ***O. carinatum***, with ***O.*** sp. A and ***Palaeomiliolina rawiensis; O. liasicum***, ***P. czestochowiensis*** and ***Nubecularia infraoolithica*** are subordinate in total numbers. This group shows a spectacular increase in abundance immediately prior to the Aalenian/Bajocian boundary (U9 and U10) and remains fairly constant in number until 2 metres into the ***discites*** Biozone (U12), after which there is a relative decrease in abundance.

Lagenids are the best represented in terms of species diversity (39 out of 55 species), but not in total abundance. Of these, lenticulinids dominate with 8 species, the most common being ***Lenticulina varians*** and ***L. quenstedti***. The former occurs throughout the section and the first appearance of the latter is coincident with the actual Aalenian/Bajocian boundary. All lenticulinids recovered are robust forms, with either umbilical bosses or limbate sutures (***L. subalata, L. gottingensis, L. varians*** and ***L. major***) or coarse ribbing/reticulation (***L. quenstedti, L. dictyodes, L. exgaleata*** and ***L. volubilis***). Next in terms of abundance and species number are the nodosariids, also with 8 species, the most common being ***Nodosaria fontinensis, N. opalini, N. metensis, N. hortensis*** and ***N. pectinata***. The numerical majority are characterised by relatively coarse ribbing, with only ***N. simplex*** (1 sample, U20) and ***N. regularis*** (M2) having a smooth external surface. Smooth wall structure typifies the dentalinid population with the large, but robust, ***Dentalina pseudocommunis*** dominating. ***D. intorta, D. torta, D. guembeli*** and ***D. propinqua*** occur throughout the section. Of the remaining lagenids, the majority are smooth forms of ***Planularia*** (3 species, commonest being ***Planularia beierana***), ***Frondicularia*** (3 species) and ***Eoguttulina*** (mainly represented by ***E. liassica***).

Agglutinated and spirillinid foraminifera are subordinate in terms of abundance and diversity, occurring mainly within the ***discites*** Biozone and topmost ***concavum*** Biozone as several disparate minor 'floods'. The agglutinated foraminifera are coarsely agglutinated and simple, uniserial forms such as ***Lagenammina difflugiformis, Reophax sterkii*** and ***R. metensis***. The only common, planispirally coiled taxa present is ***Haplophragmoides kingakensis***. Fine grained agglutinates such as ***Glomospira gordialis*** and ***Ammodiscus siliceus*** are uncommon.

Spirillinids, the least frequently recovered group, are represented by ***Spirillina tenuissima*** and ***S. infima***, of which the former is the most common. Spirillinids occur in proximity to the Aalenian/ Bajocian Boundary and throughout younger sediments as discrete abundance 'floods'.

All foraminifera recovered from Bearreraig Bay were well preserved and showed no signs of dissolution. However, some of the thinner shelled, uniserial lagenids were not complete. Whether this was a result of palaeoenvironmental factors such as destruction by transportation or later diagenetic/compaction effects could not be directly ascertained.

4.2.6. Foraminiferal Biostratigraphy

The foraminifera encountered at Bearreraig Bay tended, on the whole, to be long ranging species, either spanning the entire Jurassic stage, or characteristic of the Lower/Middle or Middle/Upper Jurassic. Benthic foraminifera, as a consequence of their ecological requirements, are essentially facies or substrate controlled in their distribution, although this facies dependence is neither the constant, nor limiting factor of distribution for all benthic foraminifera that is often cited. Some forms appear to possess the ability to colonise several differing niches and therefore facies types. Some of these taxa are also restricted in their vertical range and so can be used in biostratigraphy. Generally in the Jurassic, but particularly in the Lower and Middle Jurassic, foraminiferal marker species usually belong to the lagenid group, which were the most successful at exploiting various ecological niches. Lagenids have a more subordinate role in Cenozoic and Recent sediments, where planktonic foraminiferids are used.

The first appearances of several species amongst the general radiation of foraminiferal faunas that occurred around the Aalenian/Bajocian Stage boundary at Bearreraig Bay were useful for correlation, with the first appearance of the ammonite marker ***Hyperlioceras***. The taxa that were considered to be the most reliable, indicating a Late Aalenian/Early Bajocian age, are ***Lenticulina quenstedti, L. exgaleata, L. volubilis, L. dictyodes, Nodosaria opalini*** and ***Falsopalmula deslongchampsi***, with ***Palaeomiliolina rawiensis*** the single important representative of the miliolids (Fig. 4.3).

The conclusions drawn concerning biostratigraphy were based primarily on comparing distribution patterns derived from previously published ranges, particularly those covering Europe. Bartenstein and Brand (1937) were among the first to appreciate the usefulness of Jurassic benthic foraminifera in biostratigraphy, building on the monograph taxonomic work from the late nineteenth century, especially that of Terquem (1858-1870). Other important and more recent work on Middle Jurassic foraminiferal biostratigraphy includes articles from the Polish Lowlands (Bielecka & Styk, 1969; 1981), the German basins (Ziegler, 1959; Brand & Fahrion, 1962; Munk, 1978), and France and Switzerland (Wernli, 1971; Wernli & Septfontaine, 1971). See Figure 4.3 for a summary of the ranges of the important forms. Ohmert (1988) and Ohmert *et al.* (1991) also indicated that several of the forms found here are important in south west Germany.

The final appearance of ***L. d'orbigny*** just within the ***discites*** Biozone is consistent with records from the British Isles (Morris, 1980; 1982; Morris & Coleman, 1989; Copestake & Johnson, 1989), from Argentina (Ballent, 1984) and from France and Switzerland (Wernli, 1971; Wernli & Septfontaine, 1971).

The first appearance of ***L. quenstedti*** is considered to be the most correlatable indicator of the upper ***concavum/discites*** Biozones. Several authors have recorded this form occurring with a lithological change that characterises this boundary in European sites (eg, Wernli & Septfontaine, 1971; Wernli, 1971; Bartenstein & Brand, 1937; Frentzen, 1941). However, at Bearreraig Bay there is no perceptible lithological change heralding the stage turnover and ***L. quenstedti*** was concurrent with the first appearance of the ammonite marker, indicating that apparent gross facies dependence is not a causal effect for the presence of this form. Morris & Coleman (1989), who summarised British Geological Survey borehole data (Penn ***et al.***, 1980; Penn, 1982), indicated a first appearance within the ***concavum/murchisonae*** Biozones. This data was based on the condensed sequences that occur within the Dorset basin, where there is some doubt as to the completeness of the ammonite biostratigraphy (Callomon & Chandler, 1990). Stam (1986) and Wernli (1971) also place the first appearance of ***L. quenstedti*** within the upper ***concavum*** Biozone, which indicates that there is a diachronous correlation in comparison with the migration of

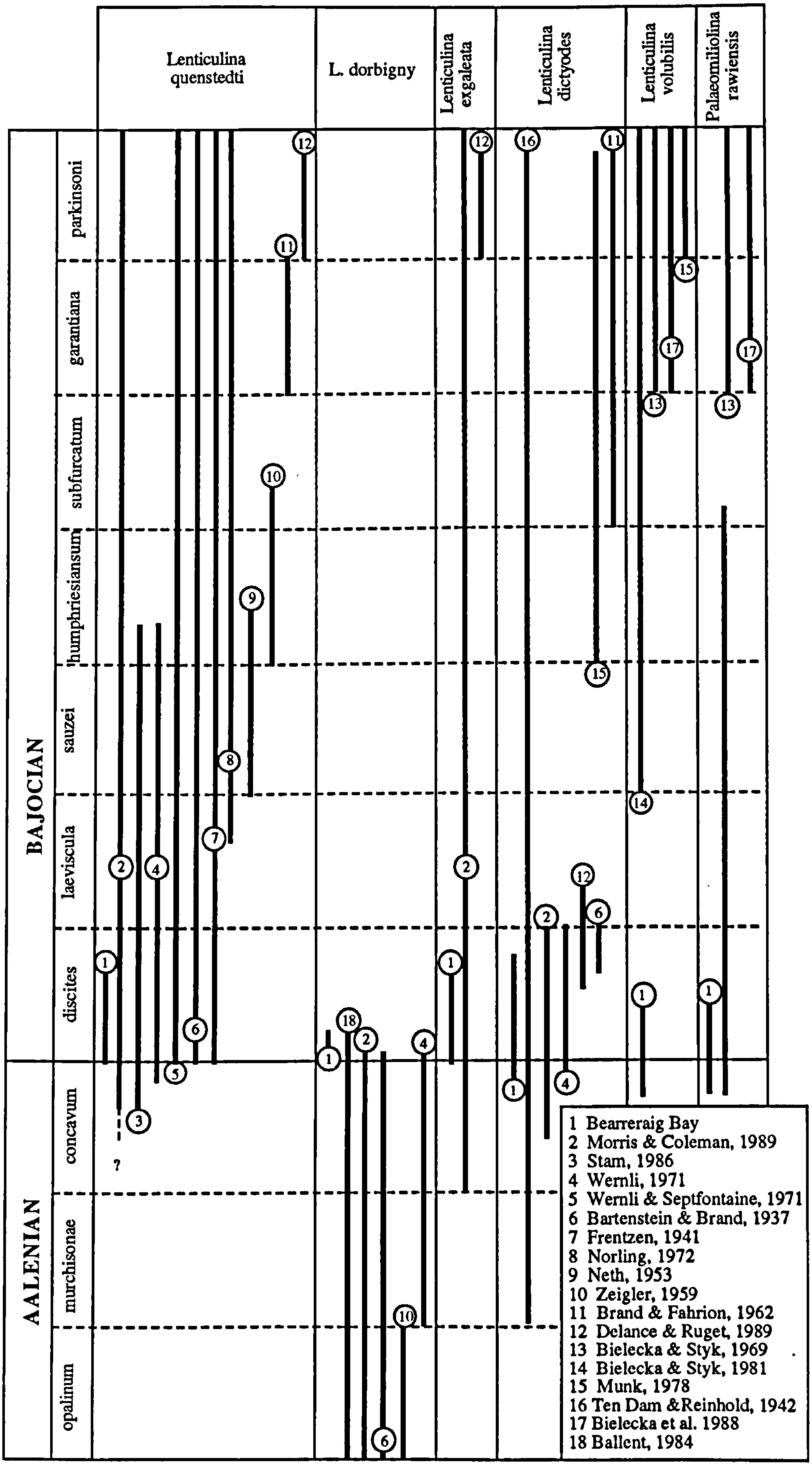


Figure 4.3. Previously recorded distribution of biostratigraphically important foraminiferal taxa of Bearrearig Bay

Hyperlioceras.

The other foraminiferal species proposed as useful indices suffer from this facies dependent distribution to a greater extent. This includes *L. dictyodes* which has a first appearance within the ***concavum*** Biozone at Bearreraig Bay and which has been recorded within the ***murchisonae Biozone*** (Dam & Reinhold, 1942 from Denmark), from within the ***concavum*** Biozone (Morris & Coleman, 1989) and almost coincidental with the ***concavum /discites*** Biozonal boundary (Wernli, 1971). Brand & Fahrion (1962) and Munk (1978), working on the German Middle Jurassic, indicated a first appearance in the ***subfurcatum*** and ***humphriesianum*** Biozones respectively. This diachronous feature could be a result of slow migration from the point of first geographical appearance and/or as a result of the Middle Jurassic transgression occurring at a differential rate over the basins involved.

The closest occurrence of ***Palaeomiliolina rawiensis*** to within the ***concavum*** Biozone was from the French and Swiss Middle Jurassic (Wernli, 1971), whilst Polish workers recorded a consistent first appearance at the base of the ***garantiana*** Biozone (Bielecka & Styk, 1969; Bielecka *et al.*, 1988). The base of ***L. volubilis*** within the upper ***concavum*** Biozone at Bearreraig Bay has extended the previously recorded range from the base of the ***laeviscula*** Biozone (Bielecka & Styk, 1981). ***Nodosaria opalini*** and ***N. pectinata*** are characteristic Middle and Upper Jurassic nodosariids that have consistent Upper Bajocian/Bathonian records in the UK (Morris & Coleman, 1989), whilst Bartenstein & Brand (1937) record the first appearance of the former within the ***opalinum*** Biozone. ***L. exgaleata*** has its lowest UK record within the ***concavum*** Biozone of the Lyme Bay borehole (Penn ***et al.***, 1980), whilst in the other boreholes from the Dorset Coast (Coleman, 1982), Bath (Coleman, 1979) and Horescombe Vale (Coleman, 1980), its inception is within the Upper Bajocian and Lower Bathonian.

4.2.7. Comparison of Aalenian/Bajocian Foraminiferal Distribution

Published work from the British Isles covering Aalenian and Bajocian foraminifera is limited, with the majority of these records covering British Geological Survey boreholes from the Dorset Coast (Coleman in Penn ***et al.***, 1980; Penn, 1982) and outcrop material from the Cotswolds (Morris, 1980, 1982; Morris & Coleman, 1989). The subcrop material covers condensed sequences from Lyme Bay, Winterborne Kingston and Horescombe Vale. Assemblages recovered from the Lyme Bay borehole, southern England by Penn *et al.* (1980) were characterised by a lagenid component similar to that at Bearreraig Bay, but miliolids were not as prevalent there. There is a faunal radiation roughly equivalent to the one developed at Bearreraig Bay within the ***murchisonae*** and ***concavum*** Biozones, with the inception of several biostratigraphical markers. Lagenids dominate with 54 out of 64 species, the majority represented by ***Nodosaria, Dentalina*** and ***Lenticulina***. There was a general increase in abundance and diversity within the top part of the ***concavum*** Biozone and basal *discites* Biozone, with a later decrease in the upper part of the section.

A poorly preserved and low abundance fauna was recovered from the Winterborne

Kingston borehole in Dorset (Coleman, 1982).

Morris (1982) published on slightly younger strata from the Middle and Upper Jurassic of the Cotswolds. The assemblages were transported and mixed, characterised by lagenids with subordinate miliolids and spirillinids. Unpublished work (Morris, 1980) from the same area showed the presence of similar impoverished faunas represented by ***L. muensteri, L. varians*** and ***Eoguttulina liassica*** from the lower part of the ***concavum*** Biozone. The ***murchisonae*** and ***discites*** Biozones were characterised by a dominance of agglutinated forms that coincided with an increase in species diversity.

A different facies type was covered by Nagy & Løfaldli (1981) from the Toarcian to Upper Bajocian outcrop at Cloughton Wyke in North Yorkshire. Only the Yons Nab Bed, which spans the ***laeviscula*** to basal ***sauzei*** Biozones, was studied. This was representative of an extremely regressive phase and reflected a restrictive interdistributory bay environment that was influenced by a freshwater input. The basal part of the Yons Nab Bed was dominated by lagenids and spirillinids such as ***Citharina, Vaginulina, Planularia*** and ***Conicospirillina***, with no agglutinated component. Overlying this assemblage was an influx of agglutinated faunas dominated by ***Ammodiscus***, with localised and subordinate ***Trochammina, Lagenammina, Ammobaculites*** and very few lagenids or spirillinids. This was taken to indicate the further influence of a brackish water palaeoenvironment.

Subcrop sequences drilled during oil exploration of the North Sea have also provided some general information. Nagy & Johansen (1991) looked at the Toarcian to Bathonian sequence where the Aalenian was not differentiated from the Bajocian. The Toarcian and Lower Bajocian were dominated by a ***Trochammina-Verneuilinoides*** assemblage in which calcareous forms were present, but subordinate. The Bajocian/Bathonian was typified by a decrease in faunal diversity from the Toarcian and was represented by an ***Ammodiscus-Trochammina*** assemblage. These assemblages were related to a prodelta (***Trochammina-Verneuilinoides***) and a later delta front palaeoenvironment (***Ammodiscus-Trochammina***).

Continental work on Aalenian/Bajocian faunas is widespread, but more patchy in its coverage, often only represented by faunal lists. In the late nineteenth century Terquem (1868, 1870a-b, 1874, 1883, 1886) published several monographic works on Middle Jurassic Foraminifera, including previously unpublished species. His work is, however, difficult to assess, as many of the forms are synonymous. Also, as the work was taxonomic in approach, little comment was made concerning specific stratigraphical control or distribution.

Faunas very similar to those encountered at Bearreraig Bay were recorded from the Middle Jurassic of the Polish lowlands by Bielecka & Styk (1969, 1981). Miliolids dominated in environments which were typified by shallow water, medium grained clastics.

The most comprehensive studies were by Polish workers who studied Upper Bajocian and Bathonian sites. There was an extensive, basin wide transgression in the Polish region during the Aalenian. Kopik (1960) indicated that optimum marine conditions were established in the Upper Aalenian, with a rapid increase in faunal abundance and diversity after an impoverished Toarcian fauna of agglutinated foraminifera. The Upper Aalenian was typified by agglutinated forms and ***Reinholdella***. Bielecka ***et al.*** (1988) summarised the previous work of Pazdrowa (1960) and Bielecka & Styk (1969, 1981) on the Polish Aalenian and Bajocian sections, which reflected a regressive to transgressive cycle, with the ***opalinum*** Biozone having an agglutinated assemblage represented by ***Trochammina*** and ***Ammodiscus***. The ***murchisonae*** Biozone was marked by a faunal radiation, with the introduction of a more diverse agglutinated fauna of ***Haplophragmoides, Recurvoides, Verneuilinoides, Trochammina, Reophax, Lagenammina*** and ***Ammobaculites***, with a few calcareous forms present. Actual Aalenian/ Bajocian boundary sediments were not well preserved due to a general widening of the basin, associated with condensed sequences. The Upper Bajocian was dominated by calcareous forms such as ***Lenticulina, Epistomina***, and particularly ***Ophthalmidium***. This trend was continued into the Bathonian, with a dominance of miliolids (particularly ***Ophthalmidium carinatum, Palaeomiliolina rawiensis*** and ***P. czestochowiensis*** as recorded by Pazdrowa, 1959, 1972).

The German Middle Jurassic has also been extensively studied. Frentzen (1941) listed the faunas from the Lower-Middle Jurassic, which were apparently dominated by lagenids (***Lenticulina, Dentalina, Nodosaria, Vaginulina*** and ***Lagena***). Ophthalmids were rare and agglutinated foraminifera almost absent across the Aalenian/Bajocian boundary.

Ziegler (1959) investigated the Braunjura, including the Aalenian with the basal Bajocian. The ***opalinum*** Biozone had a diverse lagenid fauna represented by ***Lenticulina, Marginulina, Dentalina, Nodosaria, Citharina*** and ***Eoguttulina***. The ***murchisonae, concavum*** and ***discites*** Biozones were collected together as an undifferentiated biozone that appeared to be dominated by agglutinated foraminifera such as ***Lagenammina, Reophax, Trochammina, Ammobaculites*** and ***Haplophragmoides***. Lagenids were rare and exclusively represented by ***Lenticulina*** and ***Eoguttulina***.

The Bajocian to Callovian was covered by Munk (1978), with the ***discites*** Biozone dominated by agglutinated foraminifera such as ***Haplophragmoides, Trochammina, Ammodiscus*** and ***Reophax***, with 5-10% in total of ***Lenticulina muensteri, L. varians*** and ***Planularia*** ssp. The overlying Upper Bajocian was dominated by ***Nubecularia*** (50-70%) and lagenids (up to 50%) which probably represented further transgression over this region, associated with a relative sedimentation decrease.

The Middle Jurassic of the French and Swiss Alps was covered by Wernli (1971) and Wernli & Septfontaine (1971) who recorded a very similar faunal radiation to that which occurred coincidentally with the stage boundary. The French section was apparently normal shelf marine, whilst the Swiss counter-section was considered to be bathyal. The Aalenian was represented by condensed sections whose faunas were dominated by lagenids such as ***L. muensteri, L. subalata*** and ***Citharina colliezi***. Agglutinated faunas were rare and were represented by ***Lagenammina difflugiformis*** and ***Ammobaculites coprolithiformis***. There were also sporadic occurrences of miliolids, such as ***P. rawiensis*** and ***Ophthalmidium*** spp., throughout the sections.

4.2.8. Palaeoenvironmental Interpretation

The ***concavum*** Biozone of the Aalenian stage at Bearreraig Bay is typified by a radiation of foraminifera occurring immediately prior to the base of the Bajocian. This is indicated in Figure 4.4 by the dramatic increase in the diversity (α index) of species and the absolute number of foraminifera. The microfaunal event should be tied to the major transgression marked by the passage of the Ollach Sandstone Member to the Udairn Shale Member, increasing niche availability. However, there is no perceptible corresponding facies change across this boundary, which is some 10 metres from the base of the Udairn Shale Member (Fig. 4.2). Initially, transgressions appear to be marked by an increase in deposition of organic carbon (Partington ***et al.***, 1993a, b; Hallam, 1975; Hallam & Bradshaw, 1979) which in many cases may limit faunal responses until circulation patterns have become established. The faunal radiation at Bearreraig Bay may also be related to some subtle environmental effect, which affects the foraminifera but not the benthic macrofauna. There does appear to be a change in the chemical composition of the calcareous nodules across this sequence (Morton, 1989), from calcitic to sideritic. Several important biostratigraphical marker species also occur with this event.

Palaeoecologically, miliolids dominate, particularly ***Ophthalmidium*** spp., with ***O. carinatum*** being the single most dominant form (Figs. 4.2, 4.4). Lagenids are more diverse, but are numerically subordinate to the miliolids, ***Lenticulina subalata, L. varians, L. exgaleata*** and ***Planularia beierana*** being the most common lagenids (Fig. 4.2). Spirillinids and dentalinids also occur, mainly as several minor 'floods' throughout the section. Agglutinated foraminifera are rare from this section and in terms of relative proportions decrease throughout the section, being commonest immediately next to the ***concavum/discites*** boundary and as 'floods' in the ***discites*** Biozone. The commonest forms are the simple unilocular ***Lagenammina difflugiformis*** and the uniserial ***Reophax metensis***.

This overall palaeoecological trend of a miliolid rich fauna is unusual as lagenids appear to have dominated and to have competed successfully for niches in most 'normal' marine Jurassic deposits (Gordon, 1970, Scheibnerova, 1972; Haynes, 1981; n.b. these 'normal' deposits are usually classified as shelf). There has been little published work on the palaeoecology of Jurassic miliolids. However, from facies analysis of the Udairn Shale Member it may be deduced that water depth was quite shallow, or near to the 'palaeoshoreline', as there was a relatively high incidence of mica and sand grains within the sediments and minimal transport of delicately preserved land plant material. Also, as the substrate was bioturbated and supported a wide range of infaunal and epifaunal macro fossils, a well-oxygenated and nutrient rich environment is indicated. The presence of a wide range of echinoderms including crinoids, which are effectively stenohaline limited by

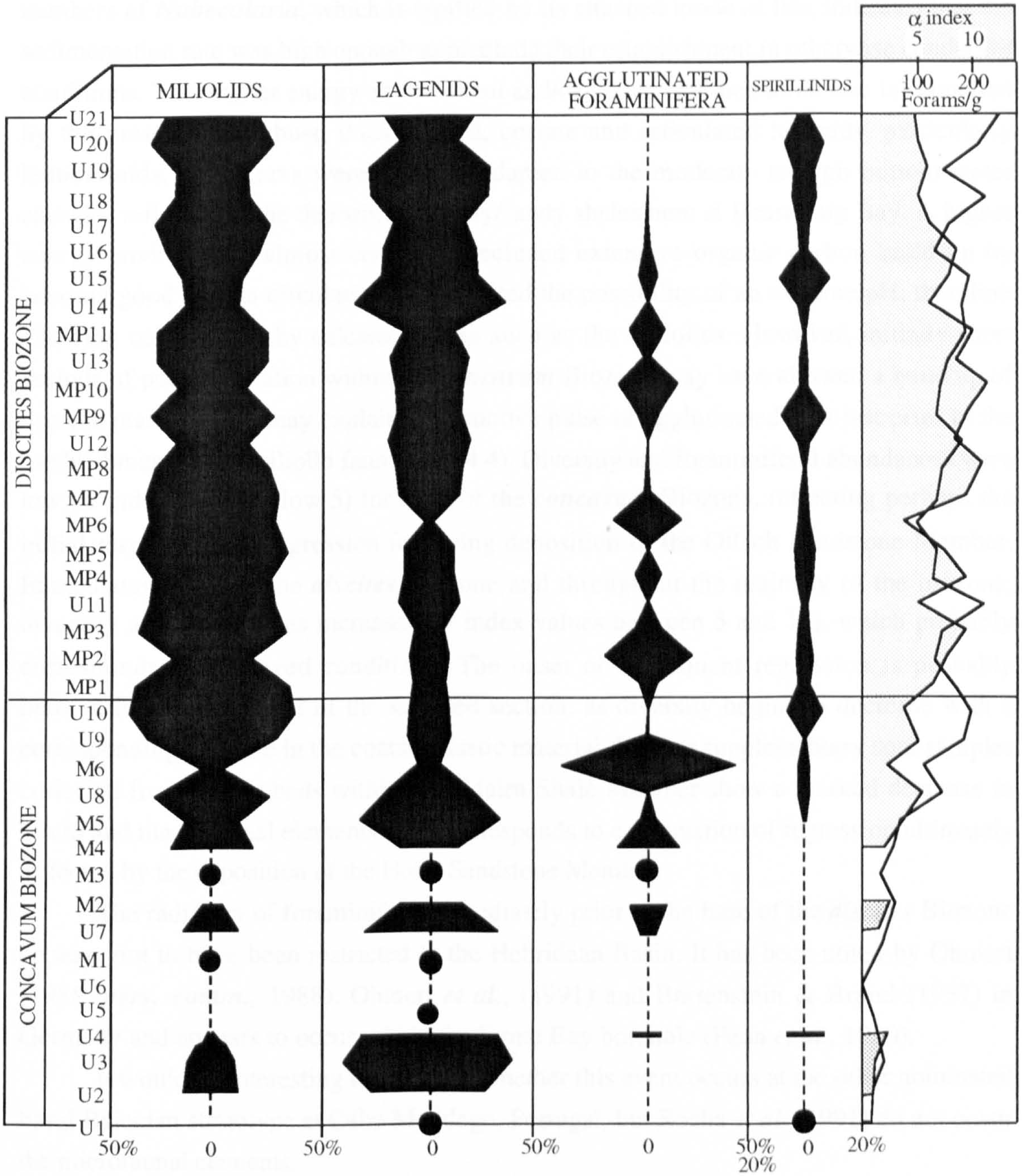


Figure 4.4. Percentage distribution of major foraminiferal groups at Bearreraig Bay with diversity and abundances (● = too few specimens to calculate a viable %)

their osmotic potential gradients, indicates a stable salinity. Recent miliolids tend to dominate in environments confined to the shallow shelf most affected by the wave base (see Murray, 1973), are adapted to inhabit a range of environments and are either infaunal, epifaunal or attached (Brasier, 1975; Haynes, 1981; Murray, 1991). The absence of large numbers of ***Nubecularia***, which is typified by its attached mode of life, indicates that the sedimentation rate was high enough to preclude their establishment in otherwise conducive conditions. This higher energy environment and/or higher sedimentation rate is supported by the presence of robust, thick shelled, costate and reticulated lagenids, particularly lenticulinids. These taxa were possibly adapted to the moderate to high bottom water energies reflected in the deposition of silty/sandy shales here at Bearreraig Bay. A higher energy environment almost certainly precluded extensive organic carbon build up by creating good bottom circulation. This limited the possibility of an extreme pH, therefore allowing colonisation by calcareous taxa such as the miliolids. However, initially short periods of poor circulation within the ***concavum*** Biozone may have allowed a build up of organic matter which may explain a distinctive pulse of agglutinated taxa just prior to the establishment of the miliolid fauna (Fig. 4.4). Diversity and foraminiferal abundances were low (α index values below 5) for most of the ***concavum*** Biozone, reflecting perhaps the initial response to transgression following deposition of the Ollach Sandstone Member. Immediately prior to the ***discites*** Biozone and throughout the majority of the biozone, diversity and abundances increased (α index values between 5 and 11), which probably corresponds to improved conditions. The onset of subsequent regression is probably marked in the upper part of the sampled section, as diversity begins to decrease with a corresponding increase in the coarser clastic material. Further supplementary spot samples collected from higher beds within the Udairn Shale Member show a marked decrease in micro and macrofaunal elements. This corresponds to continuation of regression ultimately reflected by the deposition of the Holm Sandstone Member.

The radiation of foraminifera immediately prior to the base of the ***discites*** Biozone appears not to have been restricted to the Hebridean Basin. It has been noted by Ohmert (1988, ***pers. comm.***, 1988), Ohmert ***et al.***, (1991) and Bartenstein & Brand (1937) in Germany and appears to occur within the Lyme Bay borehole (Penn ***et al.***, 1980).

It would be interesting to ascertain whether this event occurs at the other nominated basal Bajocian stratotype at Cabo Mondego, Portugal, but Rocha ***et al.*** (1991) do not cover the microfaunal elements.

4.2.9. Conclusions

The section at Bearreraig Bay has proved to be very productive in terms of foraminiferal recovery. Palaeoecologically, the faunas are dominated by miliolids, but lagenids far outweigh them in diversity. The palaeoenvironment suggested is fairly shallow, well-oxygenated and moderately high energy.

The foraminiferal biostratigraphy is used here in tandem with the established ammonite scheme and complements this biozonation, because ammonite faunas are best preserved within the numerous, but volumetrically limited, calcareous nodules. As a consequence of a predicted foraminiferal presence throughout the shales, it should be possible to further define the resolution of the events described herein by a more detailed sampling programme.

The foraminiferal species nominated at Bearreraig Bay as being biostratigraphically useful belong to the lagenid group and have been compared with several other British and continental sites. The conclusion reached is that the first appearances of several foraminifera indicate a Late Aalenian/Early Bajocian age, immediately prior to the first appearance of the basal Bajocian marker ammonite genus ***Hyperlioceras.*** Also, from this comparative study, it is evident that the often cited limitation of facies dependent distribution is neither a constant nor limiting factor for the distribution of all benthic foraminifera, particularly some lagenid taxa. This is a theme which will be discussed in Chapter 7.

A notable feature at Bearreraig Bay is a foraminiferal faunal radiation immediately prior to the Bajocian boundary, defined by good ammonite biostratigraphical control. It also appears to be present at several continental and British sites. This supplementary feature may add further weight to the proposed nomination of this section as a boundary stratotype.

4.3. Staffin Bay, Isle of Skye

4.3.1. Introduction

122 samples were collected for micropalaeontological reconnaissance from the Middle and Upper Jurassic rocks outcropping along the Staffin Bay foreshore in north east Skye (Fig. 4.5). This sequence represents a small surface exposure that provides a window through which similar offshore deposits can be compared. Staffin Bay provides an almost complete and permanently exposed Lower Callovian to Lower Kimmeridgian marine, argillaceous sequence and presents a unique opportunity to study microfaunal assemblages in an evolving basin. It offers the possibility of erecting a biostratigraphical zonation and a chance to assess the palaeoenvironmental changes reflected in the distribution of taxa through time.

Morton (1983, 1987, 1989, 1990b, 1983) established, from an extensive outcrop and sequential stratigraphic survey, that Jurassic deposition was related to three separate episodes of fairly rapid subsidence. These events occurred within the Late Triassic-earliest Toarcian, the latest Toarcian-Late Bathonian and the Early Oxfordian-Early Kimmeridgian, with major transgression within the Callovian. The latter episode is the object of interest in this study, in particular the microfaunal responses which resulted from the palaeoenvironmental changes over this period as well as the associated sea-level changes that occurred between the Callovian and Kimmeridgian.

4.3.2. Previous Micropalaeontological Research

Previous published foraminiferal work from Staffin Bay is limited to a single taxonomic study of foraminifera present in 14 samples taken from the top ***lamberti*** Biozone and part of the ***mariae*** Biozone by Cordey (1962). This interval covered the lower part of the Dunans Clay Member (Figs. 4.5, 4.7), however, the exact ammonite biozonation had not been delineated at this point. The work was mainly taxonomic in nature, reporting an abundant foraminiferal fauna, but included a few plots of population characteristics and nomination of several species and subspecies. The majority of these taxa were re-collected here and their total ranges recorded. Cordey's ***(op. cit.)*** results were later used in a comparison with corresponding Callovian/Oxfordian deposits from Dorset and other English sites by Barnard ***et al.*** (1981).

Nannofossils were recorded by Hamilton (1978) from roughly the same section as chosen by Cordey (1962), with 15 samples collected from the base of the***jason*** Biozone to the lower part of the ***cordatum*** Biozone. Samples from the ***jason*** and '***coronatum***' Biozones (Sykes, 1975a, b established that the ***coronatum*** Biozone is not represented at Staffin Bay) were barren, whilst the ***mariae*** and ***cordatum*** Biozones provided a fairly diverse flora, which was considered to be reflective of a Callovian to Oxfordian age.

Whatley (1965) recorded mainly taxonomic details of ostracoda recovered from the Callovian and Oxfordian portion of the sequence.

The Staffin Shale and Staffin Bay Formations have also provided samples for

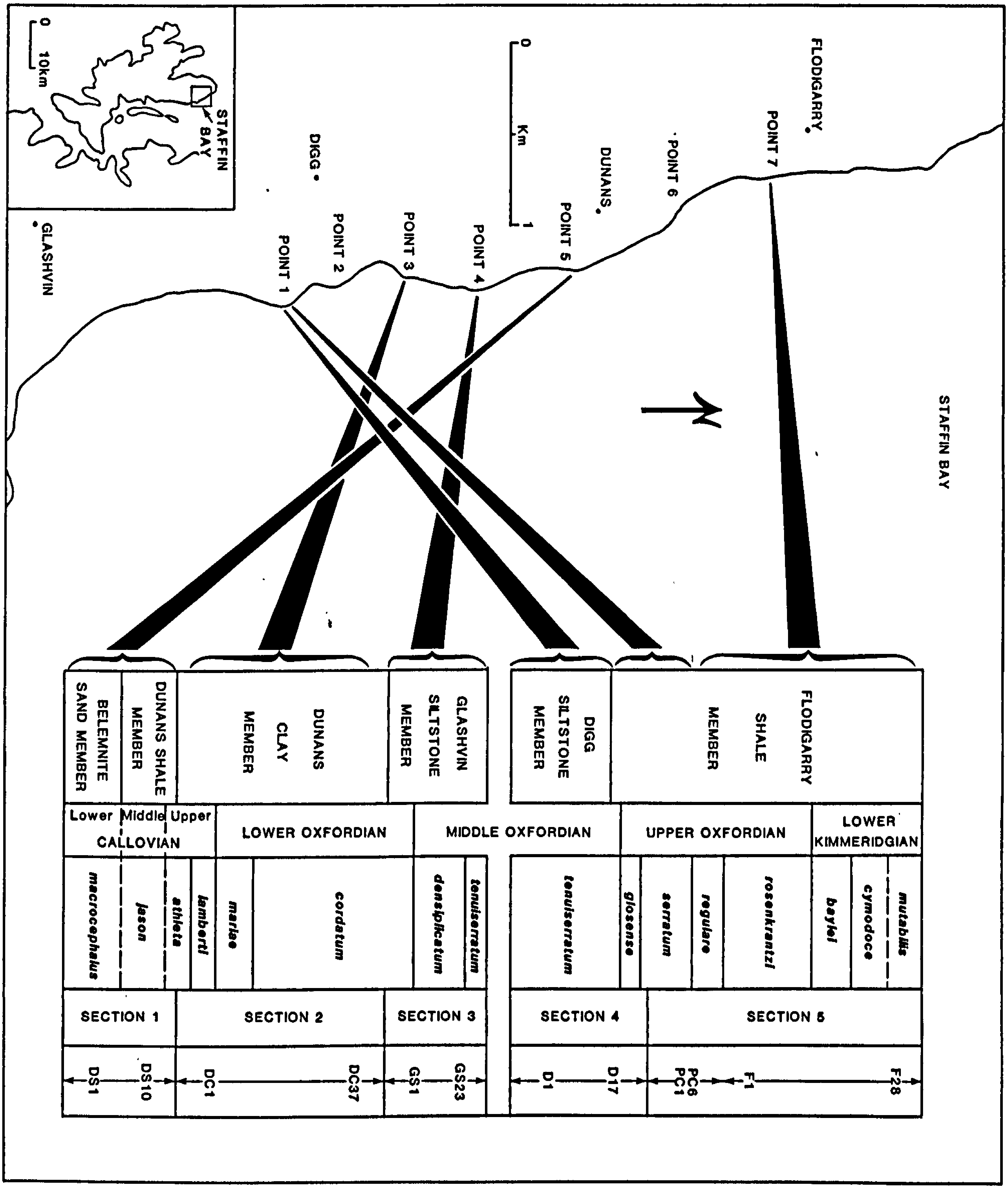


Figure 4.5. Locality map of Staffin Bay, Skye, with collection sites, lithostratigraphy, ammonite biostratigraphy and sampling details

palynological investigation primarily by Riding (1984, 1992) and Riding *et al.* (1991) who investigated dinoflagellate and miospore distribution and biostratigraphy from the Toarcian to Bathonian/Early Callovian. Stancliffe (1989) focused on microforaminiferal test linings derived from palynological preparations from the Oxfordian and also covered the dinoflagellates collected (Stancliffe, 1991) from 10 samples from the Upper Oxfordian. The latter study concentrated on taxonomy with a brief mention of the palaeoenvironmental significance of a diverse palynoflora indicative of normal marine conditions.

4.3.3. Ammonite Biostratigraphy

The Callovian to Oxfordian ammonite biozonation has been well established for the Staffin Shale Formation by Sykes (1975a, b) and Sykes & Callomon (1979). Sykes & Callomon (1979) also nominated this area, in association with sections in Jameson Land Greenland, as the type section for the Boreal Province of the Middle and Upper Oxfordian. A type section was required as a consequence of marked ammonite faunal provincialism during the Middle and Upper Oxfordian in the northern sector. It can be relatively clearly divided into 3 provinces defined on ammonite generic dominance as follows:-

1). Sub-Mediterranean Province which covers Portugal, Spain, Southern France, Crimea and the Caucaus. It is divided using the Perisphinctinidae family, which is also the primary biostratigraphical tool for the Oxfordian generally.

2). Sub-Boreal Province. This province represents a faunal mixing or overlap province between the Sub-Mediterranean and Boreal Provinces and is limited geographically to Normandy, Southern England, Northern Germany and Russia. This mixing could produce problems for correlation; additionally, the extent of the outcrop exposure at these sites is not particularly good.

3). Boreal Province which includes Scotland, Greenland, Spitsbergen, the Baltic regions, North Poland, Alaska and Canada. Its subdivision is based primarily on the Cardioceratidae family.

The Sub-Boreal Province allows a reasonably positive correlation between the Sub-Mediterranean and Boreal Provinces (Fig. 3.1). Staffin Bay and Greenland form the basis for the standard Boreal type sequences for the Middle and Upper Oxfordian as defined by Sykes (1975a, b), Sykes & Callomon (1979) and Sykes & Surlyk (1976). The work of Turner (1966, 1970), firstly on the Dunans Clay Member and then specifically on the ***bukowskii*** Sub-biozone, provided an impetus for these later investigations.

Wright (1973, 1989) delimited the ammonite biozonation for the Lower Kimmeridgian at Staffin Bay, initially indicating the presence of the ***baylei, cymodoce*** and ***mutabilis*** Biozones at Flodigarry and Digg. The latter study throws the initially positive definition of the ***mutabilis*** Biozone into some doubt, although the author intimated that there was still some evidence for the presence of the ***mutabilis*** Biozone.

The combined ammonite biozonation outlined above provides an exact template against which microfaunal distribution and palaeoecological /biostratigraphical events can be compared. From these events it may be possible to interpret the impacts of eustatic/relative sea-level changes or subsidence that occurred during the Middle and Upper Jurassic palaeoenvironments of this basin.

4.3.4. Lithostratigraphy

The Jurassic outcrop at Staffin Bay comprises a thin strip of steeply to gently dipping strata forming the tidal foreshore. MacCulloch (1819) was the first person to describe the presence of the Oxford Clay in Skye. More detailed work was carried out by Forbes (1851) and by Bryce (1873) who looked at the Great Estuarine Series and the Oxford Clay. MacGregor (1934) also described the succession in some detail. Andersen & Dunham (1966) constructed a relatively complete lithostratigraphical sequence by extensive collecting from a series of points (Fig. 4.5) along the Staffin Bay coast from Digg (GR. 47456932 to Flodigarry (GR. 46867149) and from the previous researches of Lee (1920) and Lee & Pringle (1932). The main sites of interest were at Digg, Dunans (GR. 47247081) and Flodigarry. Definition of the Callovian to Kimmeridgian formational lithostratigraphy was initially outlined by Anderson & Dunham (*op. cit.*). It was subsequently updated and tied into a detailed ammonite biostratigraphy by Sykes (1975a, b) and Sykes & Callomon (1979).

The section of interest comprises two formations designated as the Staffin Bay Formation (Hudson, 1962) and the Staffin Shale Formation (Turner, 1966). The former generally represents shallow marine to locally marginal marine conditions, whilst the latter represents a fully marine response related to the major transgressive event initiated in the Lower Callovian.

Underlying these formations is the Bathonian Great Estuarine Group which is spectacularly exposed to the south of Staffin Bay at Allt Lealt and is predominantly represented by fluvial, deltaic or freshwater lagoonal environments. Two formations, the older Lealt Shales Formation and the upper Duntulm Formation (formerly the lower Ostrea Beds of Anderson & Cox, 1948; Hudson, 1962), represent marine incursions into lagoonal settings. The palaeoenvironmental conclusions were based on the domination of monospecific oysters concentrated into distinct horizons. The final formations of the Great Estuarine Group were fluvial (Andrews & Walton, 1990).

A). Staffin Bay Formation. This formation is divided into two members:

(i). Upper Ostrea Member (?basal Lower Callovian, c.12m).

This member (formerly the Upper Ostrea Beds of Anderson & Cox, 1948) comprises dark grey shales and calcareous mudstones interbedded with shell debris beds that mark the base and which become more persistent with the inclusion of thin, light yellow sandstone horizons. The shell beds are dominated by the bivalve genera ***Neomioden*** and ***Isognomen*** in generally low diversity, but high abundance macrofaunas indicative of brackish water (Hudson, 1963, 1980).

Sykes (*op. cit.*) recorded no ammonites from this member, but reasoned due to the regional context that its age must be either Upper Bathonian or Lower Callovian. However, recent palynological dating, on 12 samples by Riding (1992), yielded a flora dominated by miospores, with few dinoflagellates. This suggested an age range totally within the basal part of the lowermost Callovian.

(ii). Belemnite Sands Member (*?macrocephalus /?calloviense* Biozone, c.10m).

The base of this member (formerly the Belemnite Sands of Anderson & Cox, 1948) was taken by Sykes (*op cit.*) at the base of the first persistent sandy horizon, with a predominant lithology consisting of argillaceous and carbonaceous sandstone. Upwards, there is a lithological change to a glauconitic rich, muddy and poorly sorted sandstone packed with belemnite guards.

The only recorded ammonite from this member (Callomon in Hudson, 1962) points to a ***macrocephalus*** Biozonal age. Sykes (1975a, b) hypothesised a ***calloviense*** Biozonal age for the upper part, based primarily on the stratigraphical position of the member in relation to the overlying Dunans Shale Member.

B). Staffin Shale Formation.

This formation is divided into 5 distinct members, whose overall major lithological characteristic is argillaceous. These members, in ascending stratigraphical order, are:-

(i). Dunans Shale Member (*jason* Biozone, c.10m; Fig. 4.6).

The base of this member is marked by an erosive and sharp change from sandstone to bituminous shales. These shales are initially interbedded with thin muddy siltstones and sandy siltstones which are rich in glauconite debris. Approximately 1 metre into the member the shales and siltstones show a concentration of belemnites.

The remainder of the Dunans Shale Member is initially dominated by bituminous shales which then become progressively less carbonaceous and more silty. A thin sandstone horizon, preceded by a thin bed of bituminous shales, marks the top of this member. Clastic input appears to have been relatively important throughout the deposition of this member.

Sykes (*op. cit.*) recorded only ***Lingula*** and belemnites from the predominant bituminous shale lithology. The siltstones are characterised by an impoverished bivalve macrofauna, with occasional concentrations of belemnite guards. Ammonites are relatively common at the base, indicative of the ***medea*** and subsequently the ***jason*** Sub-biozones. However, the remainder of this member has not yielded many ammonites, although it appears that the younger ***coronatum*** Biozonal markers are not present, indicating a period of erosion or non-deposition between the ***jason*** and ***athleta*** Biozones.

(ii). Dunans Clay Member (*athleta*-top ***cordatum*** Biozones, c.37m; Fig. 4.7).

This prominent member is characterised by minor scale cyclical bedding comprising light grey, green, silty clays and thin beds of carbonaceous rich, dark grey siltstones.

The base is marked by the first change from bituminous shales to a light grey clay,

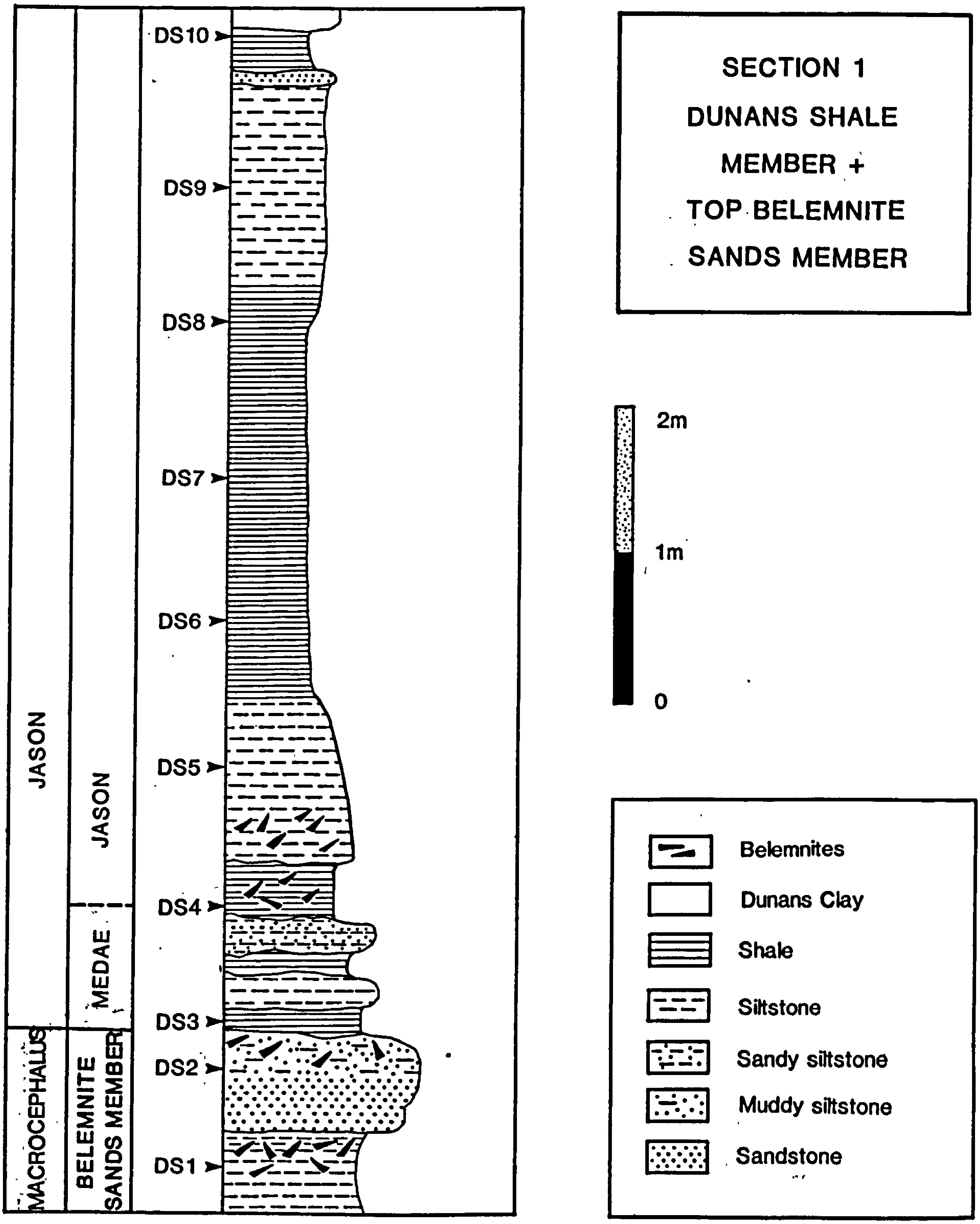


Figure 4.6. Detailed lithological log and ammonite biozonation of the Belemnite Sands and Dunans Shale Members with sampling points

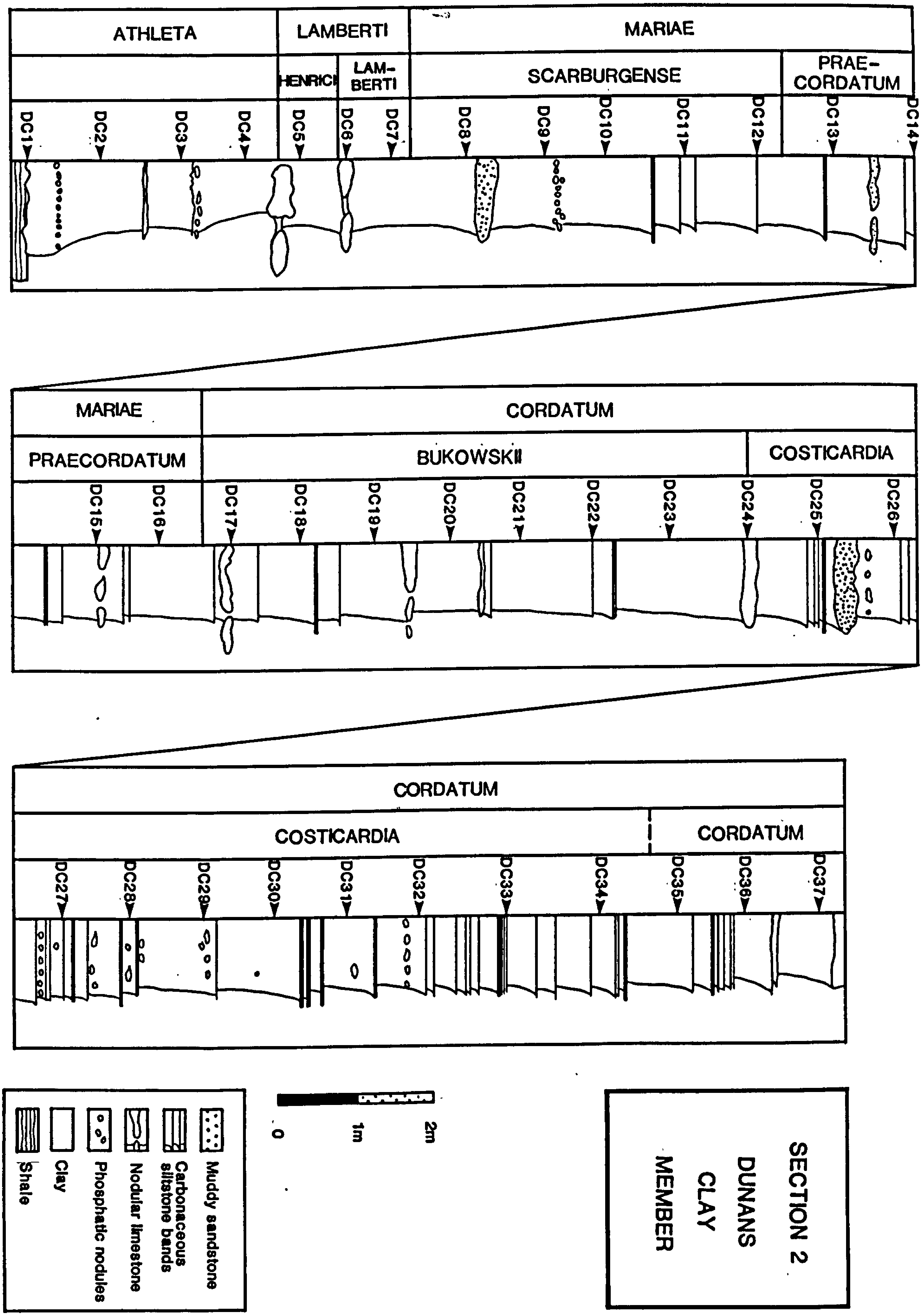


Figure 4.7. Detailed lithological log and ammonite biozonation of the Dunans Clay Member with sampling points

which is also bioturbated. The initial 1-2 metres are dominated by the bivalve ***Bositra*** and thin, discrete rows of phosphatic nodules. Two prominent red-stained, sideritic nodular limestones occur approximately 2-3 metres into the member and aid correlation along the faulted foreshore outcrop. These beds are also rich in specimens of ***Bositra***. The next prominent marker is an argillaceous sandstone, which is then overlain by a series of cycles, initially 30cm to 1 metre in thickness.

Each cyclical unit is characterised by light grey-green, silty clays and discrete, thin, dark grey to black, carbonaceous rich siltstones with irregularly interspersed limestone or phosphatic nodule horizons. Higher in the succession within the ***cordatum*** Biozone, these thin beds become more common, dividing the member into smaller units of 20-50cm in thickness. The Dunans Clay Member also becomes generally more silty and carbonaceous debris is more discernible over this interval.

The cycles initially have a discrete macrofauna (Sykes 1975a, b; Fürsich & Sykes, 1977) with the woody beds/siltstones yielding ***Oxytoma***, whilst the clays yield ***Nuculana*** and ***Dacryoma***. With the input of more silty horizons a diverse bivalve fauna occurs including ***Thracia, Camptonectes*** and ***Pinna***. Ammonites are relatively common and it appears that all the sub-biozones of the ***athleta*** Biozone may be present over this condensed interval (Sykes 1975a, b). No indications of the ***coronatum*** Biozone are seen here. All the subsequent biozonal and sub-biozonal indices have been identified (Turner, 1966, 1970; Sykes ***op. cit.***) and are indicated on Figure 4.7.

(iii). Glashvin Siltstone Member (top ***cordatum***- intra ***tenuiserratum*** Biozones, c.23m; Fig. 4.8).

This member is exposed mainly along the foreshore, but the upper parts are best exposed in the nearby cliff section (GR. 47207041). The base of the Glashvin Siltstone Member is taken at the beginning of a predominance of a dark grey-black, organic rich, finely bedded siltstone facies. Therefore, the contact with the underlying Dunans Clay Member is probably transitional.

The prevailing light grey-green, silty clay facies of the older member is also occasionally present within the Glashvin Siltstone Member. Lignite beds are also developed, which are associated with fine grained sandstones and occasional crinoid ossicle lag beds.

The siltstones are dominated by a bivalve macrofauna of large ***Pinna, Grammatodon, Pleuromya*** and ***Phlodomya***. The clays are again dominated by small specimens of ***Nuculana***. Ammonites are also common, which facilitates good biozonation.

(iv). Digg Siltstone Member (intra ***tenuiserratum*** Biozone, c.>12m; Fig. 4.9).

The contact with the underlying member is not seen along the foreshore due to poor exposure and beach debris. However, stratigraphical continuity is seen, as ammonites of the ***tenuiserratum*** Sub-biozone occur in the basal part of this member and the top of the Glashvin Siltstone Member.

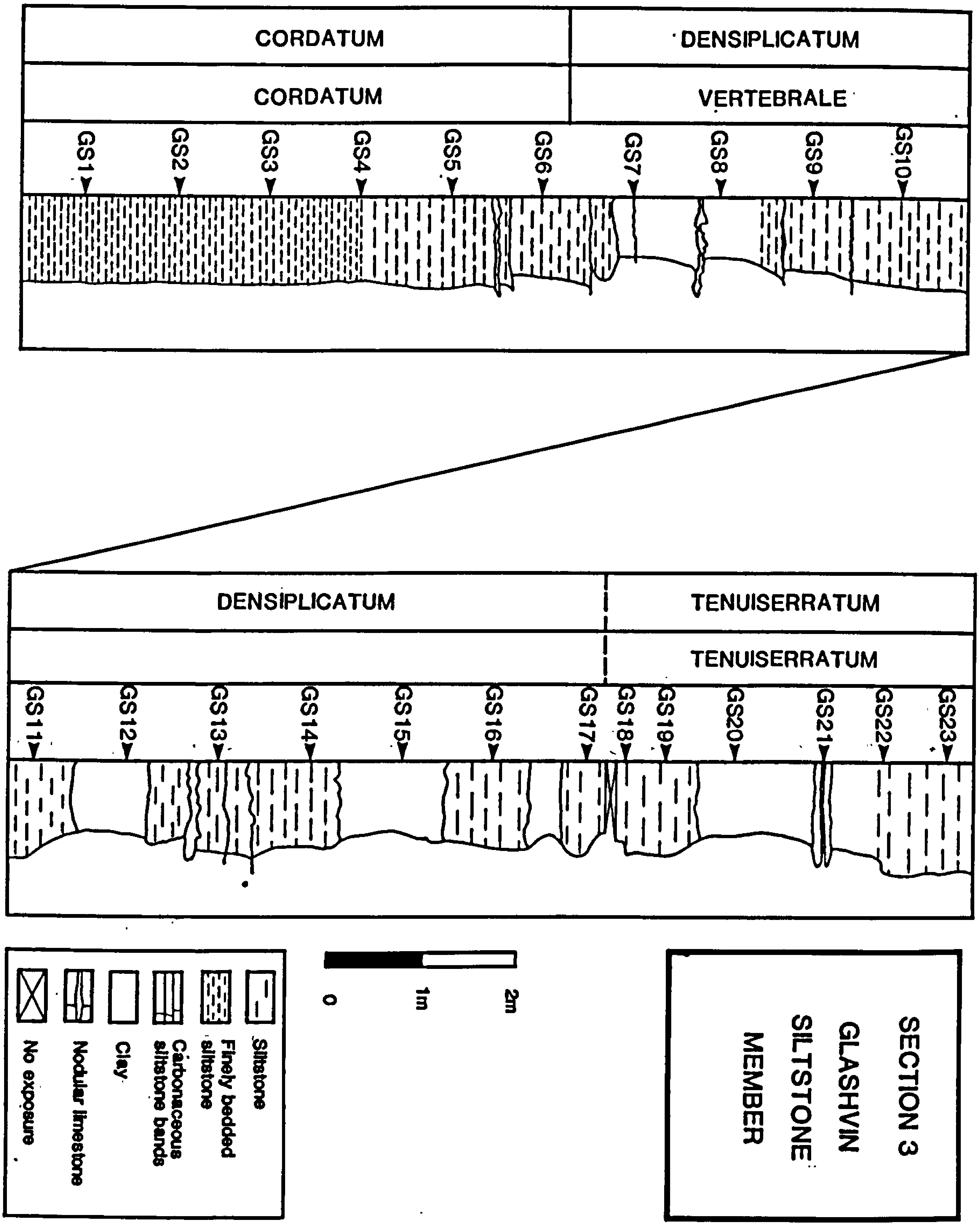


Figure 4.8. Detailed lithological log and ammonite biozonation of the Glashvin Siltstone Member with sampling points

Lithologically, grey to light grey siltstones and fine grained silty sandstones predominate. The basal beds form prominent low-lying scarps of muddy, fine grained sandstones. Near the top a dark grey, fine grained sandstone of approximately 20-30cm is developed. The final beds of the Digg Siltstone Member are a series of siltstones and muddy sandstones.

Ammonites are the dominant part of the macrofauna, associated with common specimens of the bivalve genera ***Oxytoma*** and ***Grammatodon*** (Fürsich & Sykes, 1977).

(v). Flodigarry Shale Member (topmost ***tenuiserratum-?mutabilis*** Biozones, c.38m; Figs. 4.9, 4.10). There is a sharp lithological change from the Digg Siltstone Member at the top most ***tenuiserratum*** Biozone, with the Flodigarry Shale Member mainly comprises dark grey, bituminous shales/clays. The ***baylei*** Biozone is notable for shales interbedded with several rows of limestone nodules. Fine grained, muddy sandstones also occur in the ***cymodoce*** Biozone in upper parts of this member. Several igneous dykes have been intruded into the lower parts of this member within the ***serratum*** and ***regulare*** Biozones. Ammonites are particularly common within the Upper Oxfordian to lowermost Kimmeridgian, but differentiation of the ***cymodoce/mutabilis*** Biozonal boundary is difficult as ammonites become rarer (Wright, 1990). In terms of bivalves, ***Oxytoma*** and ***Grammatodon*** dominate the basal sections, whilst ***Oxytoma*** and ***Palaeonucula*** dominate the upper sections.

4.3.5. Foraminiferal Distribution

The distribution of foraminifera is covered sequentially in terms of the members developed at Staffin Bay and this data is represented within Figures 4.11-4.21. These show absolute numbers of taxa recorded within range charts, important taxa recorded as a percentage of the total fauna, numbers of foraminifera per gram and genera recorded as a percentage of the total fauna.

i). Dunans Shale Member (Figs. 4.11-4.14).

Sample DS1 was collected from sediments which first showed evidence of a marine macrofauna from the Belemnite Sands Member and was barren of microfauna. The first foraminiferal faunas do, however, occur in the belemnite rich siltstone of this member, represented by sample DS2. These assemblages are low diversity/low abundance with only 8 taxa introduced, all of which are agglutinated foraminiferids. In terms of abundance, ***Haplophragmoides infracalloviensis*** is the most common, followed by ***Reophax sterkii*** and ***Reophax horridus***. Generically, ***Haplophragmoides*** is predominant with ***Reophax*** and ***Trochammina*** present in some numbers.

The first samples in the Dunans Shale Member (DS3, DS4), within the basal part of the ***jason*** Biozone, are marked by a minor radiation with a further 19 taxa established, which again, with the exception of rare specimens of ***Lenticulina muensteri,*** are all agglutinated taxa. This trend persists throughout the Dunans Shale Member (DS3-DS10).

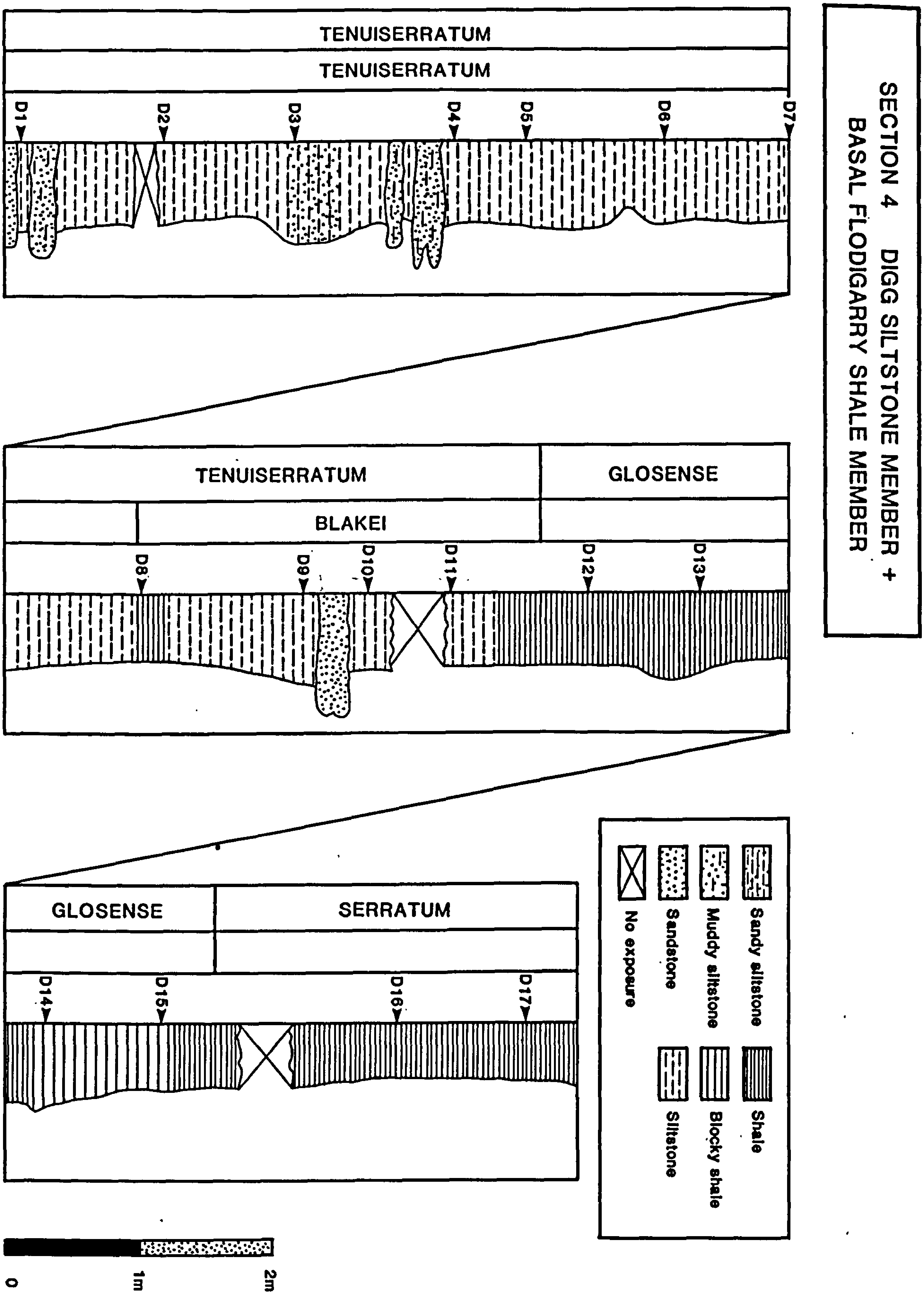


Figure 4.9. Detailed lithological log and ammonite biozonation of the Digg Siltstone and basal Flodigarry Shale Members with sampling points

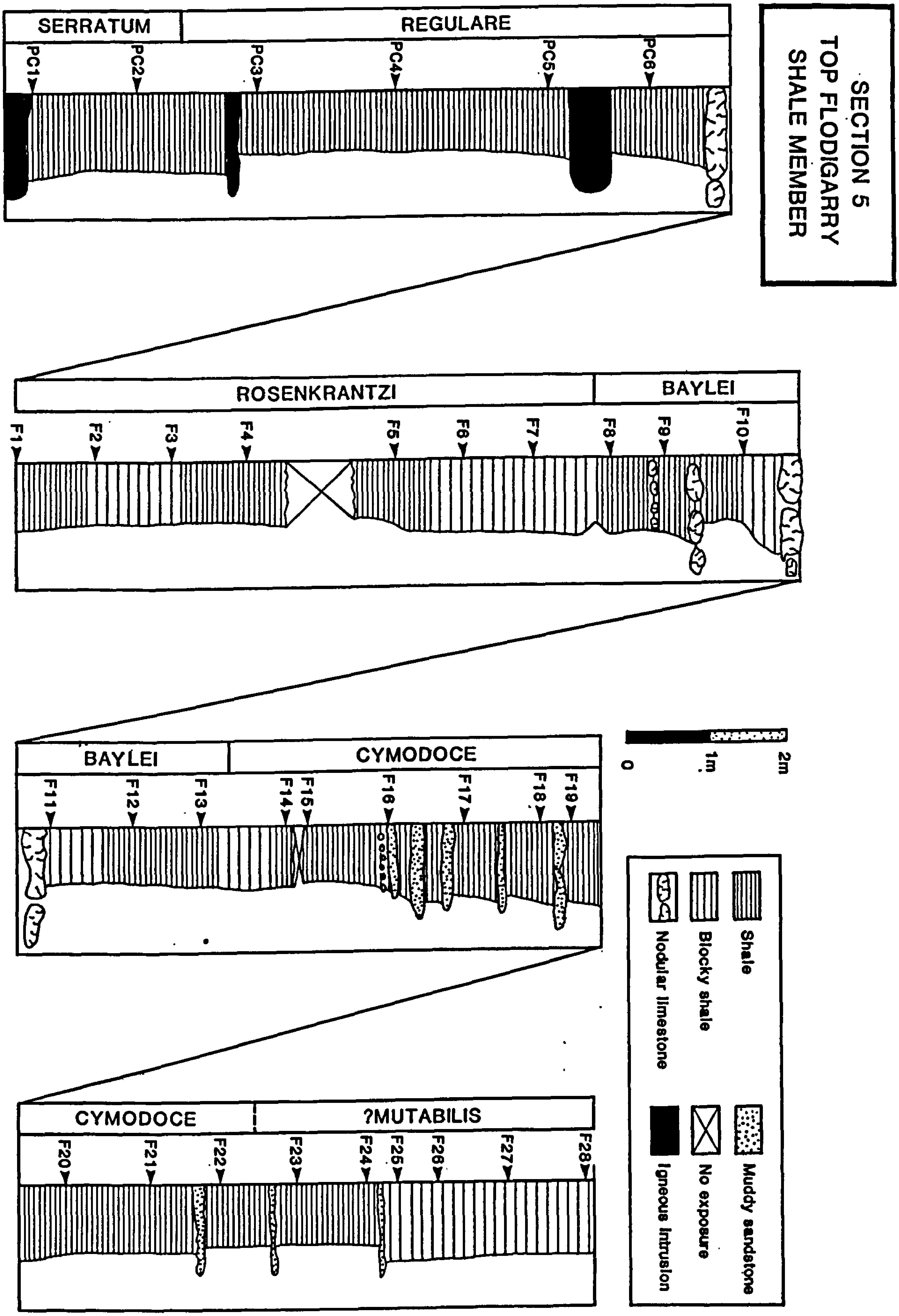


Figure 4.10. Detailed lithological log and ammonite biozonation of the Flodigarry Shale Member with sampling points

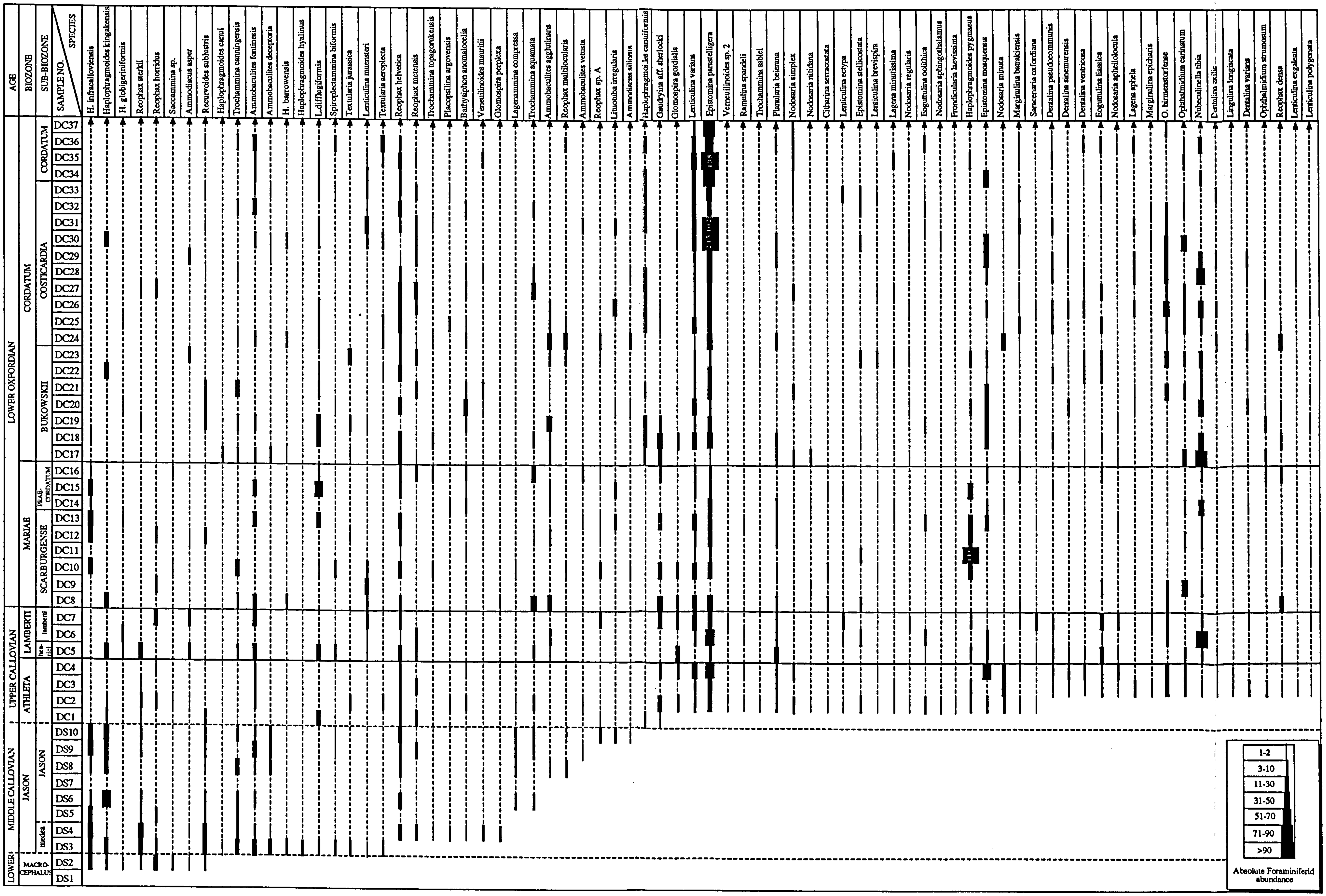


Figure 4.11. Foraminiferal distribution range chart of the Lower Callovian to Lower Oxfordian of Staffin Bay (part A)

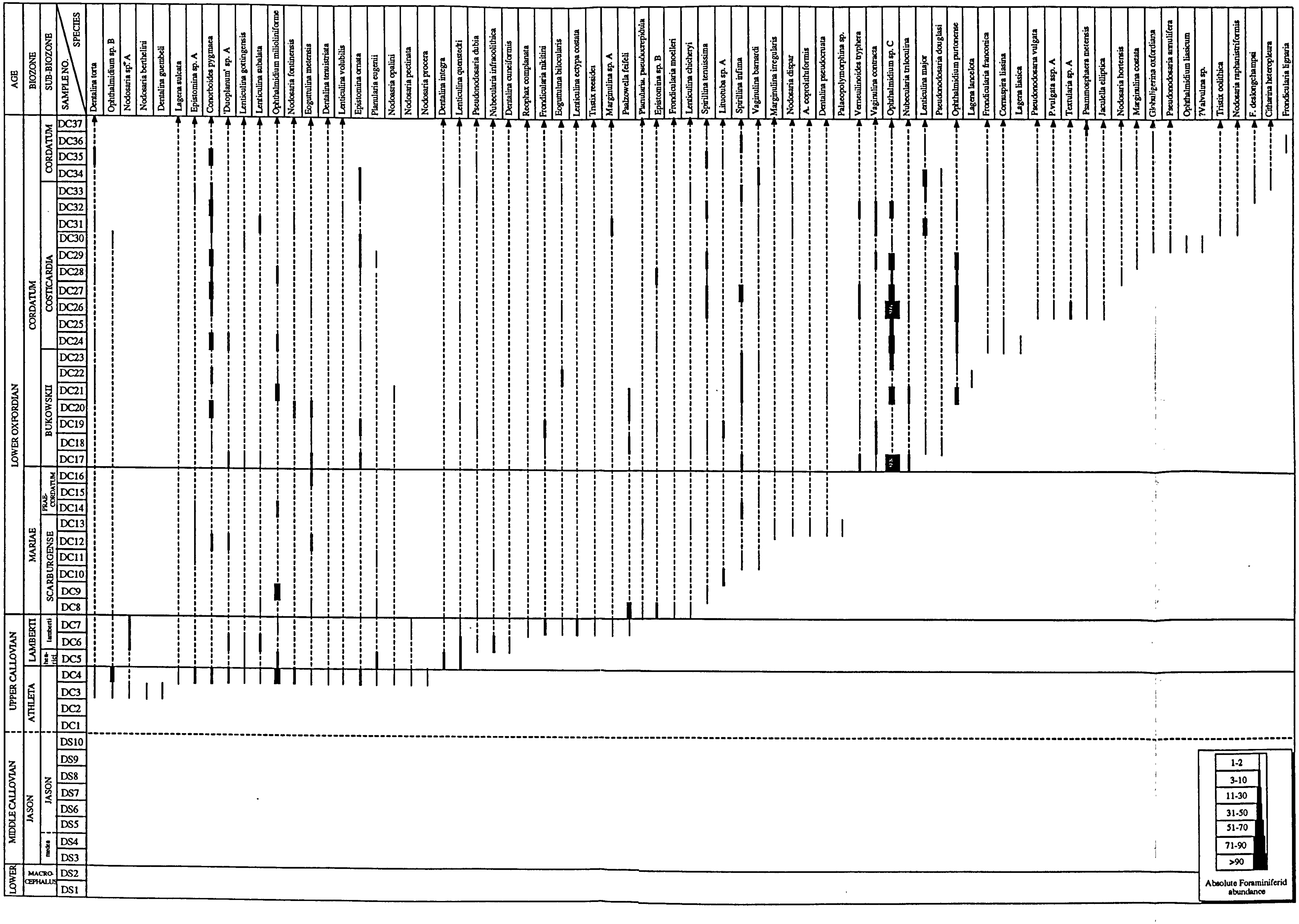


Figure 4.12. Foraminiferal distribution range chart for the Lower Callovian to Lower Oxfordian of Staffin Bay (part B)

Numerically, ***Haplophragmoides kingakensis*** represents the dominant form through the majority of the member with ***Ammobaculites fontinensis, Reophax helvetica, R. sterkii, Trochammina canningensis*** and ***Haplophragmoides infracalloviensis*** being common but subordinate. Introduction of new taxa remains fairly constant at 1 to 3 per sample after DS4. Overall, this member is characterised by an initial basal introduction of foraminifera which are dominated by agglutinated taxa having low abundances and diversity, with α indices between 1 and 5. ***Haplophragmoides*, *Reophax*** and ***Trochammina*** still dominate the sample residues.

ii). Dunans Clay Member (Figs. 4.11-4.14).

This member is lithologically distinct and characterised by minor scale cyclical deposition of clays and siltstones, interspersed sporadically with several prominent limestone markers. Foraminiferal distribution also appears to be cyclical, but is apparently limited to two trends/cycles rather than any pattern that could be tied to the minor scale sedimentary cyclicity. This poor correspondence is probably a reflection of the 1 metre reconnaissance sampling interval, which is too coarse to mirror the small scale lithological cycles. However, the overall trends are probably related to large scale changes in substrate/water depth conditions rather than to the small scale lithological fluctuations. Taken as a unit the Dunans Clay Member, is characterised by very diverse and abundant foraminiferal faunas, which are distributed in two major cycles covering the intervals between samples DC1 to DC16 and between DC17 and DC37.

The first major cycle occurs within the ***athleta*** to ***mariae*** Biozones and is initiated in sample DC1. This has a very low diversity foraminiferal fauna similar in composition to the preceding Dunans Shale Member. The remaining samples in the condensed ***athleta*** Biozone (DC2-DC4) are characterised by a phenomenal introduction of 61 appearances (DC2 with 23; DC3 with 22 and DC4 with 16 taxa respectively) and an α index value between 6 and 9 with associated high abundances. The majority of these species possess a calcareous test and in terms of abundances the aragonitic ***Epistomina parastelligera*** and ***Epistomina mosquensis*** are common, whilst the miliolids ***Ophthalmidium birmenstorfense*** and ***O. carinatum*** occur as major 'floods'. Other taxa which are subsidiary include ***Lenticulina varians, L. muensteri, Eoguttulina liassica*** and ***Reophax helvetica***. The agglutinated genera ***Haplophragmoides*** and ***Reophax*** lose their previous dominance to ***Epistomina, Lenticulina, Ophthalmidium*** and ***Nodosaria***. Within the condensed ***lamberti*** Biozone (DC5-DC7) only 12 species are introduced and diversity peaks at 12 on the α index, whilst total abundances decrease from their initial high in the ***athleta*** Biozone. There is a localised peak of the adherent miliolid ***Nubeculinella tibia***, whilst ***E. parastelligera, L. varians, Planularia beierana, E. liassica, Reophax helvetica*** and ***Ammobaculites fontinensis*** are common. The ***mariae*** Biozone (DC8-DC16) is characterised by a substantial decrease in the abundance and diversity of foraminifera (α values of 4-8). In detail, within the ***scarburgense*** Subbiozone (DC8-DC11) there are 13 first appearances and a 'flood' of ***Ophthalmidium***

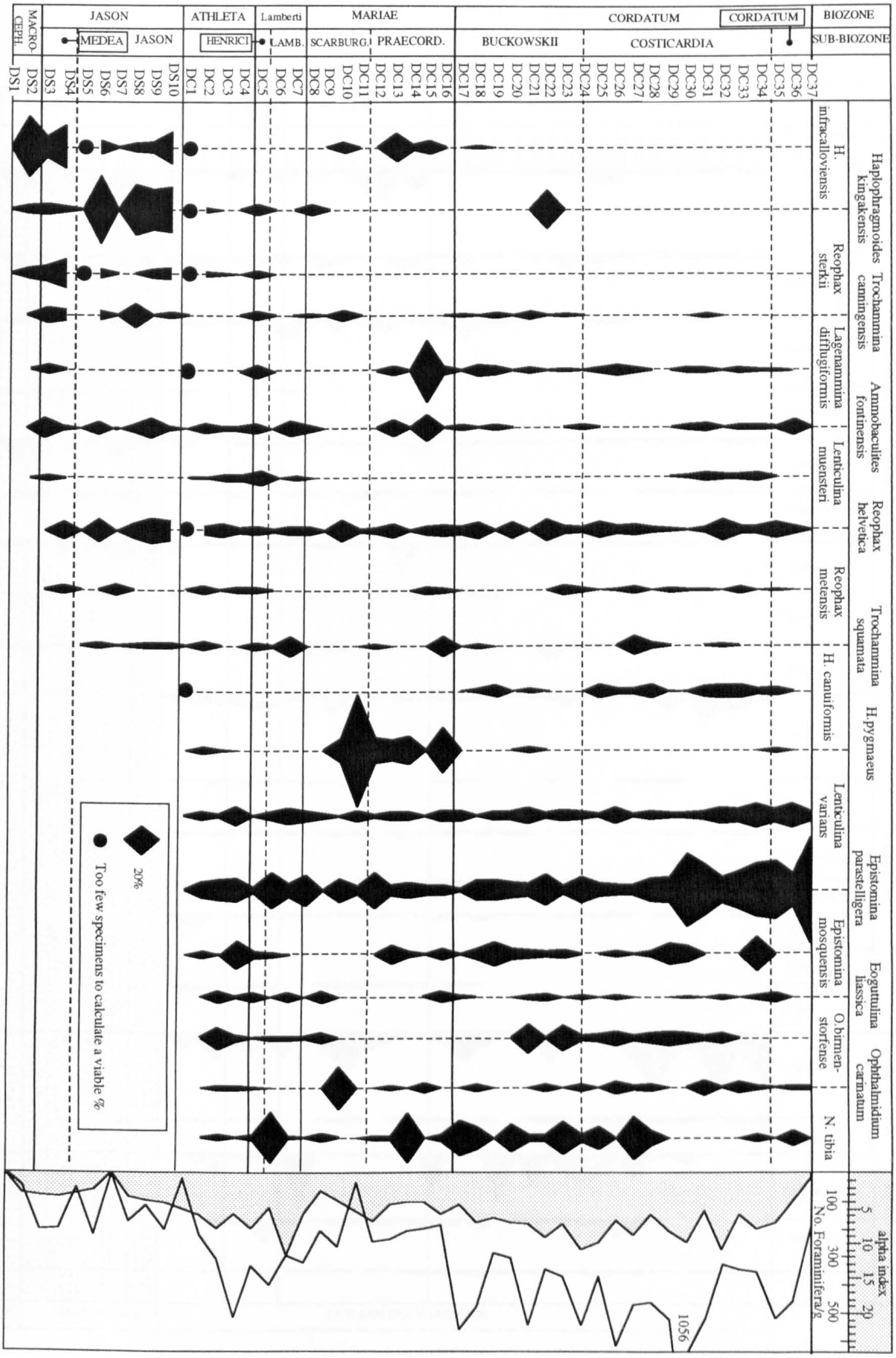


Figure 4.13. Relative distribution of selected foraminiferal taxa from the Lower Callovian to Lower Oxfordian of Staffin Bay (DS1-DS2, Belemnite Sand Member; DS3-DS10, Dunans Shale Member; DC1-DC37, Dunans Clay Member)

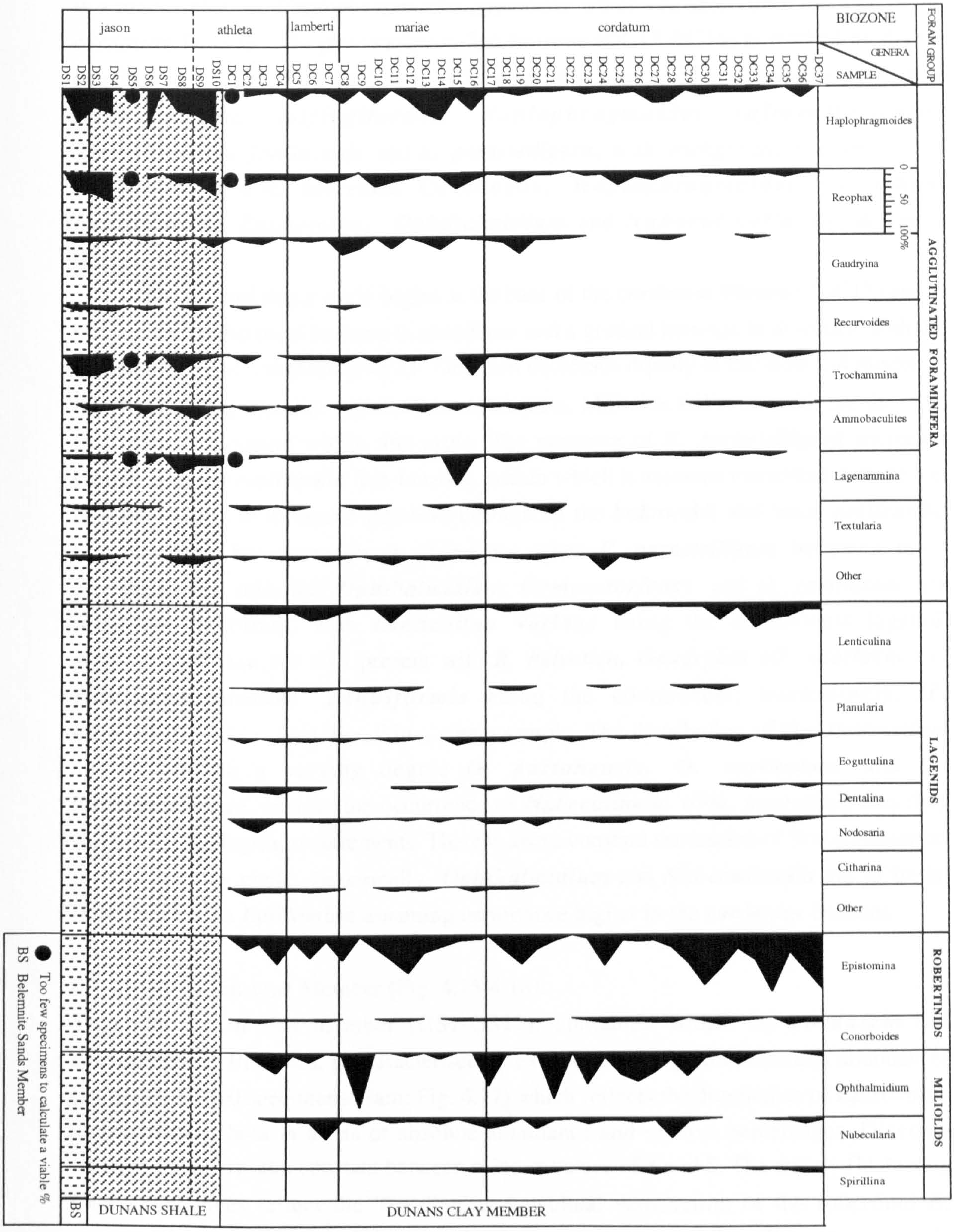


Figure 4.14. Percentage distribution of foraminiferal genera within the Callovian to Oxfordian of Staffin Bay

carinatum. The previous dominance of *N. tibia* is much reduced but ***E. parastelligera, L. varians*** and ***R. helvetica*** persist throughout. An interesting feature is a major influx of ***Haplophragmoides pygmaeus*** which continues until the base of the ***cordatum*** Biozone. The ***praecordatum*** Sub-biozone (DC12-DC16) is marked by the re-establishment of the *N. tibia* 'floods' which are also associated with relatively common ***Lagenammina difflugiformis, Haplophragmoides infracalloviensis, Ammobaculites fontinensis*** and ***E. parastelligera***, with background occurrences of ***L. varians*** and ***R. helvetica***. Generically, ***Haplophragmoides, Reophax, Lenticulina, Epistomina, Ophthalmidium*** and ***Nubeculinella*** are the most important.

The second major cycle begins at the base of the ***cordatum*** Biozone (DC17) and is marked by a substantial increase in abundance and a gradual increase in diversity, with the α index rising to a maximum of 12. This then decreases rapidly in the final 3-4 metres of the Dunans Clay Member where siltstones increase. Miliolids and robertinids are the most important component within this cycle. The presence of ***E. parastelligera*** increases slowly until the ***costicardia*** Sub-biozone, within which it assumes numerical dominance. *N. tibia* occurs in moderate numbers throughout the ***bukowskii*** and basal ***costicardia*** Sub-biozones, but decreases in abundance when ***E. parastelligera*** becomes more common. The miliolids ***Ophthalmidium birmenstorfense*** and ***O. carinatum*** are relatively important, with ***Lenticulina varians*** being the commonest lagenid. Agglutinated taxa are also present with ***R. helvetica, Gaudryina*** aff. ***sherlocki*** and ***Haplophragmoides canuiformis*** being the commonest; interestingly, ***H. kingakensis*** occurs as a 'flood' in a single sample. The distribution of ***Ophthalmidium*** sp. C, and to a varying degree ***O. purtonensis, O. carinatum*** and ***O. birmenstorfense***, mirrors the occurrence of ***Nubeculinella tibia,*** suggesting that they had similar ecological requirements. There is also a constant succession of first appearances throughout this cycle. Generically, ***Ophthalmidium*** and ***Nubeculinella*** are of initial importance with ***Epistomina*** assuming importance higher in the ***cordatum*** Biozone.

iii). Glashvin Siltstone Member (Fig. 4.15-4.18).

The majority of this member (GS1-GS17), contained within the ***cordatum*** and ***densiplicatum*** Biozones, is characterised by exceptionally high foraminiferal abundances (sometimes 1000 specimens/gram; Fig. 4.17) which reflects the dominance of ***Epistomina parastelligera*** both in terms of absolute abundance and relative percentages. Diversity remains fairly low and constant between α index values of 5 and 8. The widely fluctuating total abundances reflect the 'flooding' and cyclical distribution of the robertinid ***E. parastelligera. Ophthalmidium carinatum*** and ***Nubeculinella tibia*** also occur in localised abundant flooding events. The latter taxa appears to be mutually exclusive with regards to ***E. parastelligera. O. purtonensis*** is common within the ***densiplicatum*** Biozone. Agglutinated foraminifera are poorly represented and the commonest lagenids are ***Lenticulina varians*** and ***L. muensteri.***

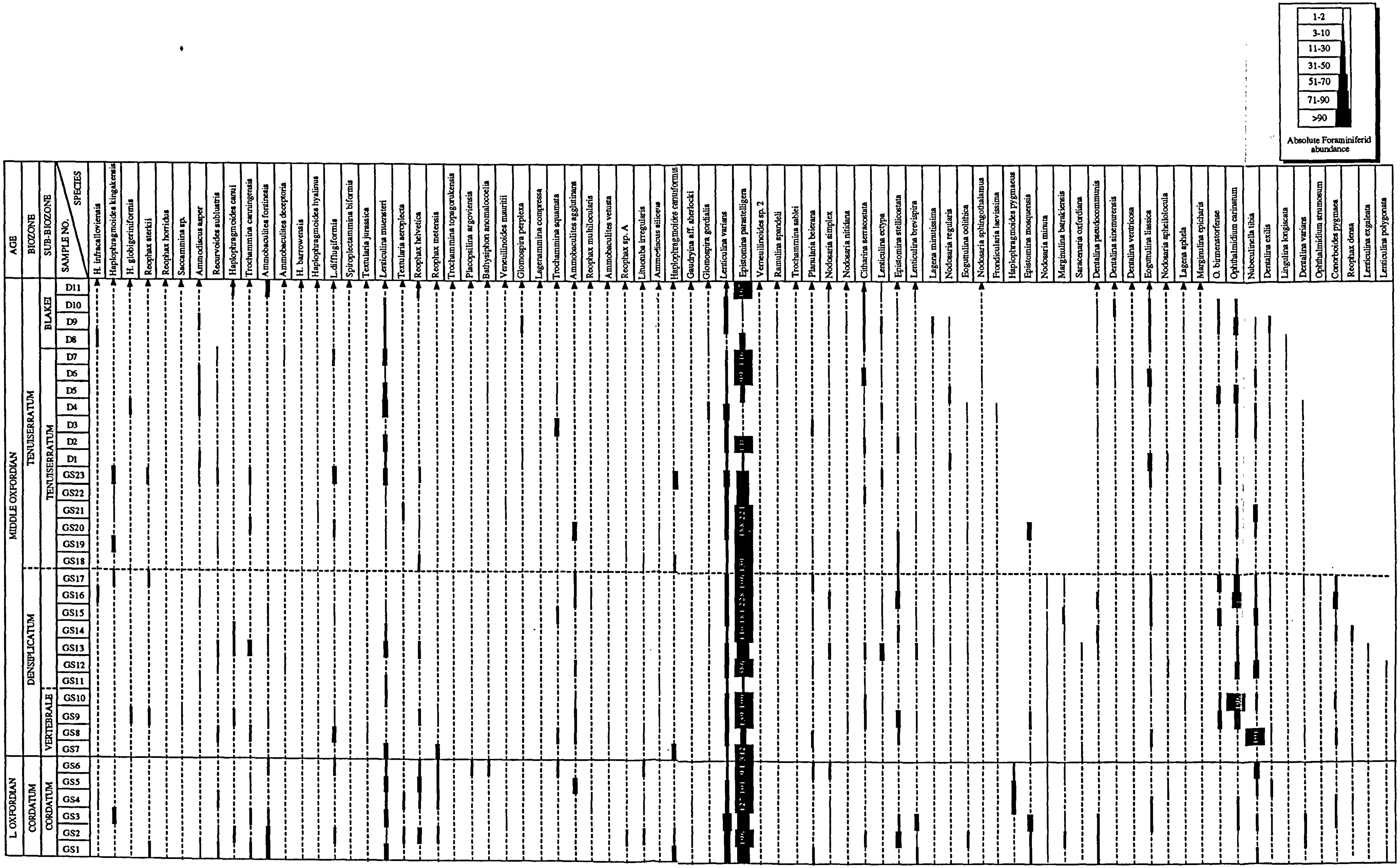


Figure 4.15. Foraminiferal distribution range chart for the Lower to Middle Oxfordian of Staffin Bay (part A)

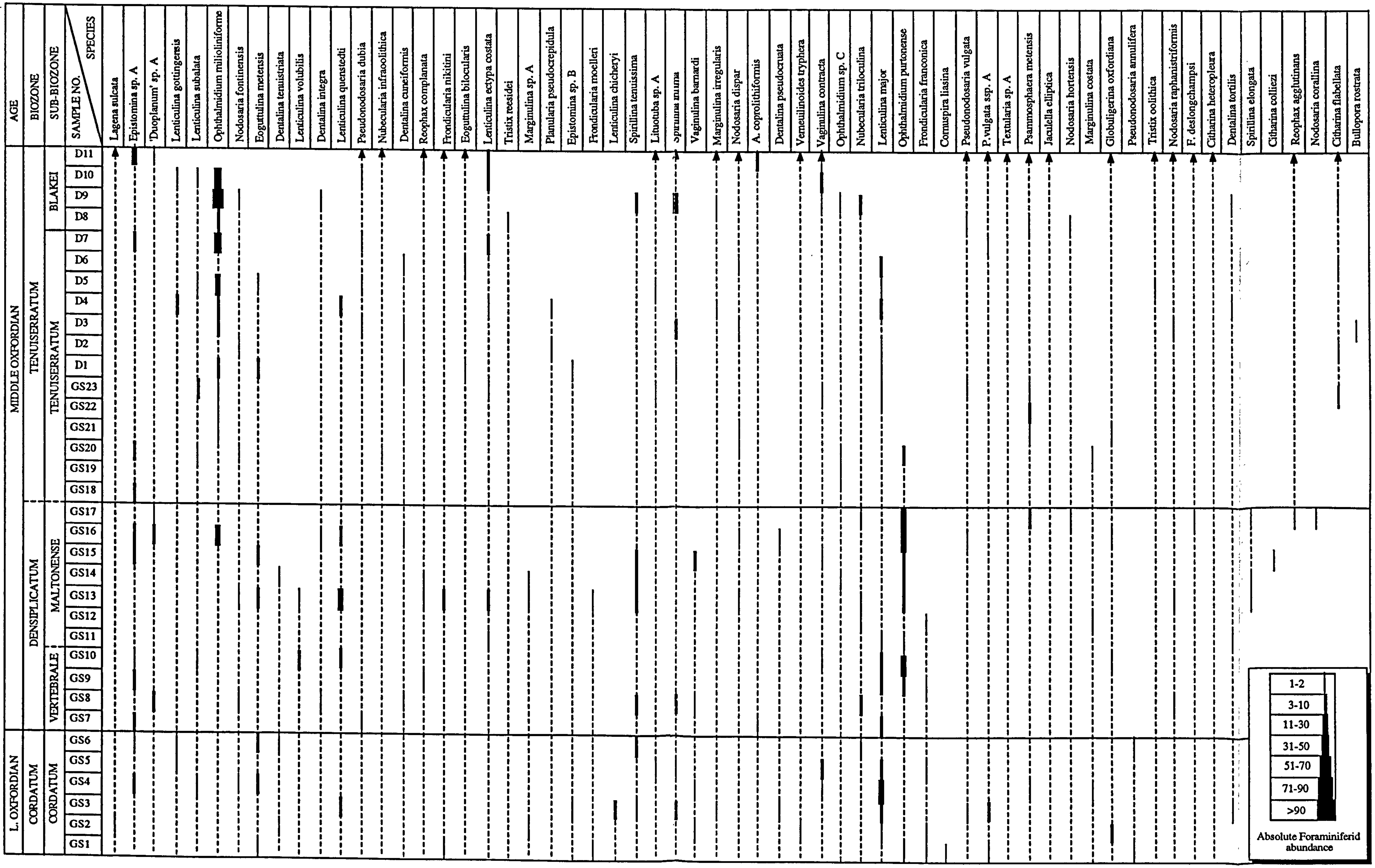


Figure 4.16. Foraminiferal distribution range chart for the Lower to Middle Oxfordian of Staffin Bay (part B)

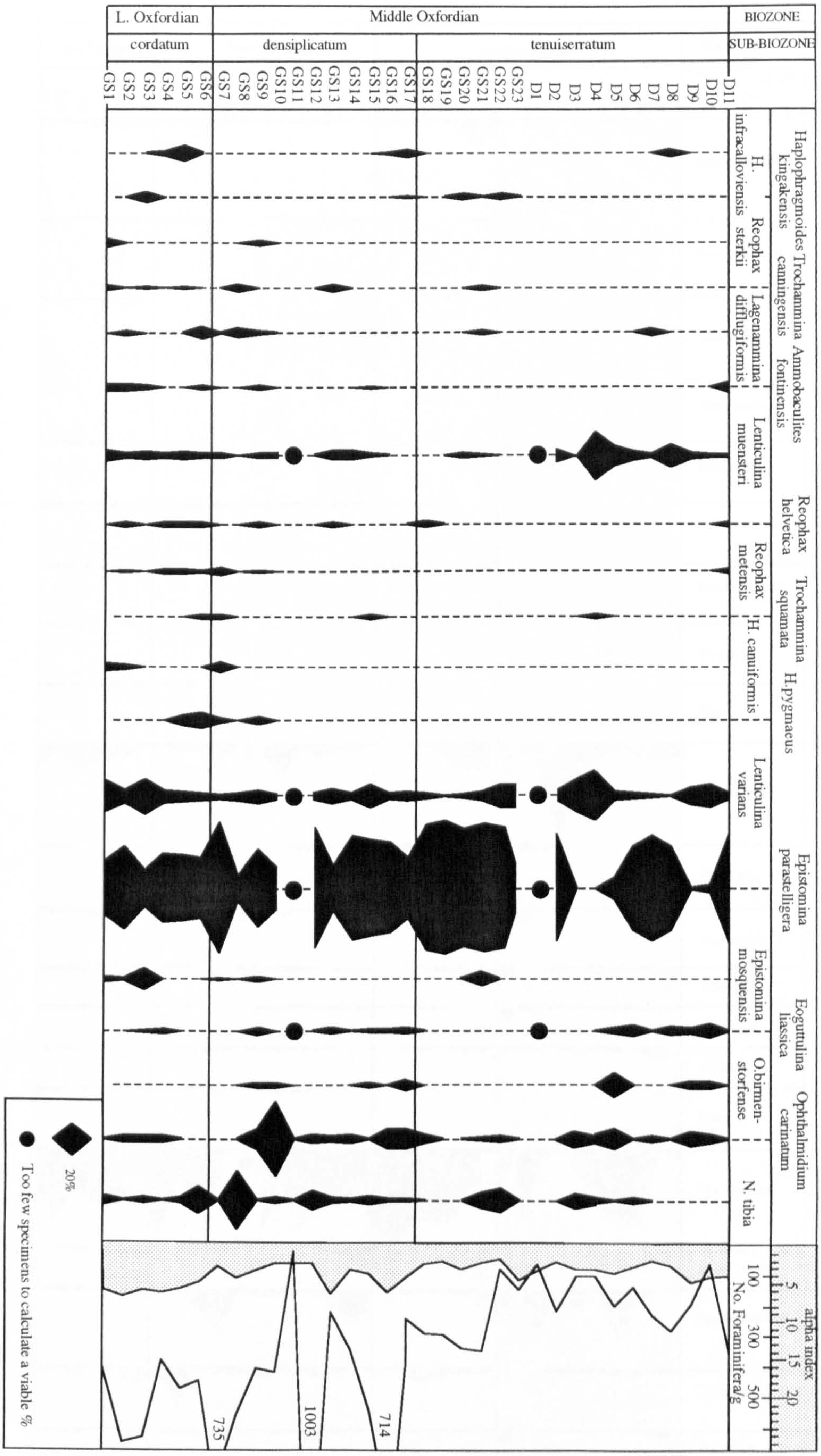


Figure 4.17. Relative distribution of selected foraminiferal taxa from the Lower to Middle Oxfordian of Staffin Bay (GS1-GS23, Glashvin Siltstone Member; D1-D11 Digg Siltstone Member)

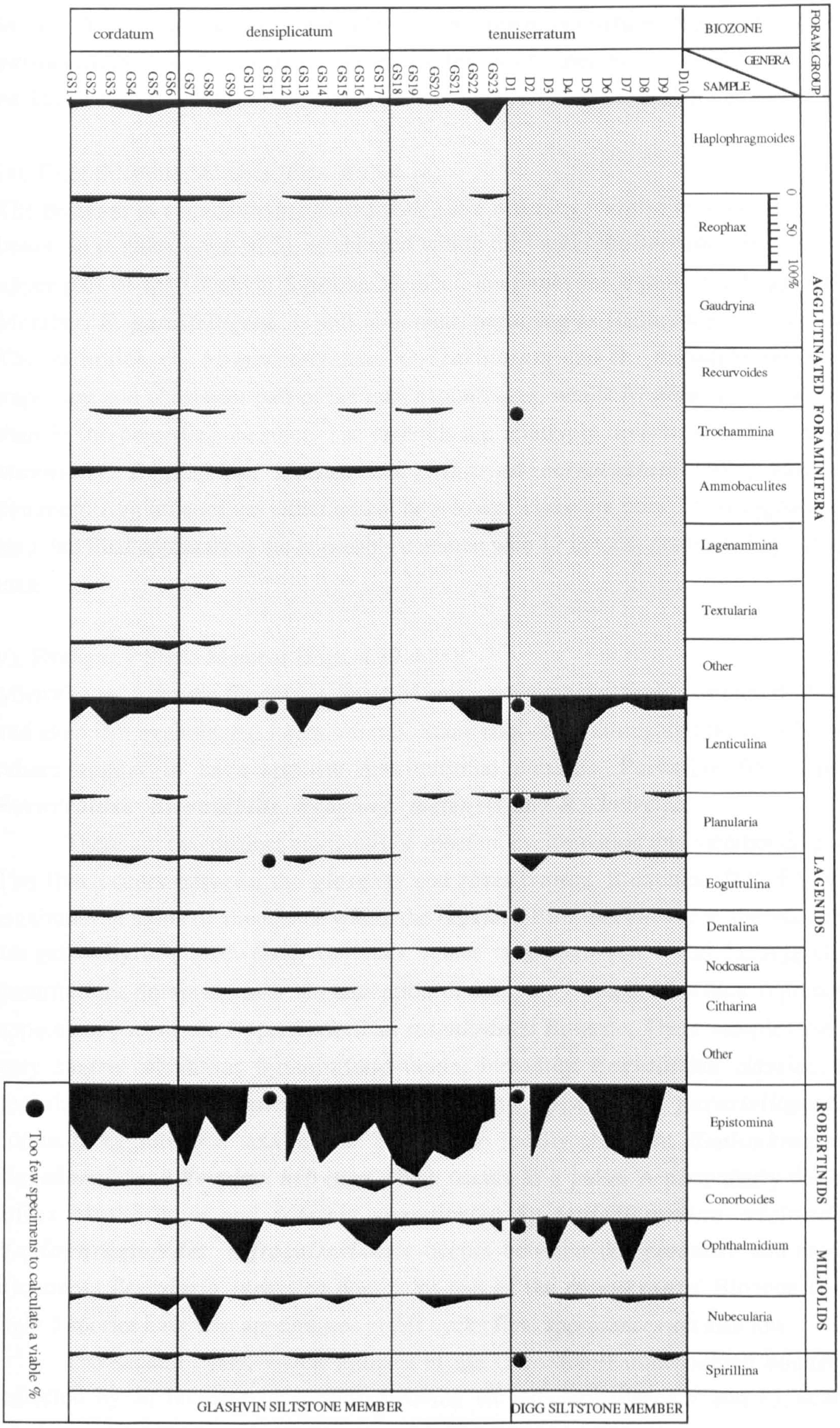


Figure 4.18. Percentage distribution of foraminiferal genera within the Oxfordian of Staffin Bay

Abundances and diversity decrease (α values between 2 and 3) markedly (Fig. 4.17) in the final 5 metres (GS18-GS23) of the ***tenuiserratum*** Biozone, where ***E. parastelligera*** dominates almost to the exclusion of other taxa except ***N. tibia*** and ***L. varians.*** First appearances within the Glashvin Siltstone Member are limited to 5 taxa.

iv). Digg Siltstone Member (Figs. 4.15-4.18).

The decrease in abundance associated with a low diversity foraminiferal fauna (generally below an α index value of 5), established within the basal ***tenuiserratum*** Biozone in the upper part of the Glashvin Siltstone Member, continues throughout the Digg Siltstone Member. ***E. parastelligera*** is still important, occurring as fluctuating flooding events. The miliolids ***O. birmenstorfense, O. carinatum*** and ***O. milioliforme*** form an important and consistent part of the total assemblages, whilst ***N. tibia*** is noticeably rarer than in the preceding member. The lagenids are relatively diverse with ***L. varians, L. muensteri, Eoguttulina liassica*** and ***Citharina serracostata*** being particularly common. Agglutinates are either absent or are rare. There are only 2 first appearances of taxa, but final appearances are noticeably common with 17 in total, dominated by calcareous taxa.

v). Flodigarry Shale Member (Figs. 4.19-4.21).

Microfaunas from the Flodigarry Shale Member are almost entirely composed of diverse and abundant agglutinated foraminiferids. Some taxa occur throughout the member whilst others appear to have specific distributional patterns. Pervasive forms include ***Recurvoides disputabilis, Reophax metensis*** and ***R. helvetica.***

There are two distinct groupings or apparent cycles within this member (Fig. 4.20). The first occurs between the ***glosense*** and ***rosenkrantzi*** Biozones (D12-F7) with a maximum in terms of abundance within the ***regulare*** Biozone. However, the assemblages are generally low in diversity (α index values range between 1 and 5). Agglutinated foraminifera dominate with the exception of samples F6 and F7 which represent the uppermost part of the Upper Oxfordian ***rosenkrantzi*** Biozone. These samples yielded a very sparse calcareous foraminiferid fauna, including ***Eoguttulina liassica,*** a few dentalinid species, ***Lenticulina muensteri*** and ***Epistomina parastelligera.*** The dominant agglutinated taxa include common to locally abundant ***Haplophragmoides kingakensis,*** and ***Reophax helvetica*** which occurs as a pulse. A particularly distinctive influx of the large and coarsely agglutinated ***Spiroplectammina vicinalis*** and ***Haplophragmoides infracalloviensis*** occurs between the ***glosense*** and ***regulare*** Biozones. ***Textularia jurassica*** dominates part of the ***rosenkrantzi*** Biozone (F4-F6). Only 5 species have first appearances in this cycle; final appearances are also low.

The second cycle, which initiates at the Oxfordian/Kimmeridgian boundary, is reflected by an increase in species diversity (α indices between 7 and 8), nearing a maximum within the ***baylei*** Biozone (F8-F13). This would appear to be as a direct

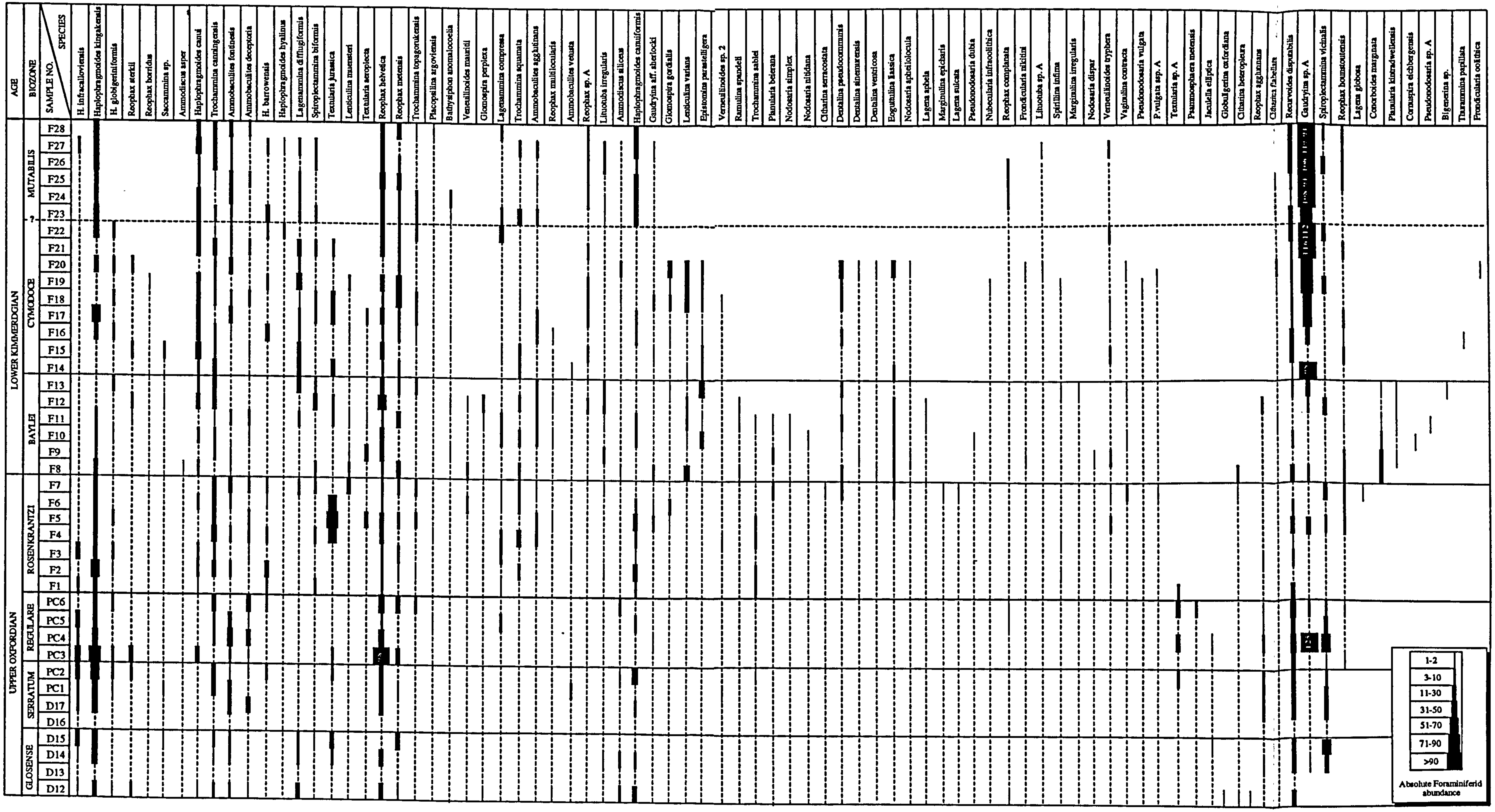


Figure 4.19. Foraminiferal distribution range chart of the Upper Oxfordian and Lower Kimmeidgian of Staffin Bay

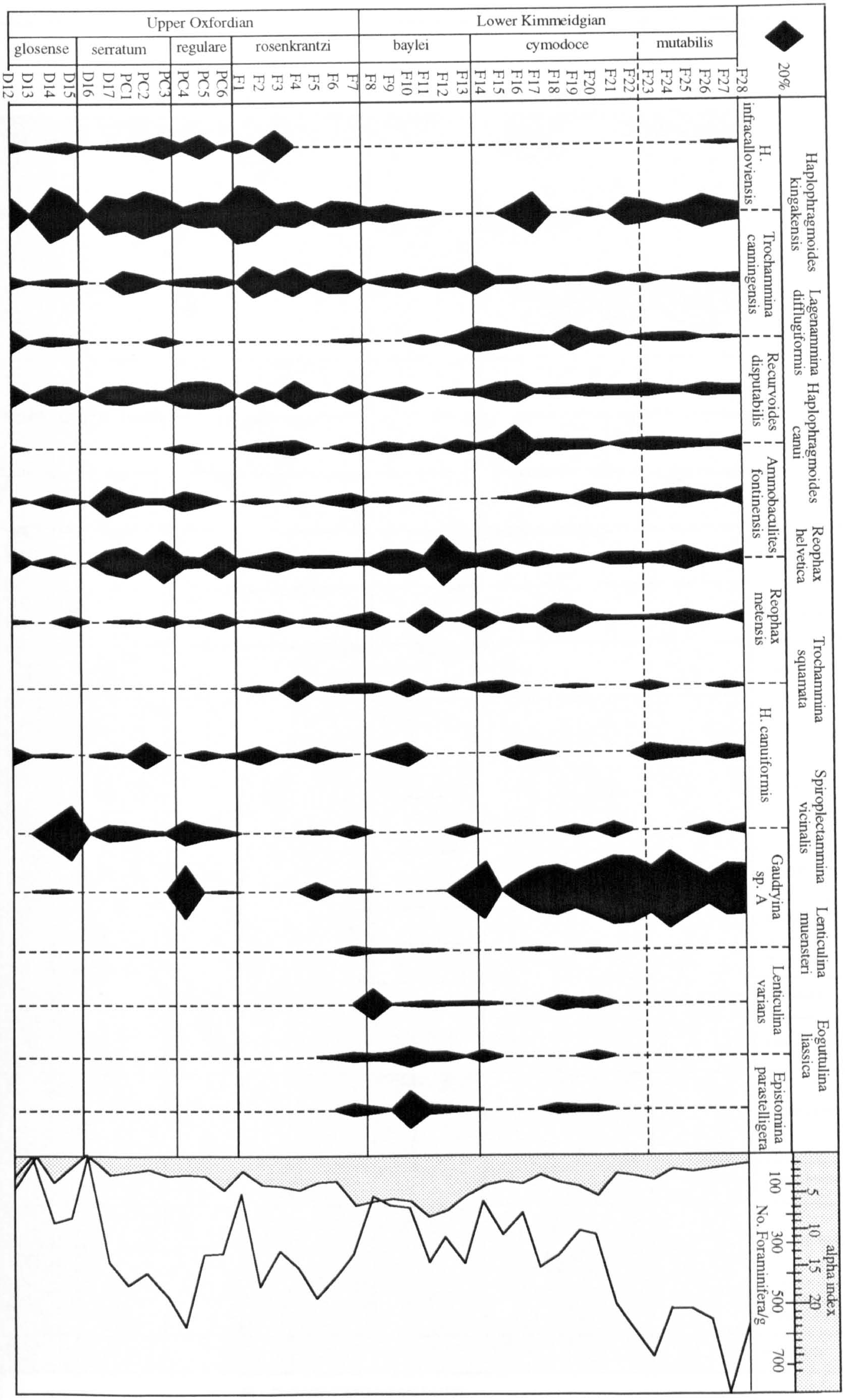


Figure 4.20. Relative distribution of selected foraminiferal taxa from the Upper Oxfordian to Lower Kimmeridgian of Staffin Bay (D12-F28, Flodigarry Shale Member)

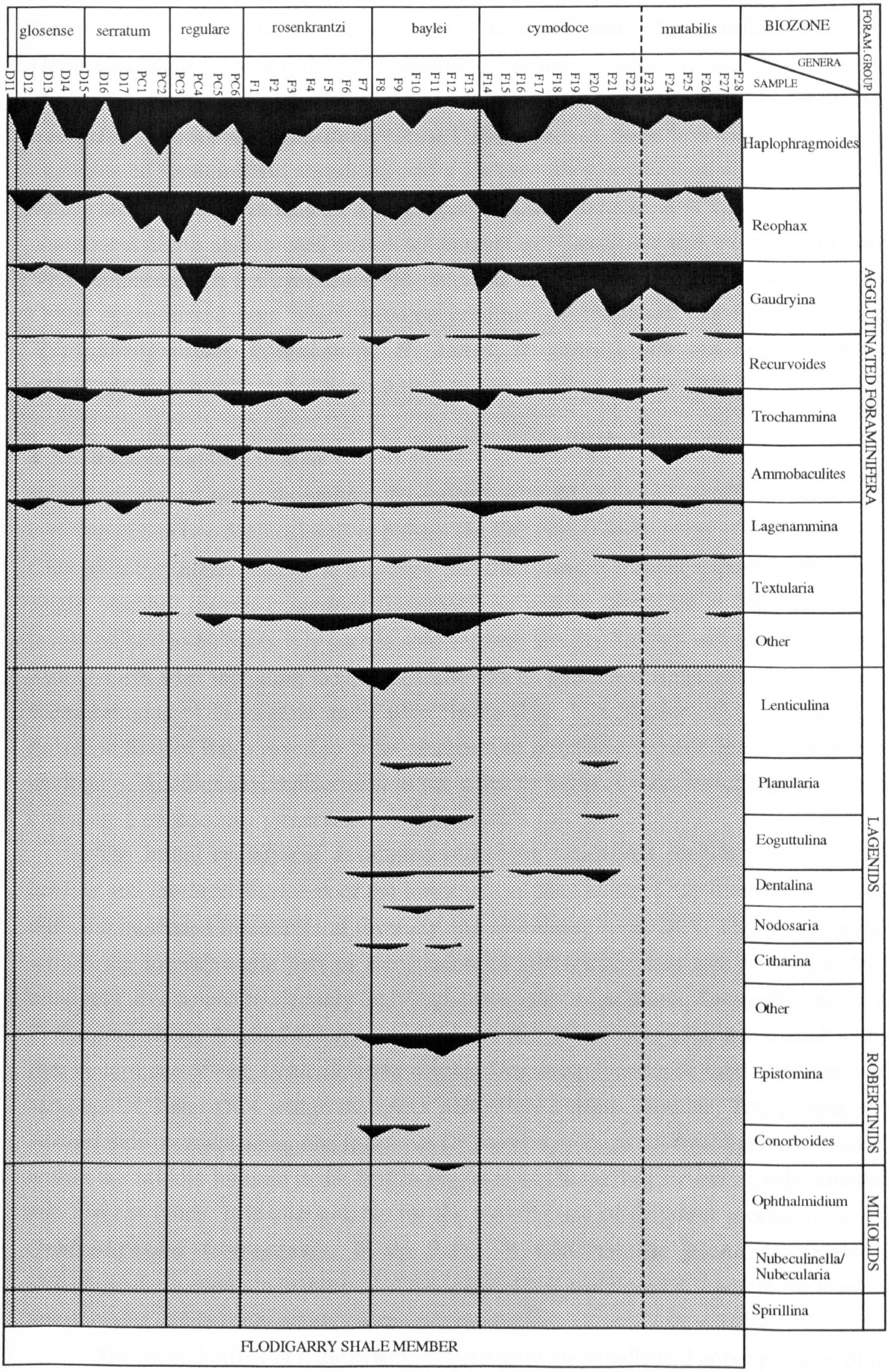


Figure 4.21. Percentage distribution of foraminiferal genera within the Upper Oxfordian to Lower Kimmeridgian of Staffin Bay

consequence of an increase in a limited number of lagenid and robertinid taxa, in particular ***Conorboides marginata, Epistomina parastelligera, Eoguttulina liassica, Dentalina pseudocommunis*** and ***Lenticulina varians.*** Several agglutinated taxa also attain their maximum abundances within the ***baylei*** Biozone, for example ***Reophax helvetica.*** Within the ***cymodoce/?mutabilis*** Biozones there is a rapid increase in agglutinated foraminiferid abundance and a corresponding decrease in diversity (α index values are generally less than 5). The presence of ***Gaudryina*** sp. A is the most noticeable component of this agglutinated dominated assemblage. Calcareous taxa are not particularly well represented in the ***cymodoce*** Biozone and disappear in the ***?mutabilis*** Biozone. Other agglutinated taxa which become prominent throughout this interval include ***Haplophragmoides kingakensis, H. canui, H. canuiformis*** and ***Lagenammina difflugiformis.***

4.3.6. Radiolarian Distribution

Radiolaria do not occur throughout the entire Staffin Bay succession (Fig. 4.22), but are concentrated in two distinct levels or pulses. The first occurs in the lower part of the Dunans Clay Member (***athleta-lamberti*** Biozones) and the second is present within the Flodigarry Shale Member (***baylei-cymodoce*** Biozones). As will be discussed in Chapter 7, these levels proved to be eminently correlatable between the Staffin Bay section and the Inner Moray Firth sites including the Upper Callovian of Brora and Balintore and the Lower Kimmeridgian of Helmsdale and Eathie Haven (Fig. 7.3). Numerically, neither of the pulses at Staffin Bay proved to be as abundant or pervasive as their Inner Moray Firth analogues. Additionally, replacement of test silica by pyrite, or occasionally glauconite, is common. Consequently preservation is often poor.

The initial cycle/pulse developed within the condensed section comprising the ***athleta*** and ***lamberti*** Biozones of the lower part of the Dunans Clay Member, coincides with the increased foraminiferal diversity and abundance from DC2. This levels occurs within the lower/middle part of the condensed ***athleta*** Biozone and is notable for a relatively diverse and moderately high abundance radiolarian fauna. ***Spongodiscus*** sp. A, ***Tricolocapsa*** sp. A and ***Stichocapsa*** sp. A are the commonest taxa, associated with a first occurrence of rare ***Orbiculiforma iniqua.*** Declining abundances and diversity mark samples DC3 and DC4 within the upper part of the ***athleta*** Biozone. The inception of ***henrici*** Sub-biozonal ammonite indices at DC5 corresponds to the final burst of radiolaria within the Middle Jurassic in the Staffin Bay area and is marked by a relatively abundant and diverse fauna. It is also notable for the introduction of different species including ***Orbiculiforma lowreyensis, O.*** sp. B and ***Pseudocrucella plana. O. iniqua*** is also particularly common in this part of the sequence. A sample at DC7 within the ***lamberti*** Sub-biozone yielded only poorly preserved cenodiscids.

The second influx of radiolarians occurs within the middle and upper portions of the Flodigarry Shale Member, in the ***baylei*** and ***cymodoce*** Biozones. The overall composition is also different compared with the initial pulse. In detail, a highly dubious and

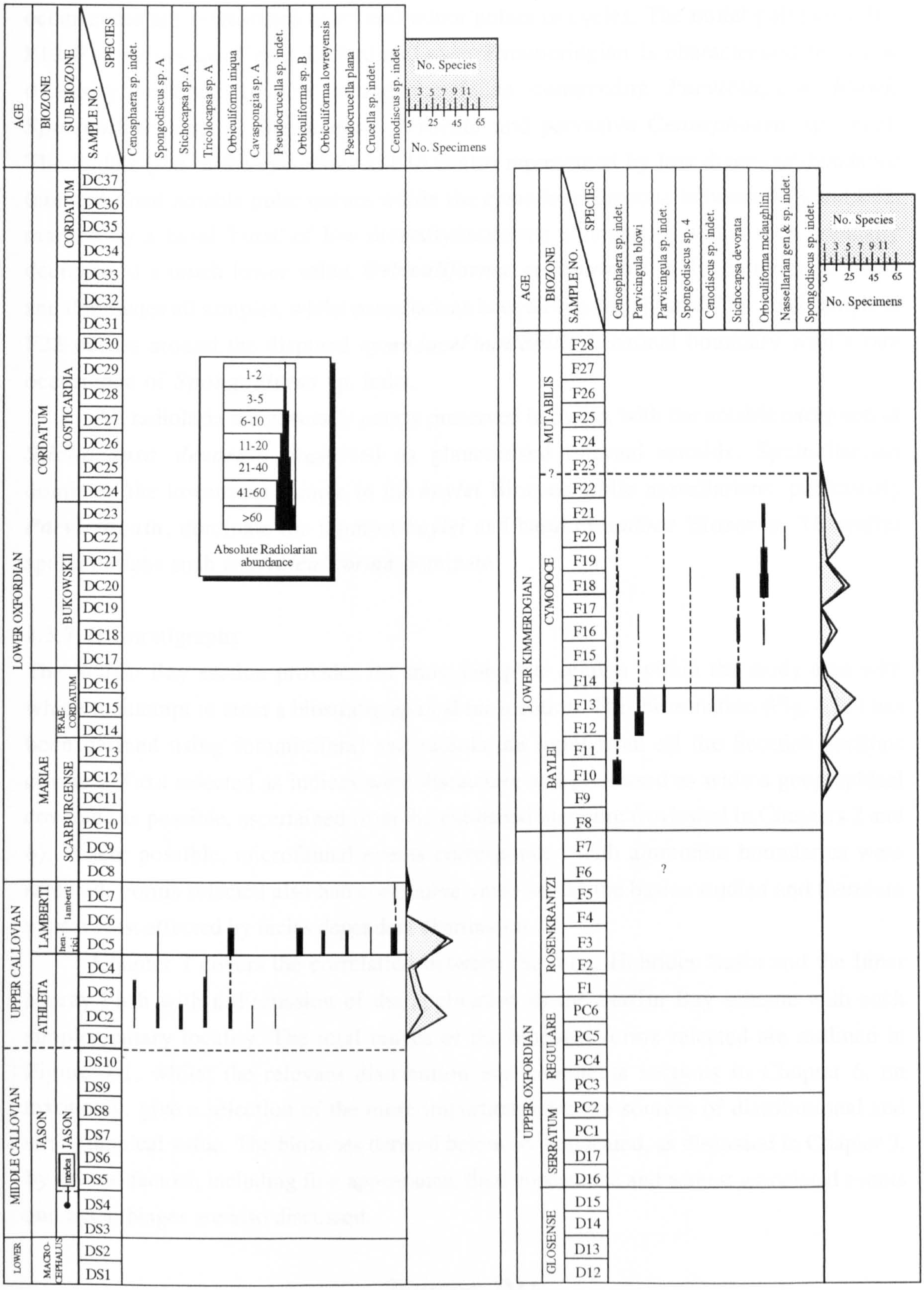


Figure 4.22. Radiolarian distribution, diversity and abundances at Staffin Bay

poorly preserved parvicingulid occurs within the upper part of the Upper Oxfordian ***rosenkrantzi*** Biozone. The first positive radiolarian occurrence occurs within the ***baylei*** Biozone, with the sample at F10 yielding poorly preserved cenodiscids. Subsequent occurrences are represented as several minor pulses or cycles. The initial pulse covering F12-F14 across the Upper Oxfordian/Lower Kimmeridgian is characterised by a low diversity/moderate to low abundance fauna comprising ***Parvicingula blowi, Spongodiscus*** sp. 4, ***Stichocapsa devorata*** and pervasive ***Cenosphaera*** sp. indet. The middle part of the ***cymodoce*** at F16 is also represented by low diversity/abundance fauna. A final notable pulse occurs within the ***cymodoce*** Biozone between F18 and F22, marked by a basal 'burst' of low diversity/moderate abundances which then gradually decrease to a much lower value. ***Orbiculiforma mclaughlini*** is the commonest taxon and dominates all samples, whilst nassellarians have all but disappeared. The final sample at F22 occurs around the disputed ***cymodoce/?mutabilis*** Biozonal boundary with a rare occurrence of ***Spongodiscus*** sp. indet.

All radiolaria are generally poorly preserved in pyrite, with the notable exception of ***Stichocapsa devorata*** preserved as glauconised internal moulds. Spumellarians dominate the lowermost sample in the ***baylei*** Biozone while nassellarians, particularly ***Parvicingula***, dominate the topmost ***baylei*** and basal ***cymodoce*** Biozones. Thereafter spumellarians such as ***Orbiculiforma*** dominate.

4.3.7. Biostratigraphy

The Staffin Bay section provides the most complete section within the study area with which to attempt to erect a biostratigraphical biozonation. This biozonation (Fig. 4.23) has been defined using foraminiferal and radiolarian input from all the Scottish sections covered. Taxa selected as indices were distinctive and possessed as wide a geographical coverage as possible, ascertained from the published literature (reviewed in Chapters 2 and 6). Where possible, microfaunal events corresponded with ammonite boundaries were selected. Forms selected also had correlative value across the basins studied and therefore appear least affected by facies dependent distribution.

Chapter 7 covers the correlation between the Inner Hebrides Basin and the Inner Moray Firth with a discussion of the application of the Staffin Bay scheme with each supplementary locality. The total ranges of the biozonal forms selected are outlined in Figure 7.1, whilst the relevant distribution and comments sections in Chapter 6, on taxonomy, give a selection of the more important literature sources of distributional and stratigraphical value. The biozones derived below are delineated, as discussed in Chapter 3, by several factors, including first appearance, final appearance and acmes; associated events and assemblages are also discussed.

Biozone JM1

Lower-Middle Callovian; intra *macrocephalus* Biozone to basal *athleta* Biozone.

This biozone, initiated within the Lower Callovian, marks a return to marine conditions with

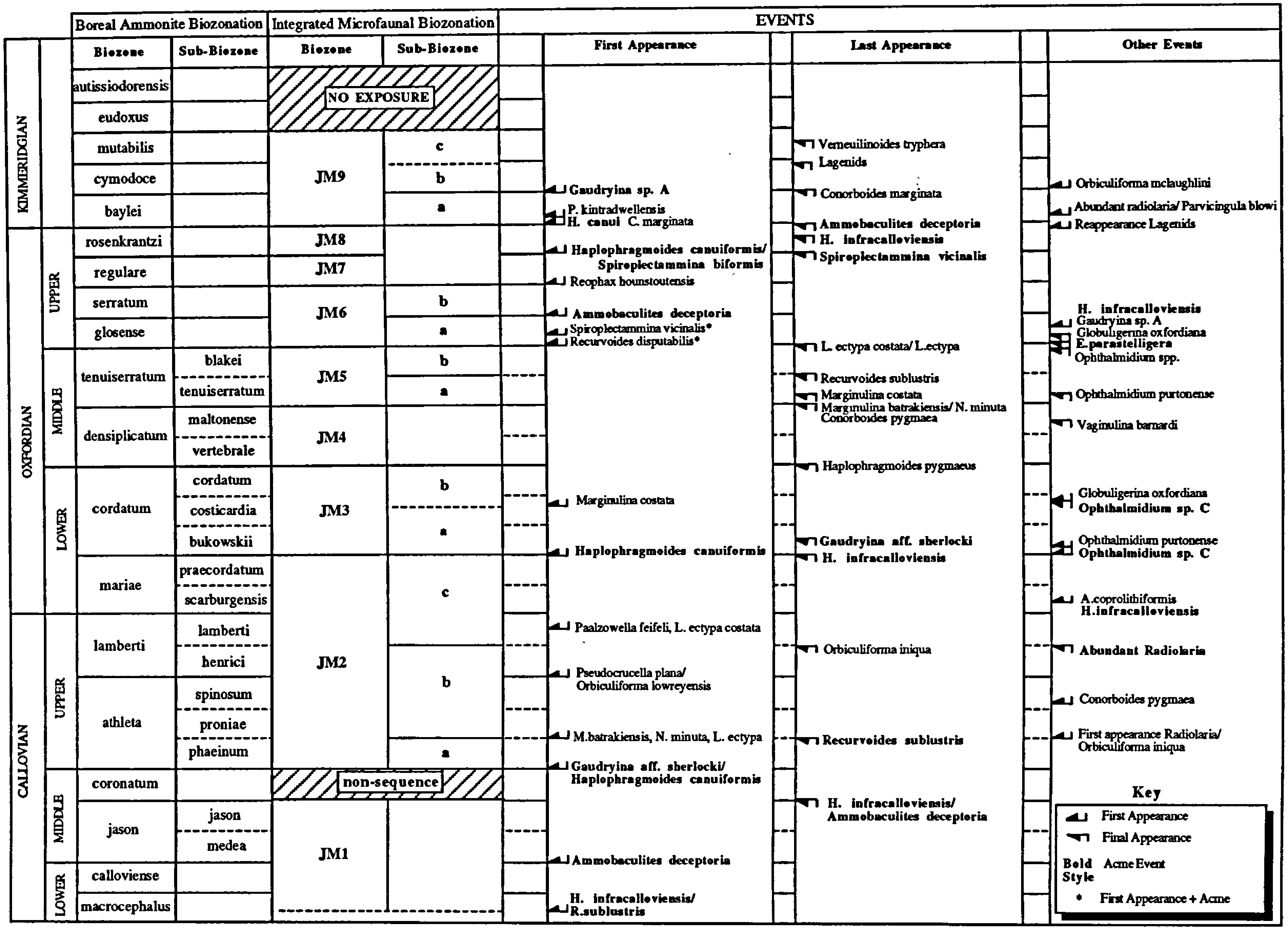


Figure 4.23. Microfaunal biozonal scheme for the Callovian to Kimmeridgian of Staffin Bay correlated against the ammonite biozonation

a basin-wide transgression and is also delineated by the first appearance of a 'fully' marine, but restricted, microfauna. Therefore, taking this factor into consideration, the definition of the base could be the most diachronous boundary within this biozonal scheme.

The top of the biozone is also poorly delineated, as rapid transgression associated with erosion or periods of non-deposition have led to the absence of the ***calloviense*** and ***coronatum*** ammonite biozones. Therefore, the top of JM1 is taken at the base of the following biozone with the first appearance of a microfauna associated with ammonites indicative of the ***athleta*** Biozone.

The base of JM1 is characterised by the first appearance of a low diversity, low/medium abundance fauna composed of relatively common agglutinated foraminiferids, the most important biostratigraphically of which are ***Haplophragmoides infracalloviensis*** and ***Recurvoides sublustris*** with ***Ammobaculites deceptoria*** also present.

Associated Assemblages.

JM1 is almost exclusively dominated by agglutinated taxa, the exception being a few rare specimens of ***Lenticulina muensteri.*** The biozone contains two distinct levels of major first appearances. The first series occurs within the ***macrocephalus*** Biozone and includes the taxa outlined above, associated with common specimens of ***Reophax sterkii, R. horridus, H. kingakensis*** and ***Ammobaculites fontinensis.***

The second level occurs at the base of the ***medea*** Sub-biozone of the ***jason*** Biozone and includes the first appearance of common specimens of ***Reophax helvetica, R. metensis*** and ***Verneuilinoides mauritii***, with ***Lagenammina compressa, Trochammina squamata*** and ***Reophax multiloculus*** occurring higher in the ***jason*** Sub-biozone.

Biozone JM2

Upper Callovian to Lower Oxfordian; base ***athleta*** Biozone to base ***cordatum*** Biozone. The base of this biozone is marked by the first appearance and common occurrence of ***Gaudryina*** aff. ***sherlocki,*** associated with the first appearance of ***Haplophragmoides canuiformis*** and the final appearance of the ***H. infracalloviensis*** acme.

Biozone JM2 is subdivided into 3 distinct sub-biozones:

Sub-Biozone JM2a

Upper Callovian; base ***athleta*** Biozone (base ***phaeinum*** Sub-biozone to base ***proniae*** Sub-biozone).

The base of Sub-biozone JM2a is defined in the same manner as for the biozone, with the top being defined by the base of JM2b. ***Gaudryina*** aff. ***sherlocki***, the index for JM2a, appears to have a well recorded first appearance at or around this level and total range as recorded in the literature from the UK (Barnard ***et al.,*** 1981; Shipp, 1989), Alaska (Souaya, 1976), France (Guyader, 1968) and Germany (Lutze, 1960). Exact ammonite biostratigraphical pinpointing of the JM2a/JM2b boundary may be affected in some way by the condensed nature of the *athleta* Biozone in the Hebrides Basin, especially in comparison with the thick succession developed at Brora with over 30 metres present.

Associated Assemblages.
JM2a is characterised by a decrease in abundance of the taxa present in Biozone JM1. However, it is still totally dominated by agglutinated taxa.

Sub-Biozone JM2b

Upper Callovian; intra *athleta* Biozone (base *proniae* Sub-biozone) to intra *lamberti* Biozone (base *lamberti* Sub-biozone).
The base of this sub-biozone is marked by the first appearances of many lagenid, ophthalmid and robertinid taxa, the most diagnostic being ***Marginulina batrakiensis, Lenticulina ectypa, Nodosaria minuta, Ophthalmidium birmenstorfense*** and ***Epistomina parastelligera.*** The final appearance of the ***Recurvoides sublustris*** acme occurs at this level. The base of JM2b is also marked by the first appearance of radiolarian taxa, particularly ***Orbiculiforma iniqua.***

The first appearance of many taxa at this level is obviously reflective of a major palaeoenvironmental change. The initiation of more normal marine conditions with the onset and widening extent of the Callovian transgression must have been conducive for foraminiferal and radiolarian colonisation. The presence of so many benthic forms must be as a consequence of their environmental requirements being met, i.e. due to facies dependence. However, ***M. batrakiensis, L. ectypa*** and to a lesser degree ***N. minuta,*** have well recorded first appearances at or around this datum from areas as widespread as the Polish Lowlands (Bielecka 1988; Bielecka *et al.*, 1988), Russian Platform (Myatluik, 1939; Efimova & Mesezhnikov, 1991) and the UK (Shipp, 1989), showing their wider uses as biostratigraphical marker taxa.

Associated Assemblages.
A large number of the foraminiferal forms encountered within the Staffin Bay sequence have their first appearances at the base of, or within Sub-biozone JM2b, showing its importance in terms of faunal introduction and inception. 23 taxa occur at the base and include ***Epistomina parastelligera, E. mosquensis*** and ***Saracenaria oxfordiana,*** with a further 40 taxa introduced within the ***phaeinum*** and ***spinosum*** Sub-biozones of the ***athleta*** Biozone. Of these 63 taxa only 4 are agglutinated foraminiferids.

Common foraminiferids present within this interval are ***Lenticulina varians, E. parastelligera, E. mosquensis, N. minuta, Ophthalmidium birmenstorfense, O.*** sp. B and ***O. milioliniforme.***

Radiolaria also occur with the introduction of ***Orbiculiforma iniqua*** at the base of JM2b, with ***Pseudocrucella plana*** and ***Orbiculiforma lowreyensis*** at the ***athleta/lamberti*** ammonite biozonal boundary.

Sub-biozone JM2c

Upper Callovian to Lower Oxfordian; intra ***lamberti*** Biozone (base ***lamberti*** Sub-biozone) to base ***cordatum*** Biozone.

The base is defined by the final appearance of common radiolaria associated with the final appearance of the radiolarian taxon ***Orbiculiforma iniqua.***

Important datums within this level include the first appearance of ***Paalzowella feifeli*** and ***Lenticulina ectypa*** ssp. ***costata*** in the ***lamberti*** Sub-biozone. Additional first appearances include ***Vaginulina barnardi, Ammobaculites coprolithiformis*** and the inception of an acme of ***Haplophragmoides infracalloviensis*** in the ***scarburgense*** Sub-biozone of the ***mariae*** Biozone.

Lenticulina ectypa ssp. ***costata,*** which has a common first appearance in Brora within the ***athleta*** Biozone, appears to be diachronous regarding its first appearance in other basins, including relatively local ones such as Brora and Balintore. However, its final appearance appears to be synchronous across many basins. ***Paalzowella feifeli*** is also a useful marker species, with well recorded first appearances within the Upper Callovian and Lower Oxfordian of Germany (Bartenstein & Brand, 1937), France (Wernli, 1971) and Poland (Bielecka ***et al.***, 1988). However, its usefulness as a biozonal form here is limited by apparent requirements for fairly shallow water conditions, as shown by its general absence in 'deeper water' palaeoenvironments at Balintore.

The distinctively striated ***Vaginulina barnardi*** was recovered from this level and has potential as an index for the ***mariae*** Biozone, having been reported from similar horizons in Dorset by Barnard ***et al.*** (1981) and Shipp (1989).

Associated Assemblages.

JM2c is characterised by a common and diverse lagenid and robertinid microfauna, with only a few agglutinated taxa represented. Important examples of the latter are common specimens of ***Gaudryina*** aff. ***sherlocki*** and ***Haplophragmoides pygmaeus.***

23 taxa have first appearances within JM2c, the majority occurring near to the ***lamberti/mariae*** Biozonal boundary. Important forms including ***Frondicularia nikitini, F. moelleri, Epistomina*** sp. B., ***Nodosaria*** sp. A and ***N. pectinata*** have final appearances at the ***lamberti/mariae*** Biozonal level.

Biozone JM3

Lower Oxfordian; base ***cordatum*** Biozone to base ***densiplicatum*** Biozone.

This biozone encompasses the ***cordatum*** Biozone and its base is marked by the first appearance of the acme of ***Haplophragmoides canuiformis***, associated with the final appearance of the ***H. infracalloviensis*** acme. An important coexistent event is the first appearance of ***Ophthalmidium*** sp. C. JM3 is divided into two Sub-biozones:

Sub-biozone JM3a

Lower Oxfordian; ***cordatum*** Biozone, (base ***bukowskii*** -intra ***costicardia*** Sub-biozones).

The base of this sub-biozone is defined in the same fashion as for the biozone. Important events include the first appearance of ***O.*** sp. C, which is a short ranging and abundant taxon although it has not been reported elsewhere and the final appearance of the acme of ***Gaudryina*** aff. ***sherlocki*** within the ***bukowskii*** Sub-biozone. Other events include the first appearance of ***Verneuilinoides tryphera*** and ***Ophthalmidium purtonensis*** within the ***bukowskii*** Sub-biozone. The latter taxon has a similar range within the English Oxford Clay as reported by Barnard *et al.* (1981). Similarly, the first appearance of ***Pseudonodosaria douglasi***, which was recorded as ***P. radiata*** by Barnard ***et al.*** (1981), also has a directly correlatable range. However, it is rare and thus has limitations as a biozonal form.

Associated Assemblages.

JM3a is characterised by an increase in diversity of taxa from the underlying biozone, with lagenids again dominating in terms of diversity and abundance, however, miliolid taxa also dominate samples in abundance. Important forms include ***Nubeculinella tibia*** and ***Ophthalmidium birmenstorfense,*** with common ***Epistomina parastelligera, Conorboides pygmaeus*** and ***Lenticulina varians***. The only numerically important agglutinated foraminiferids are ***Reophax helvetica*** and ***Haplophragmoides canuiformis***.

Several biostratigraphically less important forms have first appearances in the ***costicardia*** Sub-biozone, including the probable new species ***Textularia*** sp. A and ***Pseudonodosaria vulgata*** ssp. A.

Sub-biozone JM3b

Lower Oxfordian; intra ***cordatum*** Biozone (intra ***costicardia*** Sub-biozone)-base ***densiplicatum*** Biozone.

The base of this Sub-biozone is defined by the first appearance of ***Marginulina costata*** within the ***costicardia*** Sub-biozone. Another important event within JM3b is the first appearance of ***Globuligerina oxfordiana*** associated with the final acme appearance of the short ranging, miliolid taxon ***Ophthalmidium*** sp. C.

Associated Assemblages.

The assemblages developed within JM3b are similar to those within Sub-biozone JM3a, however, ***Epistomina parastelligera*** dominates the majority of the residues, with ***Nubeculinella tibia*** and ***O.*** sp. C being less frequent.

Tristix oolithica and ***Citharina heteropleura*** have their first occurrences within this sub-biozone, whilst the final occurrence of ***Haplophragmoides pygmaeus*** occurs at the ***cordatum/densiplicatum*** biozonal boundary.

Biozone JM4

Middle Oxfordian; base ***densiplicatum*** Biozone-base ***tenuiserratum*** Biozone.
The base of this biozone, which defines the Lower/Middle Oxfordian Boundary, is marked by the final appearance of ***Haplophragmoides pygmaeus***. Associated events include the final appearance of ***Vaginulina barnardi*** within the ***maltonense*** Sub-biozone.

Associated Assemblages.
The assemblages from Biozone JM4 and the ***densiplicatum*** Biozone are dominated by ***Epistomina parastelligera*** but also include abundant ***Ophthalmidium carinatum*** with common ***Lenticulina varians*** and ***Nubeculinella tibia***. The final appearance of common specimens of ***Ophthalmidium purtonensis*** also occurs within JM4.

Only 4 taxa have first appearances within this biozone, however, many taxa die out, the most important biostratigraphically being ***Nodosaria minuta, Marginulina batrakiensis*** and ***Conorboides pygmaeus*** at the base of JM5 (base ***tenuiserratum*** Biozone). Other taxa with final appearances within the ***densiplicatum*** Biozone include ***Lenticulina exgaleata, Frondicularia moelleri*** and ***Saracenaria oxfordiana***.

Biozone JM5

Middle Oxfordian; base ***tenuiserratum*** Biozone-base ***glosense*** Biozone.
The boundary between the ***densiplicatum*** and ***tenuiserratum*** Biozones is, besides that between the ***tenuiserratum/glosense*** Biozones, one of the most distinctive in this study area and is marked by the final occurrences of many biostratigraphically important taxa, which include ***Nodosaria minuta, Marginulina batrakiensis*** and ***Conorboides pygmaeus***.

JM5 is divided into two sub-biozones by the following criteria:

Sub-biozone JM5a

Middle Oxfordian; ***tenuiserratum*** Biozone (base ***tenuiserratum*** Sub-biozone to base ***blakei*** Sub-biozone).
The base of this sub-biozone is defined by the same marker species as for the biozone. Important datums within JM5a include the final occurrences of ***Marginulina costata*** and ***Ophthalmidium purtonensis***. The total range of ***O. purtonensis*** is very similar to that recorded by Barnard ***et al.*** (1981).

Associated Assemblages.
The diversity of lagenids decreases from JM4 to JM5a, which is dominated by the robertinid ***Epistomina parastelligera,*** with common ***Lenticulina muensteri, Ophthalmidium carinatum*** and ***O. milioliniforme***.

JM5a is also marked by an increase in final occurrences, the most important of which being ***E. mosquensis, E.*** sp. B and ***L. quenstedti***. All taxa are well established with only 2 first appearances, the most notable being that of *Citharina flabellata.*

Sub-biozone JM5b

Middle Oxfordian, intra ***tenuiserratum*** Biozone (base ***blakei*** Sub-biozone) to base ***glosense*** Biozone.

The base of Sub-biozone JM5b is delineated by the final appearance of ***Recurvoides sublustris***, which has a widely reported extinction around this level (e.g. Brooke & Braun, 1981; Nagy ***et al.***, 1990a, b), although the ammonite control on some of these reports is not precise.

Associated Assemblages.

JM5b has a lower diversity and abundance of taxa than JM5a, with ***E. parastelligera*** generally not as dominant. ***O. milioliniforme*** increases in absolute abundance in the ***blakei*** Sub-biozone.

There are no first appearances within this interval, however there are many final occurrences, particularly amongst the miliolids which include ***O. birmenstorfense, O. milioliniforme, O.*** sp. C, ***O. carinatum*** and ***Nubeculinella tibia.*** The extinction of such a large number of miliolids is probably related to facies changes. ***Lingulina longiscata*** is the most notable final occurrence amongst the lagenids.

Biozone JM6

Upper Oxfordian; base ***glosense*** Biozone to base ***regulare*** Biozone.

The base of this biozone is defined by the combined first appearance and acme of ***Recurvoides disputabilis***, along with the final appearances of ***Lenticulina ectypa*** and ***L. ectypa*** ssp. ***costata***. These events are fairly widely documented, with ***R. disputabilis*** having a recognised Upper Oxfordian first appearance and acme in Svalbard (Nagy ***et al.*** 1990a, b), Alaska (Brooke & Braun, 1981) and the Russian Kimmeridgian/Upper Oxfordian (Dain, 1948, 1972; Efimova & Mesezhnikov, 1991).

The final appearance of ***L. ectypa*** ssp. ***costata*** is similarly well documented at the end of the ***tenuiserratum*** Biozone by Shipp (1989), from an amalgamation of UK sources. Efimova & Mesezhnikov (1991) record a Middle/Upper Oxfordian age from the Russian Jurassic. Offshore data concerning the final appearances of these two forms is somewhat contradictory (see Chapter 7 for a discussion of the validity of such data). ***L. ectypa*** has a more diachronous extinction, with instances of extinction in the Upper Oxfordian and Lower Kimmeridgian from the UK (Shipp, 1989).

The overall faunal change across the Middle and Upper Oxfordian boundary in this basin is from a lagenid dominated microfauna to one comprising almost exclusively agglutinating taxa. This makes for one of the most dramatic biozonal boundaries.

Biozone JM6 can be divided into 2 sub-biozones:

Sub-biozone JM6a

Upper Oxfordian; base *glosense* Biozone to base *serratum* Biozone.
The base of this sub-biozone is defined in the same manner as for the base of the biozone.

Associated Assemblages.
Sub-biozone JM6a contains the first appearances of ***Gaudryina*** sp. A, ***Spiroplectammina vicinalis*** and a further acme occurrence of ***H. infracalloviensis.*** The assemblages are composed almost entirely of agglutinating taxa, the most common being ***Haplophragmoides kingakensis, Reophax helvetica, Lagenammina difflugiformis, S. vicinalis*** and ***R. disputabilis.***

Globuligerina oxfordiana, although rare in these deposits, has its final appearance within this biozone, in common with similar deposits in the Pechora Basin of northern Russia (Yakolova ***pers comm.***, 1991). No lagenids were recovered from this interval.

Sub-biozone JM6b

Upper Oxfordian; base *serratum* Biozone to base *regulare* Biozone.
The base of JM6b is delineated by the first appearance of an acme of ***Ammobaculites deceptoria***, with the top defined by the base of Biozone JM7, marked by the first appearance of ***Reophax hounstoutensis.***

A. deceptoria appears to have two well defined acmes within the Bathonian and the Callovian, as recorded by Morris & Coleman (1989) and Morris & Dyer (1990). Partington *et al.*, (1993a) record this taxon through to the Oxfordian/Kimmeridgian Stage boundary. Unfortunately, there appears to be no direct ammonite control for this offshore dating and palynology appears to have been the driving force of the template biozonation.

Associated assemblages.
Sub-biozone JM6b has a similar foraminiferid assemblage to Sub-biozone JM6a, with a total dominance of agglutinated taxa.

Biozone JM7

Upper Oxfordian; base ***regulare*** Biozone to base ***rosenkrantzi*** Biozone.
The base of JM7 is defined by the first appearance of ***Reophax hounstoutensis***, a distinctive form from the Upper Oxfordian and Lower Kimmeridgian of Dorset and originally described by Lloyd (1959, 1962). It has subsequently been recorded from Canada (Brooke & Braun, 1981) and Spitsbergen (Nagy ***et al.***, 1990a). The top of JM7 is defined by the base of JM8 which is marked by the first appearance of an acme of ***Haplophragmoides canuiformis*** and a final occurrence of the ***Spiroplectammina vicinalis*** acme.

Associated Assemblages.

Assemblages derived from JM7 are totally dominated by agglutinated foraminiferids, the most common taxa being ***H. infracalloviensis, H. kingakensis, Ammobaculites fontinensis***, abundant ***Trochammina canningensis, Reophax helvetica, Recurvoides disputabilis*** and intermittent, but abundant ***Gaudryina*** sp. A, and ***Spiroplectammina vicinalis.***

Biozone JM8

Upper Oxfordian; base ***rosenkrantzi*** Biozone to base ***baylei*** Biozone.

The base of this biozone is defined by the final acme occurrence of ***Spiroplectammina vicinalis*** and by the consistent first occurrence of the ***Haplophragmoides canuiformis*** acme. Associated with these events is the consistent recovery of ***Spiroplectammina biformis.***

Associated Assemblages.

This interval is characterised by a slight increase in the diversity and abundance of agglutinated foraminiferids, with ***H. kingakensis, Trochammina canningensis*** and ***Textularia jurassica*** being common. The uppermost part of this biozone is marked by the introduction of a sparse lagenid fauna, including the ubiquitous ***Lenticulina muensteri***, associated with ***Dentalina pseudocommunis, Planularia beierana, Eoguttulina liassica*** and other rare forms.

JM8 is marked by the final appearance of the acmes of ***Haplophragmoides infracalloviensis*** and ***Textularia jurassica*** and the final appearance of ***Textularia*** sp. A.

Biozone JM9

Kimmeridgian; base ***baylei*** Biozone to a top undefined, due to the lack of exposure, within the ?***mutabilis*** Biozone.

The base of JM9 is delineated by first appearances of ***Conorboides marginata*** and abundant ***Haplophragmoides canui*** and the final appearance of abundant ***Ammobaculites deceptoria.*** Morris & Coleman (1989), Morris & Dyer (1990) and Partington ***et al.*** (1993a, b) recorded a final appearance around the Oxfordian/Kimmeridgian boundary for this form. However, direct correlation with an ammonite biozonation was lacking as these offshore wells were dated palynologically. ***Planularia kintradwellensis*** has a first appearance at the base of the ***baylei*** Biozone.

The top of this biozone has not been defined due to the lack of continuous foreshore exposure of younger strata at Flodigarry.

JM9 is divided into 3 Sub-biozones:

Sub-biozone JM9a

Kimmeridgian; base *baylei* Biozone to base *cymodoce* Biozone.
The base of JM9a is defined in the same manner as for the biozone.

Associated Assemblages.

JM9a is characterised by an appreciable increase in the diversity of agglutinated foraminiferids, associated with the establishment of a low diversity and low abundance lagenid fauna. These include ***Epistomina parastelligera, Lenticulina varians, L. muensteri*** and ***Dentalina*** spp.

Radiolarian taxa are also established within JM8 and include ***Parvicingula blowi*** and ***Spongodiscus*** sp. 4.

Many taxa have their final occurrences recorded within this interval and these include ***Ammodiscus asper, Verneuilinoides mauritii, Glomospira perplexa, Trochammina sablei, Reophax agglutinans, Planularia beierana, Pseudonodosaria dubia, Nodosaria dispar*** and ***Citharina heteropleura.***

Sub-biozone JM9b

Kimmeridgian; base *cymodoce* Biozone-intra *cymodoce*/? base *mutabilis* Biozones.
The base of Sub-biozone JM9b is defined by the first appearance of common and abundant specimens of ***Gaudryina*** sp. A and the final occurrence of ***Conorboides marginata.***

The top of this Biozone is tentatively drawn at the final appearance of lagenid taxa.

Associated Assemblages.

Many taxa have final appearances within the *cymodoce* Biozone, particularly lagenids including ***Lenticulina varians, Epistomina parastelligera, Dentalina pseudocommunis, Eoguttulina liassica*** and ***Frondicularia nikitini,*** associated with several agglutinated taxa such as ***Haplophragmoides globigeriniformis, Reophax sterkii*** and ***R. horridus.*** Radiolaria are relatively common, particularly ***Stichocapsa devorata*** and ***Orbiculiforma mclaughlini.***

Sub-biozone JM9c

Kimmeridgian; intra top *cymodoce*/? intra *mutabilis* (top not seen).
The base of this tentatively designated sub-biozone is defined on the final appearance of the majority of lagenid taxa present in JM9a/JM9b and roughly correlates with the top-most *cymodoce*/basal *mutabilis* Biozone. This event may have some biostratigraphical importance, being a level of faunal turnover. However, the ammonite zonation of this level is somewhat speculative. Wright (1973) indicated the presence of the *mutabilis* Biozone at Flodigarry, and then later added a level of doubt to this assignation (Wright, 1989).

Associated Assemblages.

The assemblages are dominated by agglutinated taxa with particularly abundant specimens of ***Gaudryina*** sp. A and common ***Haplophragmoides kingakensis, H. canui, H. canuiformis, Trochammina canningensis, Reophax helvetica*** and ***Recurvoides disputabilis.***

Many taxa also have final appearances within this level, the most important being ***Verneuilinoides tryphera***, which correlates with a similar extinction level at Helmsdale and Eathie Haven.

The top of JM9c is not seen and therefore has not been designated due to the lack of continuous exposure. Younger sediments preserved at Helmsdale could not be used to add to this biozonation as the residues were barren of foraminifera and radiolaria.

4.3.8. Palaeoenvironmental Interpretation

The Staffin Bay section provides good material through a thick ammonite dated sequence in which many facies types are represented. Foraminiferal recovery from these samples was excellent and distinct distributional groupings of taxa were noted, especially with regard to facies types. In order to study the possible effects that palaeoenvironmental changes have on distribution, the foraminiferal species present in this section have been ranked firstly into range charts, then into their respective genera with selected taxa also illustrated (Figs. 4.11-4.21) and finally into suborders based on test wall composition (Figs 4.25, 4.26). From a comparison of the general generic distribution, species diversity, total abundances and the distribution of the four major sub-orders (agglutinated foraminifera, lagenids, robertinids and miliolids) through the Callovian to Lower Kimmeridgian, it is possible to define seven distinct foraminiferal assemblages (Fig. 4.24). Each assemblage is characterised either by the dominance of a single group, or by co-dominance of more than one group. There are also specific features of diversity and abundance which may be correlated to facies type or habitat. Minor differences in these specific characteristics may be related to subtle palaeoenvironmental differences and include the occasional presence of radiolarians. Analysis of the extent and distribution of these assemblages through the succession, associated with facies types, also allow the gross palaeoenvironmental changes during the Callovian to Lower Kimmeridgian in the margins of the Hebrides Basin to be deduced. The assemblages briefly introduced below are summarised in Figure 4.24 and their palaeoenvironmental relevance subsequently discussed.

Three of the assemblages are dominated by agglutinated foraminifera. Dissolution of calcareous taxa may have given rise to these agglutinated assemblages, so where possible evidence is presented as to the possible extent of post-mortem modification.

Assemblage A1 is typified by an almost total dominance of agglutinated foraminifera, typically ***Haplophragmoides, Trochammina*** and ***Reophax; Ammobaculites*** and ***Lagenammina*** occur as minor elements. The only calcareous taxon is ***Lenticulina muensteri*** which, however, is rare. In terms of general characteristics, this assemblage has a low diversity (α index of 1-5), with a corresponding low total abundance (10-<100 foraminifera/gram).

Assemblage A2 is characterised by a predominance of agglutinated forms, which are

FORAMINIFERAL ASSEMBLAGE		SPECIFIC DIVERSITY, ABUNDANCE	DOMINANT GENERA
A 1	Agglutinated foraminifera dominate with very minor lagenid component	Low diversity, low abundance (alpha index 1-5); (10-<100f/g)	Restricted number of agglutinated foram. species, mainly Haplophragmoides, Reophax and Trochammina
A2	Agglutinates»lagenids= robertinids + miliolid 'floods'	Moderate diversity, mod-high abundance (alpha index 3-8); (125-350f/g)	Relatively diverse microfauna including; Haplophragmoides, Reophax, Lagenammina, Gaudryina (small), Lenticulina, Dentalina, Eoguttulina, Epistomina and Nubeculinella
A 3	Agglutinated foraminifera dominate. Rare calcareous taxa and radiolaria present	Low/moderate diversity, very high abundance (alpha index 1-8); (125->500f/g)	Diverse agglutinates including; Haplophragmoides, Trochammina, Recurvoides, Ammobaculites, Spiroplectammina, Gaudryina (large), rare lagenids incl. Lenticulina and Eoguttulina
R 1	Robertinids»miliolids=lagenids= agglutinates	Low/mod diversity, very high abundance (alpha index 3-11); (100->700f/g)	Dominance of Epistomina. Subsidary genera include; Lenticulina, Eoguttulina, Dentalina, Citharina, Haplophragmoides, Ophthalmidium and floods of Nubeculinella
M1	Mixed assemblage. Miliolids>lagenids> agglutinates>robertinids. Radiolaria present	Mod/high diversity, moderate abundance (alpha index 6-13); (175-350f/g)	Ophthalmidium, Nubeculinella, Lenticulina, Dentalina, Nodosaria, Eoguttulina, Epistomina. Mod. diverse agglutes; Haplophragmoides, Reophax, Gaudryina, Trochammina and Ammobaculites
M2	Mixed assemblage. Miliolids≥ agglutinates>lagenids=robertinids	Mod/high diversity, high-v.high abundance (alpha index 6-11); (325-600f/g)	Nubeculinella, Ophthalmidium, Gaudryina, Haplophragmoides, Ammobaculites and Trochammina; relatively high lagenid diversity incl.; Lenticulina, Dentalina, Eoguttulina and Planularia
M3	Mixed assemblage. Lagenids≥ robertinids>miliolids≥agglutinates	Low diversity, moderate/high abundance (alpha index 3-5); (100-375f/g)	Robust and costate taxa common, including: Lenticulina, Eoguttulina, Citharina, Epistomina and Ophthalmidium. Rare Haplophragmoides

Figure 4.24. Microfaunal assemblage characterisation based primarily on foraminiferal suborders, specific diversities and abundances, and dominant generic composition

represented by a wider range of genera than in A1 and include ***Haplophragmoides, Reophax, Lagenammina,*** and ***Gaudryina.*** Calcareous taxa are subordinate, but lagenids such as ***Lenticulina, Dentalina*** and ***Eoguttulina*** can be of localised importance, along with the robertinid ***Epistomina.*** Miliolids, such as ***Nubeculinella tibia*** can occur as discrete, relatively prominent 'floods'. Foraminiferal diversity is generally moderate (α index of 3-8), whilst abundance is moderate to high (125-350 foraminifera/gram).

Assemblage A3 differs from A1 in that there is a very high total abundance (125 to >500 foraminifera/gram) with a low to moderate specific diversity (α index of 1-8), it compares, however, in the almost total dominance of agglutinated foraminifera. A3 is marked by a diverse suite of taxa belonging to ***Haplophragmoides, Trochammina, Recurvoides, Ammobaculites, Reophax, Spiroplectammina*** and ***Gaudryina.*** Calcareous taxa, where present, are minor and are limited to rare specimens of ***Lenticulina, Eoguttulina, Planularia*** and ***Dentalina.*** Robertinids such as ***Epistomina*** and ***Conorboides*** are also present in minor numbers. An interesting feature in the A3 assemblage is that, where a calcareous fauna is present, a relatively diverse radiolarian fauna also occurs.

There are four calcareous dominated assemblages at Staffin Bay, one of which is dominated by robertinids whilst the other three are classified as mixed assemblages.

Assemblage R1 is characterised by an overwhelming numerical dominance of the robertinid ***Epistomina.*** Lagenids, miliolids and agglutinated foraminiferids are subordinate, but are present in relatively equal numbers. Amongst the lagenids, ***Lenticulina*** species are commonest, with ***Eoguttulina, Dentalina, Nodosaria*** and ***Citharina*** also present. Miliolids ***Ophthalmidium*** and ***Nubeculinella*** occur in several 'flood' horizons. ***Haplophragmoides, Reophax*** and ***Trochammina*** dominate the agglutinated faunas. This assemblage has a low/moderate diversity (α index ranging between 3 and 11) with a generally very high abundance (ranging from 100 to >700 foraminifera/gram).

The final three assemblages are all defined as mixed, where no one group dominates to the total exclusion of another. There are minor differences in the relative abundances of the subsidiary groups and associated diversities and abundances which may have some palaeoenvironmental significance. These features are discussed in relation to the palaeoenvironmental interpretations.

Assemblage M1 is mixed and is characterised by a moderate/high diversity (α index ranging between 6 and 13) and a moderate abundance (ranging from 175 to 350 foraminifera per gram). Miliolids do tend to predominate, with ***Nubeculinella*** and ***Ophthalmidium*** occurring in major floods. Lagenids are well represented in diversity and numbers by ***Lenticulina, Dentalina, Eoguttulina*** and ***Nodosaria.*** Agglutinated taxa are also important, with a wide range of genera including ***Haplophragmoides, Gaudryina, Trochammina*** and ***Ammobaculites.*** Robertinids occur in cycles and are represented by ***Epistomina*** and to a lesser extent ***Conorboides.*** An interesting association with this assemblage is a moderately diverse radiolarian fauna, dominated by spumellarians.

Assemblage M2 differs from M1 in the proportions of the major foraminiferal groups, with miliolids and agglutinated groups occurring in similar numbers, whilst lagenids and robertinids are subsidiary. The level of diversity is similar to M1, being moderate/high (with an α index of 6-11) but this assemblage has a higher abundance (325-600 foraminifera/gram). Miliolid taxa are represented by ***Nubeculinella*** and several species of ***Ophthalmidium***; agglutinated taxa by ***Reophax, Gaudryina, Haplophragmoides, Ammobaculites*** and ***Trochammina***. Lagenid diversity is moderately high, with specimens of ***Lenticulina, Nodosaria, Dentalina, Eoguttulina*** and ***Planularia***. Robertinids are represented by ***Epistomina*** and ***Conorboides***.

Assemblage M3 is characterised by low diversity (α index of 3-5) and a moderate/high abundance (100-375 foraminifera/gram). Lagenids, particularly the robust taxa ***Lenticulina muensteri, L. varians, Eoguttulina liassica*** and ***Citharina*** spp., occur in predominance with the robertinid ***Epistomina parastelligera***. Miliolids are represented by ***Ophthalmidium***, with ***Nubeculinella*** being rare. Agglutinated foraminiferids are a minor constituent of this assemblage and are almost solely represented by ***Haplophragmoides***.

Preliminary conclusions concerning palaeoenvironmental changes that occurred at Staffin Bay may be deduced from a combined analysis of the microfaunal assemblages as defined above, associated with facies and macrofaunal information. These conclusions are presented below and graphically in Figures 4.25 and 4.26.

An initial or pioneer foraminiferal assemblage, characterised as A1, is mainly associated with a facies type dominated by bituminous and silty shales of the Dunans Shale Member. This member was deposited as a consequence of the well documented Callovian transgressive event (Vail *et al.*, 1984; Haq *et al.*, 1988) that followed deposition of the shallow water Belemnite Sands Member. Foraminiferal recovery from the Lower Callovian Belemnite Sands Member is poor to non-existent and this is seen as a precursor to microfaunal colonisation of the Hebrides Basin shelf. It is characterised by a low abundance/diversity agglutinated fauna represented by ***Haplophragmoides*** and ***Reophax*** (Figs. 4.13, 4.14). Fully marine conditions were unlikely to have been totally established in this initial pulse of transgression, associated with the deposition of the Belemnite Sands Member. Stenohaline macrofaunal elements are restricted to discrete belemnite horizons. It is hypothesised that large numbers of belemnites could owe their presence to 'mass mortalities' caused by fresh water influences. Wignall & Hallam (1991) suggest that an abundance of belemnites in dysaerobic or anaerobic substrate biofacies may indicate a nektobenthic habit. Therefore, their distribution was probably controlled by the bottom water conditions, leading to a mortal susceptibility to influxes of brackish water conditions. Additional stenohaline indicators such as ammonites are also rare, whilst

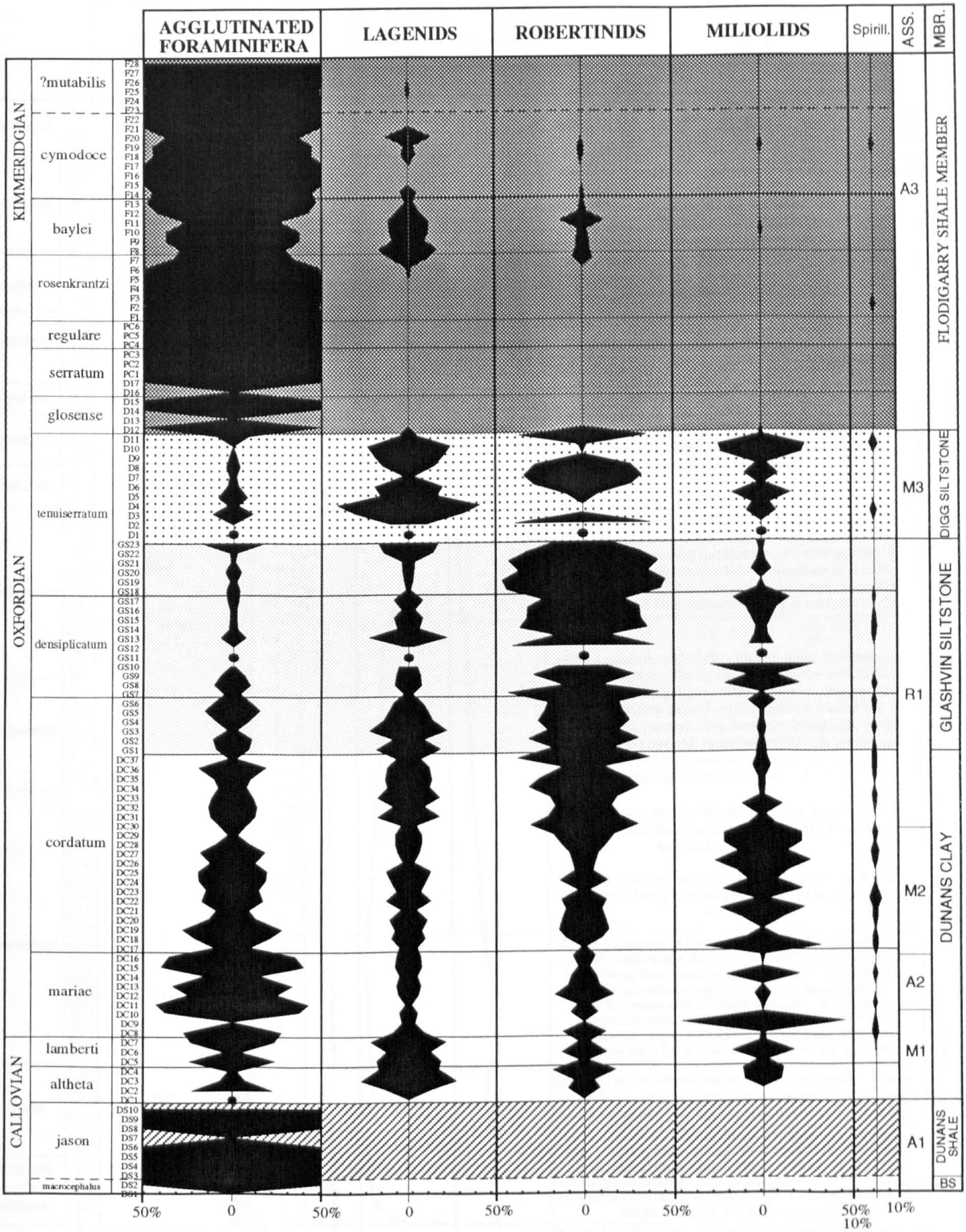
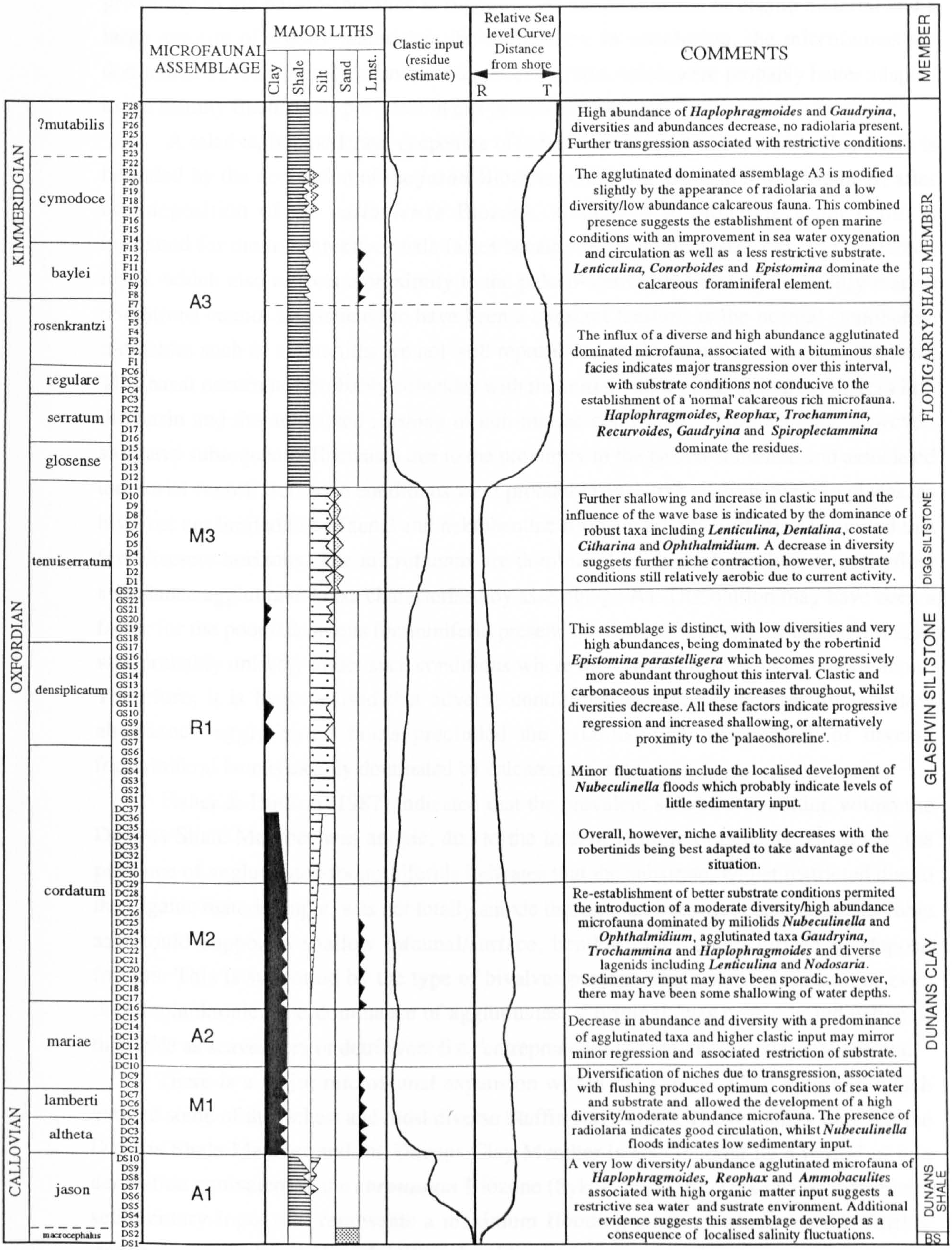


FIGURE 4.25. Percentage distribution of the major foraminiferal groups at Staffin Bay plotted against the bio and lithostratigraphy schemes (BS=Belemnite Sands Member; •= too few specimens to calculate a viable %)



High abundance of ***Haplophragmoides*** and ***Gaudryina***, diversities and abundances decrease, no radiolaria present. Further transgression associated with restrictive conditions.

The agglutinated dominated assemblage A3 is modified slightly by the appearance of radiolaria and a low diversity/low abundance calcareous fauna. This combined presence suggests the establishment of open marine conditions with an improvement in sea water oxygenation and circulation as well as a less restrictive substrate. ***Lenticulina, Conorboides*** and ***Epistomina*** dominate the calcareous foraminiferal element.

The influx of a diverse and high abundance agglutinated dominated microfauna, associated with a bituminous shale facies indicates major transgression over this interval, with substrate conditions not conducive to the establishment of a 'normal' calcareous rich microfauna. ***Haplophragmoides, Reophax, Trochammina, Recurvoides, Gaudryina*** and ***Spiroplectammina*** dominate the residues.

Further shallowing and increase in clastic input and the influence of the wave base is indicated by the dominance of robust taxa including ***Lenticulina, Dentalina***, costate ***Citharina*** and ***Ophthalmidium***. A decrease in diversity suggsets further niche contraction, however, substrate conditions still relatively aerobic due to current activity.

This assemblage is distinct, with low diversities and very high abundances, being dominated by the robertinid ***Epistomina parastelligera*** which becomes progressively more abundant throughout this interval. Clastic and carbonaceous input steadily increases throughout, whilst diversities decrease. All these factors indicate progressive regression and increased shallowing, or alternatively proximity to the 'palaeoshoreline'.

Minor fluctuations include the localised development of ***Nubeculinella*** floods which probably indicate levels of little sedimentary input.

Overall, however, niche availiblity decreases with the robertinids being best adapted to take advantage of the situation.

Re-establishment of better substrate conditions permited the introduction of a moderate diversity/high abundance microfauna dominated by miliolids ***Nubeculinella*** and ***Ophthalmidium***, agglutinated taxa ***Gaudryina, Trochammina*** and ***Haplophragmoides*** and diverse lagenids including ***Lenticulina*** and ***Nodosaria***. Sedimentary input may have been sporadic, however, there may have been some shallowing of water depths.

Decrease in abundance and diversity with a predominance of agglutinated taxa and higher clastic input may mirror minor regression and associated restriction of substrate.

Diversification of niches due to transgression, associated with flushing produced optimum conditions of sea water and substrate and allowed the development of a high diversity/moderate abundance microfauna. The presence of radiolaria indicates good circulation, whilst ***Nubeculinella*** floods indicates low sedimentary input.

A very low diversity/ abundance agglutinated microfauna of ***Haplophragmoides, Reophax*** and ***Ammobaculites*** associated with high organic matter input suggests a restrictive sea water and sustrate environment. Additional evidence suggests this assemblage developed as a consequence of localised salinity fluctuations.

Figure 4.26. Assemblage distribution, plotted against ammonite biostratigraphy, lithologies and interpreted relative sea-level changes at Staffin Bay (T=Trangrsession, R=Regression)

proximity to the palaeo-shoreline is suggested by the abundance of clastic material and a large amount of woody material in the sandstones. In conclusion, the microfaunas are dominated by low diversity/abundance agglutinated taxa which were probably better adapted to the salinity fluctuations prevalent in this palaeoenvironment.

A relative, but moderate, deepening of habitats in this part of the Staffin Bay Basin is heralded by the deposition of the ***jason*** Biozone within the Dunans Shale Member, after non-deposition of the ***calloviense*** Biozone. A shallow to moderate water depth is intimated for the transgressive shale facies because of the high clastic and organic carbon input, which also reflects a proximity to the palaeo-shoreline. Once again, totally marine conditions cannot be assumed to have been a constant feature, as the normal stenohaline indicators such as ammonites are not well represented in this member, except at the base. This basal occurrence probably coincides with the initial major pulse of marine ingress into the basin and the associated flushing of non-marine conditions. Salinities may, however, still have subsequently fluctuated due to the proximity to the palaeo-shoreline and associated terrestrial runoff. Substrate conditions were probably restrictive or dysaerobic in places, as bivalves are limited to epifaunal and nektobenthic forms, whilst bioturbation is limited to a few discrete horizons. The microfaunas are dominated exclusively by low diversity/low abundance agglutinated taxa characterised by assemblage A1. Dissolution may have been a factor for the poor calcareous foraminiferid presence, however, secretion of calcareous tests was probably unlikely under such conditions where there was a high organic carbon input. Therefore, it is hypothesised that adverse conditions reflected by a low diversity/low abundance agglutinated fauna precluded the establishment of 'normal' or diverse foraminiferal faunas usually dominated by calcareous forms.

Fisher & Hudson (1987) indicated that the prevalent substrate condition within the Dunans Shale Member was anoxic, due to the lack of benthic organisms. However, the presence of agglutinated foraminiferids indicates that the substrate, whilst restricted due to the organic material input, was not totally anoxic throughout, but was at best quasianaerobic and could support a shallow infaunal/surface, benthic fauna characterised by deposit feeders. This is supported by the type of bivalves present which were epifaunal, or even pseudoplanktonic. The dominance of agglutinates, if original, was probably indicative of their rôle as scavengers or detritivors (i.e. 'entrepreneurs') of the organic material present.

There is a major microfaunal expansion within the Dunans Clay Member, which yielded some of the richest and most diverse Staffin Bay faunas. The boundary between the Dunans Shale Member and the Dunans Clay Member is also marked by a period of non deposition equivalent to the ***coronatum*** Biozone (Sykes 1975a, b). This relates to minimal sedimentary input and represents a maximum flooding surface, which heralds further transgression in this basin. Additional evidence for transgression is suggested by the condensed nature of the Upper Callovian ***athleta*** and ***lamberti*** Biozones. Transgression led to the continuation in niche expansion and availability, caused by further moderate deepening which occurred in the lower part of the Dunans Clay Member (see Fig. 4.26 for relative indication of 'palaeodepth').

Although the Dunans Clay Member is viewed as a single lithostratigraphical unit, it can be divided into four relatively discrete foraminiferal assemblages, which reflect progressive basin development. No evidence for dissolution of calcareous taxa was noted. Overall, the Dunans Clay Member composition is of hemipelagic clays, with influxes of thin terrestrially derived carbonaceous, siltstone horizons.

The initial M1 assemblage, which covers the condensed ***athleta*** to basal ***mariae*** Biozones, is characterised by an influx of a diverse and abundant foraminiferal fauna. This corresponds to niche exploitation and diversification by diverse trophic groups and reflects optimum conditions, associated with transgressive niche expansion and subsequent filling. The establishment of diverse infaunal microfaunal morphotypes, stenohaline macrofaunal elements and bioturbation of sediments all indicate aerobic substrate conditions. Circulation and general water mass oxygenation must also have been at an optimum as radiolaria are present throughout much of this assemblage. Good circulation is suggested by the presence of phosphatic nodules which, as well as reflecting a low sedimentation rate, are assumed to be associated with high productivity due to upwelling (Brookfield, 1973; Gallois & Cox, 1977). Nutrient input is also enhanced by upwelling and is often associated with radiolarian development (Anderson, 1983). Several floods of miliolids, particularly the adherent taxon ***Nubeculinella tibia,*** also corroborate minimal sedimentation, which is an integral feature of transgressive events or pulses, as is the overall hemipelagic clay input and limestone development.

The remainder of the ***mariae*** Biozone is characterised by a distinct microfaunal change with a decrease in diversity, with radiolaria disappearing and dominance of a moderately diverse agglutinated fauna which typifies the A2 assemblage. Dissolution, either ***in situ***, or diagenetic, is not seen to be a major factor, as aragonitic epistominids have survived. Lithologically, the clays become more silty and there are fewer phosphatic or limestone horizons, suggesting that the sedimentation rate and therefore clastic input was relatively high, possibly related to a localised shallowing or regression. An increase in sedimentation is also reflected by a thicker development of the ***mariae*** Biozone. Salinities were probably in the normal marine range, as indicated by the presence of ammonites and other 'marine' macrofaunal indicators. Initially, agglutinated taxa dominate, but there must have been periods of cessation of sedimentary input, or non-deposition, as ***Nubeculinella tibia*** is well developed towards the top of the assemblage. Overall, substrate oxygenation was probably still relatively normal or aerobic, as suggested by the presence of a subordinate, calcareous microfauna. However, terrestrial sedimentary input, associated with minor regression, may have increased the organic material input. Agglutinated taxa, represented by active scavengers and deposit feeders such as ***Haplophragmoides, Reophax*** and ***Gaudryina*** were probably more successful in exploiting the change in circumstances and an influx of carbonaceous material. This is also probably reflected by the initial dominance of ***Haplophragmoides pygmaeus.***

The ***cordatum*** Biozone is marked by a distinct increase in microfaunal diversity and abundance characterised by the M2 mixed assemblage, which persists throughout the

bukowskii and lower part of the ***costicardia*** Sub-biozones. Miliolid and agglutinated taxa predominate, but robertinids (such as ***Epistomina parastelligera*** and ***E. mosquensis***) and lagenids (***Lenticulina*** and ***Eoguttulina***) are also present, which suggests that conditions were conducive for foraminiferal survival and may represent a period of stabilisation. Sedimentological evidence includes a higher incidence of limestones and nodules within relatively thick claystone beds; the incidence of siltstone input appears reduced. This integrated evidence suggests a relative deepening from the ***mariae*** Biozone, or at least an increasing distance from the influence of the palaeo-shoreline. However, the presence of the adherent ***Nubeculinella tibia*** in pervasive floods also suggests the reduced and sporadic nature of sedimentary input. However, the high incidence of miliolids overall may indicate relatively shallow water conditions, as does the slight increase of spirillinids observed throughout this assemblage. The macrofauna is diverse, with common bioturbation indicating good substrate oxygenation. This indicates a 'flushing' of any organic matter which may have built up during the development of the preceding assemblage. Agglutinated foraminifera are still common, but are represented by a different suite of taxa than the underlying A2 assemblage.

The upper part of the ***costicardia*** Sub-biozone, of the Dunans Clay Member, and the Glashvin Siltstone Member (***cordatum*** Sub-biozone and ***densiplicatum*** to basal ***tenuiserratum*** Biozones) are characterised by a distinct foraminiferal change to a robertinid dominated, R1 assemblage. This assemblage is associated with a marked increase in siltstone and carbonaceous debris (even within the upper part of the Dunans Clay Member), by a decrease in foraminiferal diversities and an increase in abundances caused by a domination of ***Epistomina parastelligera***. Normal salinities are indicated by the presence of a good ammonite and infaunal bivalve population. This assemblage appears to have developed as a response to a higher clastic sedimentary input, additionally marked by the thick ammonite zonal development, and relates to overall regression, or proximity to the palaeo-shoreline. The presence of crinoid ossicle lag horizons, which indicate a normal salinity, also suggests deposition within influence of the wave base. Proximity to the palaeo-shoreline is furthermore indicated by an increase in terrestrial input, depositing lignites and discrete carbonaceous, siltstone levels. The domination of ***Epistomina parastelligera*** may relate to its adaptation or preference for a higher sedimentation rate with an active feeding strategy suggested by its test shape. Whether this is an adaptation to the presence of more sediment, or to an increase in restrictive organic debris is, however, difficult to ascertain. There are minor microfaunal changes throughout this assemblage; agglutinated taxa decrease throughout the unit, whilst robertinids increase in absolute terms within the ***densiplicatum*** and basal ***tenuiserratum*** Biozones. This might indicate an increasing sedimentary and organic debris input, possibly associated with a higher energy environment, all of which are indicative of progressive regression. Overall, the R1 assemblage reflects a gradual degeneration of conditions established in the M2 assemblage, with a decrease in niche availability and foraminiferal diversity. However, periods of stabilisation and decrease in sedimentary input may be marked by localised events of miliolids preserved as flood horizons. This is especially relevant within the ***densiplicatum*** Biozone, which is also distinguished by localised development of hemipelagic clays present in the underlying Dunans Clay Member.

Evidence for continuation of regression and shallowing is seen in the Digg Siltstone Member (within the ***tenuiserratum*** Biozone), with an increase in clastic material, including deposition of extensive sandstone facies. There is also a microfaunal change from a robertinid dominated one to the M3 assemblage, characterised by an increase in the proportion of lagenids in relation to robertinids. Overall, diversities and particularly abundances decrease, the latter of which is probably a reflection of the decreasing proportion of epistominids present. Lagenids are for the most part robust forms including ***Lenticulina muensteri, L. varians, Dentalina*** spp. and thickly costate specimens of ***Citharina***. Miliolids are represented by species of ***Ophthalmidium***, with relatively few examples of ***Nubeculinella*** present. The presence of all of these taxa may reflect an increase in water turbulence, or energy, produced by continued shallowing and an increasing influence of the wave base. Shallow water environments must be associated with higher stress and those taxa which are most resistant will dominate. Salinities appear normal as ammonites and a well developed macrofauna are present. The sediments are bioturbated, which indicates relatively good substrate conditions, possibly as a consequence of flushing away of organic material due to increased current activity.

A striking microfaunal change corresponds to deposition of the Flodigarry Shale Member within the latter part of the ***tenuiserratum*** Biozone and continuing through to the Lower Kimmeridgian. The microfaunas are almost totally dominated by a diverse and abundant agglutinated fauna, characterised by the A3 assemblage. A major transgressive event is evident from the predominance of a bituminous shale facies from the Upper Oxfordian and this correlates to recorded instances in the Hebrides Basin by Morton (1993) and from the North Sea by Partington ***et al.*** (1993a, b) and Rattay & Hayward (1993). Dissolution of calcareous taxa may be a factor with this assemblage, but bivalve prisms within the residues did not show excessive etching features. Salinities are assumed to be within the normal marine range as ammonites are common in the majority of this member, with the exception of the uppermost part of the succession within the disputed ***mutabilis*** Biozone. The high agglutinated foraminiferid content appears to correspond to the substrate conditions, which due to prolonged transgression are shales and bituminous shales. These sediments are rich in organic carbon which may have produced a restrictive, but not anaerobic, facies which agglutinated taxa appear to have been able to exploit to a greater extent. There are, however, minor changes or modifications in the A3 assemblage which may relate to changes in the palaeoenvironment. The ***glosense*** Biozone through the majority of the ***rosenkrantzi*** Biozone is characterised by a domination of moderate diversity/high abundance agglutinated foraminifera characterised by ***Haplophragmoides kingakensis***. A slight improvement in substrate and general circulation, or overall water mass quality, is hypothesised to occur in proximity to the ***rosenkrantzi/baylei*** Biozonal boundary and continues throughout the ***baylei*** and sporadically through the ***cymodoce***

Biozones. This improvement is suggested by the presence of a relatively diverse radiolarian fauna, a low diversity, low abundance, calcareous foraminiferal fauna associated with a dominance of agglutinated foraminifera. Dissolution is probably not a major factor as aragonitic taxa such as ***Conorboides*** and ***Epistomina*** are present. Supporting lithological evidence for improved water conditions is provided by the presence of a small number of limestone marker bands in this area. These improved water and bottom conditions were not pervasive, as the remainder of the Flodigarry Shale Member is distinguished by a return to an agglutinated dominated microfauna. There is an increasingly high incidence of large ***Gaudryina*** which, in addition to the disappearance of holoplanktonic radiolaria and ammonites, suggests further transgression, or deepening, associated with the imposition of a more restrictive, quasianaerobic substrate and a decrease in overall sea water oxygenation.

4.3.9. Conclusions

A novel biostratigraphical scheme has been erected for the Staffin Bay succession, comprising 9 biozones and 12 associated sub-biozones which reflect major microfaunal events. These appear to correlate with transgressive events in the Middle and Upper Callovian, regression in the Lower and Middle Oxfordian and major transgression from the latest Middle Oxfordian through to the Early Kimmeridgian. This biozonation is subsequently compared with several successions developed in the Inner Moray Firth (Chapter 7). Where possible taxa which appear to be able to colonise a wide range of environments have been selected as biozonal indices. However, facies dependence does have a major effect on the overall benthic microfaunal composition. This correspondence allows the gross assemblage distribution, particularly of foraminifera, to be tied into palaeoenvironmental changes which occurred in the Staffin Bay area.

Initial results of this research indicate that microfaunal, and particularly foraminiferal, assemblages can be utilised in evaluation of basin margin development where there has been subsidence/uplift or eustatic sea-level changes. The resultant transgressive/regressive cycles produce niche expansion/niche contraction respectively, which depending upon the associated environmental parameters appear to be characterised by a microfaunal assemblage. In the case of the Hebrides Basin, the information provided by the Staffin Bay succession indicates that several palaeoenvironments related to relative sea-level changes were represented through the Middle and Upper Jurassic (Fig. 4.26). Initially there was a major marine transgression in the Lower and Middle Callovian, which permitted the establishment of a restricted and agglutinated dominated foraminiferal assemblage. This assemblage was probably best adapted to the presence of high levels of organic matter, possible poor circulation patterns and fluctuations in salinities. Increased oxygenation of the substrate due to the further transgression and the associated improvement of circulation, a decrease in organic carbon deposition (Fisher & Hudson, 1987) and stabilised salinities, allowed foraminifera and initially radiolaria to flourish within the Upper Callovian and Lower Oxfordian. Slight differences in sedimentation rate and organic input appear to have produced subtle variations in foraminiferal distribution. The remainder of the Lower and the majority of the Middle Oxfordian were characterised overall by regressive facies, reflected by the dominance of robertinid foraminiferids. The uppermost Middle Oxfordian through to Kimmeridgian heralded the initiation of a further major transgression, caused by a possible combination of subsidence and relative sea-level rise. This established correspondingly deeper water but restrictive substrate palaeoenvironments, reflected in the occurrence of moderately diverse and abundant agglutinated foraminifera. Within the Lower Kimmeridgian, substrate and overall water conditions appeared to improve, related to better circulation, allowing re-establishment of lagenids, robertinids and more importantly radiolaria. Subsequently, further transgression and an associated decrease in substrate and sea water oxygenation led to the re-establishment of agglutinated dominated taxa with no calcareous forms or radiolaria present.

This study has shown that it is possible to define palaeoenvironmental changes that occurred at Staffin Bay, on the Hebridean Basin margin, by the ranking of foraminiferal and associated radiolarian genera into several distinct assemblages. These assemblages are based on either dominance of one specific group such as agglutinated foraminifera, as in assemblages A1-A3 or robertinids R1, or are mixed assemblages as in M1-M3, characterised by their most abundant components.

These assemblages are not time specific, but can be seen to be related directly to facies characteristics, changes in which also reflect transgressive/regressive cycles. These relative sea-level changes respectively open up or contract niche availability and are reflected by changes of abundance and diversity of microfauna. Other factors which may be correlated to water depth or distance from the palaeo-shoreline also have an effect on the composition of the microfaunas. These parameters generally relate to substrate conditions and include amount and rate of clastic/hemipelagic sediment input, amount of freely obtainable oxygen and amount of organic carbon debris present in the substrate and sea-water.

Future possible use of this type of study is to help to define palaeoenvironmental changes that occur across shelf margins, as it is a rapid technique for assessing the nature and extent of relative sea-level fluctuations.

CHAPTER 5
INNER MORAY FIRTH BASIN

5.1. Introduction

The Inner Moray Firth Basin off the north eastern coast of Scotland is bounded to the east by several small onshore Jurassic outcrops, including the Callovian and Oxfordian foreshore exposures at Brora and Balintore and the Kimmeridgian at Eathie Haven and Helmsdale. The sections are dealt with individually here and then comparatively in Chapter 7, with the biostratigraphical details discussed in Section 7.2. All the sections provide important comparative material for similar subcrop deposits revealed in the Inner Moray Firth and North Sea Basins by commercial activity (Andrews ***et al.***, 1990; Stephen ***et al.***, 1993; Thompson & Underhill, 1993)

5.2. Brora, Sutherlandshire

5.2.1. Introduction

Bathonian to Middle Oxfordian sediments are exposed along the foreshore at Brora (GR. 90560321) as a low lying, sand-covered, wave-cut platform and along incised river bank cliffs of the River Brora (GR. 89860391). The succession was logged in detail and 53 samples were collected for micropalaeontological reconnaissance (Fig. 5.1).

The succession represents two distinct depositional regimes, the first being a thick sequence of mainly non-marine and marginal marine/brackish water deposits of the Great Estuarine Series. This is overlain by a fully marine (as yet unnamed) series, which is divided into three formations commencing with the Brora Argillaceous Formation, followed by the Brora Arenaceous Formation and finally the Balintore Formation.

These two series are divided by a major progressive, marine transgression which occurred within the Callovian and can be traced across the Inner Hebrides and Inner Moray Firth Basins.

5.2.2. Geology

Brora provides some of the thickest Callovian deposits (Fig. 1.2) available for study in northern Scotland and additionally allows comparison with the condensed sequences at Staffin Bay and Balintore. Only the Lower and lowermost Middle Oxfordian are present however, with an absence of younger surface exposure until the Kimmeridgian deposits of the Helmsdale portion of the outlier, several miles further north.

Historically, the deposits at Brora have generated much interest regarding their age and due to the presence of a high sulphur content coal deposit. This coal was first mined in 1598 and was recorded in detail by Farey (1813) who surveyed the area.

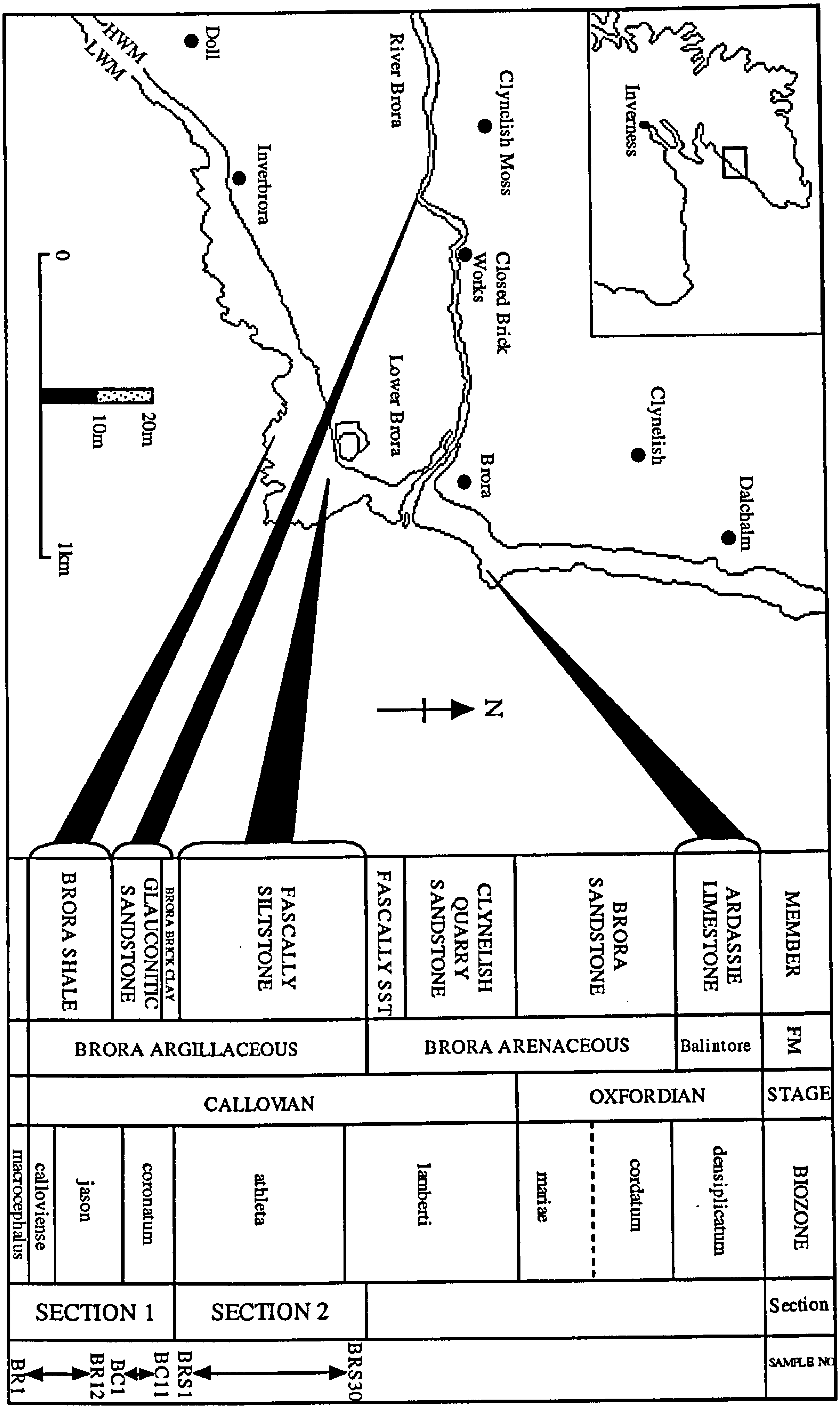


Figure 5.1. Locality map of Brora with collection sites, lithostratigraphy, ammonite biostratigraphy, sampling details and log sections

Farey's work has been evaluated by Waterston (1982), who indicated that Farey perceived the Brora Coal to be Carboniferous and not Mesozoic in age. The correct Jurassic age of this coal was first deduced by MacCulloch (1826).

Murchison (1829a) also visited the area and studied the coal beds and the Callovian/Oxfordian deposits (Murchison, 1829b, 1843), remarking on the similarities, in part, with equivalent English Oolitic rocks.

Hurst (1982, 1985), from a study of the clay mineralogy, indicated that the domination of illite/smectite and kaolinite micas was indicative of a subtropical/seasonal climate. High kaolinite concentration may indicate intense weathering of carbonate regoliths. Sediments at Brora were hypothesised to represent a near shore detrital input.

5.2.3. Ammonite Biostratigraphy

As with the similarly aged deposits of Staffin Bay, the Callovian and lowermost part of the Oxfordian are comparable with the well studied ammonite biozonation which was originally defined by Arkell (1941, 1945, 1947) and Callomon (1955, 1964) for southern England. Sykes (1975a, b) established an overall working biozonation of these deposits and, as discussed previously (Chapter 3), the Middle and Upper Oxfordian ammonite provinciality required a comparable biozonation based on the genera ***Cardioceras*** and ***Amoeboceras*** (Fig. 3.1) as opposed to the Sub-Boreal scheme utilising genera of the Perisphinctidae family.

At Brora, definite marine sediments were first established within the Lower Callovian. A more or less complete and continuous ammonite succession was established by Sykes (1975a, b), Sykes & Surlyk (1975) and Sykes & Callomon (1979). However, the Brora Brick Pit, which formed an integral part of their type sections, had reached the end of its commercial life during Sykes' (*op cit*) study and is now filled in, thereby obscuring the upper part of the ***coronatum*** Biozone and the lowermost part of the ***athleta*** Biozone. Also, the ***mariae*** and ***cordatum*** Biozones are definitely not proven, but are inferred, from stratigraphical position, to be contained within the Brora Sandstone Member.

The ***athleta*** Biozone was informally divided into 3 sub-biozones by Sykes (*op. cit.*), based on the ammonites recovered. These sub-biozones were originally designated as 'Lower', 'Middle' and 'Upper', but have now been formalised into the standard ***athleta*** Sub-biozones, namely ***phaeinum, proniae*** and ***spinosum***, by Cope ***et al.*** (1980).

5.2.4. Lithostratigraphy

Sykes (1975a, b) and Hurst (1981) formalised the lithostratigraphy of the marine and non-marine deposits respectively.

Arkell (1933) attempted to construct a lithostratigraphy for the region, which Sykes (*op. cit.*) later adapted. It now appears that Arkell (1933) did not survey the area in any great detail and relied on the works of Buckman (1923), Lee (1925) and Lee &

Pringle (1932). These earlier workers divided the Callovian and Oxfordian into the Brora Roof Bed, Brora Argillaceous Series, Brora Arenaceous Series and the Ardassie Limestone.

Sykes formalised these series into four formations, namely the basal and predominately non-marine Brora Coal Formation and three marine influenced formations comprising the Brora Argillaceous Formation, Brora Arenaceous Formation and the Balintore Formation. All of these formations have been further divided into several members. The units were logged in detail and are comprehensively discussed here in ascending stratigraphical order:-

A). Brora Coal Formation.

Hurst (1981) divided this formation into two members: the Doll Member and the overlying Inverbrora Member. Both members appear to represent lagoonal deposits with very minor marine incursions.

The Doll Member comprises grey mudstones and quartz rich sandstones with a series of channel sand deposits. ***Unio*** bivalves were found, along with significant plant debris and driftwood.

The Inverbrora Member consists of black carbonaceous shales with a top erosive surface. Thin coal seams with a high sulphur content are developed throughout. Limited marine incursions are indicated by bivalve beds dominated by ***Neomiodon*** and ***Isognomon***. MacLennan & Trewin (1989) recorded dinocysts which also characterised a limited marine water influence.

Palaeoenvironmentally, the Doll Member was mud deposited as over-bank deposits, whilst the Inverbrora Member represented fluvial abandonment with periods of stagnation evident. The lack of major rootlet beds within the final coals is indicative of pervasive shallow marine incursion.

Harris & Rest (1966) concluded that the Brora Coal was younger than similar deposits in North Yorkshire which were dated as Bajocian. Simpson (1937) indicated that angiosperm debris was present within the coal beds, although this evidence was later refuted by Hughes & Couper (1958) and Couper (1958) who recorded the material as spore dominated. This coal is now very rarely seen along the Brora foreshore due to intensive localised mining. Stopes (1907) and Sykes (1975a, b) reported that the Brora Coal Formation consisted of a drift wood rich, lignitic, highly sulphurous coal, which contained a localised silty rootlet bed, was bioturbated at the top and was overlain by a thin, woody shale/claystone.

B). Brora Argillaceous Formation.

This formation is divided into 4 members:

(i). Brora Shale Member (***calloviense*** - intra***jason*** Biozones, c.16.5m; Fig. 5.2).

The foreshore platform at Brora provided the best locality to collect this member, which includes the Brora Roof Bed and Brora Shales as originally nominated by Arkell (1933).

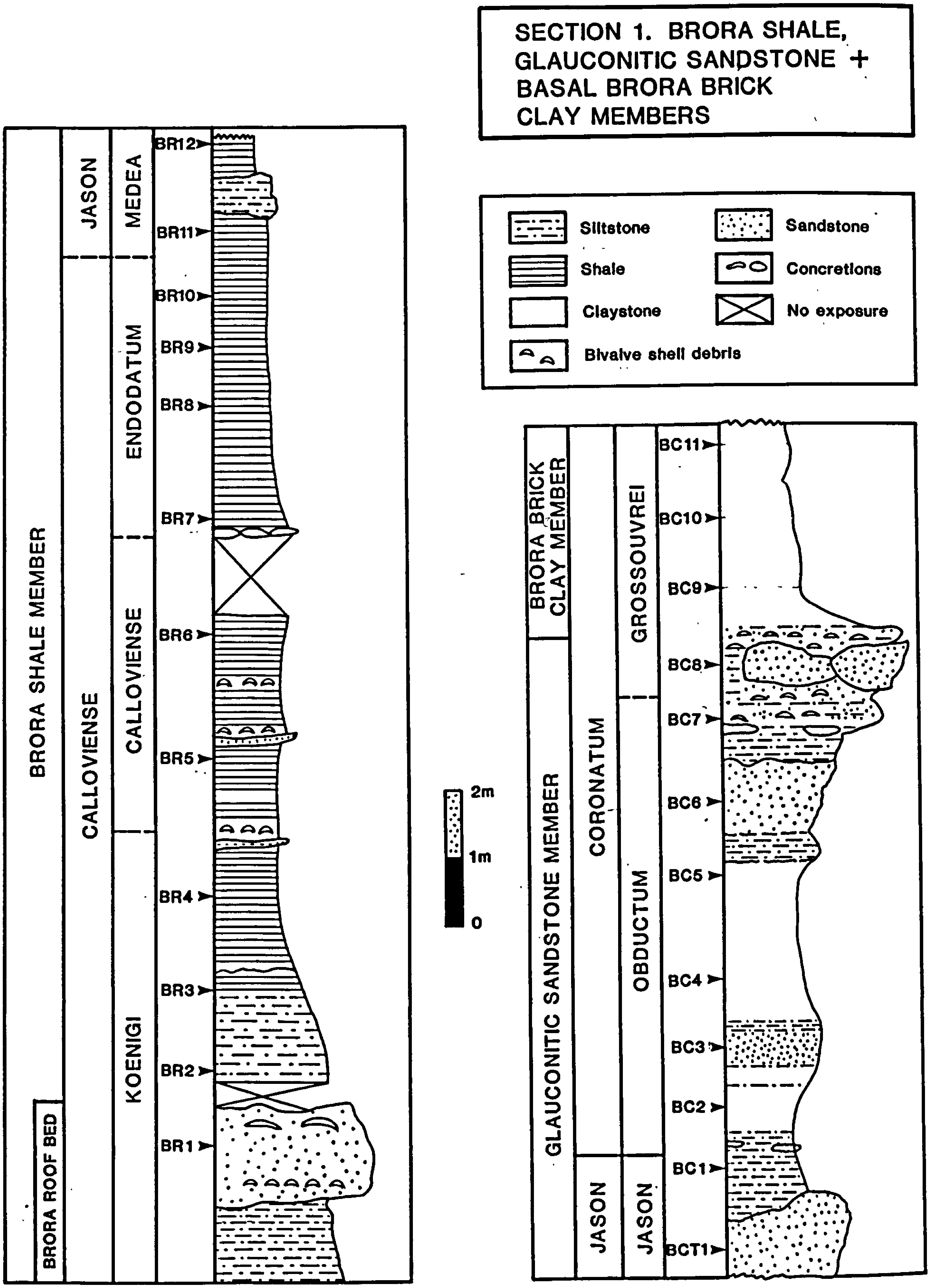


Figure 5.2. Detailed lithological log and ammonite biozonation of the Brora Shale, Glauconite Sandstone and basal Brora Brick Clay Members with sampling points

Sykes (1975a) indicated that the top part of the member was not exposed during his collection period. The upper part of the ***jason*** Biozone from the top of the Brora Shale Member could not be logged and collected for micropalaeontological study due to the lack of exposure. Sykes estimated the total thickness to be in the region of 30 metres. This original estimate was, however, based on several composite sections derived from borehole material made available to Sykes (*op. cit.*). It is conceivable that almost the entire section is present along the foreshore, as large scale faulting was not observed cutting the shales, before exposure of the overlying Glauconitic Sandstone Member. This difference in thickness could then represent a localised thinning.

The Brora Roof Bed, which occurs as the basal part of the Brora Shale Member, should possibly be formerly designated as a unit, is approximately 2 metres thick and overlies the Brora Coal Formation, with a sharp erosive surface. The Brora Roof Bed forms a relatively prominent, shallow dipping feature and comprises a fine grained sandstone, which in the lower part is carbonaceous and generally non-fossiliferous. The final 50cm or so is bioturbated with an abundant belemnite fauna.

The upper surface of the Brora Roof Bed appears to be erosive and is overlain by the shale component of the member. Initially, the lower part of the Brora Shale Member is a silty shale, which is only bioturbated in places and has thin glauconitic sandstones, which are packed with belemnite guards. The remainder of the unit is dominated by a bituminous shale with several thin beds of glauconitic rich, dark grey silts. The final metre or so becomes slightly more silty.

In terms of macrofauna, the lower parts are dominated by bivalves such as ***Bositra, Gryphaea*** and ***Protocardia***, with abundant belemnite debris. The bituminous shales higher up yield ***Thracia*** and ***Meleagrinella***. Ammonites are rare from the Brora Shale Member.

(ii). Glauconitic Sandstone Member (intra *jason*-intra ***coronatum*** Biozones, c.10m; Fig. 5.2).

This member was formally included in the Brora Shales by previous authors such as Arkell (1933). It was formally erected by Sykes (1975a, b), with a type locality developed in the cliffs along the banks of the River Brora (GR. 89860391). The member is also exposed along the foreshore (GR. 90560321), but this area was not examined as the exposure was poor and the section did not provide complete coverage. The actual section can be divided into three informal units. The basal 4 metres comprises fine grained, muddy, glauconitic sandstones interbedded with large phosphatic nodules that are rich in ***Rhaxella*** sponge spicules. Examination of the residue also provided evidence of ***Rhaxella*** and belemnite fragments. The middle unit is characteristically a bituminous, silty shale with ***Meleagrinella*** and ***Lingula*** bivalves. The upper unit of approximately 4 metres is a sandy, glauconitic facies with a horizon (1 metre) of calcareous concretions. The upper part of this unit is marked by a gradual change to sandy siltstones.

(iii). Brora Brick Clay Member (intra ***coronatum***-basal ***athleta*** Biozones, c.3m; Fig. 5.2).

The majority of the type section of this member, as defined by Sykes (*op. cit.*) at the Brora Brick Pit (GR. 89850412), is no longer exposed, having been filled in and turned into park land after 1975. Its total thickness was also defined from cored material as the brick pit did not appear to be representative of a complete section anyway. In terms of recorded macrofauna, ammonites were common, as were bivalves which were represented by ***Idonearca***, ***Palaeonucula*** and ***Entolium***.

(iv). Fascally Siltstone Member (basal *athleta-lamberti* Biozones, c.30m; Fig. 5.3).

The Fascally Siltstone Member comprises the majority of the low lying, sandy, wave-cut platform along the southern side of the River Brora seaward outlet (GR. 90566321). It encompasses almost the entire ***athleta*** Biozone and the basal part of the ***lamberti*** Biozone and represents the thickest development of the former biozone in the UK onshore sector.

At its base there is a transitional contact with the underlying Brora Brick Clay Member (Sykes, 1975a, b) and it consists of a series of upwardly coarsening cycles of siltstone to fine grained sandstones. Also, near the top of the unit, several prominent concretion levels are evident. The top of the member generally becomes more coarse grained in content.

Ammonites are relatively common, but other macrofossils tend to be rarer than in the Brora Brick Clay Member. All the ammonite sub-biozonal indicators are present for the ***athleta*** Biozone, but only the basal part of the ***lamberti*** Biozone is evident. Bivalves such as ***Grammatodon*** occur within the lower parts and ***Chlamys*** near the top (Sykes, *op. cit.*; Fürsich & Sykes, 1977).

C). Brora Arenaceous Formation.

Buckman (1923) originally designated, or provided names for, several of the members present within this formation. Unfortunately, these were not formally defined and many names only served as a rough indication of the sites that provided ammonites for his studies. Samples were not collected for micropalaeontological study, but the members are introduced for completeness.

Sykes (*op. cit.*) formalised the members, of which there are three:

(i). Fascally Sandstone Member (*lamberti* Biozone, c.6.5m).

This member is best exposed along the river bank cliff (GR. 89860391), some 1.5 kilometres west of Brora Bridge. Lithologically, it is a bioturbated, fine grained, thickly bedded sandstone, with relatively abundant ammonites and poor benthic macrofauna.

(ii). Clynelish Quarry Sandstone Member (*lamberti* Sub-biozone, c.20m).

Sykes (*op. cit.*) indicated that the type section should be taken from the southern bank

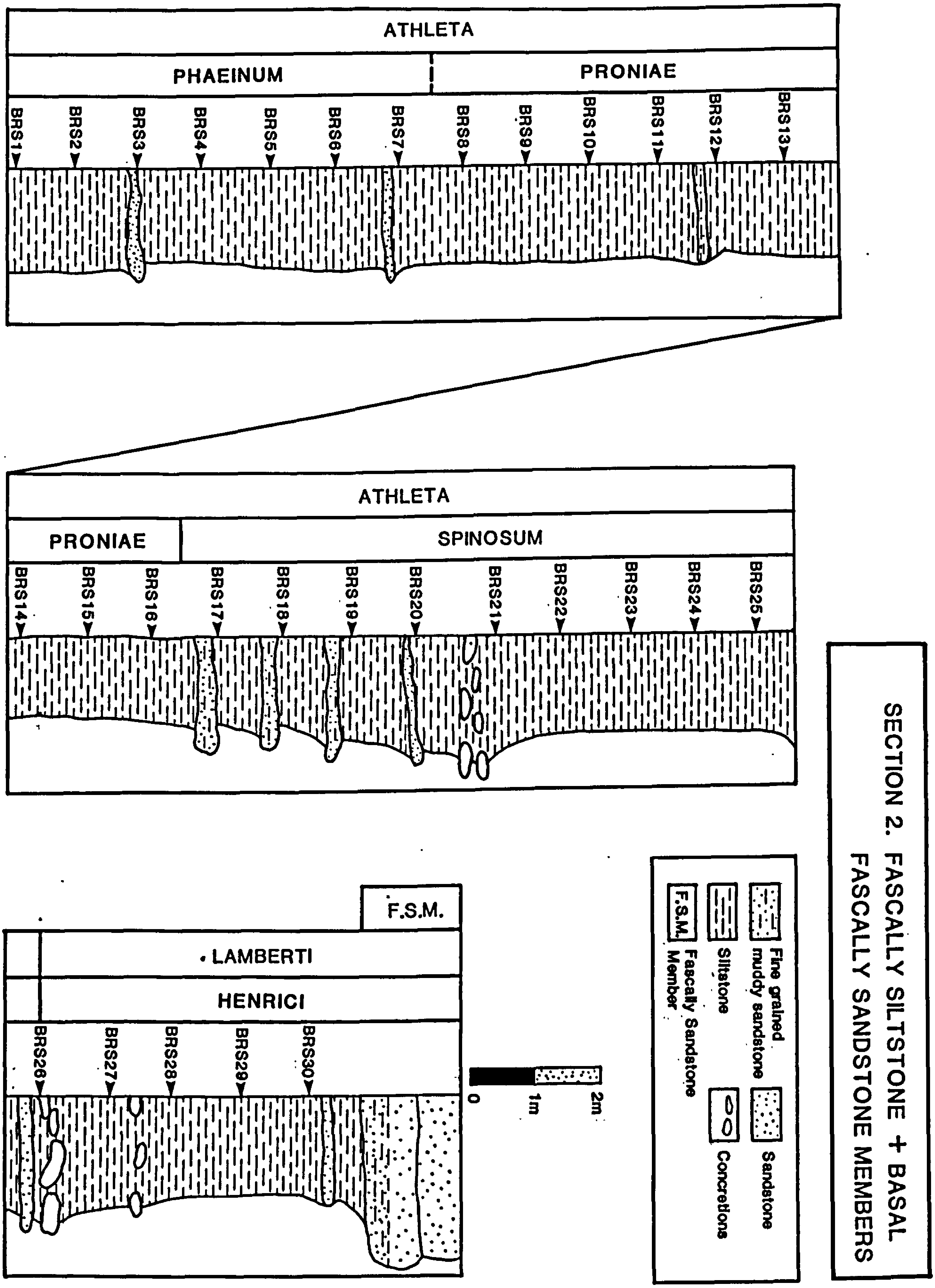


Figure 5.3. Detailed lithological log and ammonite biozonation of the Fascally Siltstone and basal Fascally Sandstone Members with sampling points

of the River Brora (GR. 89850394) and is split between two localities there. This unit is characterised by a poorly cemented, fine grained sandstone which contains bands of carbonaceous debris. Several horizons of nodular sandstones mark the upper parts.

(iii). Brora Sandstone Member (?***mariae***-?***cordatum*** Biozones, c.30m).

The main facies present is a yellow to dark yellow, fine grained sandstone which, higher in the section, has a quartz conglomerate present. Cross-bedding is also developed in the upper parts.

Ammonites have not been recovered from this member, however Sykes (1975b) indicated from stratigraphical delineation that this interval encompasses the Lower Oxfordian ***mariae*** and ***cordatum*** Biozones.

D). Balintore Formation (***densiplicatum*** Biozone, c.12m).

Only the Ardassie Member is preserved from this formation at Brora and it forms a low lying, isolated shoreline promontory to the north-east of the River Brora outlet (GR. 91310404).

It consists of a series of thin (30cm-1m) silty/muddy limestones, which are almost entirely formed of desilicified ***Rhaxella*** sponge spicules. These limestone beds are interbedded with very thin carbonaceous, fine grained, muddy sandstones.

Ammonites are common, as are bivalves, which include ***Idonearca***, ***Gryphaea*** and ***Pinna*** (Sykes, 1975a, b; Fürsich & Sykes, 1977).

5.2.5. Previous Research

Palynological and palaeobotanical studies have been particularly common at Brora due to the presence of the Brora Coal Formation. The coal beds have been the subject of many articles, covering various aspects of their palynology and macrofaunal distributions. Simpson (1937), Couper (1958) and Harris & Rest (1966) covered the fossil miospores present, whilst Seward & Bancroft (1913), Stopes (1907) and Seward (1911) recovered the macroflora of the coal bed and surrounding rocks. All dated the succession as Jurassic in age.

Recently, there has been an increase in studies on biostratigraphical palynology. Neves & Selley (1975) took several samples for a palynological reconnaissance of the entire outlier from Dunrobin in the south to Helmsdale in the north. This approach has been updated at various periods, initially by Lam & Porter (1977) and then by Porter (1988). The latter discussed his faunas in terms of microplankton provinces throughout north west Europe.

MacLennan & Trewin (1989) collected samples from the Callovian at Brora and compared them with similarly aged deposits from Balintore and with offshore sequences present in the Beatrice Field. Using palynofacies, they generated a series of palaeoenvironments and palaeogeographical reconstructions for the Bathonian to Callovian, mapping out very broadly the progression of the Callovian transgression over the Inner Moray Firth region.

Published micropalaeontological research is, however, somewhat limited with Gordon (1967) providing the first data from the now closed Brora Brick Pits. The exact ammonite biostratigraphy is not certain, but appeared to cover the ***coronatum*** and ***lamberti*** Biozones. The faunas were dominated by lagenids and agglutinated taxa.

Nagy ***et al.*** (1990a) covered the agglutinated foraminiferids from the Lower and Middle Callovian of Brora only from the argillaceous facies of the Brora Shale Member, excluding the Brora Roof Bed. They discussed the facies controlled nature of the agglutinated dominated microfauna. Their recovered faunas may not be truly representative as only the residue fraction in excess of 125µm fraction was examined (Nagy ***pers. comm.***, 1993).

5.2.6. Foraminiferal Distribution

The foraminiferal distribution patterns will be discussed in terms of the members developed in ascending stratigraphical order.

i). Brora Shale Member (Figs. 5.4-5.6, 5.11).

The Lower to basal Middle Callovian sediments of the Brora Shale Member are characterised by a low diversity/low abundance, agglutinated dominated foraminiferal assemblage comprising a total of 19 species, 13 of which are agglutinating taxa. The initial two to three metres of this member is marked by the first introduction of foraminifera, the most abundant of which is ***Haplophragmoides pygmaeus***. This taxon dominates all samples, commonly comprising 80-90% of the assemblages. Sample BR1, which occurs within the Brora Roof Bed, contains only rare specimens of ***Lagenammina difflugiformis***. Sample BR2, collected within the argillaceous facies of the Brora Shale Member, marks the first major occurrence of foraminifera at Brora, with the majority of the 19 species being introduced within the ***koenigi*** Sub-Biozone/basal ***calloviense*** Sub-Biozone. Overall, the lower part of the succession yields the most consistent and diverse assemblages.

Generally, the assemblages are represented by the agglutinates ***H. pygmaeus, Reophax helvetica, R. metensis, R. sterkii, Recurvoides sublustris*** and ***Trochammina canningensis***. ***Ammobaculites agglutinans*** and ***A. deceptoria*** appear in samples BR10 and BR12 respectively.

Lagenids are rare, with sporadic occurrences of relatively robust taxa such as ***Eoguttulina liassica, Lenticulina varians*** and ***Frondicularia franconica***. Additionally, there are very rare influxes of ***Spirillina tenuissima*** in the ***calloviense*** Biozone and ***S. infima*** in the ***jason*** Biozone; no robertinids or radiolaria were recovered. Overall the α index does not exceed 3 or 4, whilst abundances are skewed by the presence of ***H. pygmaeus***.

There is a gross cyclical distribution pattern of foraminifera from this member, with the initial seven samples marked by a moderately consistent recovery which

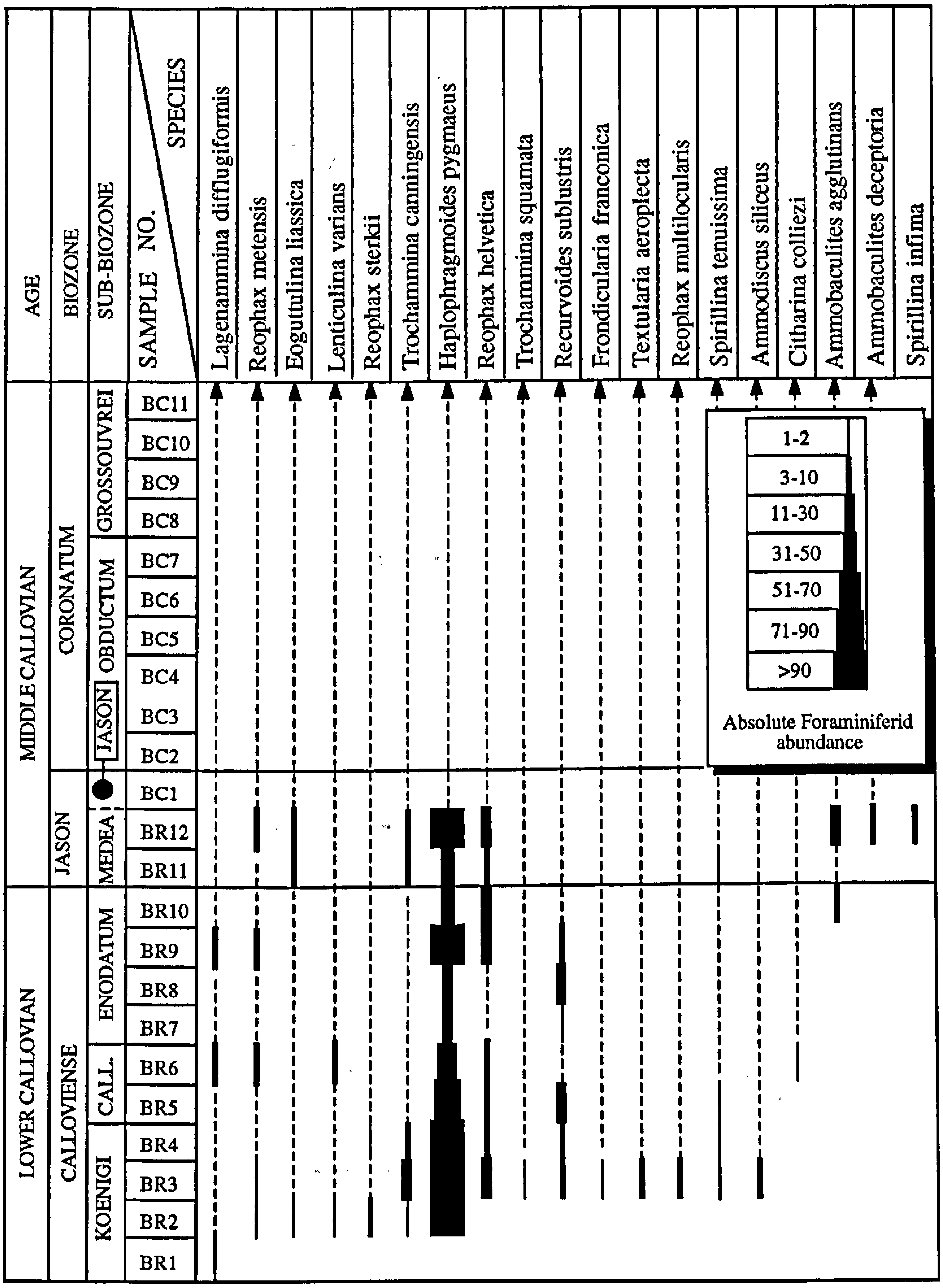


Figure 5.4. Foraminiferal distribution range chart for the Lower to Middle Callovian of Brora

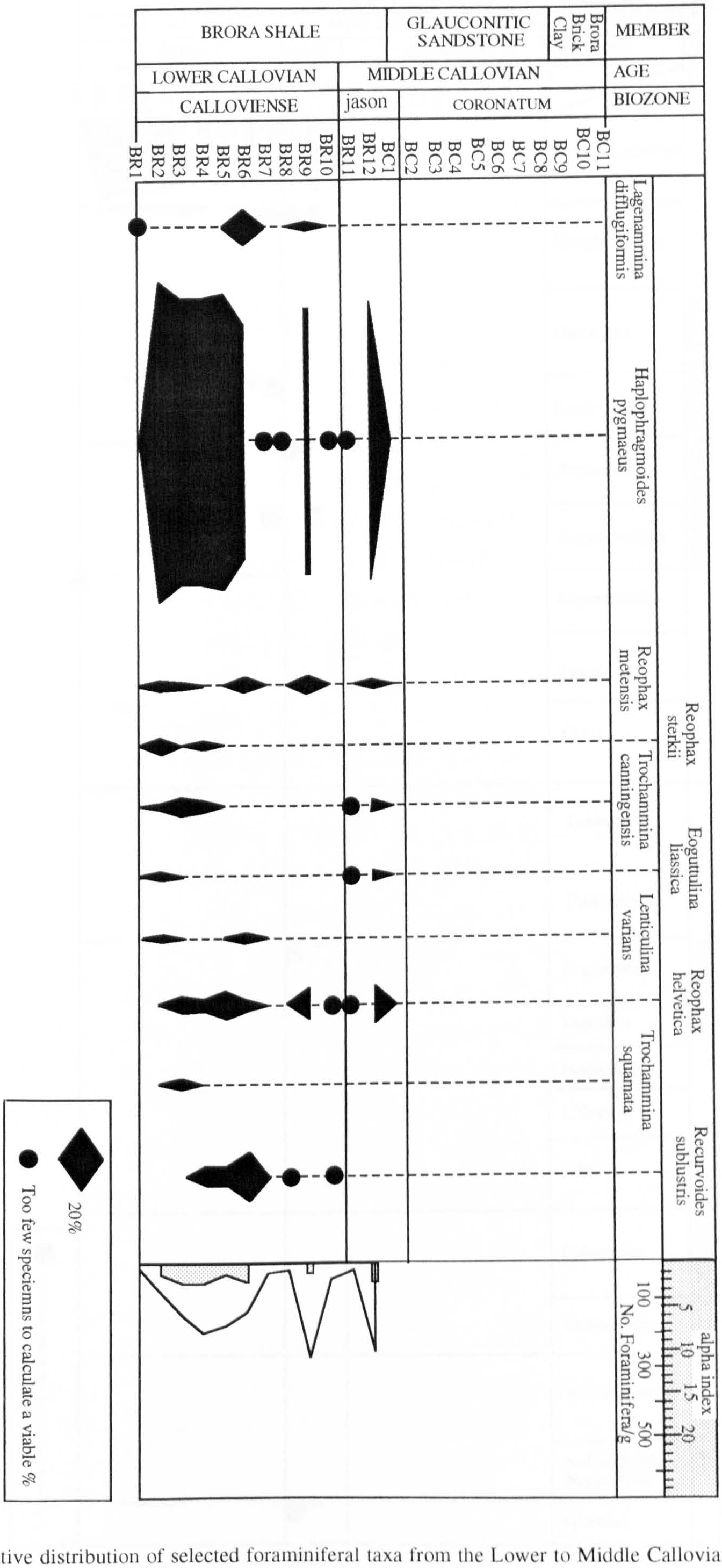


Figure 5.5. Relative distribution of selected foraminiferal taxa from the Lower to Middle Callovian of Brora

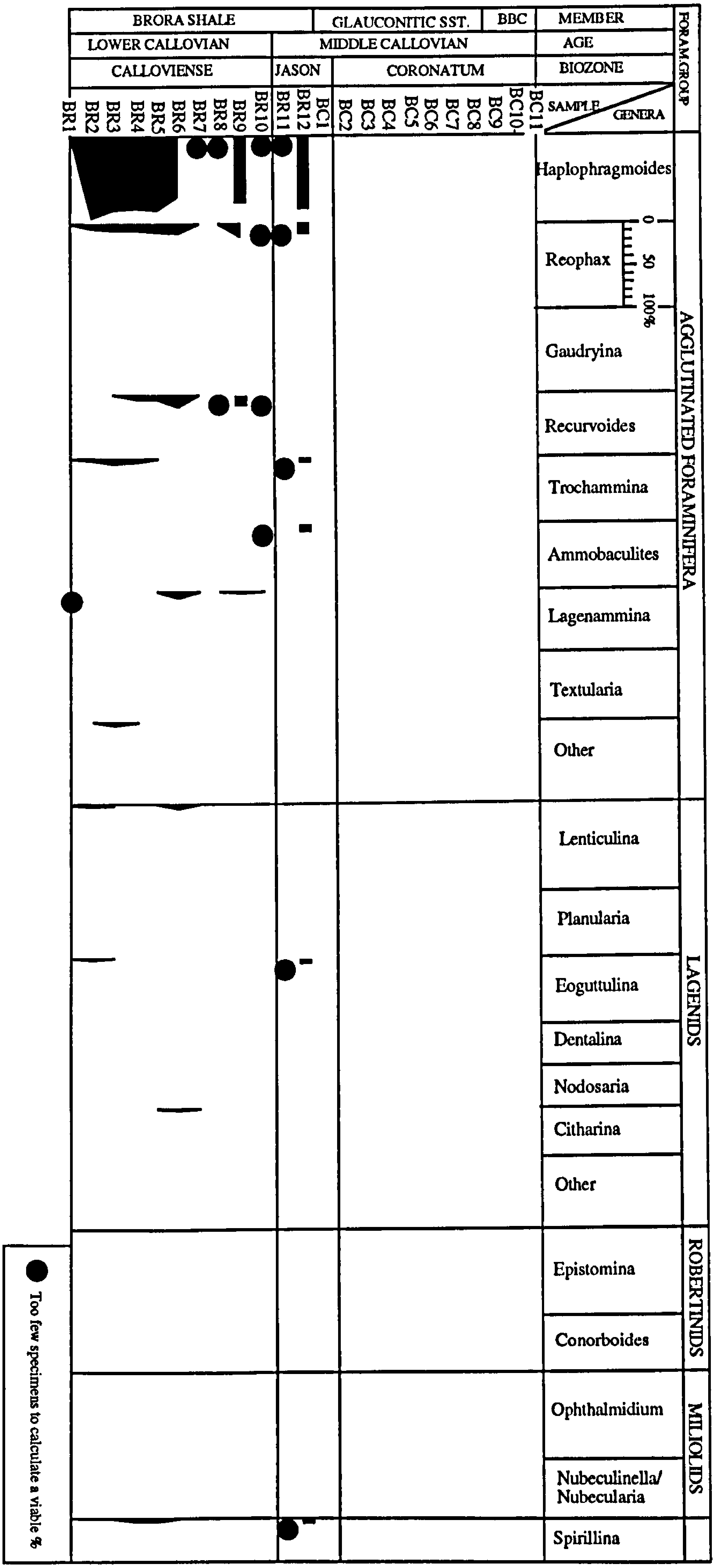


Figure 5.6. Percentage distribution of foraminiferal genera from the Lower to Middle Callovian of Brora

gradually increase. This is followed by a decrease with minor abundance 'spikes' developed in samples BR 9 and BR12. The upper ***calloviense*** Biozone is characterised by low recovery (Figs. 5.4-5.6).

ii). Glauconitic Sandstone Member (Fig. 5.11).

The Glauconitic Sandstone Member was barren of microfauna, this being unexpected due to the presence of a marine macrofauna. A possible cause for this apparent anomaly is indicated by the presence of a high degree of sulphur staining of the actual outcrop. Weathering, and the additional associated release of a weak sulphuric acid solution during processing, could have destroyed calcareous benthic and calcareous cemented agglutinated forms. Indeed, samples tested during processing showed acidic values and many of the belemnite guards and bivalve fragments were considerably affected by dissolution. This degree of dissolution was not recorded by Hewett (1980) from a belemnite study that he carried out on the small comparative section of the Glauconitic Sandstone Member preserved along the Brora foreshore. The foreshore section of this member was not collected for this micropalaeontological study, as a thicker and more complete sequence occurred along the river bank.

iii). Brora Brick Clay Member (Fig. 5.11).

The basal section, which comprises only a few metres of succession, yielded no recognisable microfaunal remains. This is surprising considering the recovery from Gordon's (1967) study of the Brora Brick Pit. One explanation may be that the present author's samples, which were collected from the River Brora, may have been affected by the weathering associated with proximity to a major cliff section of the Glauconitic Sandstone Member, leading to dissolution of the calcareous benthic and calcareous cemented agglutinated foraminiferids. Alternatively, as Gordon's sampling was limited to a few samples from the brick pit, and it appears that he did not collect from the basal parts of the Brora Brick Clay Member which are evidently only exposed along the river banks (Sykes, 1975b).

Gordon's (1967) material comprised a very diverse fauna, with lagenids dominating and agglutinated foraminiferids forming an important component. Robertinids and miliolids were rarely recovered.

iv). Fascally Siltstone Member (Figs. 5.7-5.11).

This member is notable for a substantial increase in actual foraminiferal recovery, although the lack of recovery from the Glauconitic Sandstone Member and the basal part of the Brora Brick Clay Member may be as a result of dissolution (see Section 5.2.8). The siltstone is notable for the moderate relative diversities and moderate to high abundances, with 129 taxa occurring in total throughout. Lagenids are by far the most diverse group (Fig. 5.11), but agglutinated taxa 'compete' in terms of total abundances; robertinids and miliolids are poorly represented.

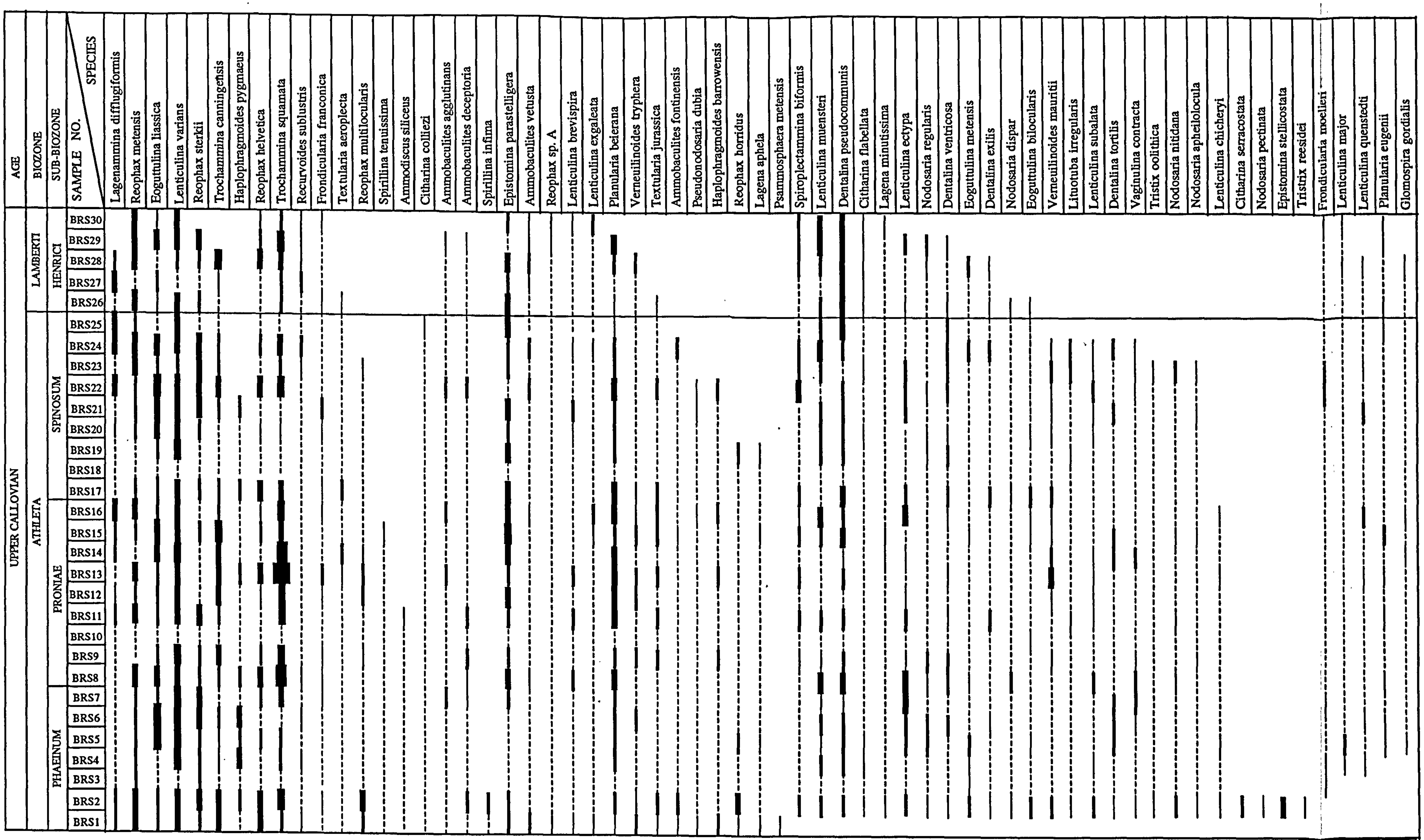
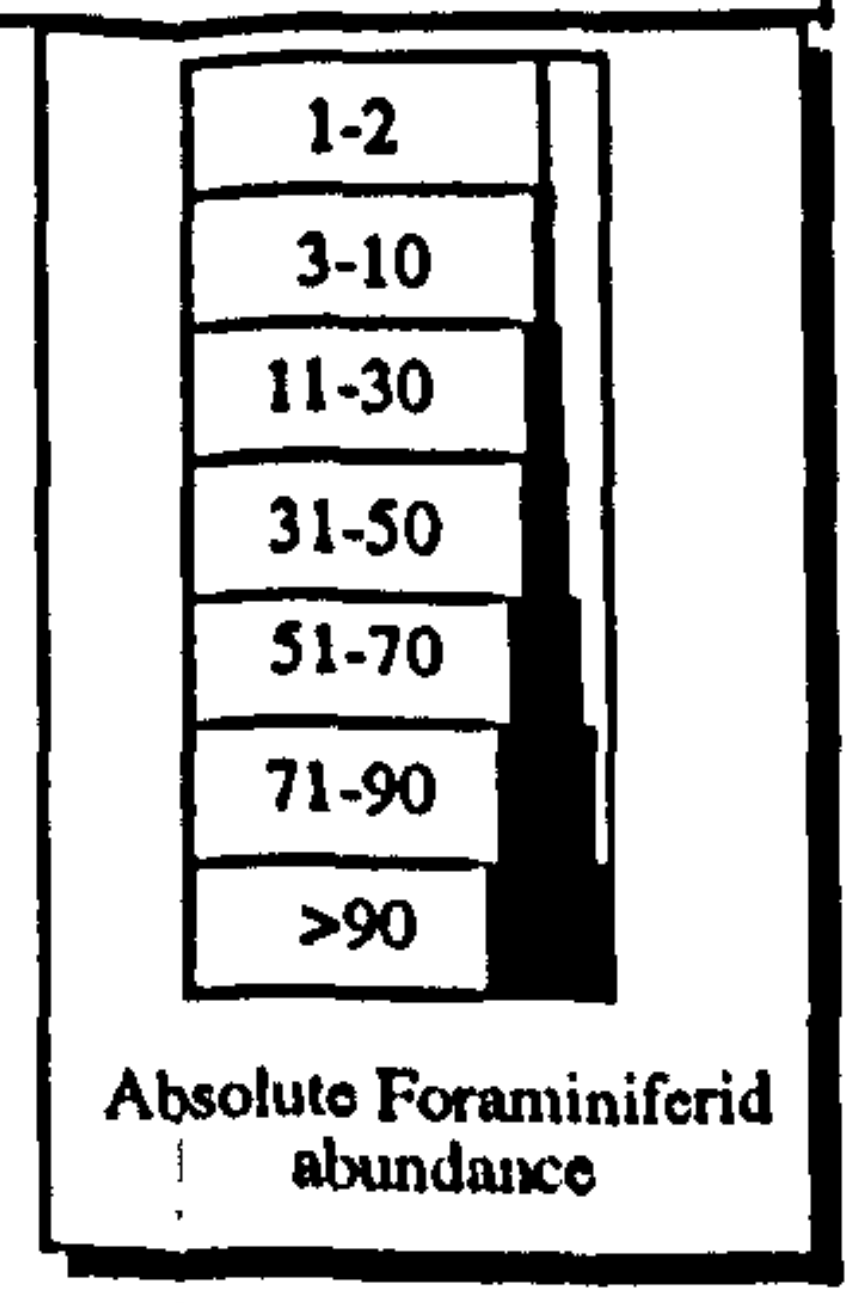


Figure 5.7. Foraminiferal distribution range chart for the Upper Callovian of Brora (Part A)



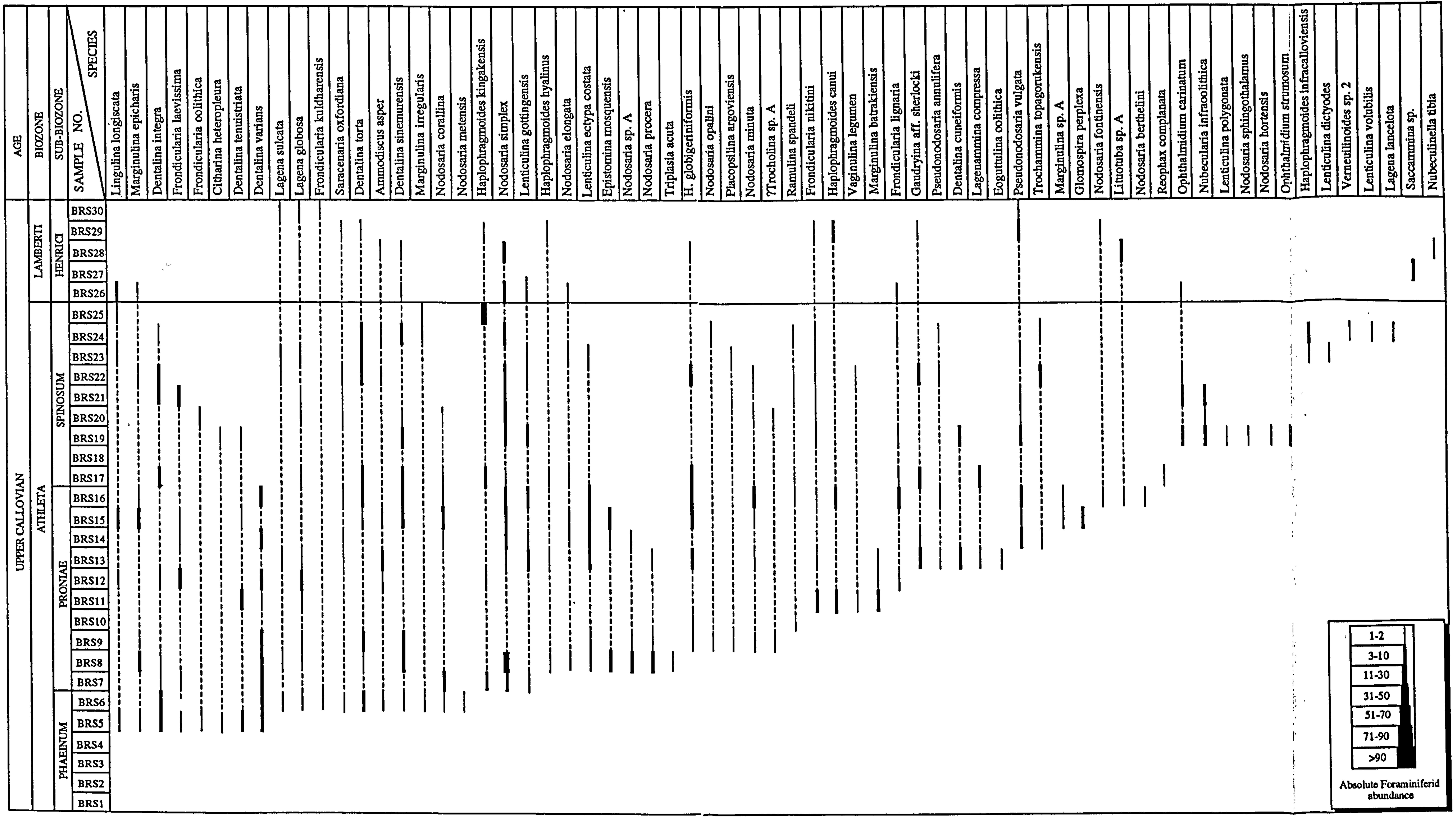


Figure 5.8. Foraminiferal distribution range chart for the Upper Callovian of Brora (Part B)

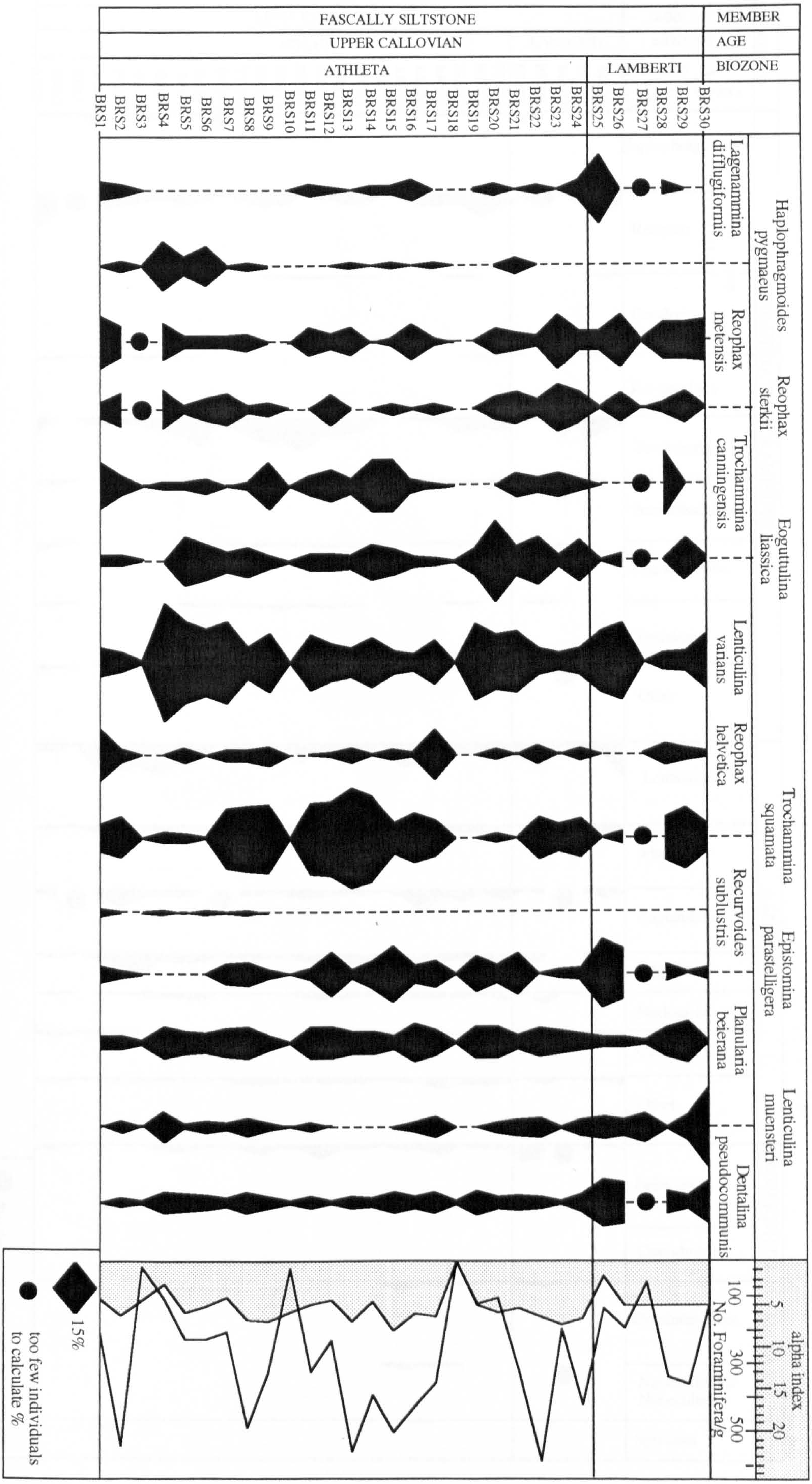


Figure 5.9. Relative distribution of selected foraminiferal taxa from the Upper Callovian of Brora

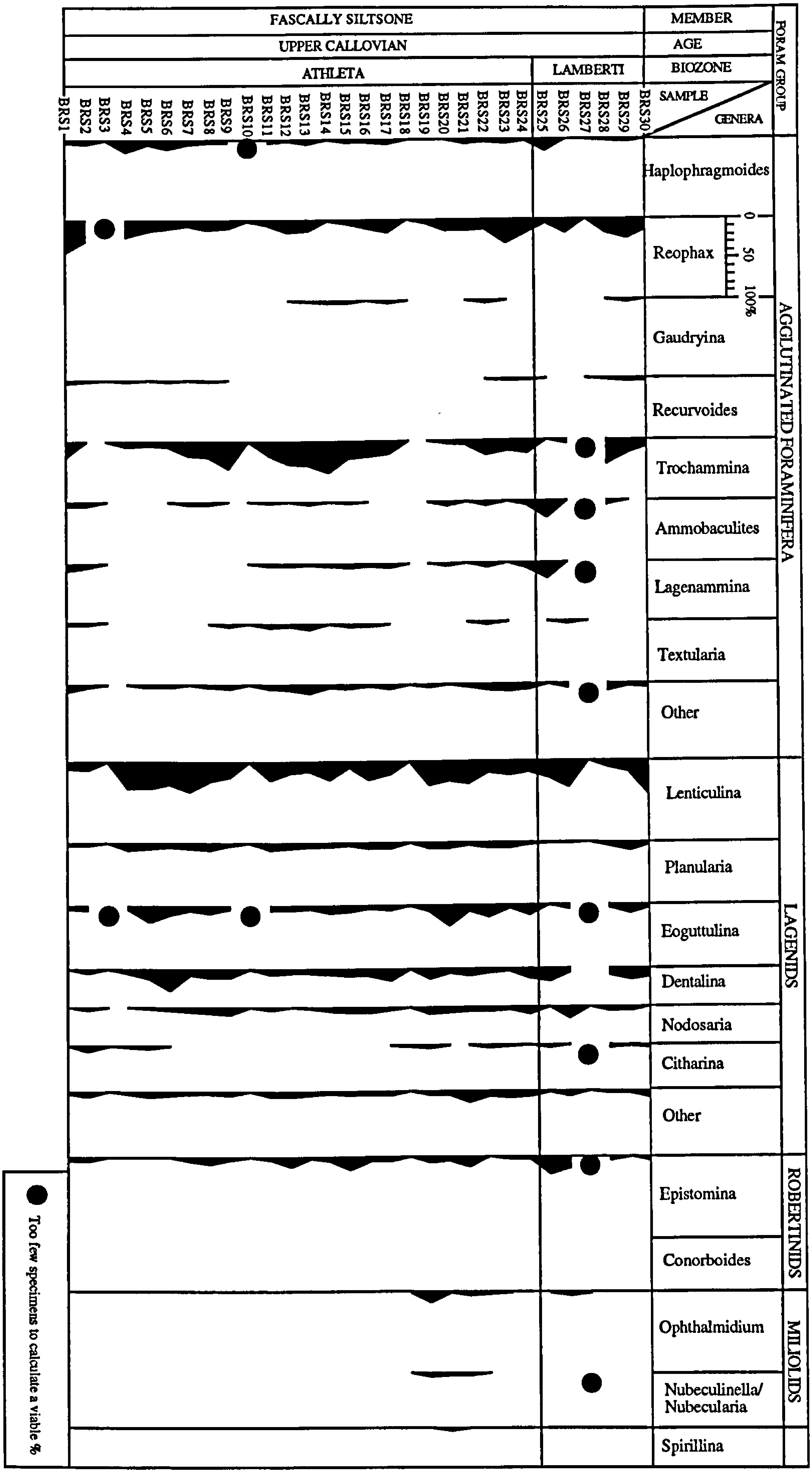


Figure 5.10. Percentage distribution of foraminiferal genera from the Upper Callovian of Brora

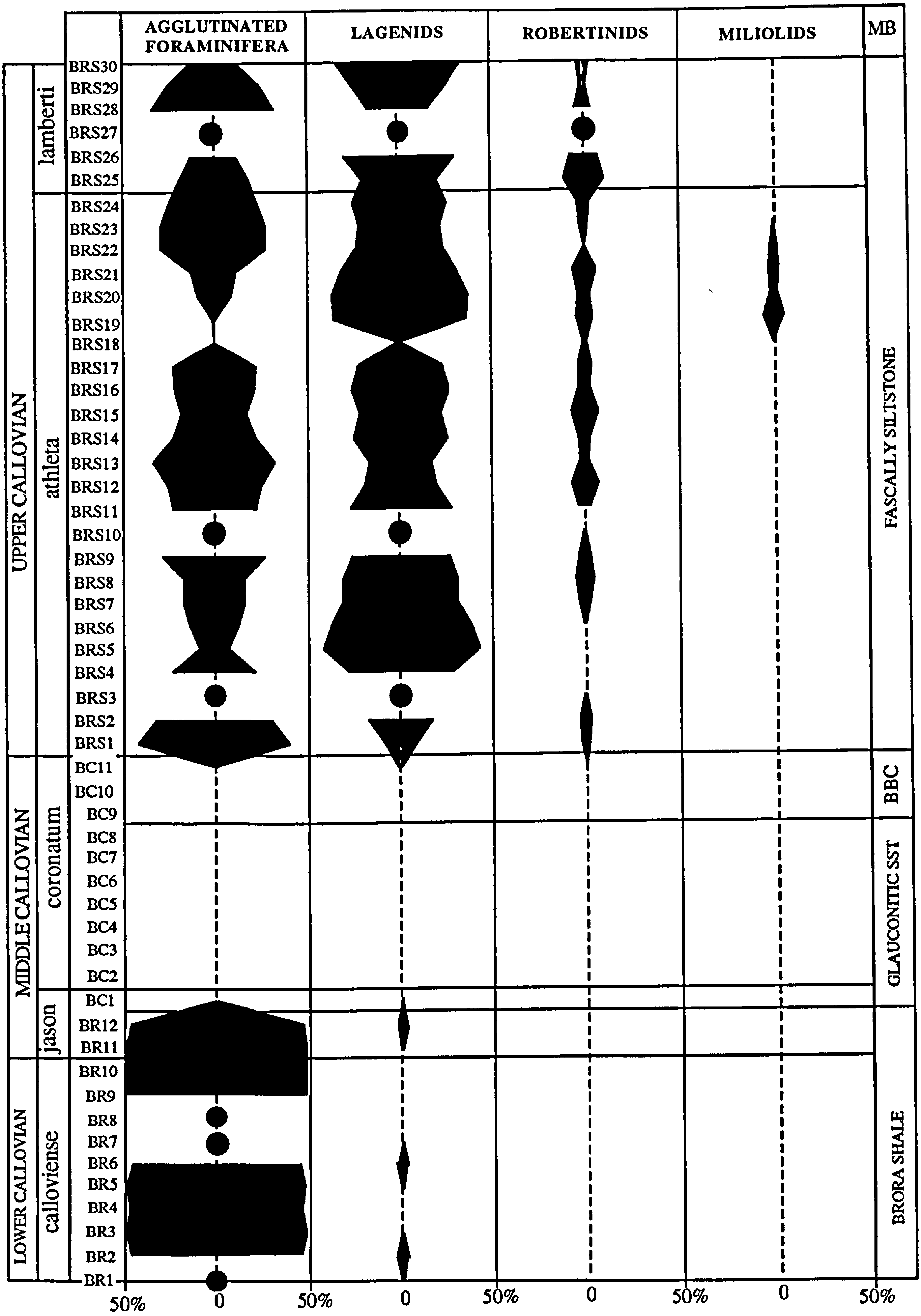


Figure 5.11. Percentage distribution of the major foraminiferal groups at Brora plotted against the bio and lithostratigraphy (circles=too few specimens to calculate a viable %)

There are apparently two diversity cycles (Fig. 5.9), as expressed by the α index, however, this relates to separation by a barren sample at BRS18. Diversity remains pretty constant without too much fluctuation in the low to moderate α index range between 3 and 7. The patterns reflecting absolute abundances do appear to be cyclical and it may be possible to delineate 4 major cycles. The basal cycle occurs between BRS1 and BRS2 in the ***phaeinum*** Sub-biozone and relates to a fairly even spread amongst many of the principal component taxa outlined in Figure 5.9. The second cycle between BRS3 and BRS9 (***phaeinum-proniae*** Sub-biozones) is in response to a dominance of ***Lenticulina varians*** with ***Eoguttulina liassica, Haplophragmoides pygmaeus*** and ***Trochammina squamata.*** The third cycle between BRS10 and BRS17, in the ***proniae*** Sub-biozone, corresponds to a dominance of ***Trochammina squamata, T. canningensis*** with relatively common ***Epistomina parastelligera*** and ***Planularia beierana.*** The fourth and final cycle between BRS19 and BRS30, comprising the ***proniae/spinosum*** Sub-biozones and the ***lamberti*** Biozone, relates to an increase in the importance of ***L. varians***, occurring with ***E. liassica, Reophax metensis*** and ***R. sterkii.*** Abundances tail off into the ***lamberti*** Biozone where there are localised peaks of ***Lagenammina difflugiformis, E. parastelligera*** and ***Dentalina pseudocommunis.***

Overall, large numbers of taxa are introduced between BRS1 and BRS2, with 16 and 25 species respectively. Thereafter, samples include up to 10 introductions. Only a few species are pervasive throughout the member, the most important of which were already established within the Brora Shale Member. ***Trochammina squamata*** is the most important element in absolute numbers whilst ***L. varians*** occurs in abundance in most samples. Other important taxa include ***E. liassica, T. canningensis, P. beierana*** and ***E. parastelligera.***

Numerically important taxa with first appearances within the Fascally Siltstone Member include ***Spiroplectammina biformis, L. muensteri*** and ***Dentalina pseudocommunis.*** Final appearances occur mainly within the ***spinosum*** Sub-biozone with 37 in total, of which ***H. pygmaeus*** is the most notable. Relatively few taxa have 'success' in the ***lamberti*** Biozone; of the 65 surviving the majority are agglutinated with the exceptions being ***L. muensteri*** and ***D. pseudocommunis.***

5.2.7. Radiolarian Distribution

Radiolaria are relatively common from the Upper Callovian and Lower Oxfordian at Brora, occurring only within the Fascally Siltstone Member. Generally, preservation is poor, with replacement commonly by pyrite and very rarely by glauconite. Post-mortem/post-depositional dissolution was obviously an important feature here. Glauconite was a commonly recovered mineral, both within the residues and from lithological examination of the sediments from the Fascally Siltstone Member.

Two cycles of radiolarian distribution in terms of species diversity and abundance

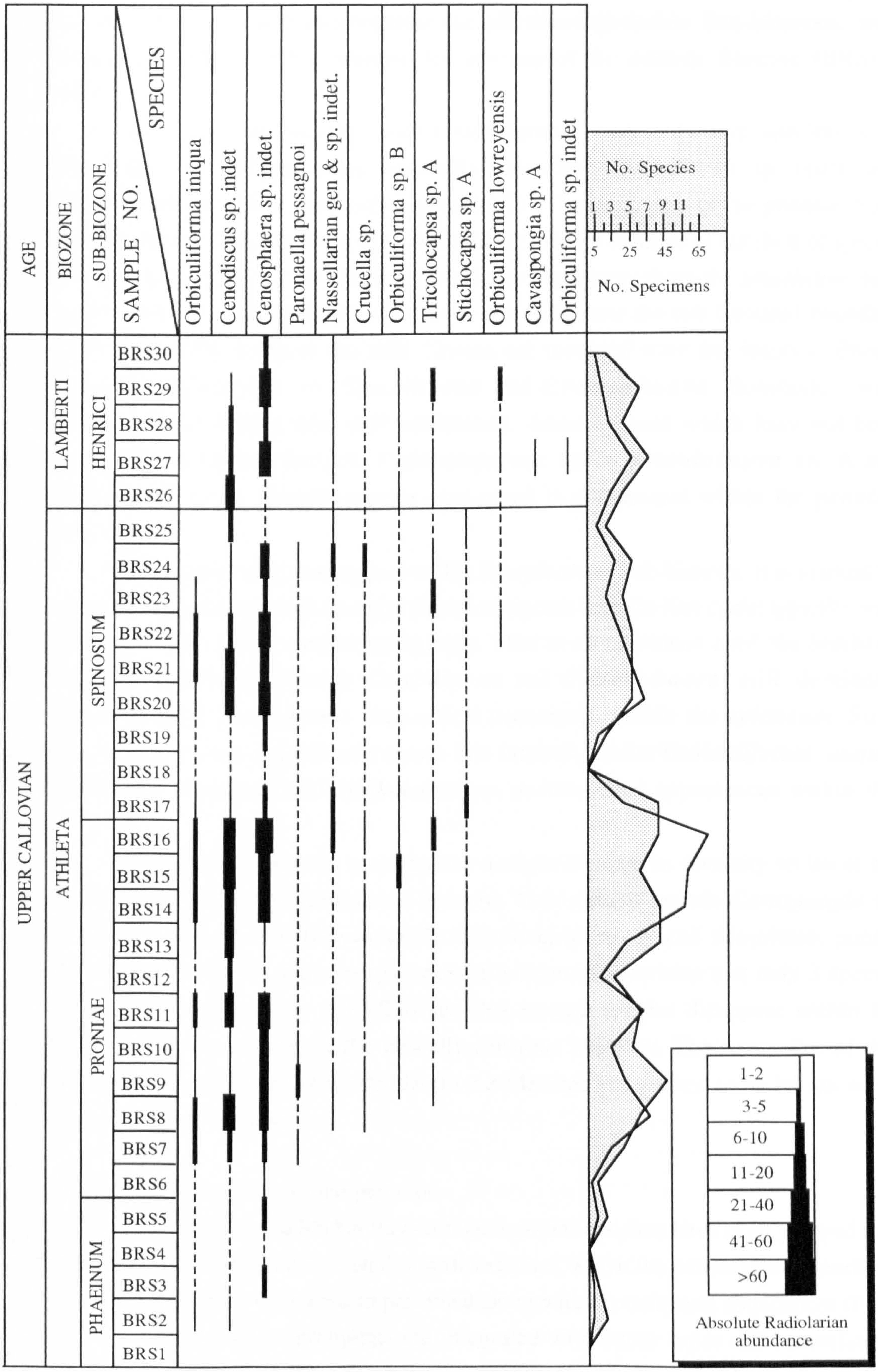


Figure 5.12. Radiolarian distribution, diversity and abundances of the Upper Callovian at Brora

can be observed (Fig. 5.12), separated by the basal ***spinosum*** Sub-biozone sample at BRS18. The first cycle encompasses the ***phaeinum/proniae*** Sub-biozones, with abundance peaking in the ***proniae*** Sub-biozone of the ***athleta*** Biozone (BRS14-BRS16).

Radiolaria are initially poorly represented, with only rare specimens of ***Orbiculiforma iniqua*** being positively identified; ***Cenodiscus*** sp. indet. and ***Cenosphaera*** sp. indet. also occur sporadically. The basal part of the ***proniae*** Sub-Biozone (BRS7) is marked by a rapid increase in diversity in terms of numbers of species and abundance (Fig. 5.12). This increase is sustained throughout the ***phaeinum*** Sub-biozone (BRS7-BRS16), with a maximum occurring near the sub-biozonal boundary (BRS14-BRS16); 9 out of the total 12 taxa are recorded over this interval. Poorly preserved specimens of ***Cenodiscus*** and ***Cenosphaera*** dominate, with ***Orbiculiforma iniqua*** now well established. Several forms which have not been previously recorded include ***Orbiculiforma*** sp. B, ***Tricolocapsa*** sp. A and ***Stichocapsa*** sp. A. ***Pseudocrucella pessagnoi*** is commonest within the ***proniae*** Sub-biozone.

The second cycle commences within the ***spinosum*** Sub-biozone. It is marked by a decrease in abundance and diversity pattern compared with the first cycle; typically with 3-5 species and 25 specimens per sample. This trend continues until the ***lamberti*** Biozone. Poorly preserved ***Cenodiscus*** and ***Cenosphaera*** still dominate. ***Orbiculiforma lowreyensis*** has a first occurrence within the ***spinosum*** Sub-biozone and occurs sporadically across this interval, whilst ***Orbiculiforma iniqua, Paronaella pessagnoi*** and ***Stichocapsa*** sp. A have final appearances within this level.

The ***lamberti*** Biozone is marked by a slight increase in diversity which is not matched by an associated abundance increase. Taxa present include ***Cavaspongia*** sp. A, ***Crucella*** sp., ***Orbiculiforma*** sp. B, ***Tricolocapsa*** sp. A and ubiquitous, poorly preserved, cenodiscids and cenosphaerids. It is interesting to note that only 3 species occur in the final sample at BRS30 and that several species disappear within the ***lamberti*** Biozone portion of the Fascally Siltstone Member. The remainder of this biozone occurs within the Fascally Sandstone Member and proved to be barren when spot tested for microfauna.

5.2.8. Palaeoenvironmental Interpretation

As previously noted at the Staffin Bay section, foraminiferal taxa have been grouped into genera and the major groups related to wall structure, whilst the percentage proportions of selected important taxa are also presented along with diversity and abundances (Figs. 5.4-5.11). These relative groupings are integrated with facies types and macrofaunal components to elucidate the gross palaeoenvironmental changes that have occurred at Brora from the Callovian through to the Lower Oxfordian.

Initial sediments at Brora, which comprise the Brora Coal Formation, are interpreted initially as representing a brackish water biofacies existing as a coastal alluvial plain or as lagoonal deposits which were incised by fluvial channels (MacLennan & Trewin, 1989; Hurst, 1981). The final stages of the Brora Coal Formation, which culminated in actual coal bed formation, represent plant rich and stagnant lagoonal conditions.

The onset of Callovian transgression and therefore marine incursion was first recorded with the deposition of the Brora Roof Bed of the Brora Shale Member within the Lower Callovian ***calloviense*** Biozone. This unit occurs as a marine transgressive sand body being deposited over lagoonal sediments (Stephen *et al.,* 1993). These sands were deposited in a very shallow environment which was greatly influenced by the wave base, as indicated by the random orientation of numerous belemnite guards. The presence of large quantities of woody debris also indicates a near shore locality. Foraminiferal recovery from the Brora Roof Bed is limited to rare specimens of the agglutinated foraminiferid ***Lagenammina difflugiformis***. This almost total absence of foraminiferal assemblages probably indicates that marine conditions were not fully established at this point and that ***Lagenammina*** was probably best adapted to salinity fluctuations and the high energy environment.

A continued relative sea-level rise and transgression provided accommodation space that allowed deposition of the remainder of the Brora Shale Member, which was initially dominated by a silty shale. The actual transition from the Brora Roof Bed sandstone dominated facies to argillaceous deposits may represent an erosive surface, or a maximum flooding surface where sediment deposition was initially low. The subsequent deposition of the remainder of the Brora Shale Member was represented by a fining upward sequence from silty shales to bituminous shales and indicates continued progress of the Callovian transgression from the ***calloviense*** through to the ***jason*** Biozones.

The initial portion of the Brora Shale Member is envisaged, at least initially, to have been relatively shallow, as indicated by the silty nature of the residues. Ammonites are rare from this sequence, being most common in the lower parts; belemnites are commoner in certain horizons. The macrofauna is characterised by shallow infaunal and epifaunal bivalves, the latter of which assume dominance in higher levels. The microfauna comprises low diversity/low abundance, agglutinated dominated foraminiferids and is notable for the dominance of ***Haplophragmoides pygmaeus*** and the rare occurrence of calcareous taxa. ***In situ*** dissolution could have been a factor in producing these agglutinated dominated microfaunas, as some bivalve debris did show evidence of dissolution. Nagy (1990a) indicated a high organic carbon content for the argillaceous facies of the Brora Shale Member and this is evident from the residues which were rich in organic woody debris. This would have produced an oxygen depleted substrate. Overall, water conditions are assumed not to be at an optimum, as indicated by the scarcity of ammonites. The dominance of ***H. pygmaeus***, associated with a proximity to the 'palaeoshoreline', may indicate that salinity conditions fluctuated and that this taxon was better adapted to such changes.

All the factors discussed above indicate that the Brora Shale Member was initially deposited as a transgressive facies in a moderately shallow shelf. Marine conditions were probably not initially consistent, until the deposition of bituminous shales. The substrate was obviously restricted in some way, as indicated by the presence of a shallow infaunal, agglutinated dominated foraminiferal fauna. These assemblages were initially consistently recovered, but then became more sporadic with the introduction of the more bituminous shales. This is attributed to the establishment of a more pervasive, oxygen depleted substrate.

The transition from the Brora Shale Member to the Glauconitic Sandstone Member during the remainder of the ***jason*** Biozone represents a coarsening upward cycle and a facies change from marine mud/shales to one dominated by sandstones, which equates to regression and progradation. The microfauna collected here was limited to abundant ***Rhaxella perforata*** sponge scleres, which may be reflective of shallow conditions. The absence of calcareous foraminifera may be related to dissolution, an effect which was evident in the etching of the belemnite guards. However, the lack of agglutinated foraminiferids cannot be convincingly explained by such dissolution factors. The presence of belemnites suggests that normal marine conditions probably existed, although there is some evidence of mass mortalities, which may be related to salinity fluctuations. Some agglutinated taxa appear to be more tolerant of salinity fluctuations, so another palaeoenvironmental limitation may have been that of deposition in a high energy environment.

The deposition of the Brora Brick Clay Member marks a further relative sea-level rise and subsequent transgression during the Middle and basal Upper Callovian, with the deposition of a clay facies. Unfortunately, exposure of the Brora Brick Clay Member is very limited since the filling of the brick pit that had provided the original type section. However, Gordon (1967) did collect several samples from this site, but unfortunately it is difficult to ascertain which intervals they came from, as the ammonite biostratigraphy had not been fully investigated by then. He recorded a diverse calcareous dominated foraminiferid fauna probably from the upper part of this member which, with the recorded presence of a rich infaunal bivalve macrofauna and ammonites (Sykes, 1975a, b), indicates probable optimum substrate and sea water conditions. This represents a possible fully marine flushing of the underlying, shallower water Glauconitic Sandstone Member with an associated improvement of the substrate conditions.

The transition of the Brora Brick Clay Member to the Fascally Siltstone Member represents a gradually coarsening upward sequence. This was as a consequence of the initiation of regression and shoaling, with the deposition of a more silty facies, and led ultimately to the deposition of the overlying, shallow water, Fascally Sandstone Member facies. A high sedimentation rate occurred during deposition of the siltstone, as indicated by the thick development of the corresponding ammonite biozones. The Fascally Siltstone Member is remarkable for the moderate diversity/moderate to high abundance foraminiferal and radiolarian microfauna. Although the assemblages have a moderate diversity in terms of the α index, actual numbers of taxa were very high, which relates to the diversity of lagenids. Agglutinated taxa were also particularly common. Substrate conditions were probably well oxygenated, supporting a wide range of infaunal foraminiferal groups and macrofaunal elements. Organic debris was not particularly evident within the residues. The lagenids were characterised by robust and costate taxa, particularly ***Lenticulina varians, Planularia beierana, Nodosaria*** spp., ***Eoguttulina liassica*** and ***Citharina*** spp. Thick test development may have improved the survival of these taxa, as this environment was probably relatively high energy. Both the lagenids and agglutinated taxa would have needed to be mobile in order to maintain their optimum infaunal/epifaunal positions relative to the substrate/water interface. Miliolids and robertinids were poorly represented, the absence of the former group possibly being directly related to a high sedimentation rate. Abundances and taxa decrease through the Fascally Siltstone Member, particularly within the upper ***athleta*** and basal ***lamberti*** Biozones. This is directly related to an increased sand input, a response to further regression which resulted in the deposition of the Fascally Sandstone Member.

The Fascally Siltstone Member is also characterised by a radiolarian fauna. Overall, spumellarians dominate the assemblages at Brora, with ***Cenosphaera*** and ***Cenodiscus*** providing the majority of specimens. In terms of species, ***Orbiculiforma*** predominate, whilst nassellarians are represented by rare and poorly preserved examples which are difficult to speciate. Nearly all samples within the ***athleta*** Biozone of the Fascally Siltstone Member yield radiolaria, so it appears that conditions allowed the development of such a fauna. It is hypothesised here that a dominance of spumellarians reflects moderately shallow water conditions, with sea water oxygenation and circulation patterns well established at this point. Unfortunately, the lack of exposure did not allow the examination of the underlying Brora Brick Clay Member for radiolaria. However, the type material deposited by Gordon (1967) in the British Museum collection from his study of this member was examined and no radiolaria were seen.

A gradual coarsening of grain size upwards in the Fascally Siltstone Member indicates shallowing, with the ultimate deposition of the Fascally Sandstone Member. This shallowing is reflected by a decrease of radiolarian diversity and abundance, particularly around the ***athleta/lamberti*** Biozonal boundary.

Regression progressed with the pervasive deposition of thick sandstone units, represented by the Clynelish Quarry Sandstone and Brora Sandstone Members. Each of these members shows evidence of cross bedding and shallow water, high energy features. Further transgression within the Middle Oxfordian resulted in the deposition of the Ardassie Limestone Member. This limestone facies represents initiation of transgression and is characterised by the abundant presence of ***Rhaxella perforata*** sponge scleres. An abundance of this group indicates that the conditions were probably shallow, whilst the presence of a shaly limestone suggests that sedimentation was low at this stage of the transgression. There is no further outcrop until the Lower Kimmeridgian sediments exposed to the north at Kintradwell (Section 5.4).

5.2.9. Conclusions

Specific conclusions are presented here concerning the Brora section, whilst conclusions covering the biostratigraphical details and palaeoenvironmental correlation of this section with others in the study area are presented in Chapter 7.

The outcrop at Brora represents initially fluvial and lagoonal deposits which were flooded by progressive marine transgressions and regressions. The palaeoenvironments resulting from these relative sea-level changes are characterised by distinct facies types, microfaunal assemblages and macrofauna.

Initial sediments at Brora, deposited within the Bathonian, are represented by freshwater and lagoonal regimes which were culminated by coal formation. This system was brought to an end by the initial transgressive phase within the Lower Callovian, ***calloviense*** Biozone with the deposition of the Brora Roof Bed. This was still an extreme, shallow water palaeoenvironment as indicated by the exceptionally poor agglutinated dominated microfauna. Further, more pervasive transgression occurred within the Lower/Middle Callovian ***calloviense*** Biozone and lower part of the ***jason*** Biozone and this established conditions that produced the Brora Shale Member. This member is characterised by a low diversity/low abundance, agglutinated dominated foraminiferal assemblage which gradually decreases in abundance and diversity. This assemblage reflects a progressively restrictive, oxygen depleted substrate especially with the subsequent deposition of a more bituminous rich shale.

Regression occurred within the Middle Callovian ***jason*** Biozone resulting in the deposition of the Glauconitic Sandstone Member. Microfaunal recovery was limited to sponge spicules, which associated with a sparse infaunal and nektonic macrofauna indicates a shallow water palaeoenvironment probably not conducive to foraminiferal colonisation. The deposition of the Brora Brick Clay Member within the Middle/Upper Callovian represented relatively major transgression, with the final establishment of an apparent diverse infaunal microfauna and macrofauna (Gordon, 1967). This reflects establishment of optimum substrate conditions. However, the initial section of the Brora Brick Clay Member (not examined by Gordon, 1967), which is the only part still exposed at Brora, was barren of microfauna. If this is an original feature it may indicate that some time was needed before circulation patterns, and hence more conducive conditions, were established.

The transition from the Brora Brick Clay Member to the Fascally Siltstone Member equates to the initiation of regression during the Upper Callovian. However, substrate and sea water conditions were still oxygenated, allowing the establishment of a moderate diversity, abundant lagenid/agglutinated dominated foraminiferal fauna and a spumellarian dominated radiolarian fauna. Conditions were moderately shallow, as well as possibly higher energy, with rapid sedimentation rates which would have hindered establishment of foraminiferal groups such as attached miliolids and spirillinids. Further shallowing in the upper parts of the Fascally Siltstone Member is reflected by a decrease in foraminiferal and radiolarian diversity and abundances. The main trends include a relative increase in agglutinated taxa and decrease in spumellarian radiolaria. Transition to a very shallow water regime deposited several sandstone members throughout the Lower Oxfordian which was culminated by transgression resulting in the deposition of the Ardassie Limestone Member facies.

5.3. Balintore, Cromarty & Ross

5.3.1. Introduction

A relatively condensed sequence of steeply dipping Callovian to Middle Oxfordian strata is exposed close to the villages of Shandwick (GR. 84817510) and Balintore (GR. 86207550) in Cromarty and Rosshire, south west of Brora. The outcrops along the foreshore at two localities at Cadh'-an-Righ (GR. 85007239) and Port-an-Righ (GR. 85317329) are separated by approximately 500 metres and a steep cliff. Both sites are bounded to the east by the Great Glen Fault, or a splay of the fault system (Underhill, 1991a, b).

These sections have been sparsely studied in comparison with other Scottish Jurassic sequences, but nonetheless provide a possible 'offshore', condensed analogue for the relatively nearshore Brora succession. The Oxfordian at Balintore is dominated by argillaceous facies, as opposed to the arenaceous facies developed at Brora. The succession was logged in detail and 57 samples were collected for micropalaeontological analysis.

5.3.2. Geology

The two outcrops combine to form a complete composite section of Bathonian to Middle Oxfordian sediments which have been faulted against the Great Glen Fault (Fig. 5.13). This tectonic activity has produced steeply dipping strata (between 90° and 40°) which have been additionally folded into a series of gently to steeply plunging open anticlines and synclines with associated stress fracturing and minor displacements caused by small scale faulting.

Prior to Sykes' (1975a, b) work there were few records of Balintore in the literature, with many authors merely commentating or adding cursory comments concerning lithologies/ ammonite distribution in comparison to the more accessible outcrops at Brora. Murchison (1829a, b) briefly described the outcrops at Port-an-Righ, noting the prominent step-like nature of the steeply dipping sediments which have the appearance of an amphitheatre. Lee (1925) and Buckman (1923) provided the lithostratigraphical terms which form the basis of the modern day scheme, with Buckman (1923) also studying the relatively abundant ammonite faunas.

Underhill & Brodie (1993) and Underhill (*pers. comm.*, 1993) reinterpreted the onshore/offshore seismic and borehole data relating to the outcrop pattern in the Easter Ross peninsula. They concluded that the presence of Jurassic exposure, particularly here at Balintore and the Kimmeridgian of Eathie Haven, is due to the occurrence, in the western part of the Great Glen Fault, of a negative flower structure which formed during the Early Tertiary (Underhill, 1991a). It represents down-faulted slivers and they suggest that the outcrops at Balintore and Eathie Haven peninsulas were an integral part of the Inner Moray Firth Basin with no significant control on basin development during the Jurassic. Indeed, Underhill (1991a, b) could find no significant horizontal translation of Jurassic isopachs across the Great Glen Fault and the total net offset after the Early

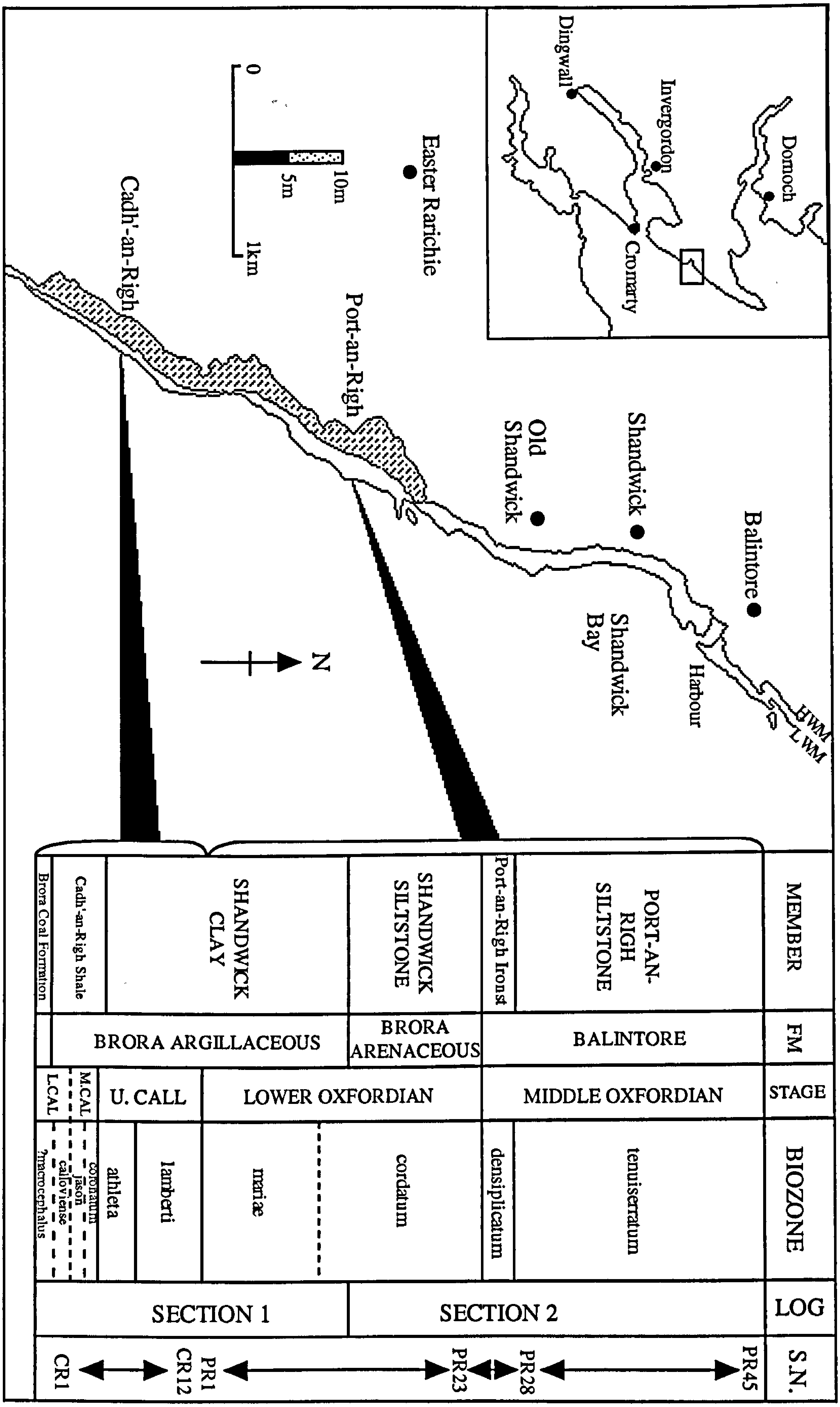


Figure 5.13. Location map of Balintore, with collection sites, lithostratigraphy, ammonite biostratigraphy and sampling details

Cretaceous was less than 10 kilometres.

5.3.3. Ammonite Biostratigraphy

Other than Buckman (1923), who collected ammonites from the succession, little work was carried out on the ammonite faunas until Sykes (1975a, b) and Sykes & Callomon (1979) produced their extensive work on Scottish Jurassic faunas. The most apparent feature at Balintore is the condensed nature of the Lower and Middle Callovian ammonite sequence when compared with Brora (Fig. 1.2); non-sequences are also apparent.

5.3.4. Lithostratigraphy

As at Brora, the formalised lithostratigraphy of Sykes (1975a, b) is accepted; he used some of the informal names designated by Lee (1925) and Buckman (1923). Also as at Brora three marine formations are developed, namely the Brora Argillaceous Formation, the Brora Arenaceous Formation and the Balintore Formation. The underlying Brora Coal Formation is very poorly represented here. These formations and their members are described briefly below.

A). Brora Coal Formation (Bathonian-?lowest Callovian, c.2m; Fig. 5.14).

The Brora Coal Formation is not well exposed, but appears to be a condensed section of approximately 2m. The majority is represented by freshwater shale and limestones (MacLennan & Trewin, 1989). The actual coal bed is poorly developed, with clay and sandy, bioturbated horizons present. This bed has a sharp base on a fine grained bioturbated sandstone which has an eroded, channelled, upper surface filled with coals and fine grained sandstones and shales; no rooted material was found. MacLennan & Trewin (1989) recovered a rich gymnosperm spore assemblage from the coal which, with sedimentary information, was taken to indicate the presence of a swamp, with the coals represented by detrital sedimentation in a lagoon.

B). Brora Argillaceous Formation.

This formation is divided into two members;

(i). Cadh'-an-Righ Shale Member (***calloviense*** -basal ***athleta*** Biozones, c.3.8m; Fig. 5.14).

The Cadh'-an-Righ Shale Member represents a much condensed equivalent to the Brora Shale, Glauconitic Sandstone and Brora Brick Clay Members as developed at Brora. It rests unconformably on the Brora Coal Formation, a limited development of the coals can be seen in the foreshore exposure as extraction has not been as prevalent as at Brora.

The basal 50-60cm of the Cadh'-an-Righ Shale Member is, as at Brora, represented by the Brora Roof Bed, which is a fine grained, bioturbated sandstone. Several horizons of bivalve shell hash are developed, whilst the irregular upper surface is remarkable for abundant, randomly oriented belemnite guards and substantial quantities of comminuted wood debris. Sykes (1975a, b) estimated the Brora Roof Bed at Balintore

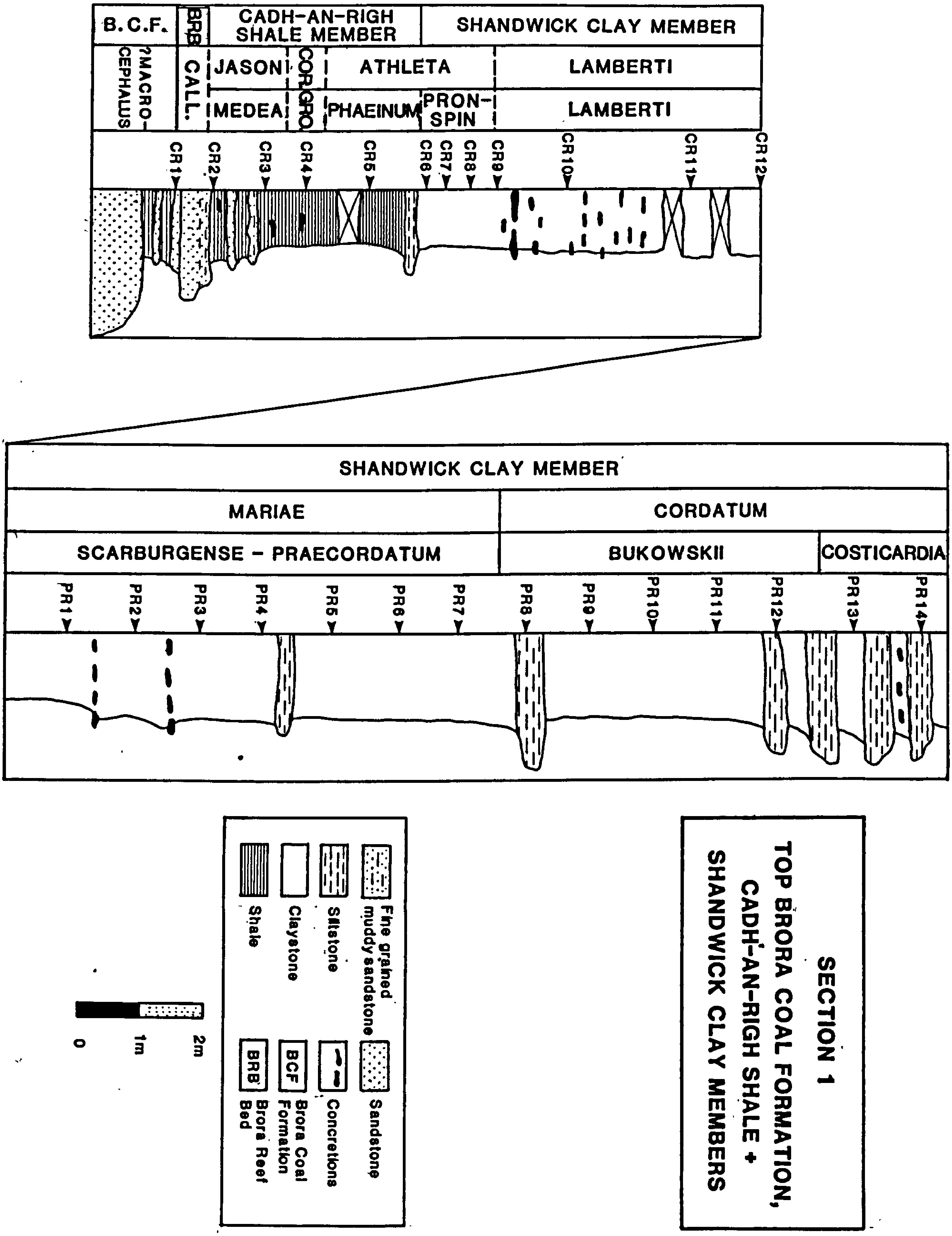


Figure 5.14. Detailed lithological log and ammonite biozonation of the Cadh'-an-Righ Shale and Shandwick Clay Members with sampling points

to be of ***calloviense*** Biozone age, but recorded no ammonites. He dated it solely on stratigraphical correlation with the Roof Bed developed at Brora, but palynological evidence presented by MacLennan & Trewin (1989) supports his conclusion. The remainder of the Cadh'-an-Righ Shale Member is a bituminous and generally unfossiliferous, silty shale with occasional small beds of isolated calcareous concretions. Sykes (1975a, b) considered this level to be equivalent to the Glauconitic Sandstone Member and to represent a non-sequence covering the ***jason*** and ***obductum*** Sub-biozones with only some of the ***grossouvrei*** Sub-biozone present. As well as the non-sequence indicated above, the ***coronatum/athleta*** Biozonal boundary is contained within this interval. Unfortunately, due to the vagaries of the tides and sand cover, small parts of the section appeared to be less exposed than when Sykes studied it. The main markers could, however, still be distinguished. Macrofaunal elements are rare, being dominated by the brachiopod ***Lingula***.

(ii). Shandwick Clay Member (intra ***athleta*** Biozone-***cordatum*** Biozone (***costicardia*** Sub-Biozone), c.21m; Fig. 5.14).

This member can only be fully constructed by the use of composite sections, with the lower part exposed at Cadh'-an-Righ and the upper exposed at Port-an-Righ. Furthermore, the lower part at Cadh'-an-Righ is poorly exposed due to the presence of beach debris.

The prominent lithology is a light-medium grey, locally silty claystone with several horizons of calcareous concretions interspersed basally with localised small phosphatic nodules. Several of these small bands of calcareous nodules mark the upper metre and basal metre of the overlying Shandwick Siltstone Member. The facies becomes decidedly more silty in the upper few metres, with the presence of discreet fine grained siltstone bands.

Ammonites are relatively abundant, however definition of the boundary between the ***proniae*** and ***spinosum*** Sub-biozones by Sykes (***op. cit.***) remains vague, mainly due to the condensed nature of the sequence and the paucity of outcrop present. ***Palaeonucula*** appears to be the only bivalve present in any numbers.

B). Brora Arenaceous Formation.

In terms of Sykes' (1975a, b) lithostratigraphical definition, this formation is represented by a condensed sequence at Balintore consisting of only a single member.

(i). Shandwick Siltstone Member intra ***cordatum*** Biozone (intra ***costicardia-cordatum*** Sub-biozones, c.9m; Fig. 5.15).

This member is marked by a gradual transition from the underlying Shandwick Clay Member; its base is taken at the first influx of bioturbated, sandy siltstones/fine grained sandstones. Several large concretions are also present at this level. The Shandwick Siltstone Member is characterised by a series of cycles of bioturbated siltstones and fine

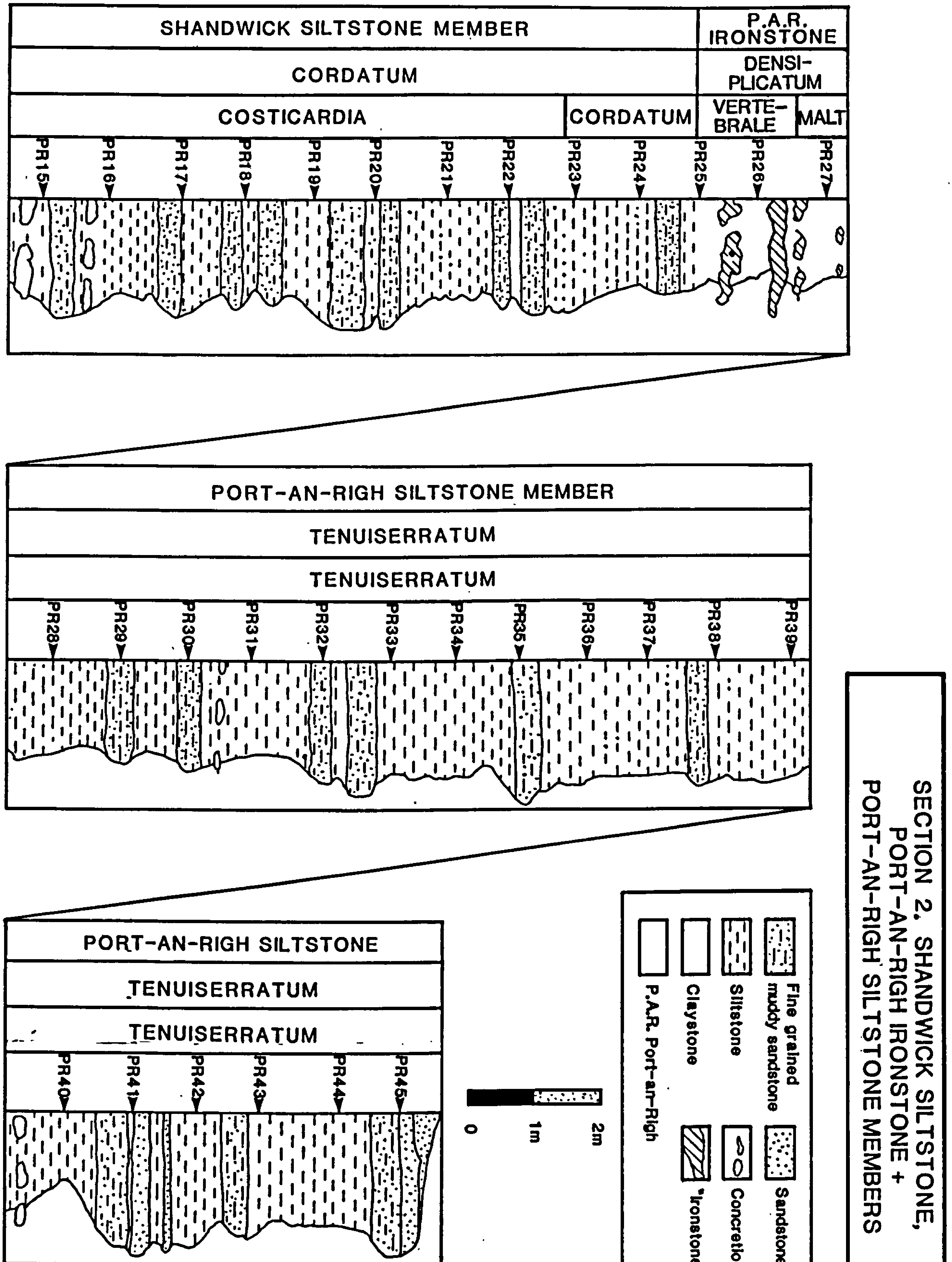


Figure 5.15. Detailed lithological log and ammonite biozonation of the Shandwick Siltstone, Port-an-Righ Ironstone and Port-an-Righ Siltstone Members with sampling points

grained sandstones which form prominent ridges along the foreshore. These cycles are some 20cm-1.2m in thickness, with an overall grainsize increase through the member.

Bivalves are common and consist of ***Modiolus, Pinna, Pleuromya*** and ***Gryphaea***, with the latter often forming discrete horizons.

D). Balintore Formation.

This formation, with its type section at Balintore, is divided into two members:

(i). Port-an-Righ Ironstone Member (***densiplicatum*** Biozone c.1.8m; Fig. 5.15).

The lithostratigraphical equivalent of this member in terms of age is the Ardassie Limestone Member developed at Brora. The Port-an-Righ Ironstone Member is a prominent marker between the two siltstone members and comprises a light grey, sandy claystone or fine grained, muddy sandstone which is subdivided by several distinctive, red weathering sideritic limestones. These limestones form either horizons of concretions or continuous bands. ***Rhaxella*** sponge spicules form an important component of the sediment.

Bivalves, particularly ***Gryphaea*** and ***Grammatodon,*** are common, as are ammonites, which allows this thin and condensed unit to be subdivided into the relevant sub-biozones of the ***densiplicatum*** Biozone.

(ii). Port-an-Righ Siltstone Member (***tenuiserratum*** Biozone c.19m; Fig. 5.15).

The basal boundary with the Port-an-Righ Ironstone Member, although a gradational one, occurs rapidly and is marked by a change to light grey shales which then grade into siltstones to produce cyclical bedding similar to that developed in the Shandwick Siltstone Member. The cycles tend to be become more distinctive, bituminous rich and thicker, within the range of 30cm to 2 metres, due to the coarser grained nature of the sediments.

The final 4 to 5 metres sees a change to coarser grained sediments, with discrete fine grained sandstones developed. Localised calcareous, micritic limestone concretions occur sporadically throughout the unit, occasionally forming horizons.

The macrofaunas are poorly developed, being represented mainly by ***Oxynotum*** and ***Grammatodon***, with few ammonites recorded.

5.3.5. Previous Micropalaeontological Research

There has been no published micropalaeontological research from Balintore, indeed there is only one published account from this area and this covers a palynofacies comparison by MacLennan & Trewin (1989). They investigated the Brora Roof Bed and the Cadh'-an-Righ Shale Member and noted a decrease in the presence of woody material between here and at Brora. They attributed this to a greater distance from shore at Balintore. The environment was initially alluvial (Doll Member) then lagoonal (Brora Coal Formation) with the Brora Roof Bed representing a marine shoreline sand which was followed by open marine deposition of shales.

5.3.6. Foraminiferal Distribution

The microfaunal distribution patterns are described in relation to the members developed below.

i). Cadh'-an-Righ Shale Member (Figs. 5.16-5.18, 5.23).

The condensed section that comprises the ***calloviense*** to intra ***athleta*** Biozones of the Cadh'-an-Righ Shale Member is marked by a sparse agglutinated foraminiferid fauna. The first sample, CR1 collected within the Brora Roof Bed in the ***calloviense*** Biozone, is barren. There is a minor microfaunal introduction in samples CR2 and CR3, within the ***jason*** Biozone. This is characterised by a low diversity, low abundance, agglutinated dominated foraminiferid fauna. ***Trochammina squamata*** is the commonest form represented, whilst ***Reophax helvetica, T. canningensis*** and ***Haplophragmoides pygmaeus*** are rare. Diversities are low, generally around an α index of 1. Samples CR4 and CR5, within the ***coronatum*** and ***athleta*** Biozones, are barren.

ii). Shandwick Clay Member (Figs. 5.16-5.23).

The transition from the Cadh'-an-Righ Shale Member to the Shandwick Clay Member is dramatic, with the introduction of relatively high diversity/high abundance foraminiferal assemblages. This member can be characterised by three foraminiferal assemblages based on overall diversity, abundances and faunal content. These are evident on Figures 5.17-5.18, 5.21-5.23. The changes between these assemblages are not always coincident with ammonite biozonal boundaries.

The first of these assemblages occurs between samples CR6 and PR3, ranging from the ***athleta*** to basal ***mariae*** Biozones. It is represented by a high diversity (α index ranging from 9-13) and moderate abundance foraminiferal fauna, which is mixed, with agglutinated, lagenid and miliolid forms co-dominating. Robertinids and spirillinids are rare. The most numerically important form is the adherent miliolid ***Nubeculinella tibia. T. canningensis, R. sterkii, Lenticulina varians, L. muensteri, Eoguttulina liassica*** and ***Ophthalmidium carinatum*** are also common. First appearances are consistently high within the ***athleta, lamberti*** and ***mariae*** Biozones and lagenids provide the widest range of taxa.

The next cycle occurs from PR4 to PR10, relating to the majority of the ***mariae*** Biozone and the basal part of the ***cordatum*** Biozone. It is characterised by moderate to low diversity (α index 5-6) and high abundances (in excess of 300 foraminifera/g), dominated by robertinids and miliolids. The high abundances are a reflection of the presence of ***Epistomina parastelligera*** and floods of the miliolids ***Nubeculinella tibia*** and ***Ophthalmidium carinatum***. Overall, first appearances are common. Agglutinated, lagenid and miliolid taxa progressively decrease throughout this cycle, whilst the robertinid ***E. parastelligera*** increases. Common taxa include

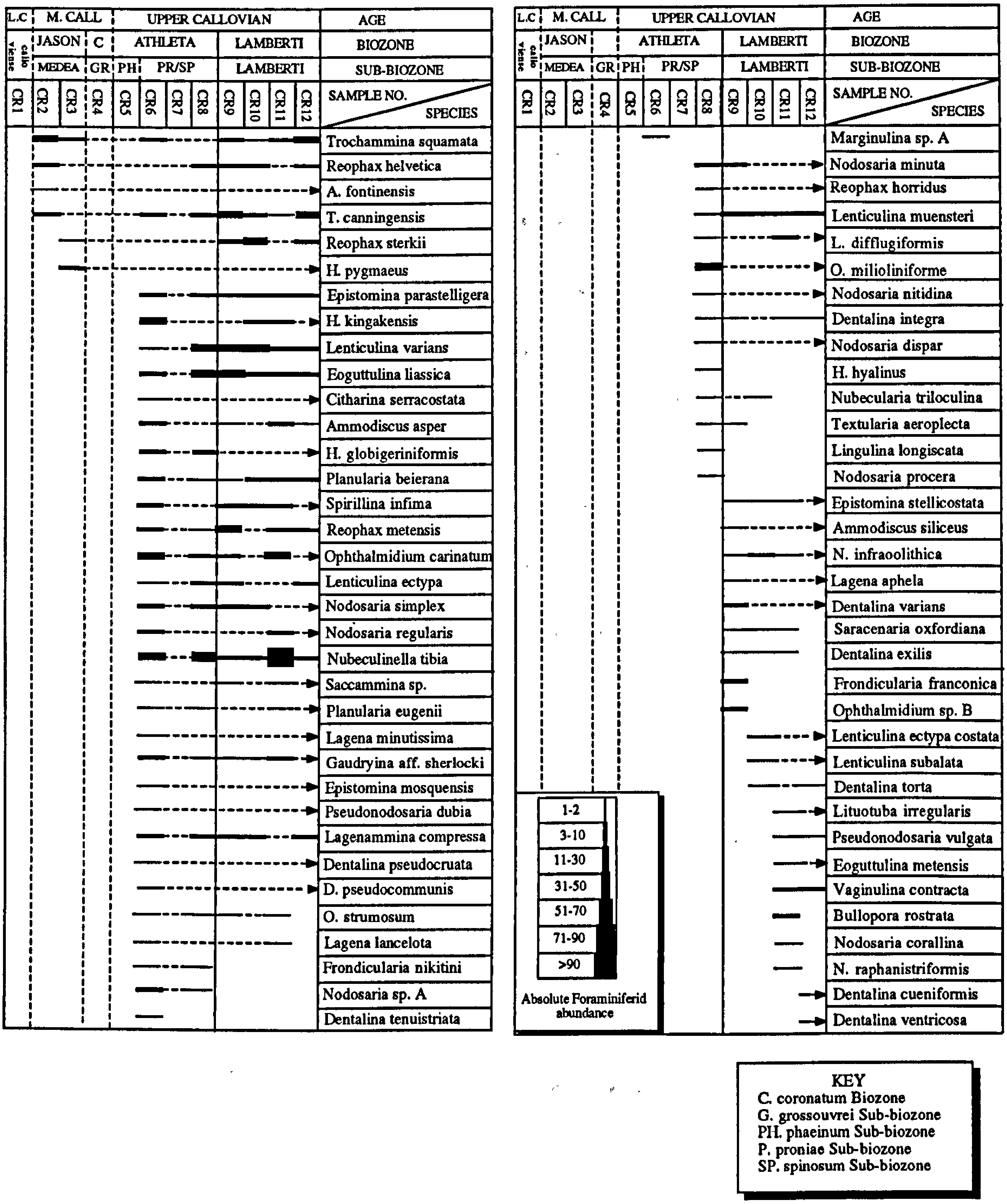


Figure 5.16. Foraminiferal distribution range chart for the Middle and Upper Callovian of Balintore

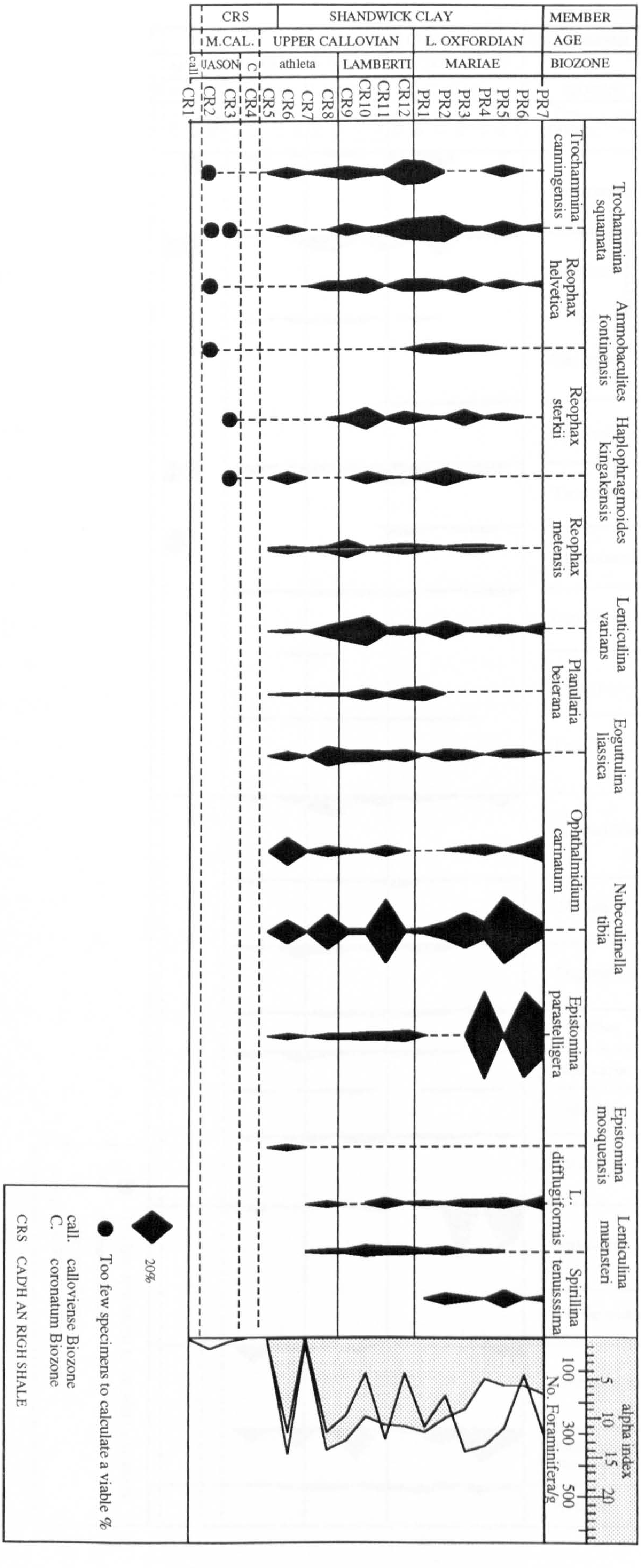


Figure 5.17. Relative distribution of selected foraminiferal taxa from the Middle Callovian to Lower Oxfordian of Balintore

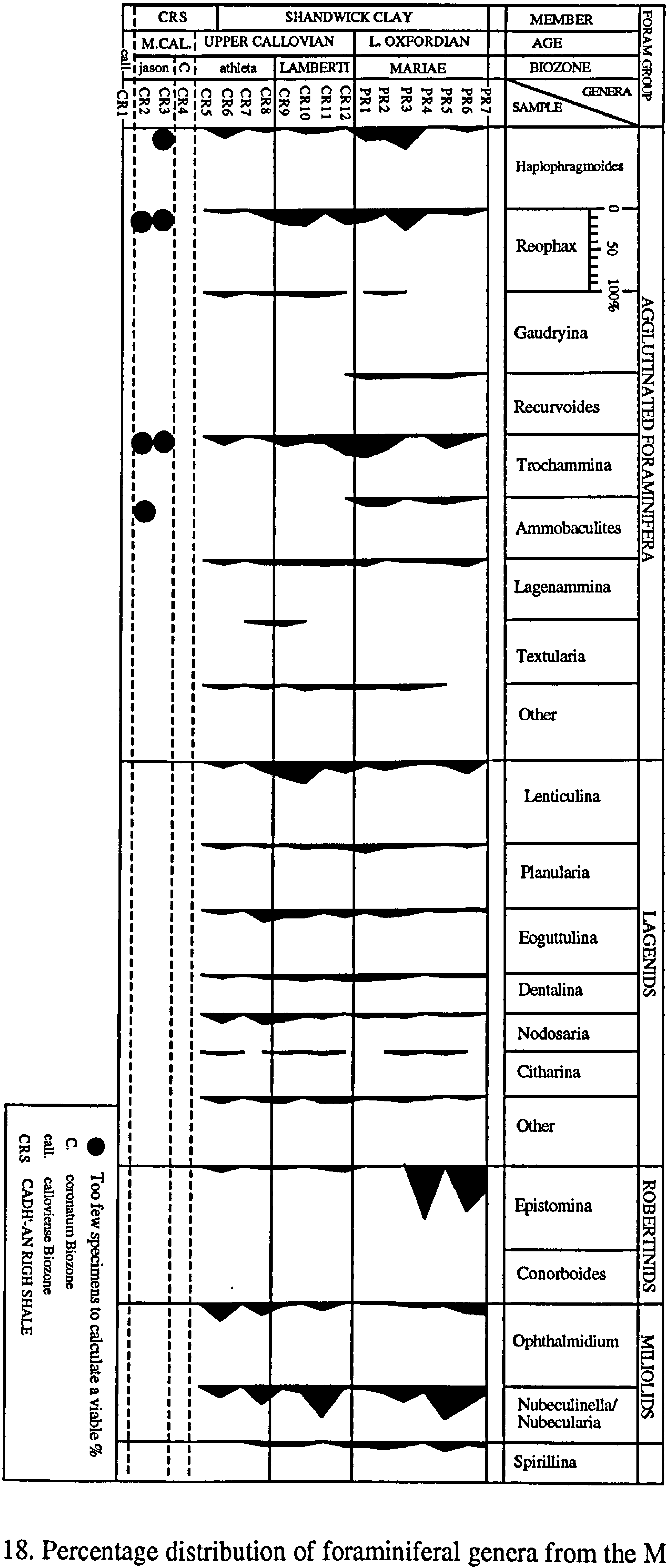


Figure 5.18. Percentage distribution of foraminiferal genera from the Middle Callovian to Lower Oxfordian of Balintore

Trochammina squamata, Reophax spp., ***Lenticulina varians, E. liassica*** and ***Spirillina tenuissima.***

The final cycle occurs in the uppermost part of the member between PR11 and PR14, within the ***cordatum*** Biozone and is marked by a low diversity (α index less than 5) and very high abundance mixed assemblage with common agglutinated foraminiferids, lagenids, robertinids and miliolids, with spirillinids increasing in abundance. An interesting feature is that miliolids and robertinids appear to be mutually exclusive in their distribution patterns (Fig. 5.23). Common taxa include ***L. varians, T. squamata*** and initially ***O. carinatum. N. tibia*** is less common in this part of the member. The final sample at PR14 is marked by a high agglutinated foraminiferid content with ***T. squamata*** and ***Ammobaculites coprolithiformis*** being particularly common.

iii). Shandwick Siltstone Member (Figs. 5.19-5.23).

This member which covers the remainder of the ***cordatum*** Biozone is characterised by sparse recovery with generally low abundances (less than 100 foraminifera/g) and low diversities (α less than 4). As far as can be ascertained from the distribution patterns, the assemblages based on wall structure are similar to the fluctuating mixed faunas established in the upper parts of the Shandwick Clay Member. This mixed fauna comprises common agglutinated, lagenid and robertinids occurring in similar proportions; however, miliolids and spirillinids are absent. In detail, ***E. parastelligera*** and ***E. mosquensis*** initially dominate (PR15-PR16), with common ***L. varians.*** Thereafter no single taxon dominates, with ***Reophax metensis, R. helvetica, R. sterkii, Lagenammina difflugiformis, Lenticulina varians, Ammodiscus asper*** and ***E. parastelligera*** being commonest.

iv) Port-an-Righ Ironstone Member (Figs. 5.19-5.23).

Samples were collected from the claystones present within this condensed member covering the ***densiplicatum*** Biozone. The initial sample at PR25 was almost barren, with only rare ***Lagena globosa*** occurring. A slight increase in diversity and abundance is seen in sample PR26, with agglutinating foraminiferids dominating, in particular ***R. metensis*** and ***Lagenammina difflugiformis.*** Calcareous benthic taxa are rare, represented by ***'Duoplanum'*** sp. A, ***Lenticulina quenstedti, Marginulina costata*** and ***L. globosa.*** PR27, within the ***maltonense*** Sub-biozone, is characterised by good recovery and an associated large increase in abundance and diversity with 17 species present. ***E. parastelligera*** is the most common, with subsidiary specimens of ***L. varians, R. metensis, L. muensteri*** and ***Lagenammina difflugiformis.*** It is difficult to assign an overall characteristic for this member due to the limited data available, with the exception of the final sample. This sample has a low diversity (α index of 6) with low to moderate abundances and yielded a mixed agglutinated, lagenid and robertinid fauna.

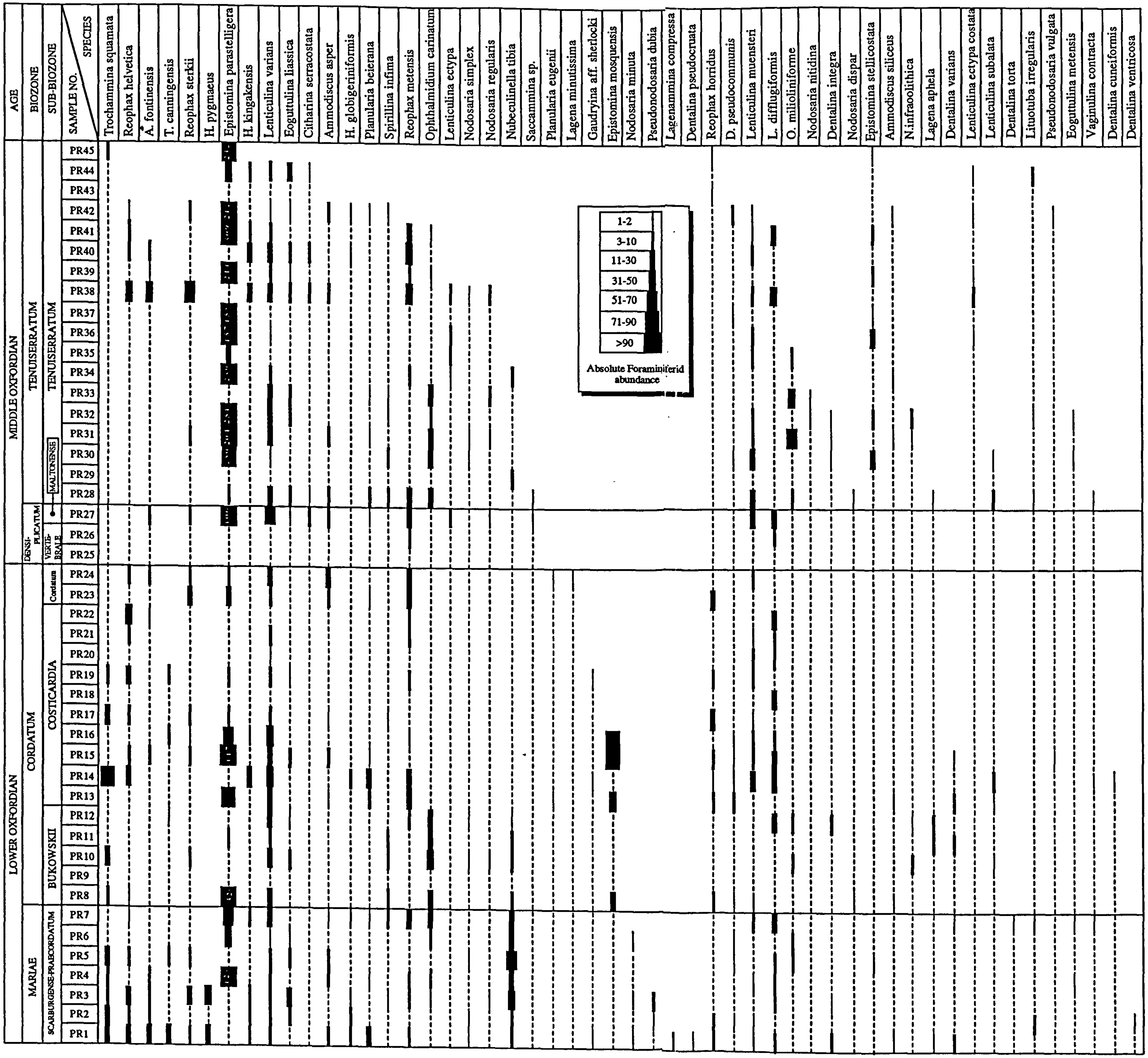


Figure 5.19. Foraminiferal distribution range chart for the Lower to Middle Oxfordian of Balintore (Part A)

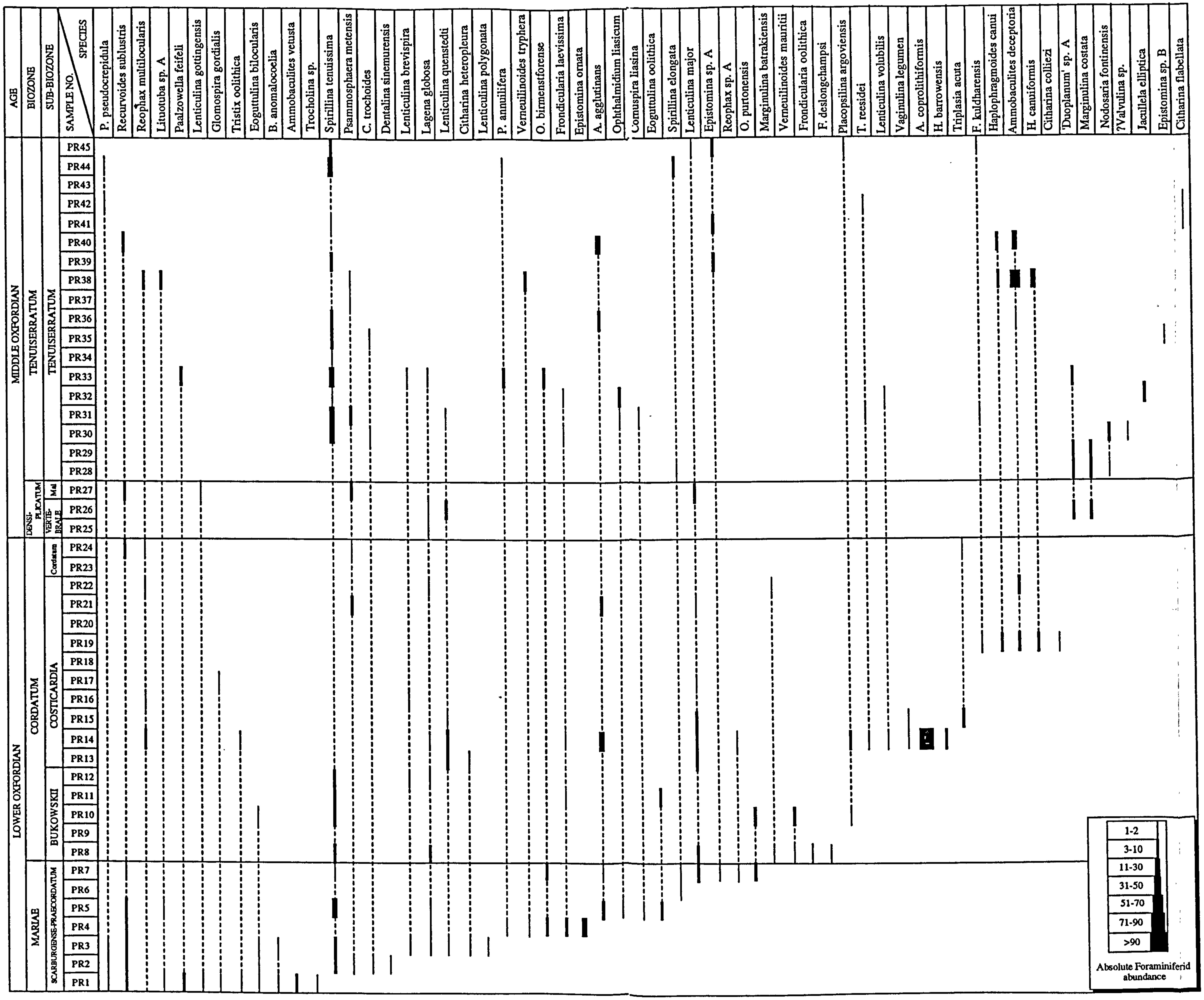


Figure 5.20. Foraminiferal distribution range chart for the Lower to Middle Oxfordian of Balintore (Part B)

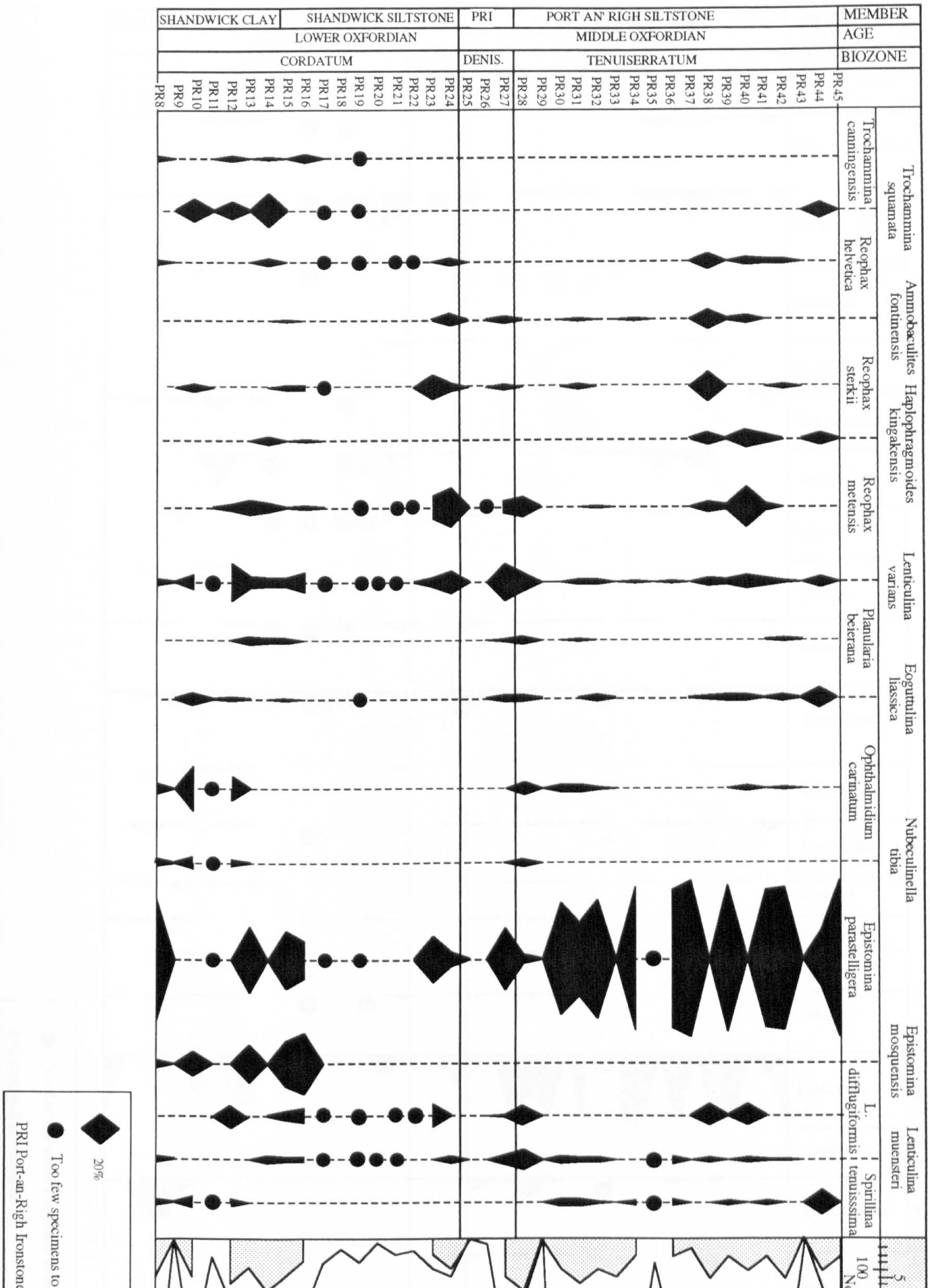


Figure 5.21. Relative distribution of selected foraminiferal taxa from the Lower and Middle Oxfordian of Balintore

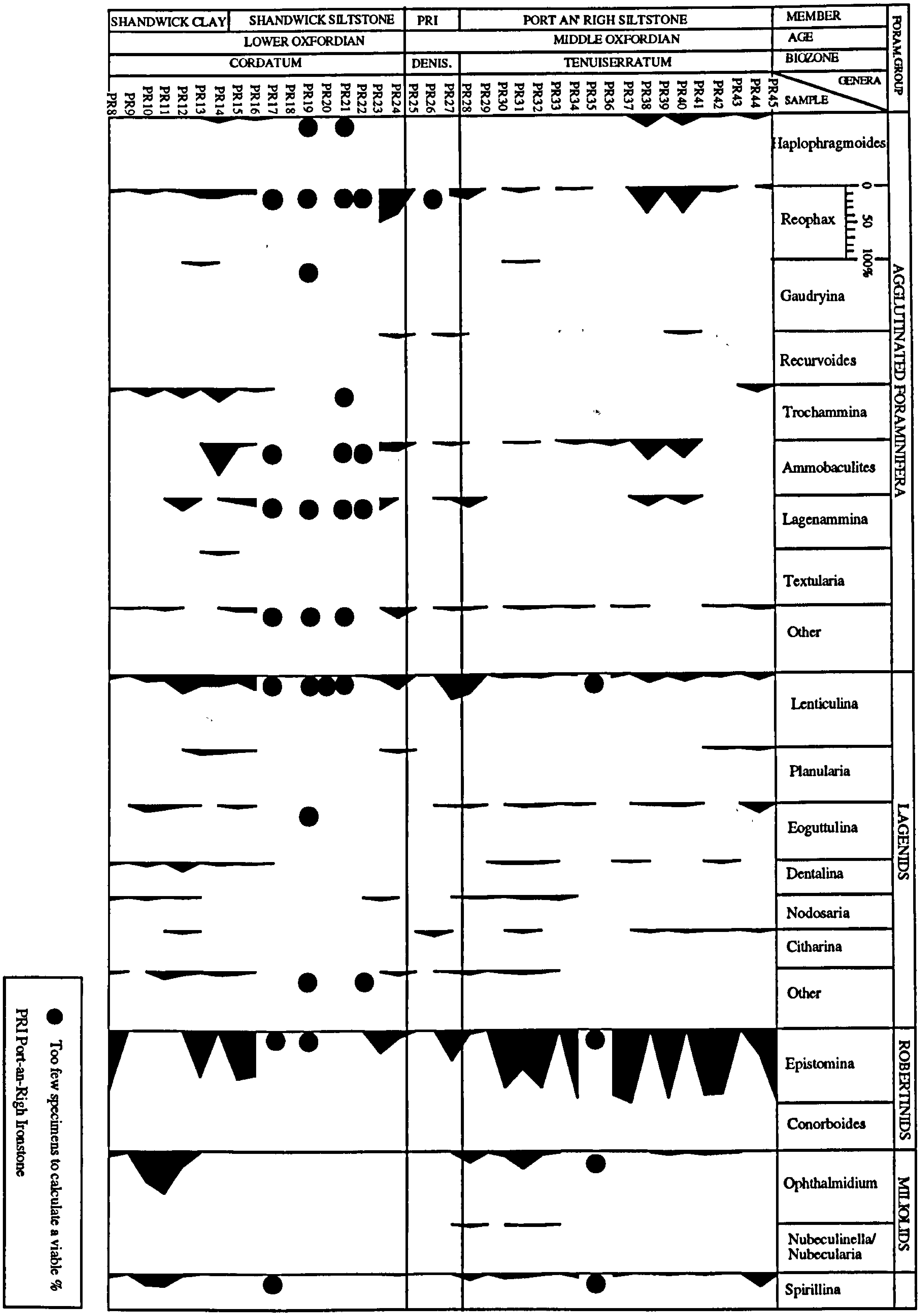


Figure 5.22. Percentage distribution of foraminiferal genera within the Lower and Middle Oxfordian of Balintore

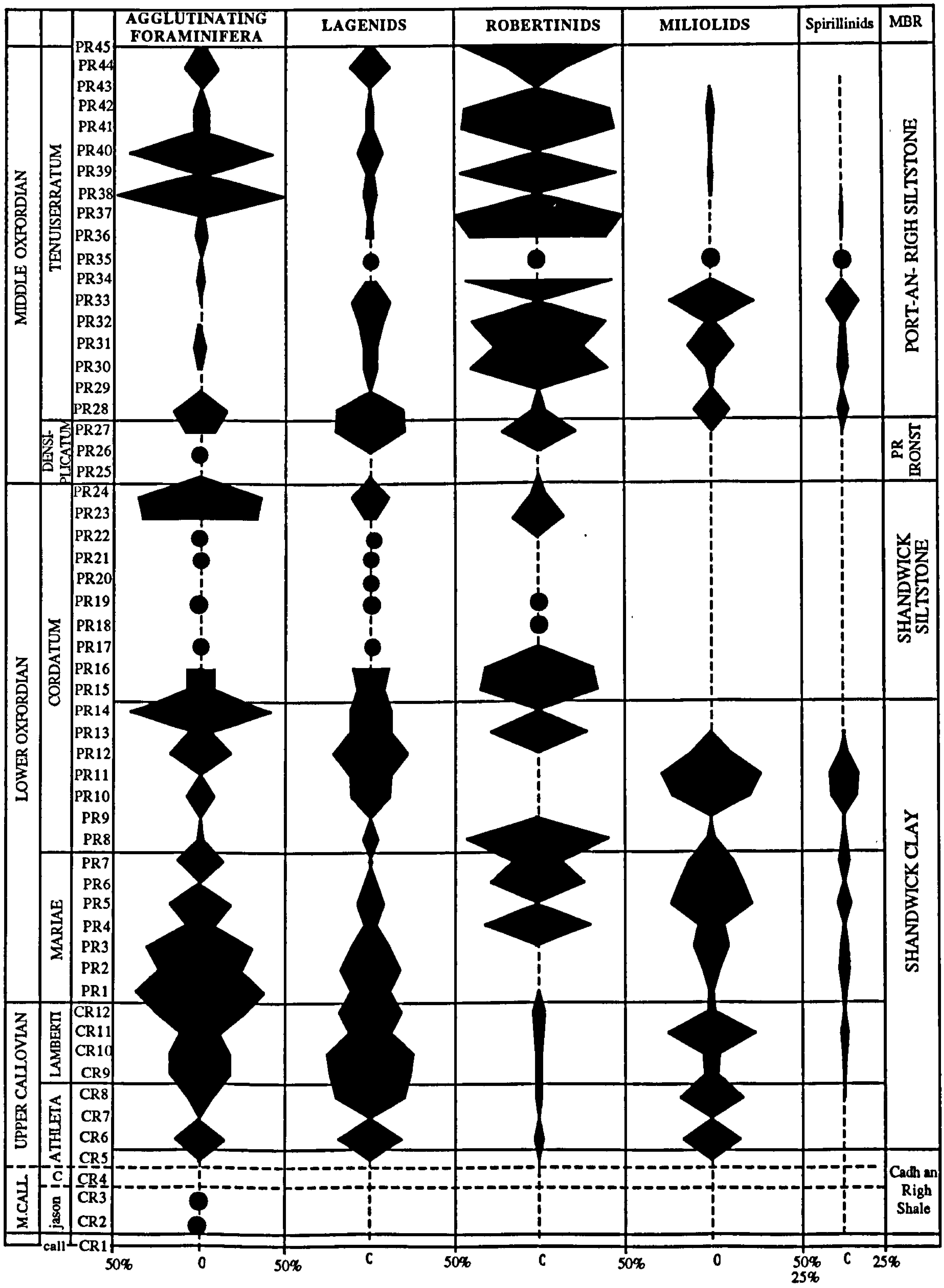


Figure 5.23. Percentage distribution of the major foraminiferal groups at Balintore plotted against the bio and lithostratigraphy schemes (Circles = samples with too few specimens to calculate a viable %)

iv). Port-an-Righ Siltstone Member (Figs. 5.19-5.23).

The foraminiferal distribution can be characterised as two major assemblages within the ***tenuiserratum*** Biozone of this member. The first cycle is developed between samples PR28 and PR35, whilst the second is between samples PR36 and PR45. It is apparent that the majority of taxa are poorly represented, with no more than 1-10 specimens per sample. However, a general robertinid dominance characterises the majority of this member, with ***E. parastelligera*** occurring in large numbers.

The initial cycle is characterised by high abundances (in excess of 300 foraminifera/g) and relatively low diversities (α index in the range of 4-6), with most samples overwhelmingly dominated by ***E. parastelligera***. Subordinate taxa such as ***Ophthalmidium carinatum*** and ***Spirillina tenuissima*** occur in floods, whilst ***Lenticulina muensteri*** is persistently common. Agglutinated taxa are poorly represented.

The upper cycle is again dominated by ***E. parastelligera***, but to a much greater extent. Miliolids and spirillinids are poorly represented in comparison to the lower cycle, whilst the lagenids ***Lenticulina varians*** and ***Eoguttulina liassica*** are moderately common. An interesting feature of this upper cycle is the development of localised agglutinated foraminiferid peaks at PR38 and PR40 which occur without ***E. parastelligera***. These agglutinated taxa include ***Haplophragmoides kingakensis, Reophax metensis*** and ***Lagenammina difflugiformis***.

In the Port-an-Righ Siltstone Member there are also a large number of apparent final appearances, which total approximately 60. It is difficult to gauge whether this is a true reflection of environmental change or whether it is a reflection of the lack of exposure. Those forms which disappear sometime before the final sample include ***Reophax metensis, O. carinatum, L. difflugiformis*** and ***O. milioliniforme***. There are only 5 forms which have first appearances and these are generally related to single sample occurrences. The most important taxa are ***Nodosaria fontinensis, Epistomina*** sp. ***B*** and ***Citharina flabellata***.

5.3.7. Radiolarian Distribution

Radiolaria are not particularly common from the sediments at Balintore and occur only in the Shandwick Clay Member from the upper part of the ***athleta*** Biozone and the entire ***lamberti*** and ***mariae*** Biozones.

Only 8 taxa occur, with ***Cenodiscus*** sp. indet being the most pervasive within the interval covering the ***athleta*** to ***mariae*** Biozones. However, poor preservation precludes positive speciation. The final sample within the ***lamberti*** Biozone (CR12) is notable for the first appearance of 4 species, including ***Orbiculiforma iniqua*** and ***Cavaspongia*** sp. A.

The ***mariae*** Biozone is marked by sporadic occurrences of ***Tricolocapsa*** sp. A and ***Crucella*** sp. indet, with ***Cenodiscus*** sp. indet. and ***Cenosphaera*** sp. indet. being the most common representatives of a rare microfauna.

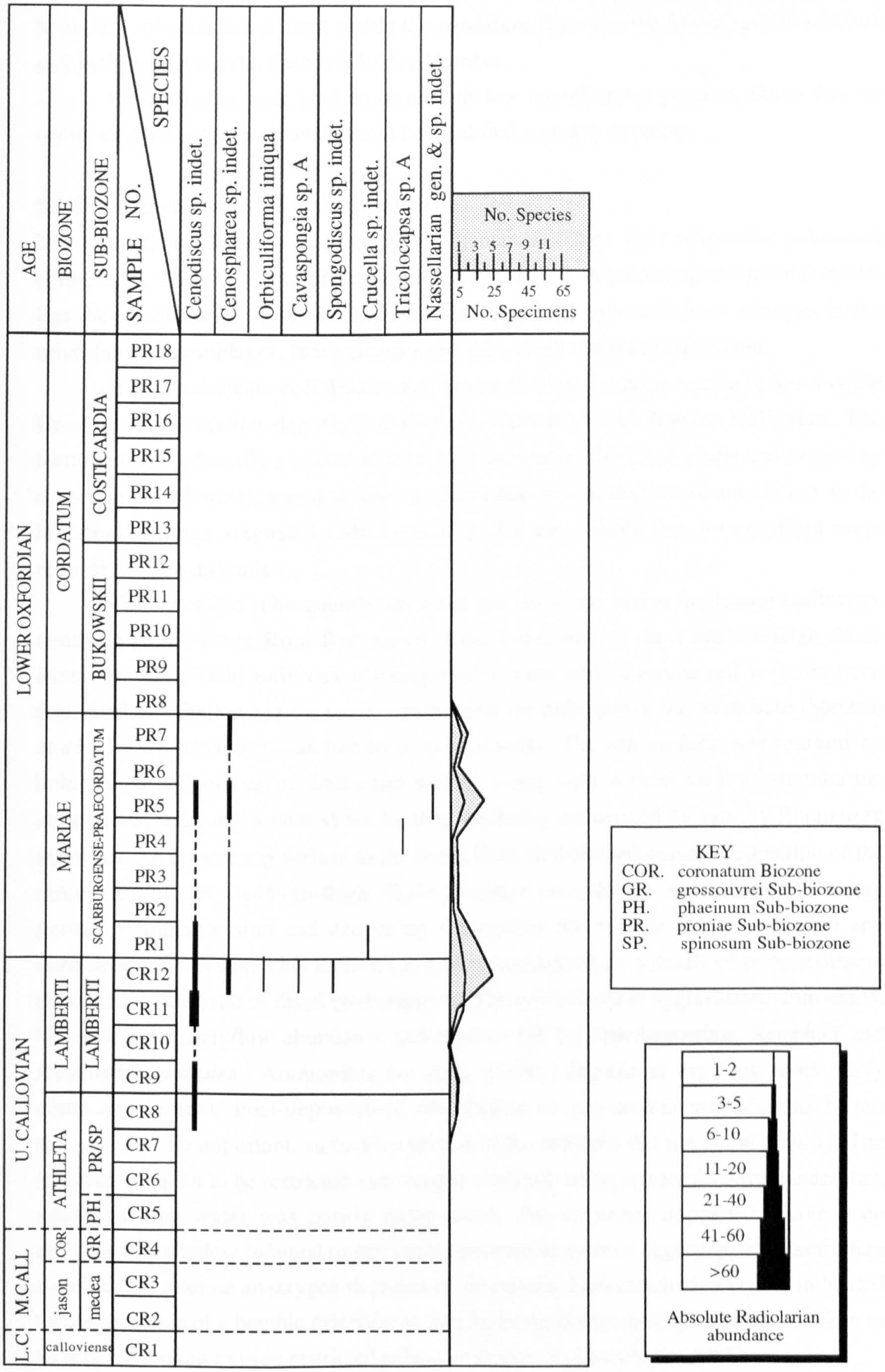


Figure 5.24. Radiolarian distribution, diversity and abundances for the Callovian and Oxfordian of Balintore

Diversity and abundances are greatest across the ***lamberti/mariae*** Biozonal boundary. No taxa are present within the ***cordatum*** Biozone, the lower part of which is still included within the Shandwick Clay Member.

Spumellarian taxa predominate, with few nassellarians present; those that do occur are poorly preserved and cannot be identified with any certainty.

5.3.8. Palaeoenvironmental Interpretation

The microfaunas have been grouped into genera and then their respective suborders (Figs. 5.18, 5.22-5.23) and proportional changes noted. A palaeoenvironmental model has then been constructed which utilises an integrated approach from changes in the microfaunal assemblages, facies changes and the overall macrofaunal content.

Initial sediments at Balintore are represented by the predominately non-marine Brora Coal Formation deposited during the Bathonian and ?lowest Callovian. The formation was primarily a coastal alluvial plain incised by fluvial channels and capped by a very thin coal which was deposited as a consequence of detrital accumulation as the lagoonal settings stagnated (MacLennan & Trewin, 1989). No foraminifera were recovered from this unit.

Transgression subsequently 'drowned out' the coals during the Lower Callovian, resulting in the Brora Roof Bed which is the lower unit of the Cadh'-an-Righ Shale Member. This basal unit was a transgressive sand and is envisaged to have been deposited in a shallow marine environment under the influence of the wave base (Stephen ***et al.***, 1993). This unit was barren of microfossils. The top surface was marked by belemnites and pieces of driftwood which, along with a total lack of stenohaline ammonites, indicates a near shore locality, probably influenced by rapidly fluctuating salinities. An erosive top surface to the Brora Roof Bed and subsequent deposition of the remainder of the Cadh'-an-Righ Shale Member records the continuation of more pervasive transgression and deepening throughout the Middle Callovian ***jason*** and ***coronatum*** Biozones. This member is highly condensed as a result of poor sediment supply, characteristic of distal environments. The microfauna is agglutinated dominated, being low diversity/low abundance and represented by ***Trochammina, Reophax*** and ***Haplophragmoides.*** Ammonites are rare, whilst ***Lingula*** is the only moderately common element. Post-depositional dissolution of calcareous microfaunas is not envisaged to be important, as bivalve prisms in the residues did not show etching. The substrate is taken to be restricted and oxygen depleted, being dysaerobic/quasianaerobic, whilst the sea water was poorly oxygenated. The substrate appears to have been colonised by shallow infaunal or epifaunal opportunist/pioneer agglutinated foraminifera which could tolerate an oxygen depleted environment. This conclusion is also indicated by the presence of a benthic macrofauna which, being dominated by ***Lingula,*** is taken to be reflective of an oxygen restricted palaeoenvironment (Oschmann, 1988).

Transition to the clay facies of the Shandwick Clay Member appears to reflect the maximum extent of transgression. This was followed by the initiation of regression, as indicated by a progressive change from a clay deposition regime to one that was more silty. A change from a transgressive to regressive regime also appears to be reflected by the gross microfaunal changes. In detail, continuation of transgression, reflected by hemipelagic clay deposition, permitted the subsequent establishment of relatively good water conditions which persisted throughout the Upper Callovian and lowest Lower Oxfordian. All indications are of a well oxygenated, aerobic substrate which allowed the establishment of a diverse and abundant microfauna, common infaunal bivalves and bioturbation. The foraminiferal assemblages are initially mixed, with agglutinated, lagenid and miliolid taxa dominating. Robertinids assume more importance higher up in the member. A large number of taxa have first appearances over this interval. The presence of radiolaria confirms that general sea water conditions were well oxygenated, with possible upwelling, as reflected by the presence of some phosphatic nodules. However, water depth could not have been too great here as the radiolarian faunas are not diverse. The presence of large numbers of the attached miliolid ***Nubeculinella tibia*** in the lower part of the member is taken to indicate that sedimentation rate was low.

The microfauna changes dramatically in the upper parts of the Shandwick Clay Member, during the ***mariae*** Biozone of the Lower Oxfordian, with the disappearance of radiolaria, a marked decrease in foraminiferal diversities and a corresponding substantial increase in the numbers of the robertinid ***Epistomina parastelligera.*** This, taken in association with a marked increase in clastic material and carbonaceous debris, indicates the onset of regression and shallowing. The substrate is still seen to be relatively oxygenated, as it is bioturbated. However, an increase in the sedimentation rate may have precluded deeper infaunal or less mobile microfaunal taxa such as the miliolids ***N. tibia*** and ***Ophthalmidium carinatum,*** which disappear as ***E. parastelligera*** increases. Attached forms, such as ***Spirillina,*** are also present in localised horizons, which may indicate a higher energy environment. Water conditions are concluded to be shallower due to the lack of radiolaria.

The regression initiated in the upper parts of the Shandwick Clay Member continued with the deposition of the Shandwick Siltstone Member during the ***cordatum*** Biozone. Overall foraminiferal recovery was poor over this member, with mixed faunas dominated by ***Epistomina parastelligera.*** Ammonites were common, indicating that sea water conditions were at least oxygenated. The presence of occasional levels of bioturbation and bivalves, represented by ***Pinna*** and ***Pholadomya,*** indicate that the substrate was partially aerobic. Another possible conclusion for the decreased microfaunal distribution may therefore come from the conclusions of Wignall (1990) and Oschmann (1988) who indicated that the bivalves present here were high level infaunal to epifaunal in their lifestyles. The increased silt and sand input in this member, associated with a higher carbonaceous level, may suggest that although bivalves could survive as a consequence of their size and mobility, foraminifera, with the exception of more mobile forms, could not.

The Shandwick Siltstone Member is overlain by the very distinct and condensed

Port-an-Righ Ironstone Member, which encompasses the entire ***densiplicatum*** Biozone. This latter member probably represents a transgressive episode, with associated sediment starvation and condensation reflected in the presence of bioturbated sediments and the subsequent development of limestone facies. Unfortunately, foraminiferal recovery was not consistent over this unit, which may be as a consequence of spot sampling of oxygen depleted micro habitats. However, the final sample did yield a microfauna, which comprised relatively diverse, mixed assemblages, and is probably indicative of an aerobic substrate. Ammonites were common, as were semi-infaunal and epifaunal bivalve taxa such as ***Modiolus*** and ***Gryphaea***. The presence of such bivalves, associated with bioturbation, may indicate the initial formation of hard grounds, which a foraminiferal fauna did not colonise until the establishment of sediment. Were this the case however, epifaunal attached taxa such as *N. tibia* or ***Spirillina*** should be expected in the microfaunas and they were not recovered.

The deposition of the Port-an-Righ Siltstone Member reflects a major facies change, with an increasing clastic input as a consequence of major regression during the ***tenuiserratum*** Biozone. Foraminiferal faunas were represented by a dominance of robertinids, particularly ***E. parastelligera.*** Agglutinated taxa were more common in the upper parts. Ammonites were rare, whilst the bivalves present were epifaunal to shallow infaunal. The facies were initially silts and later fine sands, with an increasing carbonaceous content. Therefore, ***E. parastelligera*** was possibly best adapted to the relatively high sedimentation rate associated with substrates, which were probably becoming increasingly oxygen depleted. The disappearance of many foraminiferal taxa over this member probably corroborates this oxygen depleted conclusion, whilst the isolated increases in agglutinated taxa may indicate the worsening of substrate conditions in the upper parts of this member. No younger sediments are preserved at Balintore.

5.3.9. Conclusions

Specific palaeoenvironmental conclusions are presented here concerning the Balintore section, whilst detailed conclusions covering the biostratigraphical and generalised palaeoenvironmental correlations of this section with others in the Inner Moray Firth and Hebrides Basins are presented in Chapter 7.

Several facies types are present at Balintore, and these mirror the development of the palaeoenvironment, and hence relative sea-level changes, through the Upper Bathonian to the Middle Oxfordian. These changes also appear to be reflected in the gross foraminiferal and radiolarian faunas recovered.

Initial sediments at Brora, deposited within the Bathonian, are represented by freshwater and lagoonal regimes which culminated in coal formation. This system was flooded out and terminated by an initial Lower Callovian transgressive phase which then resulted in the deposition of the Brora Roof Bed during the ***calloviense*** Biozone. A shallow water, high energy palaeoenvironment is envisaged here, which was possibly affected by salinity fluctuations. Further, more pervasive transgression occurred within the remainder of the Lower and Middle Callovian (*jason* Biozone to the lower part of the ***athleta*** Biozone) and established conditions that produced the highly condensed Cadh'-an-Righ Shale Member. It was characterised in sampling by either barren samples or by a low diversity/low abundance, agglutinated dominated foraminiferal assemblage. This assemblage reflects a restrictive, oxygen depleted substrate, with a sparse associated bivalve fauna.

The transition from the Cadh'-an-Righ Shale Member to the Shandwick Clay Member, within the ***athleta*** Biozone, equates to the subsequent establishment of a well oxygenated substrate and sea water conditions, as an outcome of further transgression. This is indicated by the presence initially of a diverse and abundant foraminiferal fauna and by radiolaria during the ***athleta*** to ***mariae*** Biozones. Within the upper parts of the Shandwick Clay Member, during the ***mariae*** Biozone, it appears that shallowing occurred, which excluded a radiolarian fauna and produced a more impoverished foraminiferal fauna dominated by robertinids. Continued regression during the ***cordatum*** Biozone resulted in the deposition of the Shandwick Siltstone Member which was dominated in parts by ***Epistomina parastelligera,*** which may reflect a higher clastic input. An associated carbonaceous input may account for the presence of agglutinated foraminiferids.

Transgression occurred within the Middle Oxfordian ***densiplicatum*** Biozone, with the deposition of the highly condensed Port-an-Righ Ironstone Member. This yielded a mixed agglutinated, lagenid and robertinid foraminiferal assemblage, indicating a moderately oxygenated palaeoenvironment.

Deposition of the thick Port-an-Righ Siltstone Member, which encompasses the ***tenuiserratum*** Sub-biozone, indicates pervasive regression which produced a prograding unit of increasing clastic input. The overall foraminiferal assemblage is dominated by the robertinid ***E. parastelligera***, with agglutinated taxa dominating a few final samples. These taxa may have been best adapted to a rapid deposition rate and an increasing carbon content of the substrate. Robust lagenids are also present, which may indicate their adaptation to a higher energy environment. Younger sediments are not exposed at Balintore.

5.4. Helmsdale, Sutherlandshire

5.4.1. Introduction

The foreshore exposure along the coast from Kintradwell (GR. 925507138) to Dun Glas (GR. 04151555) provides some of the most extensive Upper Jurassic outcrop in Scotland, ranging from the Kimmeridgian to Portlandian (***cymodoce*** to basal ***albani*** Biozones). Initial research by Gregory (1986, 1989) provided the first information of microfaunas, in particular data concerning radiolaria and foraminifera from the Lower Kimmeridgian (***cymodoce*** to ***eudoxus*** Biozones), and also formed the impetus for further study in this region. Unfortunately, the younger sediments subsequently analysed from the ***autissiodorensis*** to ***albani*** Biozones proved to be almost totally barren of microfaunal recovery.

A total of 109 samples were collected for reconnaissance, with 45 from the lower section at approximately 1 metre intervals and 64 from the upper succession at a greater interval. 45 samples from the basal section forming the basis of the previous study by Gregory (*op. cit.*) were re-examined here, particularly the radiolarian faunas, to provide biostratigraphical and palaeoenvironmental data for correlation with the Lower Kimmeridgian sediments at Eathie Haven (Inner Moray Firth Basin) and Staffin Bay (Inner Hebrides Basin). Results from the sediments covering the ***autissiodorensis*** to ***albani*** Biozones, although negative in terms of foraminifera and radiolaria, are assessed with regard to the poor recovery.

5.4.2. Geology

The coastal exposure from Golspie to the Ord of Caithness of east Sutherland comprises a thin strip outlier of Mesozoic strata. These range from the Late Triassic through to the Late Jurassic (Volgian/Portlandian). The outlier is bounded to the west by the Helmsdale Fault. This has been shown to have been active during the Kimmeridgian, having profound effects on sedimentation and an integral role in producing the deposition of the spectacular Boulder Beds (Bailey & Weir, 1932). Old Red Sandstone, metamorphosed Moine Schists and the Helmsdale Granite crop out to the west of the Helmsdale Fault. There is a break in the outcrop exposure between the Middle Oxfordian and the Lower Kimmeridgian along the foreshore between North Brora (GR. 91310404) and Kintradwell Farm (GR. 925507138). The section between Kintradwell Farm and Sron Rubha na Goaithe (GR. 99251160) provided samples for initial research (Gregory, 1986, 1989, 1992) from the ***cymodoce*** to ***autissiodorensis*** Biozones. Later sampling was concentrated on the ***elegans*** through to ***albani*** Biozones from Crackaig Links (GR. 96501010) to Dun Glas in the north (Fig. 5.25).

A mode of origin for the boulder beds has elicited many conflicting hypotheses. Bonney (1902) speculated that they were produced as talus from a mountainous district, with weathering by heavy rain, snow fall or glaciers, whilst Blake (1902) thought the process was one of debris produced at an ice sheet foot. MacGregor (1916) postulated for the first time the proximity of a Jurassic 'palaeoshoreline' with a substantial talus,

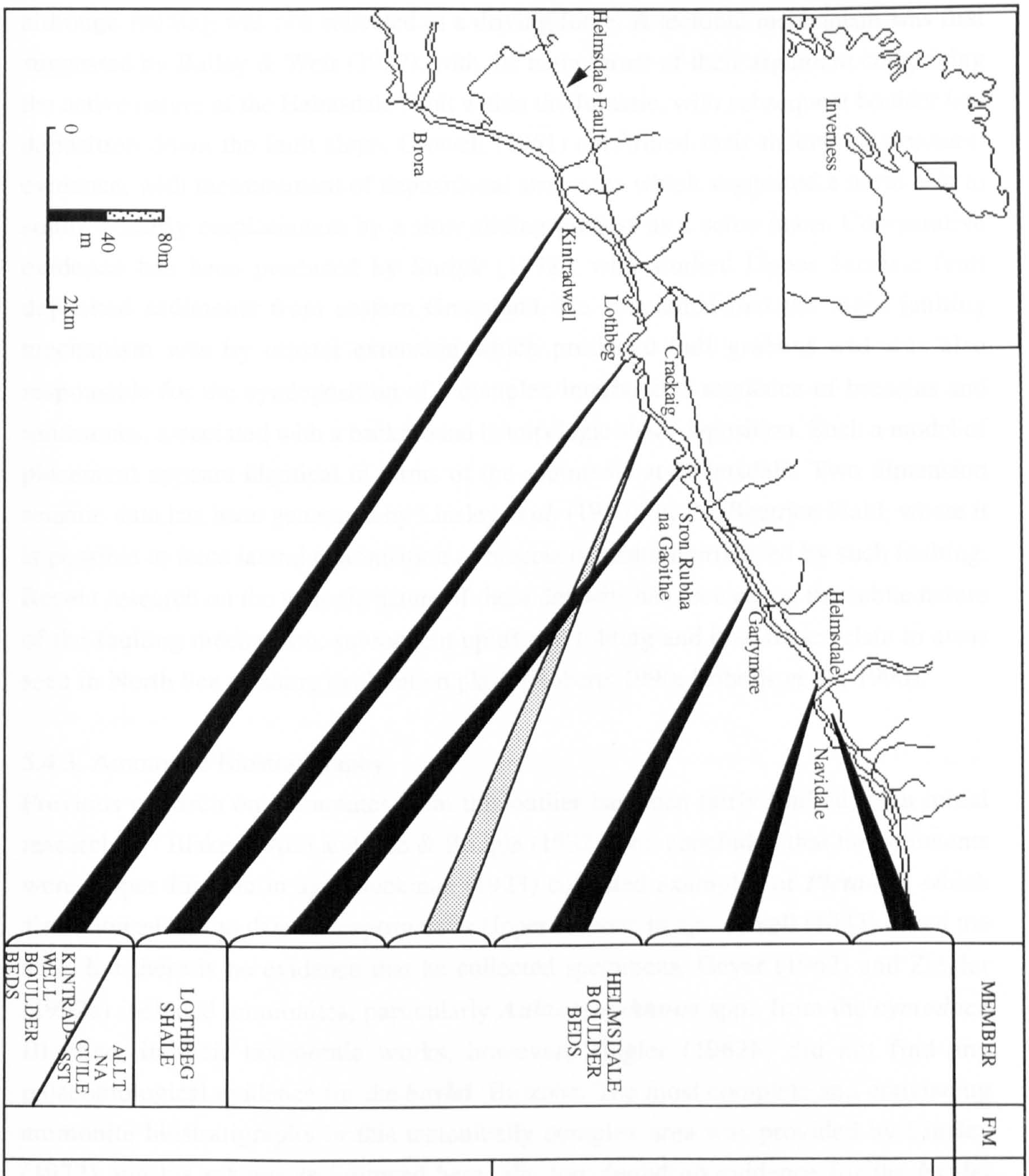


Figure 5.25. Locality map of Helmsdale, with collection sites, lithostratigraphy, ammonite biostratigraphy and sampling details

although faulting was not indicated as a driving force. A tectonic mechanism was first suggested by Bailey & Weir (1932), with the main thrust of their argument comprising the active nature of the Helmsdale Fault within the Jurassic, with subsequent boulder bed deposition down the fault slope. Crowell (1961) confirmed their theory by structural evidence, with measurement of depositional structures which suggested a north east to south westerly emplacement by a slow sliding process as a scree mass. Comparative evidence has been produced by Surlyk (1978), who studied Upper Jurassic fault deposited sediments from eastern Greenland. He concluded that the main faulting mechanism was by crustal extension which produced half grabens and was also responsible for the syndeposition of a complex interbedded sequence of breccias and sandstones, associated with a background hemipelagic shale deposition. Such a model of placement appears identical in terms of the sediments at Helmsdale. Two dimension seismic data has been generated by Linsley *et al.* (1980) for the Beatrice Field, where it is possible to trace lateral continuation of breccia deposition produced by such faulting. Recent research on the tectonic nature of these deposits has focused on the subtle nature of the faulting mechanism, subsequent uplift and folding and how these relate to areas seen in North Sea offshore exploration plays (Roberts 1990; Roberts *et al.*, 1990).

5.4.3. Ammonite Biostratigraphy

Previous research on ammonites from this outlier has been fairly limited, with initial research by Blake (1902) and Lee & Pringle (1932) who concluded that the sediments were Upper Jurassic in age. Buckman (1923) collected examples of ***Pictonia***, which also allowed him to date the exposures as Upper Jurassic in age. Arkell (1933) zoned the area, but there is no evidence that he collected specimens. Geyer (1962) and Ziegler (1962a) included ammonites, particularly ***Aulacostephanus*** spp., from the ***cymodoce*** Biozone, in their taxonomic works, however, Ziegler (1962b) did not find any palaeontological evidence for the ***baylei*** Biozone. The most complete and convincing ammonite biostratigraphy in this tectonically complex area was provided by Linsley (1972) and his scheme is followed here. He, too, found no evidence for the ***baylei*** Biozone. As some of the index ammonites appear not to be present at Helmsdale, Linsley (***op. cit.***) indicated that certain faunal assemblages could be used instead; for example at Kintradwell, ***Rasenia*** aff. ***involuta***, with associated Pictoniinae and cardioceratids, indicate that strata belong to the middle and upper part of the ***cymodoce*** Biozone. Also the ***eudoxus*** Biozone is not indicated by the biozonal form, but by the longer ranging ***Aulacostephanus volgensis***. Problems with using ammonites become apparent when attempting to corroborate the presence of the ***elegans*** Biozone and subsequent younger strata, due to the general rarity of index forms and the ammonite faunas themselves. This is particularly relevant with the ***pallasioides*** to ***albani*** Biozones. Consequently, in the uppermost Kimmeridgian and Portlandian, it has been argued (Barron, 1989) that palynomorph data has provided more detailed clues to the biozonal breakdown than the ammonites themselves. Brookfield (1973) indicated that this lack of ammonite control was an environmental effect due to the isolated palaeogeographical nature of the basin. Studies of ammonite fragments from oil company cores indicate that ammonites may be present in fairly large numbers further offshore (Callomon, 1975; Dyer, ***pers. comm.***, 1987). Boldy & Brealey (1990) suggest that there may also be a problem of consistent correlation of standard offshore and onshore palynological data with ammonite biozones, which may have serious implications for the implementation of such palynologically driven datings.

The oldest Kimmeridgian sediments developed at Helmsdale belong to the ***cymodoce*** Biozone; sediments between this and the older Middle Oxfordian exposed at Brora (as the Ardassie Limestone of ***densiplicatum*** Biozone age) are unexposed or lost by faulting. All of the Lower Kimmeridgian biozones developed at Helmsdale attain considerable thicknesses when compared with other similarly aged sediments throughout the British Isles, as well as at Eathie Haven to the south. This greater thickness must be related to rapid sedimentation and to the relatively large accommodation space, both of which were attained as a response to the syndepositionary tectonic activity associated with the Helmsdale Fault.

5.4.4. Lithostratigraphy

The lithostratigraphy is based the work of Linsley (1972), Neves & Selley (1975), Lam & Porter (1977) and Pickering (1983, 1984). This in turn is based upon the earlier surveys carried out by Murchison (1829a), Judd (1873), Lee (1925) and Lee & Pringle (1932). The lithostratigraphical members, which were logged in detail, were previously defined by the above authors as units and have been elevated in status here. They are described below in ascending stratigraphical order:-

(i). Kintradwell Boulder Bed Member (***cymodoce*** Biozone; 103m; Fig. 5.26, Log 1).
The boulder beds, developed at the base and particularly at the top of this member, are exposed along the foreshore at Kintradwell and are notable for large numbers of randomly oriented, angular blocks. These show relatively little evidence of erosion and are composed of mainly well bedded, yellowish grey, well sorted, quartz rich sandstones. Bailey & Weir (1932) were the first to highlight a similarity between these large clasts and the Caithness Sandstone now exposed to the west of the Helmsdale Fault. Other clasts include organic debris such as corals, bivalves, brachiopods and commuted organic debris, which were obviously derived from another area.

Boulder bed horizons are characteristically irregular and typically laterally discontinuous, extending from a few metres to several tens of metres in thickness. They also interdigitate with, and deform, relatively thick argillaceous sediments, ranging from black shales interbedded to soft siltstones and thin, hard, fine-grained calcareous sandstones. The calcareous sandstones are sometimes bioturbated.

This member was previously included within the Helmsdale Boulder Bed Member (as the Helmsdale Boulder Beds) by Neves & Selley (1975). However, present field

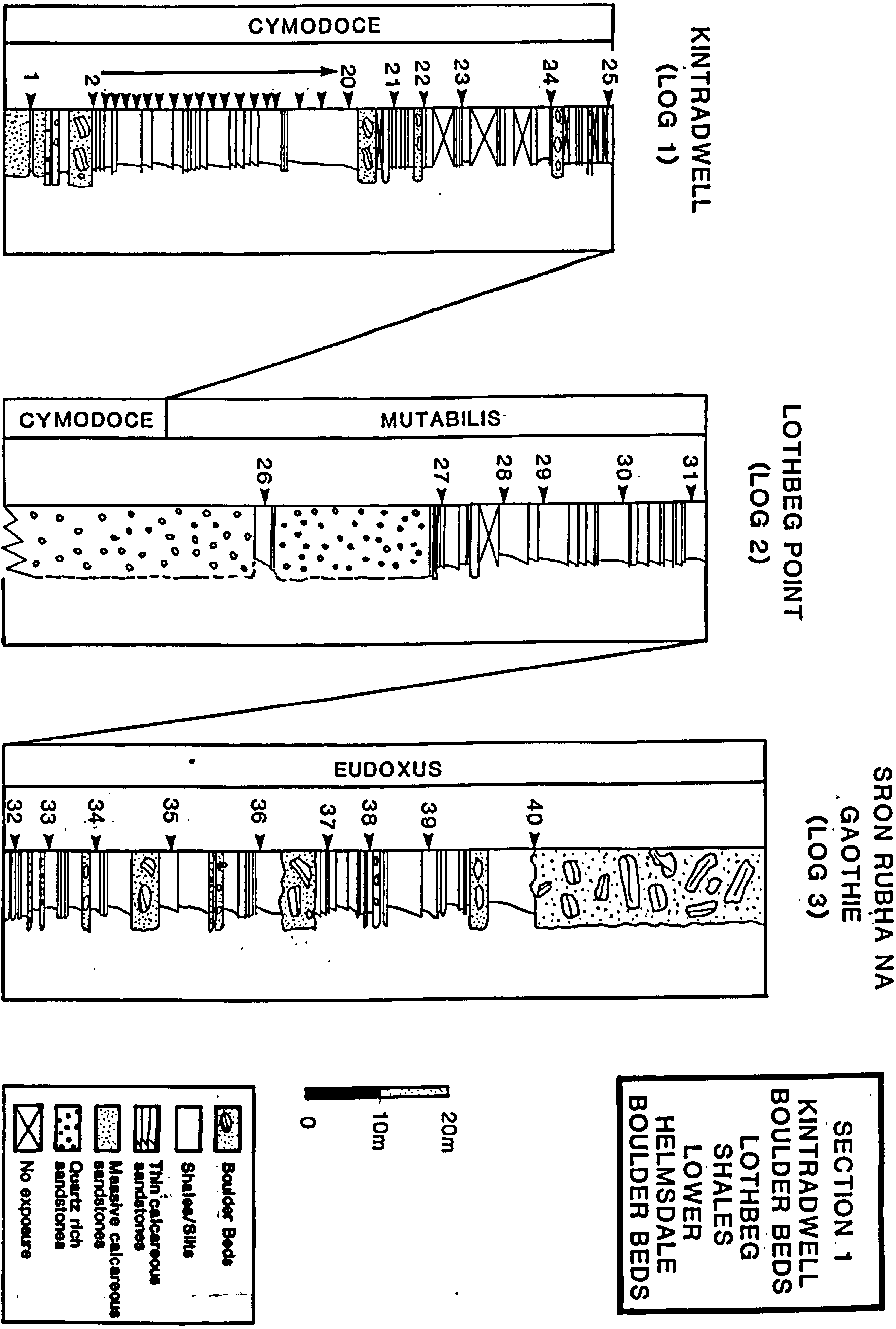


Figure 5.26. Detailed lithological logs and ammonite biozonation of the Kintradwell Boulder Bed, Lothbeg Shale and Lower Helmsdale Boulder Bed Members

mapping shows that there are two stratigraphically distinct boulder bed members, which can be separated by the Lothbeg Shale Member.

(ii). Allt na Cuile Sandstone Member (?***cymodoce-mutabilis*** Biozones; c.100m; Fig 5.26, Log 2).

This is a major unit exposed in an open fold from Lothbeg Point (GR. 96000948) to the north of Kintradwell and is composed of evenly to irregularly bedded, well sorted, white to orange, coarse to medium grained, quartz rich sandstones. These sandstones have erosive bases and sharp top surfaces. Internally, there is a coarse lamination with localised graded bedding associated with coarse, large scale cross-bedding and thin layers of carbonaceous rich debris. Occasional autobrecciation is seen in some of the basal units exposed in the low cliff sections along the foreshore. The age of this unit has not been exactly determined due to the scarcity of fossils. The upper part of the Allt na Cuile Sandstone Member is overlain by the Lothbeg Shale Member which contains ammonites indicative of a ***mutabilis*** Biozone age. Buckman (1923) collected representatives of ***Rasenia*** and ***Pictonia*** ammonites, whilst Brookfield (1976) tentatively identified the sparse bivalve and generally non-age diagnostic ammonite faunas to be representative of an age range between the basal ***cymodoce*** Biozone and the ***mutabilis*** Biozone. This conclusion has also been expressed by Linsley (1972), Lam & Porter (1977) and Pickering (1984).

Sedimentological data presented by, amongst others, Linsley (1972), Neves & Selley (1975) and Pickering (1984) suggest that these sandstones represent chasm deposits that bypassed the Helmsdale Fault scarp system. Taken in conjunction with the limited palaeontological data, this suggests that the Allt na Cuile Sandstone Member is, in part, coeval with the Kintradwell Boulder Bed Member. However, direct field evidence for this conclusion is lacking.

(iii). Lothbeg Shale Member (***mutabilis*** Biozone; c.40m; Fig. 5.26, Log 2).

This part of the sequence is equivalent to the Loth River Shales of Lam & Porter (1977). The foreshore and riverbank deposits at Lothbeg (GR. 96000948) comprise approximately 40 metres of mainly black to grey, carbonaceous rich shales and sandy shales interbedded with thin, hard, calcareous siltstones or fine grained, soft sandstones. In the lower section there is some intercalation with the Allt na Cuile Sandstone type facies, indicating that there was a fluctuating depositional regime present at this time.

Van der Burgh & Van Konijnenberg van Crittert (1984) studied the macrofloral presence and indicated that the environment was a subwave base, marine shale deposit which was influenced by a nearby delta with a diverse flora. However, they appear not to have taken into account the palaeoenvironmental evidence indicating that the majority of sediments were deposited during syndepositionary activity along the Helmsdale Fault. The Lothbeg Shale Member was probably deposited below the wave base in an extended period of acquiescence of this activity, with hemipelagic shale deposition being the most important component. The ammonite fauna is quite extensive in some beds and is indicative of a ***mutabilis*** Biozonal age.

(iv). Helmsdale Boulder Bed Member (***eudoxus-albani*** Biozones; c. 900m; Figs. 5.26-5.28, Logs 3-9).

The Helmsdale Boulder Bed Member represents an apparently similar facies to the lower Kintradwell Boulder Bed Member and is exposed from Sron Rubha na Gaoithe in the south to Dun Glas in the north. The ammonite data tends to become less reliable the younger the sediments become and there is a parallel increase in shallow water commuted fossil debris including spectacular clasts of coral. The bivalves associated with the boulder beds are dominated by epifaunal oyster taxa such as ***Nanogyra*** and ***Liostrea***. The background hemipelagic shale deposition appears to be not as prevalent as in the older member, being replaced by silty to sandy facies (the Tiger Stripe Facies Association of Pickering, 1983, 1984). ***In situ*** macrofauna of these deposits is rare and dominated by nests of the epifaunal/nektobenthic bivalve ***Buchia***. The boulder beds themselves are more pervasive laterally, being generally thicker and more common in terms of total sediment than the older Kintradwell Boulder Bed Member.

5.4.5. Previous Micropalaeontological Research

For such an important region, located in proximity to commercial activity in the North Sea Jurassic deposits, the Kimmeridgian and Portlandian of Helmsdale are remarkable for few previously published micropalaeontological studies, with the exception of those which have arisen as a consequence of this project (Gregory, 1989, 1992). Palynological studies, however, have been more extensive, with the initial reconnaissance work of Gitmez (1970) and Gitmez & Sergeant (1972) providing the impetus for further studies, which were initiated by the work of Lam & Porter (1977). All of these authors used a widely spaced sampling interval, but this still established the importance of using palynomorphs for biostratigraphical work along the Helmsdale outlier. Lam & Porter (1977) concluded that only Kimmeridgian sediments were present. Riley (1980) proved the presence of the Portlandian, based on 4 samples from the Helmsdale Boulder Bed Member. Tyson (1989) produced a palynofacies trend for deposits at Helmsdale in a comparison with the type Kimmeridgian at Dorset and with sequences offshore. He differentiated between proximal and distal facies based on the relative enrichment in black wood and dinocysts. A more detailed biostratigraphical study was carried out by Barron (1989), who produced a more refined and complete biozonation, which may prove to be more reliable than ammonite biozonation alone for the uppermost Kimmeridgian and Portlandian. A problem with his study was the lateral correlation of unsampled boulder beds, which were included in the same ammonite biozones. These correlations may prove to be incorrect, as the laterally discontinuous boulder beds cannot be followed with any great degree of certainty. His correlated horizons probably need more extensive lateral sampling.

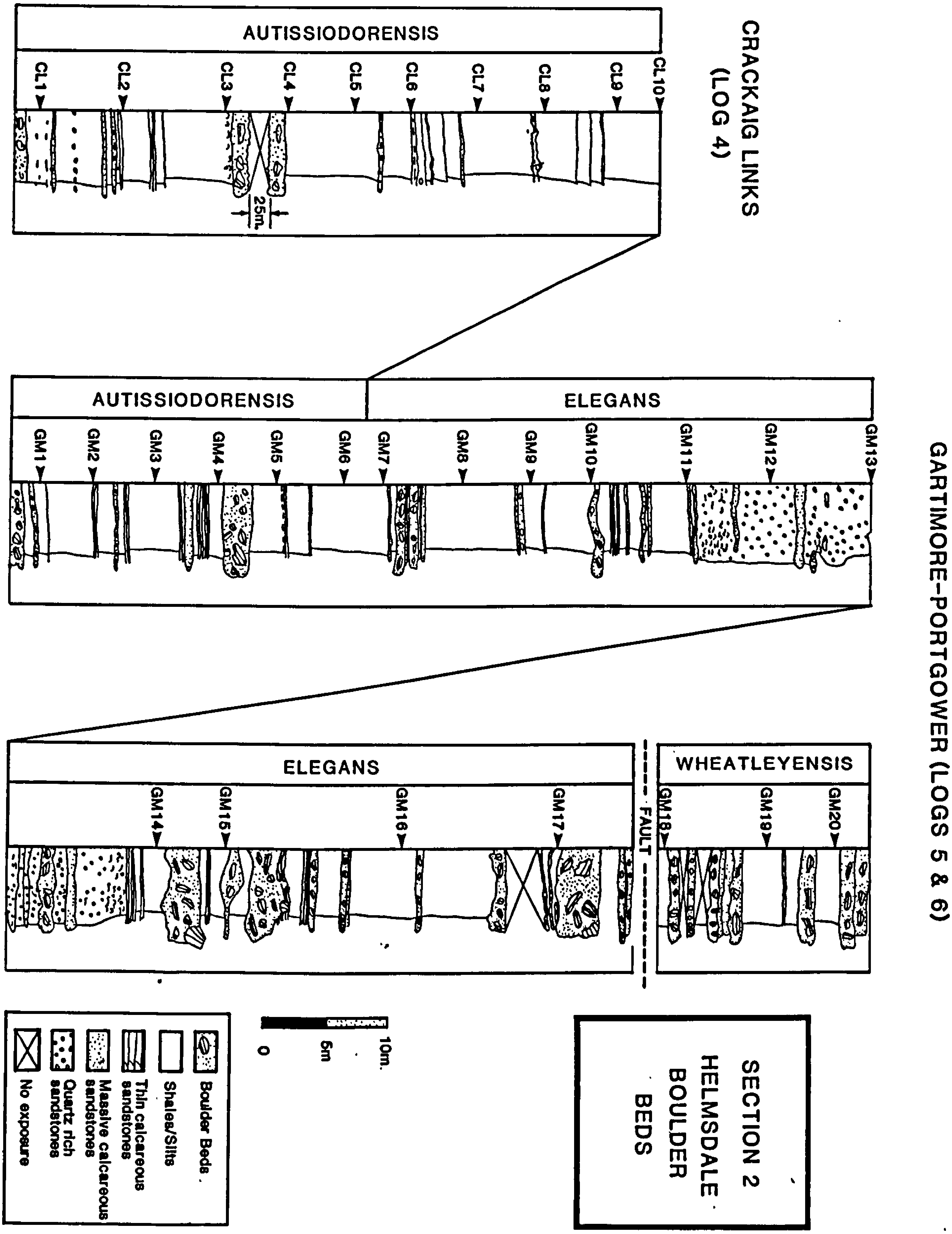


Figure 5.27. Detailed lithological logs and ammonite biozonation of the Helmsdale Boulder Bed Member with sampling points

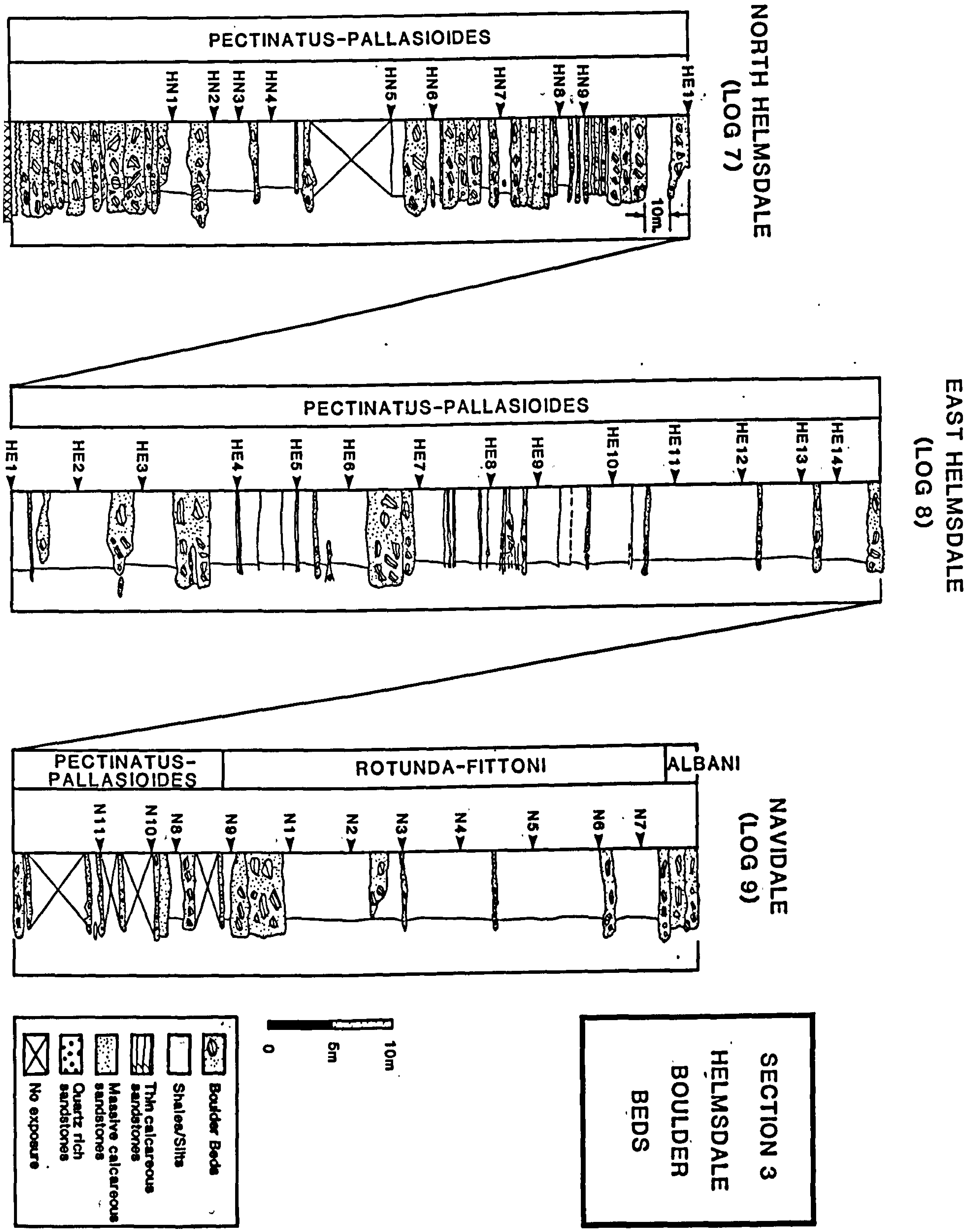


Figure 5.28. Detailed lithological logs and ammonite biozonation of the upper Helmsdale Boulder Bed Member with sampling points

5.4.6. Foraminiferal Distribution

Of the total of 109 samples collected, only those from the ***cymodoce*** to ***eudoxus*** Biozones (Fig. 5.29) provided evidence of foraminiferal and radiolarian recovery (Gregory, 1986, 1989). Samples from younger sediments (***autissiodorensis-albani*** Biozones) were characterised by an increasingly high abundance of sponge spicules, particularly triad and tetrad axons (see Plate 25 for illustration of axon types). This is unusual in North Sea deposits, as the most commonly recovered sponge spicule is the sub-spherical ***Rhaxella perforata*** (Plate 25, Fig. 1), which occurs, sometimes in great abundance, from the Callovian and Oxfordian at Brora (herein) and from the Oxfordian to Volgian of the North Sea offshore province (Partington ***et al.***, 1993a, b; Price ***et al.***, 1993).

The 40 samples from the ***cymodoce*** to ***eudoxus*** Biozones which provided all the microfauna (Gregory, 1986, 1989), were also notable in that 20 were barren (Figs. 5.29, 5.30). These barren samples are concentrated in the ***mutabilis*** and ***eudoxus*** Biozones of the Lothbeg Shale Member and the basal Helmsdale Boulder Bed Member. The assemblages recovered are typified by low abundance and low diversity, with only 25 species recovered in total; all samples that yield microfauna exhibit low α index values, with the majority being in the range 3 to 4, and a maximum of 6 occurs within the ***cymodoce*** Biozone of the Kintradwell Boulder Bed Member. This member also provides the most consistent microfaunal recovery, with the inception of taxa in the basal ***cymodoce*** Biozone (at sample 3). The actual faunal composition remains relatively consistent, but there are gradual changes in the principal faunal components. All samples are dominated by calcareous taxa, particularly the spirillinid ***Spirillina tenuissima*** and, to a lesser extent, robust and costate lagenids. Most samples contain less than 14 species. Recovery from the basal part of the ***cymodoce*** Biozone (samples 3 to 9) is initially dominated by ***Lenticulina varians*** and ***Spirillina tenuissima*** and to a lesser extent ***S. infima***, ***Pseudonodosaria vulgata*** and ***Planularia beierana***, associated with rare specimens of the agglutinated foraminiferids ***Haplophragmoides kingakensis*** and ***H. canui***. Thereafter, particularly from sample 13, ***S. tenuissima*** dominates the residues, with ***Spirillina infima***, ***Eoguttulina liassica***, ***L. varians***, ***P. vulgata*** and the costate ***Nodosaria raphanistriformis*** being relatively common. Recovery is more sporadic within the upper part (e.g. samples at 22 and 25) of the Kintradwell Boulder Bed Member, but ***S. tenuissima*** still dominates the foraminiferal faunas, with relatively common examples of ***S. infima***, ***Conicospirillina trochoides*** and robust, sometimes costate, calcareous taxa including ***Lenticulina varians***, ***Citharina*** spp., ***Frondicularia franconica***, ***F. moelleri*** and ***Planularia kintradwellensis***. Agglutinated taxa are rare, being represented by ***Haplophragmoides canui***, ***H. kingakensis***, ***Verneuilinoides tryphera*** and ***Reophax helvetica***.

Recovery from the Lothbeg Shale and Helmsdale Boulder Bed Members,

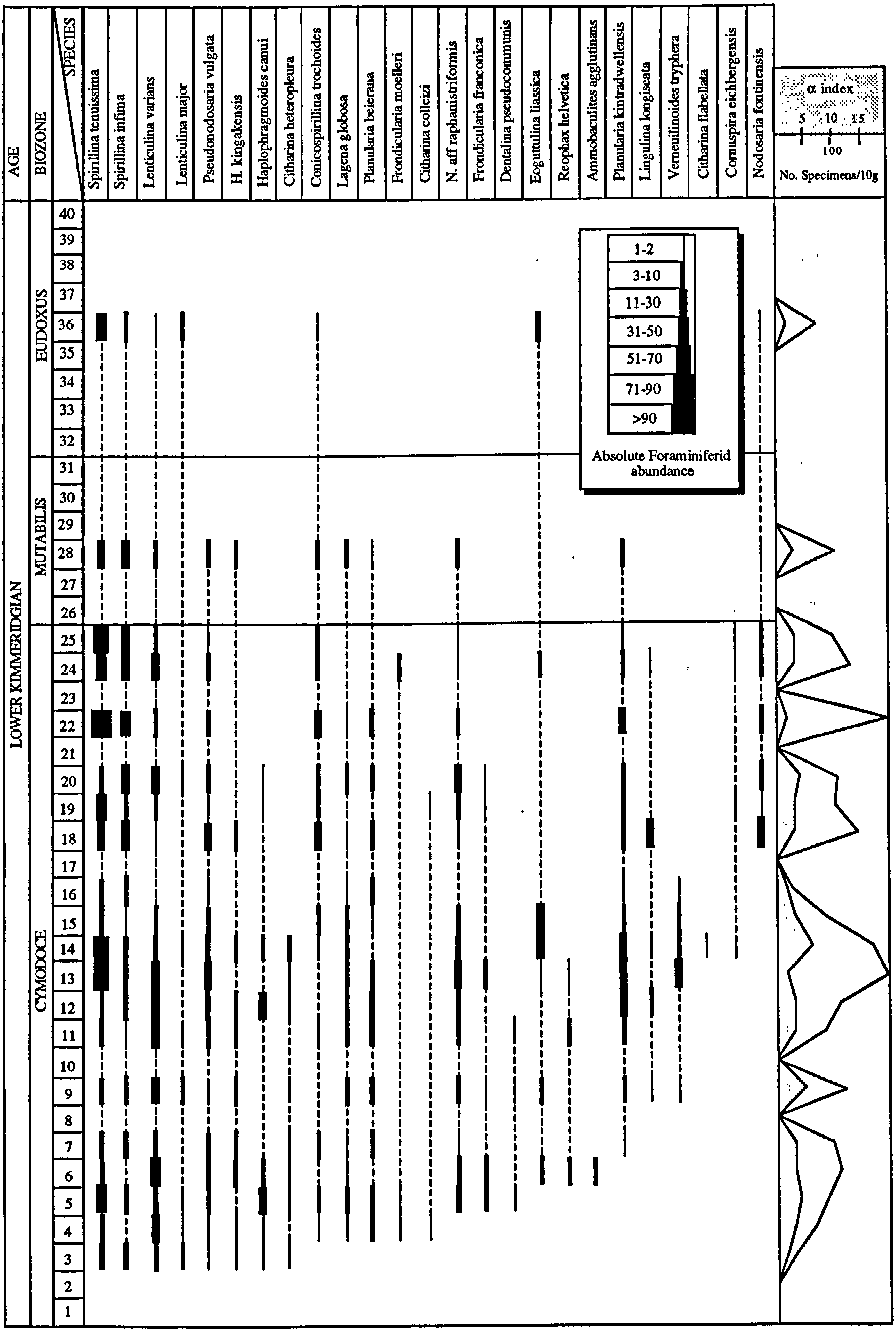


Figure 5.29. Foraminiferal distribution range chart for the Kimmeridgian of Helmsdale plotted with diversity and abundances

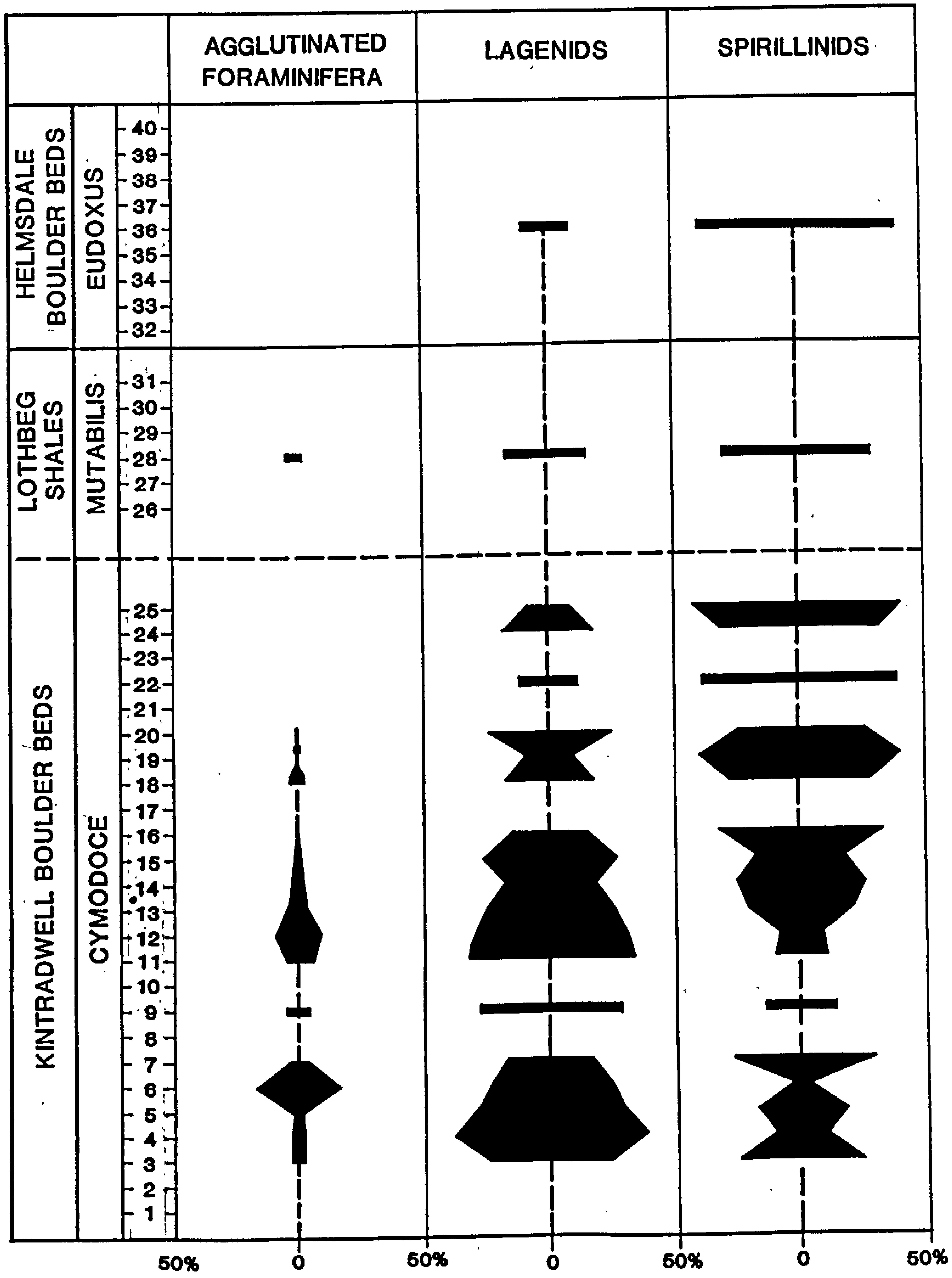


Figure 5.30. Percentage distribution of the major foraminiferal groups at Helmsdale plotted against the bio and lithostratigraphy schemes

covering the ***mutabilis*** and ***eudoxus*** Biozones, is limited to a single sample from each biozone. Each sample yielded a fauna dominated by ***S. tenuissima*** and ***S. infima***, with decreasing representatives of other calcareous and agglutinated taxa; diversities are low, being in the α index range of 2-3.

In conclusion, there is an initial proportional dominance of lagenids within the basal ***cymodoce*** Biozone, after which there is an ever increasing proportion of ***S. tenuissima*** associated with ***S. infima***. All the assemblages exhibit low diversities, generally in the range of α indices of 2 to 4, and have an overall dominance of spirillinids. The other suborders are rare, with agglutinated tax being commonest. Miliolids are very rare, represented only by ***Cornuspira eichbergensis***, and there are no robertinids.

The biostratigraphical breakdown and correlation within the Inner Moray Firth and with the Staffin Bay succession is discussed in Chapter 7.

5.4.7. Radiolarian Distribution

Radiolarian recovery from Helmsdale (Fig. 5.31), as for the foraminifera, is limited to the Kintradwell Boulder Bed Member (***cymodoce*** Biozone) and the Lothbeg Shale Member (***mutabilis*** Biozone) and also follows a discontinuous distributional pattern. Basically, there are several pulses, initially commencing several metres into the ***cymodoce*** Biozone between samples 5 and 11. This initial pulse is marked by the introduction of the nassellarians ***Parvicingula blowi*** and ***P. blowi*** ssp. A, which are numerically the most important taxa. ***Hsuum*** sp. 1, ***Orbiculiforma mclaughlini, Spongodiscus*** sp. 4, ***Parvicingula*** sp. A, ***Cenosphaera*** sp. 1 and ***Stichocapsa devorata*** are all subsidiary and have first appearances between samples 5 and 7. The basal part of the pulse is marked by moderate diversity and abundance, whilst the upper part is distinguished by low diversity and abundance.

The second pulse occurs in samples 15 and 16 (intra ***cymodoce*** Biozone) and is marked by the highest diversities and abundances of all the pulses, with ***P. blowi*** ssp. A dominating. ***P. blowi*** is still important, along with ***Hsuum*** sp. 1; ***Cenodiscus*** sp. A has a final appearance at sample 15.

There are three other unconnected minor influxes, occurring as single sample points and all have generally low diversities and moderate abundances. The first of these influxes occurs at sample 20 with only ***P. blowi*** ssp. A and ***P. blowi*** present. The second influx occurs at sample 24 near the ***cymodoce/mutabilis*** boundary and is again dominated by ***P. blowi*** and ***P. blowi*** ssp. A, with ***P.*** aff. ***jonesi*** and ***Stichocapsa devorata*** disappearing. The final pulse occurs in the ***mutabilis*** Biozone within the Lothbeg Shale Member, with ***P. blowi, P. blowi*** ssp. A and ***Cenosphaera*** sp. 1 dominating. This final pulse is marked by moderate diversities and abundances.

Nassellarian taxa dominate all the samples studied.

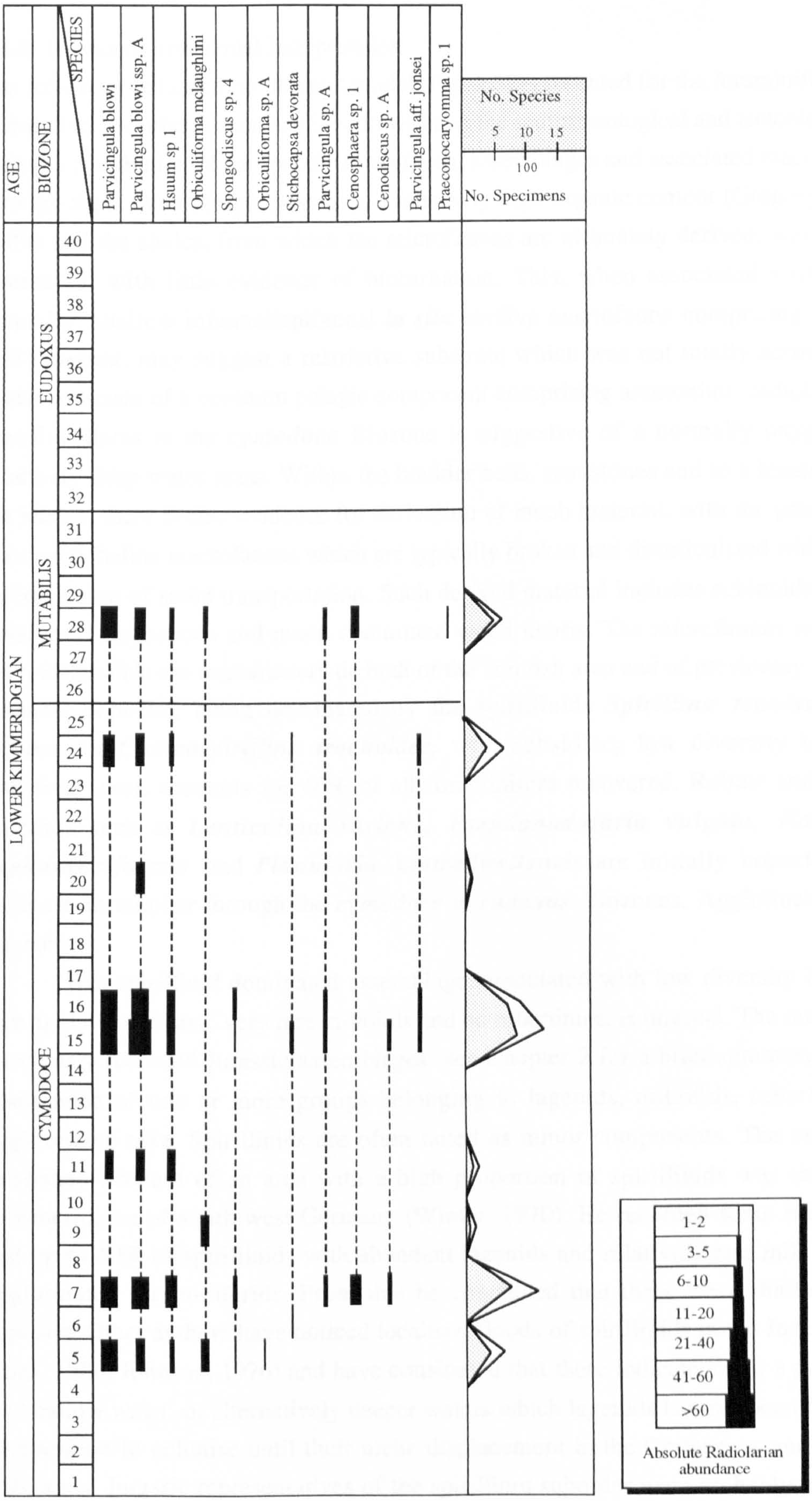


Figure 5.31. Radiolarian distribution, diversity and abundances for the Kimmeridgian of Helmsdale

5.4.8. Palaeoenvironmental Interpretation

The following palaeoenvironmental model (Fig. 5.32) presented for the foraminiferal and radiolarian assemblage composition, draws upon the sedimentological and tectonic setting with the distribution of the specific microfaunal assemblages and associated macrofaunas through time. Each sample possesses a relatively high organic content (Gregory, 1986, 1989) and the shales, from which the microfaunas are ultimately derived, were finely laminated, with little evidence of bioturbation. This, when associated with a low diversity, shallow infaunal/epifaunal ***in situ*** bivalve macrofauna comprising ***Buchia*** and ***Liostrea***, may suggest a restrictive substrate which was not totally aerobic. The initial presence of a common pelagic component comprising ammonites, radiolaria and dinoflagellates in the ***cymodoce*** Biozone is suggestive of a normally oxygenated, relatively deep water mass. Within the boulder beds, sandstones and to a lesser degree the shales, there is also evidence for derivation of much material, with the presence of good stenohaline macrofaunas which are typically broken and disarticulated which must be indicative of some transportation. Such derived material includes echinoids, corals, bivalves, brachiopods and much commuted wood debris. The microfaunas recovered from Helmsdale are uncharacteristic both of the Scottish area and of previously reported Jurassic deposits, being dominated by the spirillinids ***Spirillina tenuissima, S. infima*** and ***Conicospirillina trochoides,*** with subsidiary low diversity lagenids. The first taxon accounts for 40% of all foraminifera recovered. Robust and costate lagenids such as ***Lenticulina varians, Pseudonodosaria vulgata, Nodosaria raphanistriformis*** and ***Planularia kintradwellensis*** are initially important, but decrease in number through the ***cymodoce*** to ***eudoxus*** Biozones. Agglutinating taxa are rare.

This spirillinid dominated assemblage, associated with low diversity lagenids, rare agglutinated taxa, very rare miliolids and no robertinids, is unusual. The majority of previously recorded Jurassic assemblages (see Chapter 2 for a brief summary) record dominance of one or more groups belonging to lagenids, miliolids, robertinids or agglutinated taxa. Spirillinids are often noted as minor components. The only other published account of an area with a high proportion of spirillinids was the Lower Kimmeridgian of south west Germany (Winter, 1970). He recorded some sites which had up to 40% of spirillinids with abundant lagenids and relatively rare miliolids and agglutinated foraminiferids. From this he concluded that these were shallow water deposits. Other authors have noticed localised floods of spirillinids in the Jurassic (e.g. Stam, 1986; Johnson, 1976) and have considered that these indicate either a preference for shallow water, or alternatively deeper waters which lagenids had not been forced by competition to colonise until their niche displacement in the Cretaceous and younger sediments. Jurassic representatives of the spirillinid suborder were probably present in similar habitat as today, where they dominate in areas with material such as seaweed upon which they are attached (e.g. Myers, 1935, 1936; Brasier, 1975; Haynes, 1981). Within Recent sediments, they also as a group appear to have a well defined, relatively

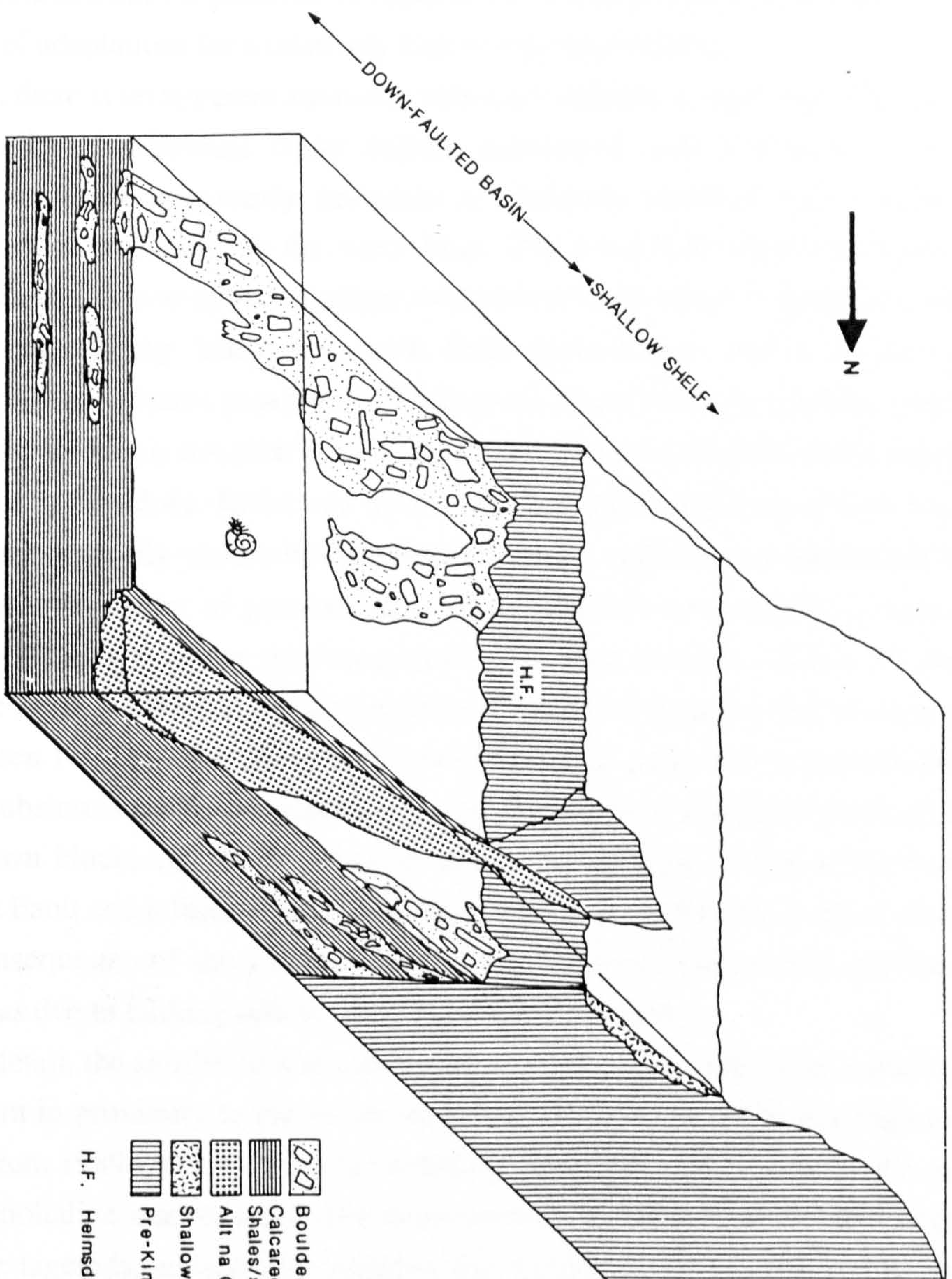


Figure 5.32. Palaeoenvironmental model for the Helmsdale region during the Kimmeridgian (after Gregory, 1989)

static niche range and requirements, probably indicative of a shallow, moderate energy, oxygenated environment. Supportive evidence at Helmsdale for such an environment and substrate comes from the presence of lagenids, which were also robust and often costate, indicative of adaptations for a relatively high energy environment.

So, there is an apparent anomaly, with a microfauna comprising radiolaria, which usually indicates moderate water depths, associated with a benthic foraminiferal assemblage which apparently indicates a relatively shallow water, high energy environment, in proximity to the wave base. This combined microfauna additionally occurs within a low energy, hemipelagic, bituminous shale which is apparently anaerobic to dysaerobic, being laminated, with little bioturbation and a limited ***in situ*** infaunal/epifaunal bivalve population. Evidence of microfaunal dissolution, either ***in situ*** or post-depositional, is not seen in etching of either the microfaunas, or the macrofaunal elements in the residues. Restricted dysaerobic substrate conditions which are high in organic carbon usually yield a low/moderate diversity agglutinated dominated fauna, as shown by the summary of previous research in northern areas of the Jurassic Boreal Province. Therefore, when the integrated facies and tectonic setting of the active Helmsdale Fault is taken into consideration, it becomes apparent that there must have initially been two separate palaeoenvironments. These palaeoenvironments possessed differing substrate conditions, representing on the one hand a shallow shelf, situated on the upthrown block, and on the other, a basinal hemipelagic setting at the foot of the Helmsdale Fault scarp face. What is preserved today, along the foreshore of Helmsdale, is as a consequence of the shallow water deposits being transported into the deeper basinal areas due to faulting activity during the Kimmeridgian.

In detail, the spirillinid dominated foraminiferal faunas represent a shallow water environment in proximity to the 'palaeoshoreline' (also suggested by the high miospore count, Barron, 1989). Normal marine conditions prevailed, as indicated by the relatively diverse stenohaline macrofaunas. The dominance of spirillinids, associated with robust and costate lagenids, additionally suggests that the substrate was affected by the wave base and may have been a relatively high energy environment. The spirillinids were probably attached to organic material present, whilst the lagenids were adapted to buffeting in this shallow environment. The only miliolid recovered, ***Cornuspira eichbergensis***, is interestingly also an attached form. Its test shape is often distorted as a consequence of its attached mode of life. These faunas were then sporadically removed from this upthrown block environment, with transport initiated either by the periodic seismic activity along the Helmsdale Fault, or by climatic or tidal factors. Removal from this shallow environment occurred by gravity-induced turbidite flows down the Helmsdale Fault scarp into the down faulted basin. This accounts for the mixed shallow water foraminiferal assemblages, associated with deeper water, hemipelagic sediments and common radiolarian faunas. The boulder beds, silts, calcareous sands and the generally degraded macrofaunas were derived in the same fashion. The sands which form the Allt na Cuile Sand Member bypassed this fault scarp and represented chasms deposits

(Neves & Selley, 1975; Pickering, 1983, 1984). The increasing incidence of spirillinids through the ***cymodoce*** to ***eudoxus*** Biozones may indicate a 'relative' shallowing or niche contraction affecting the upthrown block. Whether this regression was due to a sea-level drop, or as a consequence of tectonic uplift of the fault block, is difficult to ascertain.

The substrates present at the fault scarp base, represented as a half graben, were dominated by the basinal hemipelagic shales with a high associated detrital organic content. These sediments were probably poorly oxygenated as suggested by their laminated nature and by the presence of 'oxygen deficient' indicator bivalves such as ***Buchia*** (as outlined by Oschmann, 1988). Bioturbation, when present, occurs mainly within the thin calcareous sandstones and may represent flushing of the basinal deposits by sporadic turbidites. This allowed the initial establishment of highly opportunistic burrowing organisms before the reinstatement of the restrictive substrate conditions, which subsequently eliminated them. Dissolution of the derived calcareous taxa may have occurred in such an environment, but the rapid deposition of quantities of derived material may have lessened the incidence of such an effect.

The absence of a relatively diverse agglutinated dominated microfauna, which appear able to colonise Jurassic oxygen deficient environments (as shown by the relatively large number of reports from northern Boreal deposits, see Chapters 2 and 7), suggests that this basinal substrate may have been anaerobic at the sampling levels chosen. The very small number of agglutinated taxa recovered could be derived from either the shallow water areas, or represent this group's attempt at colonising the shales.

The initial presence of ammonites and radiolaria within the ***cymodoce*** Biozone indicates that the general water column conditions were relatively deep, at least oxygenated and capable of supporting a 'normal' planktonic fauna. The actual survival of a fossil radiolarian fauna from dissolution in a reducing environment was probably due to rapid burial. De Wever (1983) noted such a correlation for radiolarian test survival in organic rich sediments. However, post burial diagenetic influences still acted upon the siliceous test, as many of the radiolaria show evidence of alteration to calcite or even secondary opaline silica.

The decrease in radiolarian occurrence from the upper part of the ***cymodoce*** Biozone and through the ***mutabilis*** Biozone, which mirrors the foraminiferal data, may indicate a restriction of the environment either by shallowing, or by oxygen deficiency. However, the absence of radiolaria from the Helmsdale Boulder Bed Member, covering the interval from the ***eudoxus*** Biozone to the ***fittoni*** Biozone, requires more consideration. This is because, in the North Sea commercial sector, radiolarian faunas have been consistently recovered from sediments equivalent to the deposits at Helmsdale ranging from the Lower Kimmeridgian through to the Ryazanian (e.g. Dyer & Copestake, 1989; Partington ***et al.***, 1993a, b; Price ***et al.***, 1993). Siliceous dissolution could be invoked as a possible contributory factor, as it has been remarked elsewhere that silica is unstable and dissolution of sponge spicules is an established occurrence in modern sediments (Land, 1976). However, most of the samples collected, from the ***eudoxus*** Biozone upwards, yielded abundant sponge spicules comprising tetrad/triad axon morphologies (see Plate 25 for illustration). These could not have been moved too far as they show few signs of abrasion and their 'spiky' morphology would probably hinder any transport if a substrate was present. Therefore, a possible explanation for the lack of radiolarian faunas is that the accommodation space adjacent to the Helmsdale Fault scarp, which forms the present day outcrop, had gradually been filled by the boulder beds and associated sediments. This created a relatively shallow water environment which precluded radiolarian faunas. Additionally, the lack of a benthos, such as microfauna, and the general scarcity of ammonites also point to the possibility of the development of an oxygen deficient environment, which would also be detrimental to radiolarian colonisation.

Regional evidence of background eustatic Jurassic sea-levels from the Moray Firth Basin and the North Sea, derived by Partington ***et al.*** (1993a, b) from an extensive offshore database, appears to show relative deepening from the Middle Oxfordian through to the ***eudoxus*** Biozone of the Kimmeridgian. Subsequently, during the ***eudoxus*** Biozone, there was a deepening followed by moderately deep basinal environments. Relative shallowing occurred in the North Sea area during the Portlandian ***fittoni*** Biozone.

This pattern has some relevance for the Helmsdale area, but is a regional pattern derived for the deeper offshore Jurassic deposits of the North Sea. Helmsdale represents the margin of this regional area and as such was more greatly influenced by slope morphology and tectonic activity. Additionally, the accommodation space occupied by the studied area probably decreased as a consequence of material derived by tectonic activity in proximity to the Helmsdale Fault. This gave rise to an increasing influence of shallow waters as indicated by sponge spicules and coarser components of the boulder bed facies type. Overall, the thickness of the water column on the margins would influence the distribution of radiolaria and ammonites. This probably decreased from its greatest development during the ***cymodoce*** Biozone. It must be emphasised however, that this conclusion should be treated with caution as the sampling interval was rather large in the upper parts of the Helmsdale Boulder Bed Member.

5.4.9. Conclusions

Specific conclusions are presented here concerning the Helmsdale section, whilst detailed conclusions covering the biostratigraphical and generalised palaeoenvironmental correlation of this area with Eathie Haven and Staffin Bay are presented in Chapter 7.

The Helmsdale area provides some of the thickest onshore Upper Jurassic deposits and is interesting both tectonically and as a marginal representative of the North Sea offshore basins. During the Lower Kimmeridgian, two distinct palaeoenvironments were created by submarine faulting along the Helmsdale Fault. The first, represented by the upthrown block, was a shallow water, shelf environment which has since been removed by erosion. The second was a deeper water, half graben type basin, whose sediments are now exposed along the Sutherlandshire coast. These palaeoenvironments were separated by the Helmsdale Fault scarp. Periodic tectonic activity, possibly associated with climatic effects, derived material from the shallow into the deeper environment. This material included the boulder beds and sandstones as well as the fossil debris including foraminifera.

Productive samples from Helmsdale yielded both benthic foraminifera and planktonic radiolaria. The foraminiferal assemblages, which occurred initially in the ***cymodoce*** Biozone and sporadically range up to the ***eudoxus*** Biozone, are characterised by low diversities and abundance. They are dominated by spirillinids, associated with robust and costate lagenids, which indicate derivation from a shallow water palaeoenvironment, which was additionally probably high energy, but oxygenated. This is corroborated by the benthic macrofauna which includes corals. An increasing proportion of spirillinids associated with a decrease in lagenids and the rare agglutinated taxa through the ***cymodoce*** to ***eudoxus*** Biozones may indicate a shallowing on the upthrown block. The juxtaposed basinal deposits were probably dysaerobic/anaerobic and restrictive, as indicated by the low diversity ***in situ*** epifaunal bivalves, and probably did not have a ***in situ*** benthic microfauna. Into this environment were deposited the shallow water foraminifera and the radiolarian microfauna, the latter of which characterise the ***cymodoce*** and ***mutabilis*** Biozones. The radiolarian faunas are dominated by nassellarians, which suggests that a moderate water depth was attained, that the upper water column at least was oxygenated and that there was connection to the more distal and possibly deeper water deeper North Sea areas (e.g. Eathie Haven, North Sea).

Therefore, the microfauna preserved represents a mixture of shallow water foraminifera with deeper water radiolarians. Radiolaria obviously could also have been present in the shallower waters, but these will have been also derived into the basinal deposits. A decrease in foraminiferal and particularly radiolarian faunas from the ***eudoxus*** Biozone may indicate either shallowing, or imposition of more restrictive water conditions, the latter of which is seen in the more distal North Sea area (Tyson, 1989). The presence of abundant sponge spicule debris may suggest the former hypothesis, but very little is known about Jurassic sponge palaeoecological requirements.

5.5. Eathie Haven, Black Isle, Cromarty

5.5.1. Introduction

A diminutive outcrop of Lower Kimmeridgian strata exists on the Black Isle at Eathie Haven (GR. 77796325; Fig. 5.33). It is perhaps best known for its association with the nineteenth century geologist/lay preacher Hugh Miller from Cromarty who, in a series of classic articles and books (1847, 1854, 1857, 1869), covered the rich fossil plant and fish remains. Part of the reason for the lack of detailed published work probably lies in the inaccessibility of the foreshore outcrop which occurs at the foot of steep 600ft cliffs. The succession was logged in detail for this study and 45 samples were collected for micropalaeontological analysis and reconnaissance.

5.5.2. Geology

Eathie Haven is one of the narrow coastal strips that bound the Inner Moray Firth Basin and is of comparable age to the deposits further north at Helmsdale. Jurassic outcrop at Eathie Haven lies in proximity to the Great Glen Fault, whilst Helmsdale is bound to the east by the Helmsdale Fault. The cliffs surrounding the foreshore outcrop comprise Moine Gneiss/Schists and Old Red Sandstone which extend in a broad syncline over the Black Isle. Shales and limestones of Jurassic age have been faulted against these older rocks.

The original palaeogeographical position of Eathie Haven during the Jurassic, with regard especially to Helmsdale, has been open to debate until recently. Sykes (1975a, b) and McQuillin *et al.* (1982) suggested that reinstatement of the site's original position could be judged by the removal of the proposed Jurassic movement along the Great Glen Fault . This would place Eathie Haven as a juxtaposed, deeper water deposit to the proximal shallower water deposits at Helmsdale during the Lower Kimmeridgian. However, this view of strike-slip movement during the Jurassic is probably incorrect, as suggested by the more recent studies which have utilised detailed offshore seismic data (Underhill, 1991a, b; Underhill & Brodie, 1993; Underhill *pers. comm.*, 1991, 1992). The deposits at Helmsdale and Eathie Haven still, however, represent a respective proximal/distal depositional pairing, as suggested by the micro and macrofaunal distribution and sedimentological evidence.

The whole section comprises clays, shales and limestones, all of which are interrupted by minor faulting. Some of the faulting appears to have been syndepositionary, or occurred soon after burial, producing prominent 'neptunian' sandstone dykes, the presence of which were noted by Strickland (1839), Miller (1859) and Waterston (1950). The majority of minor faulting, noted during logging, cuts these sedimentary dykes and appears to be related to post Cretaceus tectonic activity (Thompson & Underhill, 1993)

The foreshore at Eathie Haven is dominated by a fairly uniform, steeply dipping succession of organic rich shales some 45m in thickness, which can be divided into members by distinctive lithology.

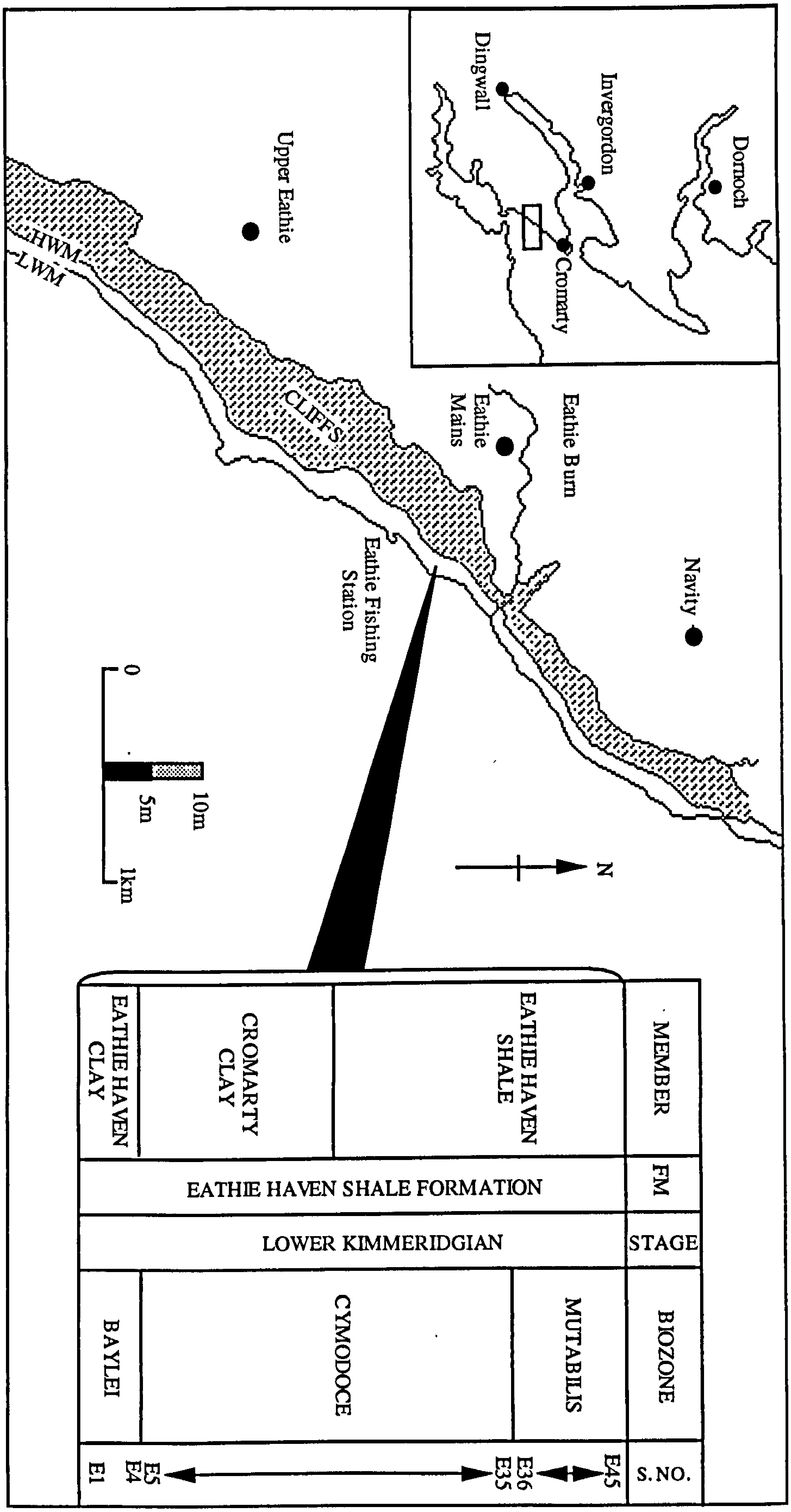


Figure 5.33. Locality map of Eathie Haven with collection sites, lithostratigraphy, ammonite biostratigraphy and sampling details

5.5.3. Ammonite Biostratigraphy

Murchison (1829a, b) visited the area, but concentrated on the more extensive outcrops at Helmsdale. He concluded that the shales and limestones at Eathie Haven were equivalent to the Lias at Watchet Bay in England and formed the base of the Jurassic in East Scotland. Judd (1873) produced the first general geological sketch of the strata at Eathie Haven and correctly indicated that these deposits were Upper Oolite in age and equivalent to the Middle and Lower Kimmeridgian of England. Seward and Bankroft (1913) studied the Jurassic macroflora, recording several new species of plants. Buckman (1923), from a study of the ammonites, estimated the age of these deposits to be Lower Kimmeridgian from the presence of rasenid ammonites, as did Lee (1925) and Lee and Pringle (1932), who assigned these deposits to the ***cymodoce*** and possibly ***mutabilis*** Biozones.

Waterston (1950, 1951) was the first person to map these deposits in detail. He refined the succession and included the basal part of the section in the top of the ***baylei*** Biozone. The distribution of ammonites compare favourably with the comments of Arkell (1935) and Ziegler (1962b) on the suitability of ***Rasenia*** as a biozonal form for the ***cymodoce*** Biozone. Ziegler (1962a) collected ammonites from Eathie and his results agree with those of Waterston (***op cit.***). Sykes (1975a, b), in his work on the ammonite faunas and facies types of the Middle and Upper Jurassic of Scotland, mentions the very small outcrop at Bow Boy Skerry, some 100m from the main outcrop which is usually covered by the tide and was dated by ammonites as Upper Oxfordian in age.

Birkelund ***et al.*** (1978) compared the distribution of rasenid ammonite faunas from Norway to Market Rasen, East Greenland and Scotland with the possibility of dividing the ***cymodoce*** Biozone into two discrete sub-biozones; the lower ***cymodoce*** Sub-biozone and the upper ***uralenis*** Sub-biozone. However, this division appears to be difficult to recognise within the Eathie Haven area. Birkelund ***et al.*** (1983) indicated that the base of the ***mutabilis*** Biozone occurred between the prominent limestone beds in the bituminous rich shale.

5.5.4. Lithostratigraphy

As there is no formal lithostratigraphy erected for the sediments present, a new scheme is proposed here. The entire exposed section is designated the Eathie Haven Shale Formation. Unfortunately, the lower boundary is fault bounded and the upper boundary cannot be seen due to lack of foreshore exposure seawards. This formation was logged in detail and is at least 45 metres thick; it comprises three proposed members, which are described in ascending stratigraphical order below:-

(i). Eathie Haven Clay Member (***baylei*** Biozone, c.4m; Fig. 5.34).

The base of this member cannot be seen at outcrop as it abuts the Old Red Sandstone at a faulted contact. Lithologically, it comprises green/grey calcareous clays and shales interbedded with discontinuous limestones and calcareous nodules. Macrofaunal elements

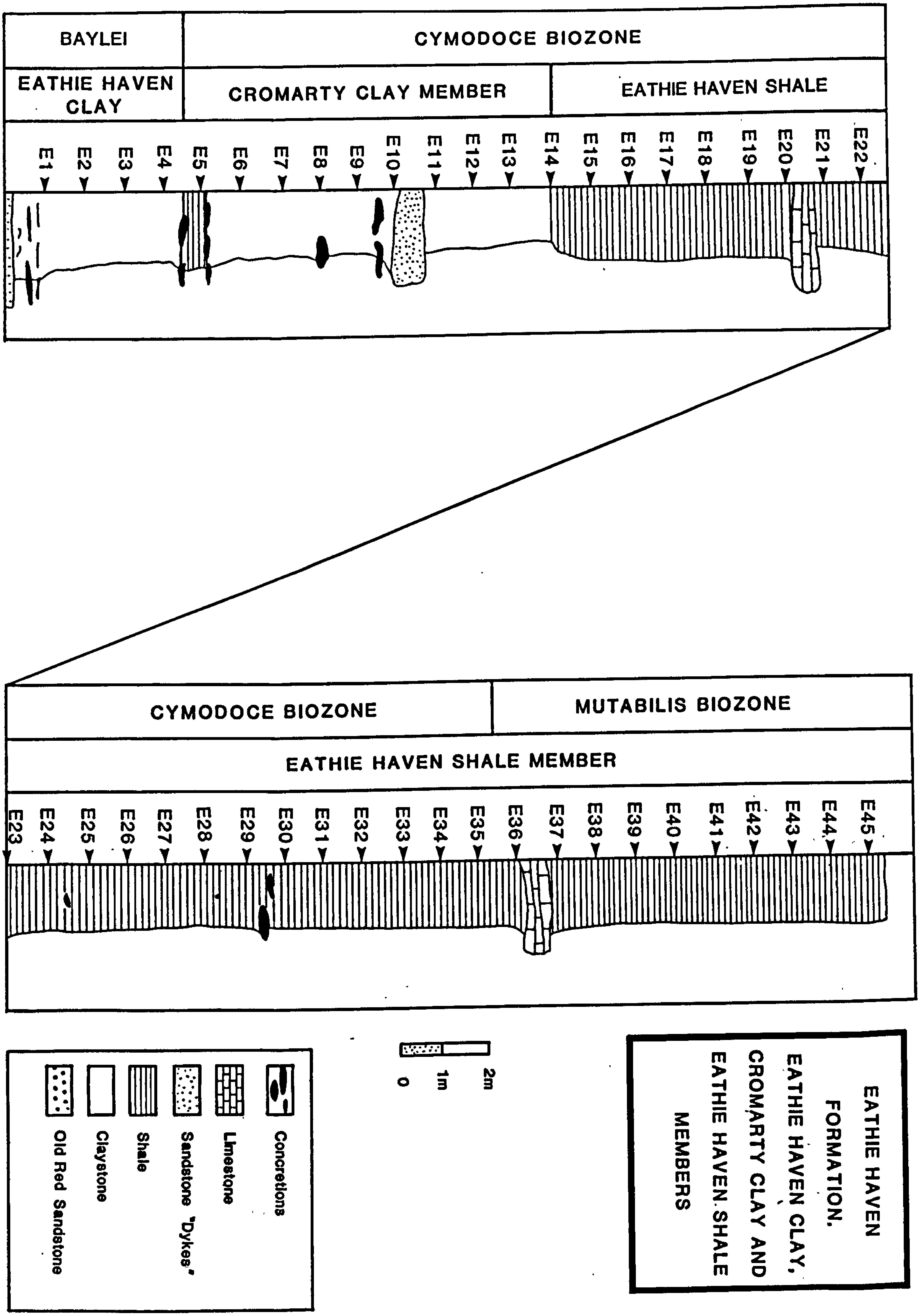


Figure 5.34. Detailed lithological log and ammonite biozonation of the Eathie Haven Formation with sampling points

excluding ammonite remains are moderately rare and are represented by the bivalve ***Camptonectes.***

(ii). Cromarty Clay Member (***cymodoce*** Biozone, c.9m; Fig. 5.34).
The base of this member is marked by a half metre thick bed of black shales which has a conformable boundary with the lower member. This shale is densely populated with bivalves and ammonite material. The remainder of this member is composed of a grey shale/mudstone, the '***Astarte***' muds of Waterston (1951), which is interbedded with several bands of septarian calcareous nodules. This unit is very fossiliferous with the bivalve ***Astarte***, gastropods and ammonites. A prominent sandstone 'neptunian' dyke interrupts this member approximately 5 metres into the line of traverse.

(iii). Eathie Haven Shale Member (***cymodoce-mutabilis*** Biozones, c.31m; Fig. 5.34).
The remainder of the sequence is a black, bituminous, organic-rich shale with marcasite and calcareous nodules. It is sporadically fossiliferous throughout in plant debris, bivalve material, such as ***Buchia*** and ***Ostrea,*** and ammonites. This member (the black shales of Waterston, 1951) is divided by several marker beds which include two thick, sandy limestones and calcareous nodules.

5.5.5. Previous Research

Very little research has been conducted at Eathie Haven. Indeed, until recently the only published record is that by Waterston (1951) who, in his geological survey of the area, covered the macrofauna and provided a detailed list of bivalves, belemnites, ammonites and gastropods; he also recorded the presence of foraminifera from several samples (Waterston ***pers. comm.***, 1987). More importantly, Waterston was the first person to have noted Jurassic radiolaria from Scotland and indeed from the UK as a whole. Gregory (1989, 1992) compared the distribution of a particularly distinctive lagenid taxon between Eathie Haven, Helmsdale and Staffin Bay.

5.5.6. Foraminiferal Distribution

Foraminifera are not consistently recovered from the succession, but are concentrated within the ***baylei*** and basal ***cymodoce*** Biozones (Figs. 5.35-5.37). All productive samples are dominated by agglutinated foraminiferids, sometimes with a minor calcareous component. The diversity and abundance of foraminifera at Eathie Haven both reach a maximum within the basal sampling interval between samples E2 and E13 included entirely within the Eathie Haven Clay and Cromarty Clay Members. 52 out of the total of 53 foraminiferal species recovered are established here. Diversities are at their highest around the ***baylei/cymodoce*** Biozonal boundary, within the α index range of 8 to 11; this then decreases throughout the remainder of the Cromarty Clay Member to an average of 6. Thereafter, distribution becomes more sporadic and less consistent, which correlates with an associated facies change from the clays of the Cromarty Clay Member

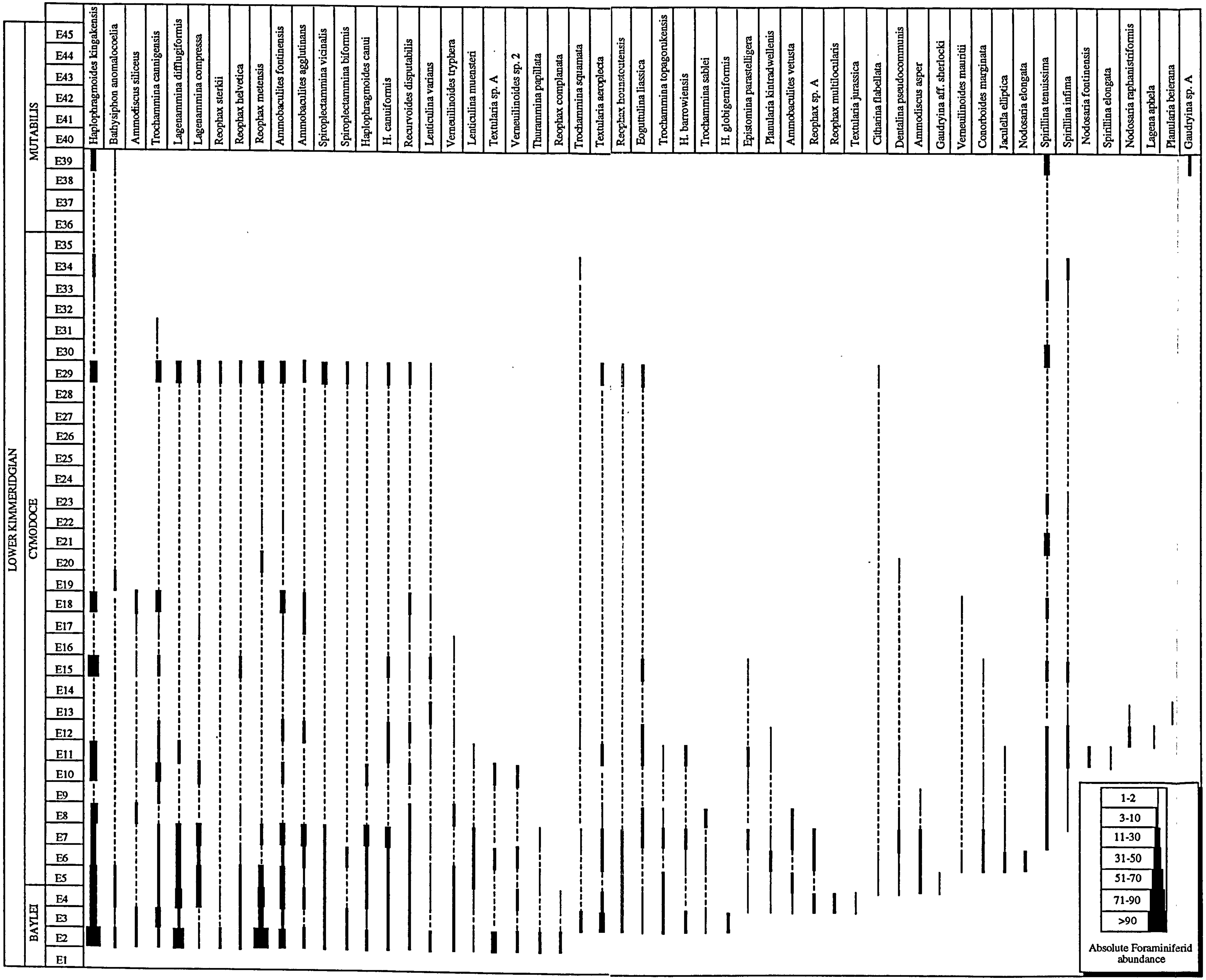


Figure 5.35. Foraminiferal distribution range chart for the Lower Kimmeridgian of Eathie Haven

to the black, bituminous shales of the Eathie Haven Shale Member. Diversity (α index generally in the range 2-4) and abundance figures decrease rapidly, with many barren samples. These barren samples are particularly prevalent in the upper ***cymodoce*** and ***mutabilis*** Biozones between samples E19 to E28 and again between E30 to E45. Only one sample at E29 in the ***cymodoce*** Biozone, within the interval E19 to E45, possesses a relatively rich foraminiferal fauna.

In detail, the intervals covered above are characterised by the following foraminiferal taxa. Samples E2 to E8 are typified by consistent recovery, with moderate diversities (α index of between 5 and 10) and abundances (Fig. 5.36), being dominated by agglutinated taxa (37 out of a total fauna of 47), the most common of which being ***Haplophragmoides kingakenis, Lagenammina difflugiformis*** and ***Reophax metensis***. Other notable occurrences include ***L. compressa*** and ***Ammobaculites fontinensis***. Calcareous taxa, comprising a mixture of lagenids, robertinids and spirillinids, are not common, with only 10 species (out of a total of 16) present over this interval. Indeed, calcareous taxa are less well represented in younger sediments here after E11. The commonest calcareous foraminiferids include ***Lenticulina varians, L. muensteri, Eoguttulina liassica, Planularia kintradwellensis, Epistomina parastelligera*** and ***Conorboides marginata. Spirillina tenuissima*** and ***S. infima*** occur in minor floods.

The interval encompassed by samples E9 to E13 of the upper Cromarty Clay Member is marked by a decrease in abundance and diversity (α index of 3-6), with 12 final appearances. Agglutinated taxa still predominate, however there is a minor flood of calcareous foraminiferids between E11 and E13, including ***Nodosaria fontinensis*** and ***N. raphanistriformis. Haplophragmoides kingakenis*** still dominates the agglutinated fauna, with ***Trochammina canningensis*** next in terms of abundance. An increase in the number of barren samples occurs with the facies change to the Eathie Haven Shale Member from sample E14, within the ***cymodoce*** Biozone. Productive samples are almost totally dominated by low diversity (α index 3-4) and low abundance agglutinated taxa. ***H. kingakensis*** dominates, with ***Ammodiscus siliceus, T. canningensis, A. fontinensis*** and ***A. agglutinans*** assuming some prominence. ***Spirillina tenuissima*** and to a lesser extent ***S. infima*** occur as minor, sporadic floods.

No foraminifera were recovered between samples E23 and E28. Sample E29 marks the only major development of foraminifera in this part of the section, with 16 species of agglutinated foraminifera but only ***L. varians, Eoguttulina liassica*** and ***Citharina flabellata*** representing the lagenids. The majority of samples between E30 and E39 are barren, with only E30, E31, E33 and E34 being productive in terms of recovery. This recovery is very poor, however, with specimens of ***H. kingakensis, Bathysiphon anomalocoelia*** and ***T. squamata. S. tenuissima*** and ***S. infima*** are the only calcareous foraminiferids present. Samples E40 to E45, within the ***mutabilis*** Biozone, are barren of foraminifera.

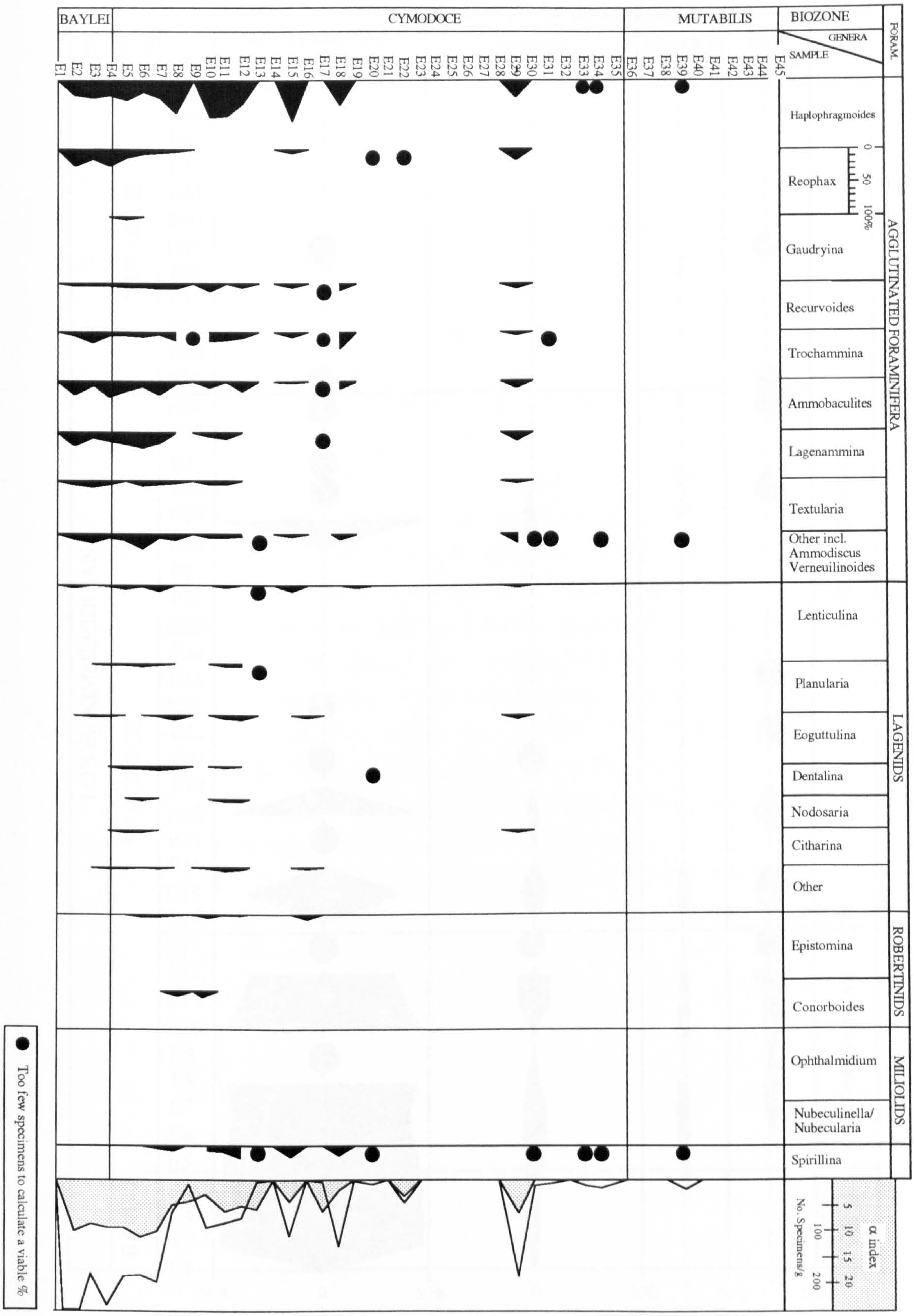


Figure 5.36. Percentage distribution of foraminiferal genera from the Kimmeridgian of Eathie Haven, plotted with diversity and abundances

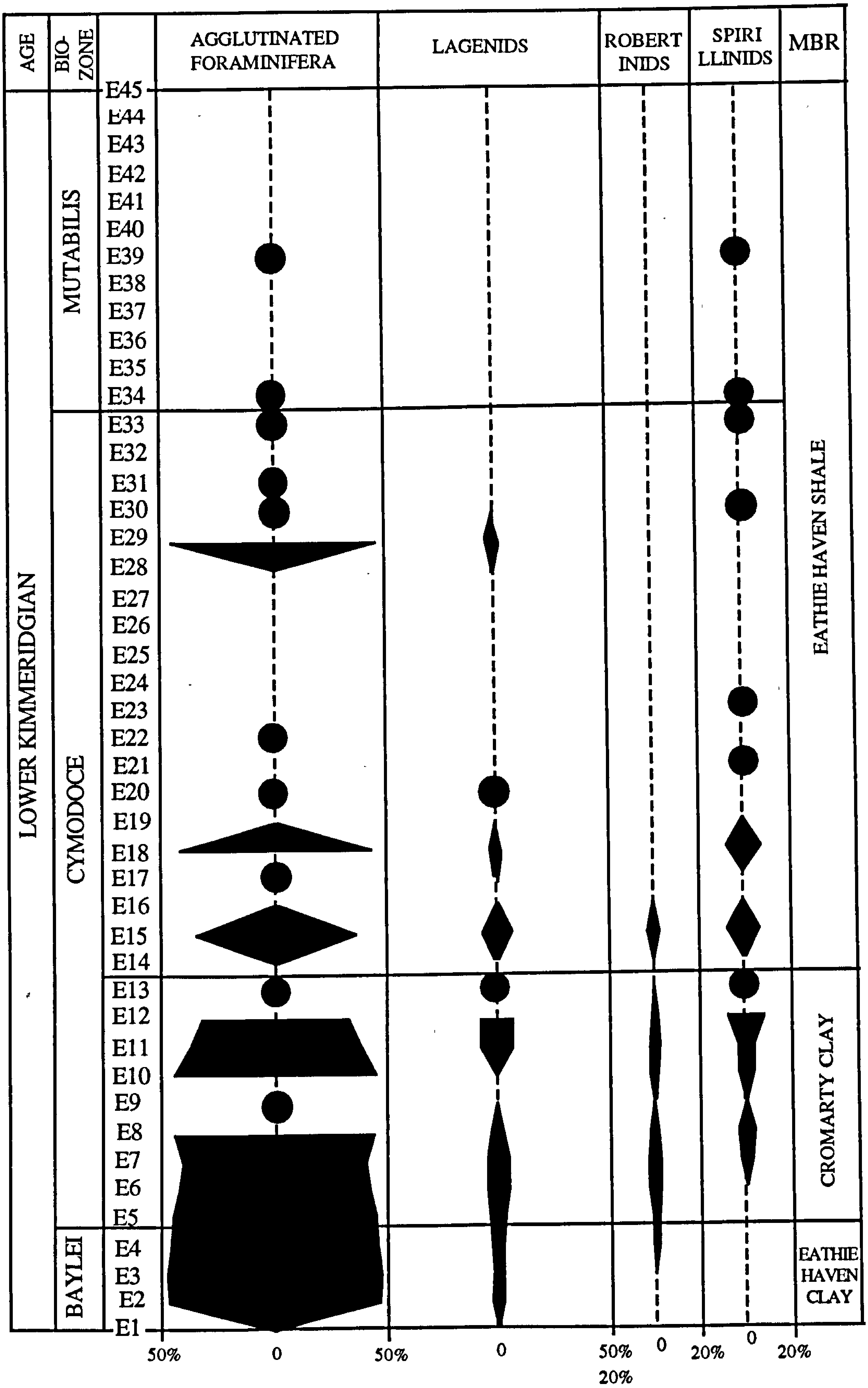


Figure 5.37. Percentage distribution of the major foraminiferal groups at Eathie Haven plotted against the bio and lithostratigraphy schemes (circles=too few specimens to calculate a viable %)

5.5.7. Radiolarian Distribution

Within the study area, radiolarian microfaunas are at their most diverse and abundant at Eathie Haven, but they roughly mirror the stratigraphical distribution patterns seen at Helmsdale. Three major phases or pulses of radiolarian abundances and diversity are described below (Fig. 5.38).

Initially, samples from the top ***baylei*** and basal ***cymodoce*** Biozones (E1-E12) are dominated by foraminiferal assemblages, with only rare specimens of the nassellarian taxa ***Parvicingula blowi*** appearing within the lower part of the ***cymodoce*** Biozone, associated with rare and sporadic occurrences of ***Cenodiscus*** sp. 1 and ***Praeconocaryomma hexagona.***

The first major cycle occurs between samples E13 and E22, within the ***cymodoce*** Biozone, and is characterised by a dramatic profusion of abundant and diverse radiolaria, with 18 out of a total of 19 taxa occurring within this interval. E13 yields the first appearance of a diverse radiolarian fauna, the most noticeable being superabundant ***Parvicingula blowi*** which reaches a maximum of 247 specimens in E20. ***Hsuum*** sp. 1 is initially an important component, but becomes less so from sample E15 onwards. ***Cenosphaera*** sp. 1 shows a similar pattern of development over this interval. A converse distribution is seen for ***Parvicingula blowi*** ssp. A, which becomes more prevalent from sample E16 to E21. Other less numerically important forms include ***Cenodiscus*** sp. A, ***Cenosphaera*** sp. A, ***Parvicingula*** sp. A and ***Stichocapsa devorata.*** Diversity is relatively high with between 5 and 12 species recovered, with nassellarians dominating. Absolute abundance is particularly high here, with the majority of samples yielding in excess of 150 specimens.

Samples recovered between E23 and E26 are totally devoid of microfauna. The second pulse, between E27 and E34, commences with a few specimens of ***P. blowi, P.*** aff. ***jonesi*** and ***S. devorata*** between E27 and E30. Between samples E31 and E34 diversity and abundance increase with ***Cenodiscus*** sp. A and ***Cenosphaera*** sp. 1 being the most common. Sporadically, ***P. blowi, Hsuum*** sp. 1 and ***P. blowi*** ssp. A increase to become more prevalent. This second cycle matches the first in terms of diversity and abundance, but there is an increase in the proportion of spumellarian taxa that means the two groups are roughly equal in numbers.

Before the next phase of radiolarian development there are four barren samples between E35 and E38. In terms of diversity, the third cycle is the most distinct and occurs within the ***mutabilis*** Biozone between samples E39 and E45. ***P. blowi*** is less frequent, whilst ***Cenodiscus*** sp. A and ***Cenosphaera*** sp. 1 are most common. ***Orbiculiforma mclaughlini*** and ***O.*** sp. A are also relatively common over this interval. Diversity and abundances are generally high with spumellarian taxa dominating.

5.5.8. Palaeoenvironmental Interpretation

With the lack of basal exposure at Eathie Haven, it is difficult to ascertain with certainty

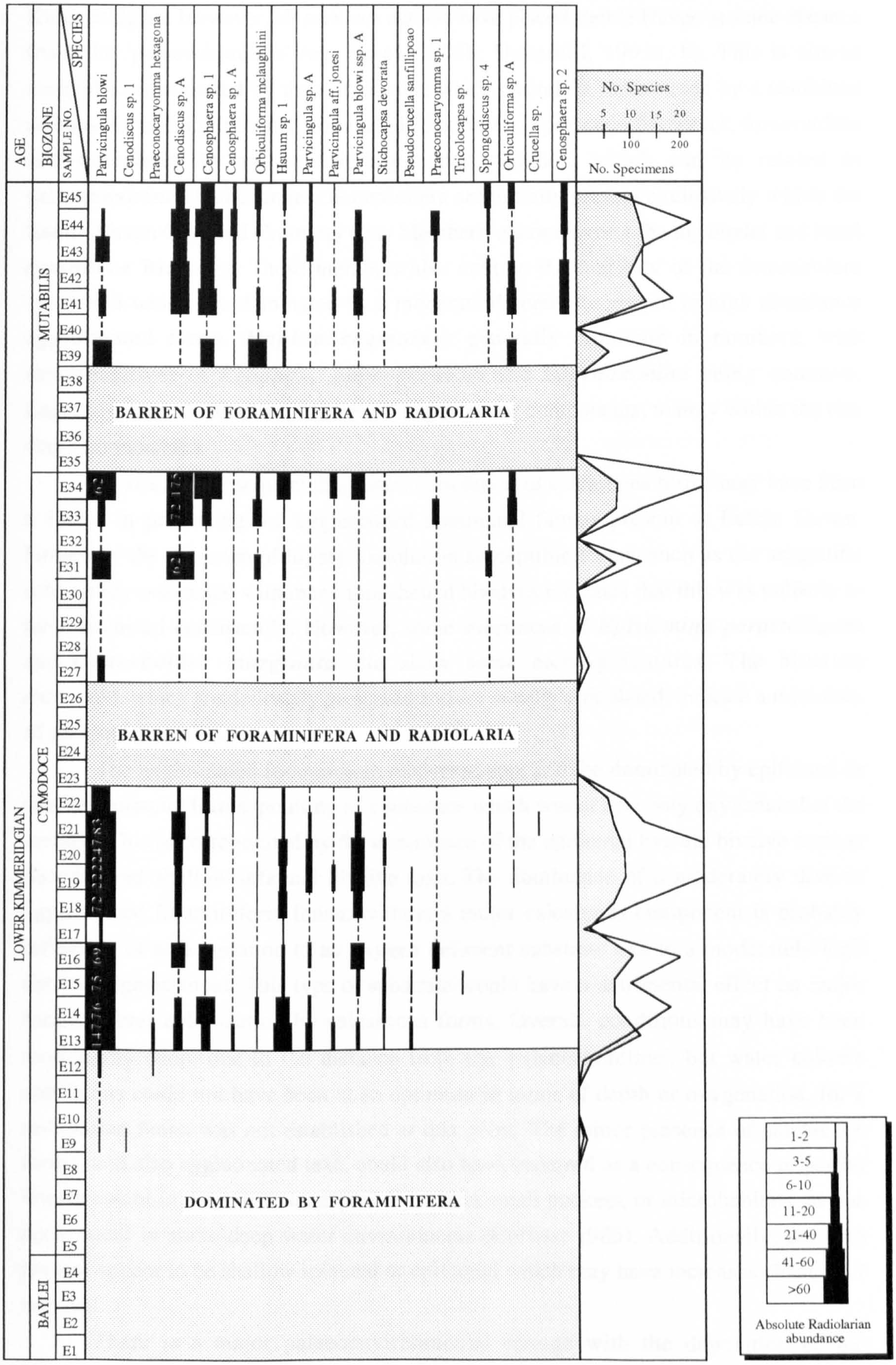


Figure 5.38. Radiolarian distribution, diversity and abundances for the Kimmeridgian of Eathie Haven

the initial progression of basin development until the ***baylei*** Biozone of the Lower Kimmeridgian. However, all previous authors have placed Eathie Haven at some distance from the 'palaeoshoreline' (eg. Sykes, 1975b; Underhill, 1991a, b). This is almost certainly corroborated by the microfauna, which overall is represented by a combined radiolarian and agglutinated dominated foraminiferal presence. However, foraminifera and radiolaria do not consistently occur together, which can be related to palaeoenvironmental changes. Foraminifera are initially present exclusively within the Eathie Haven Clay and Cromarty Clay Members, encompassing the top ***baylei*** and basal ***cymodoce*** Biozones. These members also contain the majority of the foraminifera recovered which are dominated by a moderate diversity/moderate to high abundance agglutinated fauna. ***Haplophragmoides*** generally dominate in numbers, with representatives of ***Reophax, Ammobaculites*** and ***Lagenammina*** being common. Lagenids, robertinids and spirillinids occur as minor components, mainly within the two clay rich members.

In situ, or subsequent diagenetic dissolution of calcareous forms may have been a factor in producing the agglutinated dominated faunas present at Eathie Haven. However, the presence of highly dissolution susceptible forms, such as the aragonitic robertinids associated with many thin shelled bivalves indicates that this was unlikely to have occurred consistently. However, some specimens of ***Epistomina parastelligera*** and ***Conorboides marginata*** did show some etching features. The bivalves recovered, which are delicately preserved and are usually articulated, indicate a minimum of post-mortem transport.

The agglutinated foraminifera recovered appear to be dominated by epifaunal or shallow infaunal forms, pointing to a substrate which was at best only oxygenated at the surface. This is corroborated by the dominance of the epifaunal byssate bivalve such as ***Astarte*** and shallow infaunal bivalve taxa. The dominance of a moderately diverse agglutinated foraminiferid fauna, without a major calcareous component is probably reflective of an adaptation to an oxygen deficient substrate and to a moderately high detrital organic input. This type of substrate would have a detrimental effect on major foraminiferal colonisation by calcareous forms. Overall, conditions may have been moderately deep, due to the distance from the 'palaeoshoreline', but water column conditions could not have been at an optimum in terms of depth or oxygenation, for a radiolarian fauna was not established at this point. The minor presence of calcareous forms, and also agglutinated taxa, could also have occurred as a consequence of partial improvement in the substrate, especially within small pockets, or microhabitats, as has been noted in some deep water environments (Corliss, 1985). Additionally, the taxa present appear to be shallow infaunal or epifaunal which may have increases chances of survival.

There is a major palaeoenvironmental change with the deposition of the bituminous rich Eathie Haven Shale Member which spans the rest of the succession from the ***cymodoce*** to ***mutabilis*** Biozones. This facies change is marked by the introduction of bituminous shales, with corresponding substrate conditions degrading as detrital organic debris input increased. This is reflected by a dramatic decrease in the abundance and diversity of the benthic agglutinated faunas present, with an increase in the number of barren samples. The bivalves present appear to be predominately epifaunal, particularly in the case of ***Buchia*** which also appears to be byssally attached (often to ammonite tests) or even nektobenthic, as suggested by Crame (1985). ***Meleagrinella***, which also occurs in discrete bands, has also been characterised as a benthic opportunists by Wignall (1990). The general water column appears to have deepened as a consequence of the regional transgression (Partington ***et al.*** 1993a, b) in this area, which reaches a maximum within the ***eüdoxus*** Biozone. The Eathie Haven Shale Member is characterised by abundant and diverse radiolaria, which are often associated with the establishment of transgressions. Substrate conditions worsened, initially sporadically, as indicated by the presence of agglutinated dominated assemblages at certain horizons. The water column, however, supported a flourishing radiolarian fauna, which indicates that, whilst the substrate conditions were worsening, the general circulation patterns were established and allowed the introduction and continued presence of radiolaria. This situation may also have arisen due to water mass stratification, a model that Tyson ***et al.*** (1979) have suggested for the organic rich Kimmeridgian deposits at the type section in Dorset. The Eathie Haven Shale Member was initially dominated by nassellarian radiolaria, which are generally taken to indicate a relatively thick water column. Substrate conditions continued to worsen, especially in the uppermost ***cymodoce*** and ***mutabilis*** Biozones, as indicated by the paucity, or total lack, of the benthic micro and macrofaunal components. The radiolarian fauna also shows some changes, from one dominated by nassellarians, through a cycle of equivalence to one dominated by spumellarian taxa. The presence of large numbers of spumellarians has been used by some authors to indicate a shallower water depth, (e.g. Koutsoukos & Hart, 1990b). However, in the context of the North Sea there was a continued transgression and hence deepening within the ***mutabilis*** Biozone with culmination in the ***eudoxus*** Biozone (Tyson, 1989; Partington ***et al.***, 1993a, b), which equates here with a dominance of spumellarian taxa.

5.5.9. Conclusions

Specific conclusions are presented here concerning the Eathie Haven section, whilst detailed conclusions covering the regional biostratigraphical and generalised palaeoenvironmental correlation of this section with others in the study area are presented in Chapter 7.

Eathie Haven yielded some of the most abundant radiolarian faunas from the study area, which are additionally associated with a moderate to poorly diverse/moderate abundance agglutinated foraminiferal fauna. Distinct distributional patterns are evident which, when compared with microfaunal data and facies, provide some clues to the palaeoenvironmental development and regimes of the region. The uppermost ***baylei*** and ***cymodoce*** Biozones are characterised by agglutinated dominated faunas, which are associated with a low diversity/low abundance calcareous foraminiferal fauna which, in conjunction with the palaeogeographical location, indicates a moderately deep water, oxygen depleted substrate. An influx of radiolaria occurs within the ***cymodoce*** Biozone and continues up to the ***mutabilis*** Biozone. This is associated with a distinct facies change, a progressive decrease in foraminiferal diversities and abundances and a change from nassellarian to spumellarian dominated radiolaria. This indicates continuation of transgression which, whilst sustaining the oxygenation of majority of the water mass, appears to have been responsible for producing an oxygen depleted substrate. The radiolarian fauna changes in composition from one that is dominated by nassellarians to one that is dominated by spumellarians which, in conjunction with regional data from the neighbouring North Sea area suggests that transgression was progressive and water conditions deepen. Transgression was associated with oxygen depleted to anaerobic substrates that were finally rarely colonised by a benthic microfauna.

CHAPTER 6 SYSTEMATICS

6.1. Foraminiferal Taxonomy

6.1.1. Introduction

The monumental, suprageneric classification of foraminiferids by Loeblich & Tappan (1987) is utilised here, which in turn is based on their earlier exploratory works (Loeblich & Tappan, 1964, 1974, 1984). The number of nominated suprageneric groups have more than doubled in the period 1964-1988, with an increase from five to twelve suborders. Important to this study are the elevations in the hierarchical system of Spirillinina, Lagenina, Robertinina and Globigerinina to suborders.

Loeblich & Tappan (1987) continue to group all foraminifera within one order following the recommendations of the protozoan classification committee of Levine *et al.* (1980). However, various authors advocate the elevation of foraminifera to class or subclass (e.g. Haynes, 1990), or even to phylum level (Margulis, 1974). In the absence of consensus in opinion on this issue, the higher classificatory system of Levine *et al.* (1980) is accepted here.

The classification of Loeblich & Tappan is the most complete and up to date scheme available and is used here, but with some reservations and adaptations. Firstly, the authors tend to be somewhat over-zealous in the taxonomic splitting of genera using surface ornamentation. For example ***Dentalina*** is now reserved for only longitudinally costate forms. Smooth or discontinuously costate forms are now collected within ***Prodentalina***, ***Paradentalina***, ***Mesodentalina*** or ***Laevidentalina***. Their stated purpose in following this practice is to allow evolutionary sequences to be more naturally defined; but, as environment is also observed to control the development of these features, such splitting must be used with caution. Also splitting of genera tends to be somewhat cumbersome and confusing to non-specialists. Hence, for this work genera such as ***Dentalina*** includes, (as it did previously; Loeblich & Tappan, 1964) all the various forms, whether costate or smooth.

Secondly, some reservations appear to be held (e.g. Jenkins, 1989) concerning the lack of use of the subgenus category; and indeed, some subgenera appear to have been allocated generic status without discussion.

Thirdly, Haynes (1990) pointed out that there are some inconsistencies in Loeblich & Tappan's characterisation and definition of genera with septa, i.e. non-septate aragonitic Involutinids are separated from the septate Robertinina, whereas both non-septate and septate forms are accommodated together within Spirillinina and Textulariina.

Following the publication of their classification scheme, Loeblich & Tappan (1989) have recognised the new suborder of Trochamminina as defined by Brönnimann & Whittaker (1988) and have reinstated the suborders Haplophragmiina and Astrorhizina.

Concerning nomenclature, the following conventions are used for foraminiferal and radiolarian systematics:-

1). Genus sp. A or Species sp. A, etc. denotes forms that are considered to be new to science and will not be named here. This is so as not to invalidate the forms nominated, as a doctoral thesis is not considered to be a suitable vehicle for designating new forms, under the rules of Zoological Nomenclature (Ride, 1975).
2). sp. indicates that the material can be assigned to a particular genus, but not with any confidence to a specific form. This is generally as a result of poor preservation of specimens.
3). ? inserted prior to a generic or specific name indicates that this form is being tentatively assigned.
4). aff. indicates that there are affinities between the original type published material and that collected here, but the differences are great enough to cast doubt.
5). cf. indicates either that a lack of material, or poorly preserved features precludes definite identification.

6.1.2. Foraminiferal Taxonomy

Subkingdom PROTOZOA
Phylum SARCOMASTIGOPHORA Honingberg & Balamuth, 1963
Subphylum SARCODINA Schmarda, 1871
Superclass RHIZOPODA von Seibold, 1845
Class GRANULORETICULOSEA de Saedeleer, 1934
Order FORAMINIFERIDA Eichwold, 1830
Suborder Textulariina Delage & Hérouard, 1896
Superfamily Astrorhizacea Brady, 1881
Family Bathysiphonidae Avnmelech, 1952
Genus ***Bathysiphon*** Sars, 1872

Bathysiphon anomalocoelia Tappan, 1955
(Plate 1, Figure 1)

1955 ***Bathysiphon anomalocoelia*** Tappan; p. 35, pl. 7, figs. 1-3.
1976 ***Bathysiphon anomalocoelia*** Tappan; Souaya, p. 263, pl. 8, fig. 5.

Description. Test medium to large, parallel sided, straight, elongate tube, compressed in cross-section; tube open at both ends; test wall finely arenaceous.

Remarks. Most specimens recovered were fragmented, making differentiation from other forms difficult. This taxon resembles ***Bathysiphon*** sp. 219 Brooke & Braun (1981) and ***Bathysiphon brosgui*** Tappan, as illustrated by Souaya (1976).

Material. 98 specimens.
Distribution.

78 from Staffin Bay; rare throughout, commonest between the ***jason*** Biozone-***cordatum*** Biozone.
2 from Balintore; ***scarburgense*** Sub-biozone.
18 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone, commonest in the ***baylei*** Biozone.

This form has been recorded from the Lower-Upper Jurassic of Alaska (Tappan, 1955) and the Oxfordian-Kimmeridgian of Canada (Souaya, 1976).

Family Psammosphaeridae Haeckel, 1894

Subfamily Psammosphaerinae Haeckel, 1894

Genus ***Psammosphaera*** Schulze, 1875

Psammosphaera metensis (Terquem), 1862

(Plate 1, Figure 2)

1862 ***Annulina metensis*** Terquem; p. 433, pl. 5, figs. 6a-b; pl. 3, figs. 13a-b.
1958 ***Annulina*** cf. ***metensis*** Terquem; Said & Barakat, p. 244, pl. 4, fig. 13.
1964 ***Annulina metensis*** Terquem; Kristian-Tollman, p. 168.
1980 ***Psammosphaera metensis*** (Terquem); Løfaldli & Nagy, p. 75, pl. 1, fig. 13.
1990a ***Psammosphaera metensis*** (Terquem); Nagy ***et al.***, p. 989, pl. 1, fig. 1.

Description. Test free, globular to flattened discoidal, only single chambers were recovered, many with a central depression, test coarsely agglutinated, with many interstitial pores; no discernible aperture.

Remarks. Loeblich & Tappan (1988) indicated that members of ***Psammosphaera*** are usually multilocular, but all forms recovered the Scottish sections were single chambers that had been flattened by compression due to its thin wall. The intergranular pores are hypothesised to serve as apertures.

Material. 36 specimens.
Distribution.
20 from Staffin Bay; occurred sporadically between the ***cordatum*** Sub-biozone and ***regulare*** Biozone.
15 Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***tenuiserratum*** Biozone.
1 from Brora; lower ***athleta*** Biozone.

Family Saccamminidae Brady, 1884

Subfamily Saccammininae Brady, 1884

Genus *Lagenammina* Rhumbler, 1911

Lagenammina compressa (Paalzow), 1932

(Plate 1, Figure 3)

1932 ***Proteonina compressa*** Paalzow; p. 90, pl. 4, fig. 3.
1941 ***Proteonina ampullacea*** Brady; Frentzen, p. 300, pl. 1, figs. 2-4.
1959 ***Proteonina fusiformis*** Williamson; Ziegler, p. 96, pl. 1, fig. 3.
1960 ***Proteonina compressa*** Paalzow; Seibold & Seibold, p. 315, text-fig. 2a, pl. 8, fig. 5.
1968 ***Lagenammina compressa*** (Paalzow); Oesterle, p. 703.
1978 ***Reophax compressus*** (Paalzow); Munk, p. 36.
1988 ***Lagenammina compressa*** (Paalzow); Riegraf, p. 461, pl. 1, figs. 7-8.

Description. Test variable in size, unilocular; single chamber spherical to pyriform and compressed; test wall finely agglutinated, with a large amount of cement; distal end marked by a squat, tubular neck; aperture is a simple opening at end of the tubular neck.

Remarks. Gordon (1965) indicated that unilocular, flask shaped foraminifera previously referred to ***Proteonina*** Williamson should be placed within ***Lagenammina***. All specimens recovered were flattened or compressed.

Material. 181 specimens.
Distribution.
81 from Staffin Bay; total range was from the ***jason*** Biozone-***mariae*** Biozone, with acmes between the ***jason-athleta*** Biozones and the ***regulare*** to ***mutabilis*** Biozones.
27 from Balintore; abundant only between the ***athleta*** Biozone and ***mariae*** Biozone.
11 from Brora; only present in the ***athleta*** Biozone.
62 from Eathie Haven; ranging between the ***baylei*** and ***cymodoce*** Biozones.

Lagenammina difflugiformis (Brady), 1879

(Plate 1, Figure 4)

1879 ***Reophax difflugiformis*** Brady; p. 51, pl. 4, fig. 3a-b.
1883a ***Reophax scorpiurus*** Montfort; Haeusler, p. 27, pl. 2, fig. 7.
1937 ***Proteonina difflugiformis*** (Brady); Bartenstein & Brand, p. 128, pl. 1a, fig. 1; pl. 1b, figs. 1-2; pl. 2a, fig. 1; pl. 2b, fig. 3; pl. 3, fig. 1; pl. 4, fig. 1; pl. 5, fig. 1; pl. 8, figs. 1a-d; pl. 10, figs. 1a-c; pl. 11, figs. 1a-c.
1959 ***Proteonina jurassica*** Barnard; p. 134, pl. 11, figs. 6-8.
1967 ***Lagenammina difflugiformis*** (Brady); Gordon, p. 832, text-fig. 3, figs. 8-11.
1972 ***Lagenammina*** ex. gr. ***difflugiformis*** (Brady); Norling, p. 40, fig. 13A.
1984 ***Lagenammina jurassica*** (Barnard); Riegraf ***et al.***, p. 679, pl. 1, fig. 7.

1985 *Lagenammina jurassica* (Barnard); Riegraf, p. 92, pl. 5, figs. 19-20.

Description. Large unilocular, pyriform test, proximal part of chamber sometimes aplicate; wall coarsely arenaceous and comprised of angular siliceous and micaceous material; distinct long thin neck composed of fine-medium agglutinated grains; aperture is a simple opening at end of the tubular neck.

Remarks. Variation occurs mainly in the length of the neck, which may be an environmentally controlled feature reflecting the prevalent sedimentation rate that affected this infaunal protozoan.

Material. 1109 specimens.
Distribution.
123 from Bearreraig Bay; ***concavum-discites*** Biozones.
428 from Staffin Bay; common throughout, but concentrated in the intervals between the ***mariae*** Biozone and ***cordatum*** Biozone and between the ***baylei*** Biozone and ***mutabilis*** Biozone.
221 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Biozone.
128 from Brora; total range: ***calloviense*** Biozone-***lamberti*** Biozone, with an acme in the mid-upper ***athleta*** Biozone.
209 from Eathie Haven; ***baylei-cymodoce*** Biozones.

This is an extremely important component of all the sections studied occurring throughout, but is mainly represented in acmes which appear to be generally associated with periods of initial transgression that occurred across the Scottish basins. There were no discernible differences between the Jurassic and Recent material as illustrated by Brady (1879).

Genus *Saccammina* Carpenter, 1911

Saccammina sp.

(Plate 1, Figure 5)

Description. Small-medium sized, spherical test; surface coarsely agglutinated; aperture where visible is a simple, single, circular opening.

Remarks. The lack of any distinct salient features and general poor preservation precludes attempts at speciation. Also, saccammanids are poorly documented from the Jurassic.

Material. 27 specimens.
Distribution.
18 from Staffin Bay; very rare throughout.
6 from Balintore; rare from the ***athleta*** Biozone-***tenuiserratum*** Biozone.
3 from Brora; ***lamberti*** Biozone

Subfamily Thuramminінae Miklukho-Maklay, 1963

Genus *Thurammina* Brady, 1879

Thurammina papillata Brady, 1879

(Plate 1, Figure 6)

1879 ***Thurammina papillata*** Brady; p. 45.

1883b ***Thurammina papillata*** Brady; Haeusler, p. 60, pl. 4, figs. 10-13.

1941 ***Thurammina papillata*** Brady; Frentzen, p. 301, pl. 1, fig. 5.

1944 ***Thurammina gracilis*** Frentzen; p. 325, pl. 17, fig. 10.

1961 ***Thurammina papillata*** Brady var. ***elegantissima*** Haeusler; Luterbacher, p. 584, pl. 1, fig. 13.

1979 ***Thurammina jurensis*** Franke; Exton, p. 2, pl. 8, fig. 1.

1988 ***Thurammina hemisphaerica*** Haeusler; Riegraf, pl. 1, figs. 9-10.

Description. Small, roughly spherical test that is marked by several irregularly spaced, low conical, mound-like protuberances; test wall finely agglutinated and smooth; apertures apparently located at the tips of the projections.

Remarks. ***T. papillata*** can be distinguished from ***T. jurensis*** Franke which possesses large numbers of spike like projections that cover the surface regularly. Variation in the external morphology of this form from spherical to oblate appears to include ***T. hemispharica*** Haeusler as described by Riegraf (1988).

Material. 11 specimens.
Distribution.
2 from Staffin Bay; ***cymodoce*** Biozone.
9 from Eathie Haven; ***baylei*** Biozone.

Superfamily Hippocrepinacea Rhumbler, 1895

Family Hippocrepinidae Rhumbler, 1895

Subfamily Hippocrepininae Rhumbler, 1895

Genus *Jaculella* Brady, 1879

Jaculella elliptica (Deeke), 1884

(Plate 1, Figure 7)

1884 ***Rhabdammina elliptica*** Deeke; p. 23, pl. 1, figs. 1, 1b.

1937 ***Jaculella liassica*** Bartenstein & Brand; p. 129, pl. 2b, fig. 1; pl. 3, figs. 4a-b; pl. 4, fig. 3; pl. 5, fig. 4; pl. 7, fig. 5.

1955 ***Jaculella elliptica*** (Deecke); Tappan, p. 35, pl. 7, figs. 4-5.

1964 ***Jaculella anulata*** Barbieri; p. 744, pl. 56, fig. 1.

1968 ***Jaculella liassica*** Bartenstein & Brand; Welzel, p. 4, pl. 1, fig. 2.

1991 ***Jaculella liassica*** Brand; Nagy & Johansen, p. 17, pl. 1, figs. 7-9.

Description. Test medium, elongate and initially rapidly flaring, before becoming parallel sided; initially aplicate, small proloculus is followed by a long, flaring second chamber; test wall finely arenaceous; aperture open at the end of the tubular, final chamber.

Remarks. ***J. elliptica*** is similar to ***J. anulata*** as figured by Riegraf ***et al.*** (1984), which however, possesses more distinct, concentric thickenings and an irregular outline.

Material. 14 specimens.
Distribution.
4 from Staffin Bay; ***cordatum*** Sub-biozone-***regulare*** Biozone.
3 from Balintore; ***tenuiserratum*** Sub-biozone.
7 from Eathie Haven; ***baylei*** Biozone.

Superfamily Ammodiscacea Reuss, 1862
Family Ammodiscidae Reuss, 1862
Subfamily Ammodiscinae Reuss, 1862
Genus ***Ammodiscus*** Reuss, 1862
emend. Loeblich & Tappan, 1954; Macfadyen, 1962
Ammodiscus asper (Terquem), 1863
(Plate 1, Figure 8)

1863 ***Involutina aspera*** Terquem; p. 221, pl. 10, fig. 21.
1936 ***Ammodiscus infimus*** (Strickland); Franke, p. 15, pl. 1, figs. 14a-b.
1969 ***Ammodiscus asper*** (Terquem); Brouwer, p. 24, pl. 1, fig. 6.
1984 ***Ammodiscus siliceus asper*** (Terquem); Riegraf ***et al.***, p. 679, pl. 4, figs. 114, 117.
1991 ***Ammodiscus asper*** (Terquem); Nagy & Johansen, p. 17, pl. 1, fig. 10.

Description. Test medium-large, biconcave, and consists of an unseptated, planispiral tube of 4-6 volutions; tube increases gradually in diameter; spiral suture only distinct on final whorl and is depressed; test wall coarsely agglutinated; aperture is a simple opening at the end of the tube.

Remarks. The central region is usually poorly preserved, being obscured by adventitious material. Several authors (e.g. Copestake, 1978, Riegraf ***et al.***, 1984 and Copestake & Johnson, 1989) have considered ***A. asper*** and ***A. siliceus*** to be morphological variants of the same species, with the former being coarsely agglutinated whilst the latter consists of finely agglutinated material. However, the differences appear to be sufficient to consider them as separate forms with ***A. siliceus*** having a more rapidly increasing whorl diameter.

Material. 192 specimens.
Distribution.
77 from Staffin Bay; occurs sporadically throughout the section.
97 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.
18 from Eathie Haven; ***baylei*** Biozone only.

Most reported occurrences are from the Lower and Middle Jurassic.

Ammodiscus siliceus (Terquem), 1862

(Plate 1, Figure 9)

1862 ***Involutina silicea*** Terquem; p. 450, pl. 6, figs. 11a-b.
1908 ***Ammodiscus infimus*** Strickland; Issler, p. 40, figs. 4-8.
1959 ***Involutina silicea*** Terquem; Ziegler, p. 97, pl. 2, fig. 19.
1968 ***Ammodiscus siliceus*** (Terquem); Welzel, p. 5, pl. 1, fig. 11.
1978 ***Ammodiscus siliceus*** (Terquem); Munk, p. 36.
1989 ***Ammodiscus siliceus*** (Terquem); Copestake & Johnson, p. 164, pl. 6.2.1, fig. 1.

Description. Small-medium discoidal-ovate test; small, spherical proloculus is followed by a slightly involute, flattened, unseptated and planispiral tube of 5-7 volutions; tube width rapidly increases as added; spiral suture indistinct and weakly depressed; test wall smooth, consisting of finely agglutinated material; aperture is a simple opening at end of the tube.

Material. 103 specimens.
Distribution.
13 from Bearreraig Bay; top ***concavum*** Biozone-basal ***discites*** Biozone.
34 from Staffin Bay; very rare throughout.
8 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Biozone.
6 from Brora; ***calloviense*** Biozone-mid ***athleta*** Biozone.
42 from Eathie Haven; ***baylei-mutabilis*** Biozones.

Subfamily Ammovertellininae Saidova, 1981

Genus ***Glomospira*** Rzehak, 1885

Glomospira gordialis (Jones & Parker), 1860

(Plate 2, Figure 1)

1860 ***Trochammina squamata gordialis*** Jones & Parker; p. 304.
1892 ***Glomospira gordialis*** (Jones & Parker); Chapman, p. 327, pl. 6, fig. 13.
1942 ***Glomospira gordialis*** (Jones & Parker); Frentzen, p. 307, pl. 1, figs. 15-17.
1960 ***Glomospira gordialis*** (Jones & Parker); Bielecka, p. 114, pl. 1, figs. 2-3.
1964 ***Glomospira gordialis*** (Jones & Parker); Kristian-Tollman, p. 33, pl. 3, figs. 12-15.

1974 ***Glomospira gordialis*** (Jones & Parker); Bartenstein, p. 686, pl. 2, figs. 51-54; pl. 3, figs. 1-3.
1988 ***Glomospira variabilis*** (Kübler & Zwingli); Riegraf, p. 463, pl. 2, figs. 13-15.
1990 ***Glomospira gordialis*** (Jones & Parker); Charnock & Jones, p. 156, pl. 2, fig. 12; pl. 14, fig. 9.

Description. Medium-large, ovate to discoidal test; large spherical proloculus is followed by an irregularly wound tube that does not deviate much from a planispire; tube spherical in cross-section with an irregular overlap, final whorl planispirally wound, and is slightly involute; test wall smooth and very finely agglutinated; aperture is a simple, terminal opening.

Remarks. As pointed out by Berggren & Kaminiski (1990) ***Glomospira gordialis*** should be generally restricted to forms that exhibit more or less regular coiling. There are no discernible differences in the Scottish examples to the material illustrated by Charnock & Jones (1990) from the Valanginian-Oligocene of the North Sea deposits. It can be distinguished from ***G. perplexa*** by its more regular coiling and finely agglutinated test.

Material. 79 specimens.
Distribution.
4 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
72 from Staffin Bay; rare throughout.
3 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***cordatum*** Biozone.

Glomospira perplexa Franke, 1936
(Plate 2, Figure 2)

1936 ***Glomospira perplexa*** Franke; p. 18, pl. 1, fig. 12.
1955 ***Glomospira perplexa*** Franke; Tappan, p. 41, pl. 9, fig. 10.
1964 ***Glomospira perplexa*** Franke; Kristian-Tollman, p. 33, pl. 3, figs. 3-11.
1990 ***Glomospira perplexa*** Franke; Quilty, p. 351, pl. 1, fig. 5.

Description. Test variable in size and consists of a single, irregularly wound and unseptated tube; proloculus obscured; suture distinct, depressed; test wall finely to coarsely agglutinated; aperture not visible.

Remarks. ***Glomospira perplexa*** is a highly variable form with no apparent consistency in coiling direction.

Material. 26 specimens.
Distribution. ***G. perplexa*** was a rare form, with 20 specimens from Staffin Bay between the ***densiplicatum*** Biozone and ***baylei*** Biozone and 6 specimens from the

athleta Biozone at Brora.

Superfamily Hormosinacae Haeckel, 1894

Family Hormosinidae Haeckel, 1895

Subfamily Reophacinae Cushman, 1910

Genus ***Reophax*** de Montfort, 1808

emend. Brönnimann & Whittaker, 1988

Reophax sp. A

(Plate 2, Figure 3)

Description. Large, robust, inflated, rectilinear test with up to 5 chambers, margins slightly divergent, almost parallel; proloculus large and ovoid; chambers sub-rectangular, broader than high and do not increase much in size as added; sutures indistinct, depressed and are curved towards the aperture; test wall very coarsely agglutinated, with very little cement; aperture where visible is a flush, central, circular opening.

Remarks. No similar forms appear to have been previously reported and it is typified by a robust, few chambered test. ***R*** . sp. A can be distinguished from ***R. hounstoutensis***, which is more elongate and has constricted sutures and from ***R. densa*** which has more chambers that are also broader. ***R.*** sp. A also possesses almost parallel margins.

Material. 82 specimens.

Distribution.

62 from Staffin Bay; rare throughout the section being concentrated within the Lower Kimmeridgian between the ***baylei*** and ***mutabilis*** Biozones.

3 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***cordatum*** Biozone (***bukowskii*** Sub-biozone.

5 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

12 from Eathie Haven; ***baylei*** Biozone.

Reophax agglutinans (Terquem), 1870

(Plate 2, Figure 4)

1870b ***Nodosaria agglutinans*** Terquem; p. 354, pl. 29, figs. 18a-b.

1950a ***Reophax sundancensis*** Loeblich & Tappan; p. 41, pl. 11, fig. 1.

1953 ***Reophax homoagglutinans*** Seibold & Seibold; p. 39, pl. 5, fig. 3.

1965 ***Reophax agglutinans*** (Terquem); Gordon, p. 832, text-fig. 3, figs. 23-24.

1976 ***Reophax homoagglutinans*** Gründler; Souaya, p. 266, pl. 9, fig. 25.

1988 ***Reophax agglutinans*** (Terquem); Riegraf, p. 466, pl. 3, figs. 12-14.

Description. Test medium to large in size, with up to 5 chambers in an uniserial arrangement; proloculus small, spherical and followed by chambers that are initially equiant, becoming more elongate as added producing test margins that are divergent, final chamber inflated; sutures constricted and straight-curved; test wall finely agglutinated; aperture is a simple, terminal, circular-irregular opening.

Remarks. ***R. agglutinans*** can be distinguished from ***R. helvetica***, which has more parallel margins and equiant chambers.

Material. 46 specimens.
Distribution. Only recovered from Staffin Bay, with a total range from the ***densiplicatum*** Biozone to ***baylei*** Biozone, with an acme between the ***serratum*** Biozone and ***baylei*** Biozone.

Reophax complanata Franke, 1936
(Plate 2, Figure 5)

1936 ***Reophdx complanata*** Franke; p. 20, pl. 1, fig. 23.

Description. Medium sized, compressed, uniserial test with lobulate margins and up to 6 chambers arranged in a rectilinear series, which are often distorted into an irregular axis by compression; proloculus spherical and always flattened; chambers rectangular, being broader than high and increase gradually in width as added, final chamber inflated; sutures depressed and horizontal; agglutinated test composed of medium to fine grained material; aperture is a central, circular opening on the final chamber.

Remarks. Franke (1936) illustrated this form with a specimen that was flattened by compression. This was also the typical state of preservation in the Scottish material, which was probably due to a thin test wall.

Material. 43 specimens.
Distribution. 37 specimens were recovered from the ***lamberti*** Biozone to ***mutabilis*** Biozone at Staffin Bay, with 2 from the ***athleta*** Biozone at Brora and 4 specimens from the ***baylei*** Biozone at Eathie Haven.

R. complanata has only previously been reported from the Lower Jurassic of Germany by Franke (1936).

Reophax densa Tappan, 1955
(Plate 2, Figure 6)

1955 ***Reophax densa*** Tappan; p. 35, pl. 8, figs. 1-6.
1964 ***Reophax eominutus*** Kristian-Tollman; p. 28, pl. 1, figs. 15-19.
1976 ***Reophax densus*** Tappan; Souaya, p. 266, pl. 5, fig. 12.
1989 ***Reophax eominutus*** Kristian-Tollman; Hornibrook ***et al.***, p. 89, pl. 6, fig. 7.

Description. Test small-medium in size, broad, squat and rectilinear with up to 6 chambers; proloculus sub-rectangular, much broader than high; chambers broader than high, sub-rectangular, increasing only in breadth as added, final chamber is slightly inflated and rounded distally; sutures arcuate and depressed; test wall consists of fine-medium agglutinated material; aperture is a central, flush, circular opening.

Remarks. ***R. densa*** was originally described from Alaska by Tappan (1955) and has priority over the form nominated as ***R. eominutus*** by Kristian-Tollman (1964) from the Triassic/Lower Jurassic of Europe. This taxon has only previously been described from the Triassic and Lower Jurassic and not from the British Isles. It can be distinguished from ***R. hounstoutensis***, which is similar, by its broader test, consistently broader chambers and smaller size.

Material. 63 specimens.
Distribution. Only recovered from the Staffin Bay section, mainly from the ***athleta*** Biozone-***densiplicatum*** Biozone.

Reophax helvetica (Haeusler), 1881
(Plate 2, Figure 7)

1881a ***Dentalina helvetica*** Haeusler; p. 34, pl. 2, fig. 45.
1890 ***Reophax helvetica*** Haeusler p. 28, pl. 3, figs. 15-17.
1944 ***Reophax scorpiurus*** Montfort; Frentzen, p. 329, pl. 18, figs. 6-8.
1959 ***Reophax helveticus*** (Haeusler); Lloyd, p. 308, pl. 54, fig. 8.
1984 ***Reophax helveticus*** (Haeusler); Riegraf ***et al.***, p. 680, pl. 8, fig. 196.
1989 ***Reophax helvetica*** (Haeusler); Gregory, p. 183, pl. 1, fig. 3.

Description. Test large, uniserial and straight with 5-10 chambers, margins are lobulate and has almost parallel sides; proloculus spherical, chambers rectangular to sub-spherical and are either equiant, or gradually increase in size as added; sutures depressed and straight; test wall generally composed of medium-coarse agglutinated material; aperture is a terminal, circular opening.

Remarks. ***R. helvetica*** is the commonest form of the genus ***Reophax*** recovered in this study and is generally associated with the initial stages of transgressive facies and has been previously recorded from the Lower to Upper Jurassic.

Material. 1661 specimens.
Distribution.
1143 from Staffin Bay; mainly occurs within 2 acmes: between the ***jason*** and ***densiplicatum*** Biozones and between the ***serratum*** Biozone-***mutabilis*** Biozone.
226 from Balintore; ***jason*** Biozone-***tenuiserratum*** Biozone.
249 from Brora; occurs in 2 acmes between the ***calloviense*** Biozone and ***jason*** Biozone

and between the ***athleta*** Biozone and ***lamberti*** Biozone.
38 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.
5 from Kintradwell; ***cymodoce*** Biozone.

Reophax horridus (Schwager), 1865

(Plate 2, Figure 8)

1865 ***Haplostiche horrida*** Schwager; p. 92, pl. 2, figs. 2a-c.
1917 ***Nodulina pilulifera*** Brady; Paalzow, p. 218, pl. 41, fig. 9.
1941 ***Reophax horridus*** (Schwager); Frentzen, p. 308, pl. 1, figs. 24-36.
1964 ***Reophax horridus*** (Schwager); Kristian-Tollman, p. 28, pl. 1, figs. 12-14.
1989 ***Reophax horridus*** (Schwager); Hornibrook ***et al.***, p. 89, pl. 8, fig. 2.

Description. Test large, uniserial, parallel sided with up to 6 chambers and extremely lobulate margins; proloculus large, spherical to sub-rectangular; chambers sub-rectangular and equal in size, final chamber pyriform; sutures extremely constricted and straight; test wall coarsely agglutinated; aperture is a terminal, central, circular opening on a produced neck.

Material. 156 specimens.
Distribution.
74 from Staffin Bay; ***jason*** Biozone-***mariae*** Biozone (***scarburgense*** Sub-biozone).
59 from Balintore; ***lamberti*** Sub-biozone-***tenuiserratum*** Sub-biozone with an acme between the ***lamberti*** Biozone and ***cordatum*** Sub-biozone.
23 from Brora; lower-middle ***athleta*** Biozone.

Reophax hounstoutensis Lloyd, 1959

(Plate 2, Figure 9)

1959 ***Reophax hounstoutensis*** Lloyd; p. 308, pl. 54, Figs.. 7a-b; text-figs. 5d-e.
1981 ***Reophax hounstoutensis*** Lloyd; Brooke & Braun, p. 13, pl. 1, figs. 32-36.
1990a ***Reophax*** aff. ***hounstoutensis*** Lloyd; Nagy ***et al.***, p. 991, pl. 2, figs. 1-2 (not fig. 3).

Description. Large, flattened, uniserial and lobulate test of up to 6 chambers; proloculus rectangular to ovoid and is always smaller than the following chambers; chambers initially broader than high, increasing slightly more rapidly in length as added; sutures very constricted and straight; test wall usually coarsely agglutinated; aperture when visible is a circular opening present on a short neck.

Remarks. Nagy ***et al.*** (1990a) considered that their material differed from the original descriptions of Lloyd's by possessing a distinct aperture, however Lloyd (1958, 1959) illustrated material that was identical. This form is similar to ***R. densa*** which is marked in possessing a more squat, broader test. There is some variation in the development of chambers in ***R. hounstoutensis***, with the final chamber being quite irregular in outline.

Material. 90 specimens.

Distribution. This form was limited to the upper most Oxfordian and Lower Kimmeridgian, with 62 specimens from the ***regulare*** Biozone to ***mutabilis*** Biozone of Staffin Bay and 28 from the ***baylei*** Biozone-***mutabilis*** Biozone of Eathie Haven.

R. hounstoutensis has only been recorded from the Upper Oxfordian and Lower Kimmeridgian of Dorset, Canada and the North Sea and as such may be a useful marker species.

Reophax metensis Franke, 1936
(Plate 2, Figure 10)

1936 ***Reophax metensis*** Franke; p. 19, pl. 1, figs. 17a-b.
1936 ***Reophax dentaliniformis*** Franke, p. 19, pl. 1, fig. 20.
1937 ***Reophax metensis*** Franke; Bartenstein & Brand, p. 133, pl. 10, fig. 8; pl. 13, figs. 1a-b, 4.
1958 ***Reophax metensis*** Franke; Barnard, p. 135, pl. 11, figs. 11-12.
1983a ***Reophax liasica*** Franke; Wall, pl. 1, fig. 14.
1985 ***Reophax metensis*** Franke; Riegraf, p. 96, pl. 5, figs. 27-32.
1989 ***Reophax metensis*** Franke; Nagy & Johansen, p. 343, pl. 1, figs. 1-16 (not 10-12, 14-15 & 17-25); pl. 2, figs. 8-13 (not 1-7).

Description. Medium-large, uniserial test with an arcuate axis and 2-3 irregularly developed, flask shaped chambers, final chamber is elongated, generally tapering to a drawn out neck; proloculus spherical to irregular; sutures distinct, perpendicular to oblique and constricted; test wall coarsely agglutinated; aperture is a terminal, simple opening at the end of the tubular neck.

Remarks. Nagy & Johansen (1989) appear to have included morphotypes that can be directly attributed to ***Lagenammina difflugiformis***. They record large numbers of ***R. metensis*** from the Lower to Middle Jurassic of the Brent Formation of the North Sea. As is common with their material, the majority of Scottish forms recovered have been deformed by compression.

Material. 1317 specimens.

Distribution.

92 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.

442 from Staffin Bay; common throughout and concentrated between the ***regulare*** Biozone-***mutabilis*** Biozone.

274 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.

315 from Brora; ***calloviense*** Biozone-***lamberti*** Biozone, with an acme between the ***athleta*** Biozone and ***lamberti*** Biozone.
194 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.

Reophax multilocularis Haeusler, 1883

(Plate 2, Figure 11)

1883a ***Reophax multilocularis*** Haeusler; p. 26.
1890 ***Reophax adunca*** Brady; Haeusler, p. 30, pl. 3, fig. 12.
1937 ***Reophax scorpiurus*** Bartenstein & Brand; p. 137, pl. 4, fig. 7; pl. 15, fig. 9.
1959 ***Reophax multilocularis*** Haeusler; Cifelli, p. 282, pl. 1, figs. 6-7.
1968 ***Reophax multilocularis*** Haeusler; Oesterle, p. 719, fig. 16.

Description. Test medium-large, uniserial about a sinuous and irregular axis, with 6-14 small, equi-dimensional chambers; sutures distinct, oblique-straight and deeply depressed; proloculus small, ovoid and equal in size to the remaining chambers; agglutinated test wall of fine-medium grained material; aperture is a terminal, circular opening that is either flush on the final chamber or raised on a short squat neck.

Material. 98 specimens.
Distribution.
36 from Staffin Bay; ***jason*** Biozone-***cordatum*** Biozone.
21 from Balintore; ***scarburgense*** Sub-biozone-***tenuiserratum*** Sub-biozone.
37 from Brora; ***calloviense*** Biozone-mid ***athleta*** Biozone.
4 from Eathie Haven; ***baylei*** Biozone.

Reophax sterkii Haeusler, 1890

(Plate 2, Figure 12)

1890 ***Reophax sterkii*** Haeusler; p. 29, pl. 3, fig. 23.
1955 ***Reophax suevica*** Franke; Tappan, p. 37, pl. 7, figs. 7-8 (not 9-10).
1959 ***Reophax sterkii*** Haeusler; Lloyd, p. 307, pl. 54, fig. 6a-b.
1967 ***Reophax sterkii*** Haeusler; Gordon, p. 449, pl. 1, figs. 16-17.
1989 ***Reophax sterkii*** Haeusler; Morris & Coleman, p. 208, pl. 6.3.1, fig. 2.
1990a ***Reophax sterkii*** Haeusler; Nagy ***et al.***, p. 991, pl. 1, figs. 27-28.

Description. Medium-large, uniserial, arcuate test of up to 4, but usually 3 chambers; proloculus very irregular and elongate; chambers irregularly developed, being much longer than broad, final chamber pyriform and extended to a broad, long neck; sutures irregular, depressed; test wall coarsely agglutinated; aperture is a simple opening at end of the neck.

Remarks. This form is very variable, especially in the degree of axis curvature and irregularity of chamber growth. It can be distinguished from ***R. horridus***, which has a much more irregular chamber development.

Material. 626 specimens.
Distribution.
25 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
188 from Staffin Bay; with acmes between the ***jason*** Biozone and ***lamberti*** Biozone (***henrici*** Sub-biozone) and the ***regulare*** Biozone to ***cordatum*** Biozone.
172 from Balintore; ***jason*** Biozone-***tenuiserratum*** Biozone.
228 from Brora; ***calloviense*** Biozone-***lamberti*** Biozone, with an acme between the ***athleta*** Biozone and ***lamberti*** Biozone.
13 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.

Superfamily Lituolacea de Blainville, 1827
Family Haplophragmoididae Maync, 1952
Genus ***Haplophragmoides*** Cushman, 1910
Haplophragmoides barrowensis Tappan, 1951
(Plate 3, Figure 1)

1951 ***Haplophragmoides barrowensis*** Tappan; p. 1, pl. 1, fig. 5.
1955 ***Haplophragmoides barrowensis*** Tappan; Tappan, p. 42, pl. 11, figs. 1-5.
1976 ***Haplophragmoides barrowensis*** Tappan; Souaya, p. 267, pl. 5, fig. 5.
1984 ***Haplophragmoides barrowensis*** Tappan; Riegraf ***et al.***, p. 680, pl. 1, fig. 11.
1990 ***Haplophragmoides*** cf. ***barrowensis*** Tappan; Quilty, p. 351, pl. 1, fig. 6.

Description. Small-medium, evolute, biumbilicate flattened planispire of $1^1/_2$-2 whorls; periphery angular and lobate; proloculus small, rounded; chambers sub-triangular to rounded and increase rapidly in size as added; final whorl inflated with up to 9 chambers; sutures distinct in final whorl and converge to umbilical regions, being depressed and straight; test wall finely agglutinated; aperture obscured.

Remarks. This material compares well with Tappan's (1951, 1955) type descriptions of collections from the Lower Jurassic of Alaska. Variation occurs in the degree of enrollment, with some forms appearing to uncoil in the final half whorl. However, the chambers are still in contact with the preceding whorl. ***H. barrowensis*** can be distinguished from most forms by its highly evolute character.

Material. 155 specimens.
Distribution.
118 from Staffin Bay; rare throughout the section from the ***jason*** Biozone through to the ***mutabilis*** Zone, with an acme between the ***cymodoce*** Biozone and ***mutabilis*** Biozone.

7 from Balintore; ***cordatum*** Sub-biozone.
19 from Brora; lower ***athleta*** Biozone.
11 from Eathie Haven; ***baylei*** Biozone.

Partington ***et al.*** (1993a, b) record a localised final appearance for this taxon within the Lower Callovian of the North Sea.

Haplophragmoides canui Cushman, 1930
(Plate 3, Figure 2)

1930 ***Haplophragmoides canui*** Cushman; p. 133, pl. 4, fig. 1a-b.
1955 ***Haplophragmoides canui*** Cushman; Tappan, p. 42, pl. 9, figs. 11-15.
1958 ***Haplophragmoides canui*** Cushman; Bizon, p. 7, pl. 3, fig. 3; pl. 4, figs. 1-3.
1959 ***Ammobaculites laevigatus*** Lozo; Lloyd, p. 25, pl. 4, figs. 1-4.
1967 ***Ammobaculites canui*** (Cushman); Gordon, p. 449, pl. 1, fig. 1.
1972 ***Cribrostomoides canui*** (Cushman); Dain, pl. 7, figs. 3-4; pl. 8, fig. 1.
1981 ***Haplophragmoides*** cf. ***canui*** Cushman; Brooke & Braun, p. 14, pl. 2, figs. 9-21.
1988 ***Haplophragmoides canui*** Cushman; Bielecka, p. 22, pl. 82, fig. 2.
1989 ***Haplophragmoides canui*** Cushman; Shipp, p. 252, pl. 6.4.1, figs. 5-6.
1989 ***Haplophragmoides canui*** Cushman; Morris & Coleman, p. 230, pl. 6.3.10, figs. 4-6.

Description. Test is a medium-large, biumbilicate and involute planispire of up to 10 chambers in the final whorl, periphery rounded, non-lobulate, umbilical region and proloculus are obscured; chambers elongate, sub-triangular, greater in length and gradually increase in size as added; sutures converge umbilically and are curved and depressed; test wall composed of fine-medium grained, agglutinated material; aperture is often obscured and appears to be areal on the final chamber.

Remarks. A commonly reported form from the Callovian-Oxfordian. A description of a form as ***H.*** cf. ***canui*** by Norling (1972, p. 43) from the Lower Jurassic appears to be much more evolute.

Material. 437 specimens.
Distribution.
306 from Staffin Bay; rare between the ***jason*** Biozone and ***glosense*** Biozone, with an acme between the ***regulare*** and ***mutabilis*** Biozones.
15 from Balintore; ***cordatum*** Sub-biozone-***tenuiserratum*** Sub-biozone.
10 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.
41 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.
65 from Helmsdale; ***cymodoce*** Biozone

Originally recorded from the Oxfordian of France (Cushman, 1930) ***H. canui*** has been recovered from the Oxfordian and Kimmeridgian of Canada, Alaska, Poland and the UK as well as from the North Sea Upper Jurassic (Partington ***et al.***, 1993a, b). The latter authors record a complex pattern of distribution related to localised final appearances in the Lower Callovian, at the top of the ***lamberti*** Biozone, the top of the ***baylei*** Biozone and within the Middle Volgian.

Haplophragmoides canuiformis Dain, 1972

(Plate 3, Figure 5)

1972 ***Haplophragmoides ?canuiformis*** Dain; p. 48, pl. 8, figs. 2-3.

1981 ***Haplophragmoides canuiformis*** Dain; Brooke & Braun, p. 14, pl. 2, figs. 22-30.

1990a ***Haplophragmoides ?canuiformis*** Dain; Nagy ***et al.***, p. 999, pl. 2, figs. 1-3.

Description. Test medium-large, planispiral, biumbilicate and usually evolute with a medium-wide umbilical region; periphery lobulate; 8-12 chambers in final whorl, chambers triangular in shape, sometimes irregular; sutures depressed, radial, arcuate; test wall built up from medium-coarse grained, agglutinated material; aperture obscured, where visible is an areal opening on the final chamber.

Remarks. This species was originally described by Dain (1972) from the Lower Kimmeridgian of Siberia. Nagy ***et al.*** (1990a) considered ***H. canuiformis*** to be restricted to the Lower Kimmeridgian to Volgian in Spitsbergen. It can be distinguished from ***H. barrowensis*** which has fewer chambers that are also more globular and from ***H. canui*** which has a more involute test.

Material. 551 specimens.

Distribution.

473 from Staffin Bay; total range ***athleta*** to ***mutabilis*** Biozones, concentrated in 2 acmes, firstly within the ***cordatum*** Biozone (***bukowskii*** Sub-biozone-***cordatum*** Sub-biozone) and between the ***glosense*** Biozone and ***serratum*** Biozone.

22 from Balintore; ***cordatum*** Sub-biozone-***tenuiserratum*** Sub-biozone.

56 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.

Haplophragmoides globigeriniformis (Haeusler), 1882

(Plate 3, Figure 3)

1882a ***Trochammina globigeriniformis*** Haeusler; p. 352, pl. 15, figs. 8-9.

1960 ***Haplophragmoides globigeriniformis*** (Haeusler); Seibold & Seibold, p. 326, pl. 7, fig. 12.

1970 ***Haplophragmoides globigeriniformis*** (Haeusler); Winter, p. 7, pl. 2, fig. 34.

1984 ***Haplophragmoides globigeriniformis*** (Haeusler); Riegraf ***et al.***, p. 680, pl. 8, fig. 190.

Description. Medium-large, involute, biumbilicate, inflated, planispiral test with up to $1^1/_2$ whorls and 6 chambers in the final whorl; periphery rounded, lobulate; chambers inflated, globular; sutures radial and straight, depressed, but are generally indistinct; test wall finely agglutinated; aperture where visible is a small opening at the base of the final chamber.

Remarks. This form was originally placed within ***Trochammina*** by Haeusler (1882a), but does not show any evidence of a trochospiral coiling mode.

Material. 105 specimens.
Distribution.
77 from Staffin Bay; rare from the ***jason*** Biozone-***mutabilis*** Biozone.
25 from Balintore; total range is from the ***athleta*** Biozone to ***tenuiserratum*** Biozone, concentrated between the ***athleta*** and ***mariae*** Biozones.
3 from Eathie Haven; only recovered from the ***mutabilis*** Biozone.

Haplophragmoides hyalinus (Haeusler), 1886

(Plate 3, Figure 4)

1886 ***Trochammina hyalina*** Haeusler; p. 3, pl. 5, fig. 27.
1968 ***Haplophragmoides hyalinus*** (Haeusler); Oesterle, p. 729, text-figs. 25b, 26, 28c.
1984 ***Haplophragmoides hyalinus*** (Haeusler); Riegraf ***et al.***, p. 680, pl. 8, fig. 191.

Description. Very small, involute, biumbilical and planispiral test, with 4-5 chambers in the final whorl; periphery rounded and very lobulate; chambers globular and generally increase gradually in size as added; sutures distinct, depressed and radial; test wall finely agglutinated, with much cement; aperture is present at the base of the final chamber.

Material. 13 specimens.
Distribution. 11 rare specimens between the ***jason*** Biozone and ***mutabilis*** Biozone of Staffin Bay and 2 from the ***lamberti*** Biozone at Balintore.

Haplophragmoides infracalloviensis Dain, 1948

(Plate 3, Figure 6)

1948 ***Haplophragmoides infracalloviensis*** Dain; p. 68, pl. 1, fig. 1.
1983 ***Haplophragmoides infracalloviensis*** Dain; Løfaldli & Nagy, p. 100, pl. 1, figs. 4-5.
1989 ***Haplophragmoides infracalloviensis*** Dain; Morris & Coleman, p. 230, pl. 6.3.10, figs. 10-12.

Description. Very large planispiral, biumbilicate, involute test with a raised umbilical ridge that surrounds a wide, umbilical region; periphery angular; final whorl consists of 10-14 chambers; chambers elongate, sub-triangular, higher than wide and increase gradually as added; sutures straight, radial and limbate; test wall coarsely agglutinated; aperture obscured.

Remarks. Variation occurs mainly in the degree of involution and the extent of development of the raised umbilical ridge.

Material. 425 specimens.
Distribution. The Scottish material was limited between the Lower Callovian and Upper Oxfordian, with the majority of specimens being recovered from Staffin Bay in several acmes; between the ***macrocephalus*** Biozone and ***jason*** Biozone, within the ***mariae*** Biozone (***scarburgense*** Sub-biozone-***praecordatum*** Sub-biozone) and between the ***glosense*** Biozone and ***rosenkrantzi*** Biozone. 9 specimens came from the ***athleta*** Biozone at Brora.

This form so far has only been recorded from Middle and Upper Jurassic deposits in Siberia, Svalbard and offshore North Sea sequences. Partington ***et al.*** (1993a, b) record acme final appearances at the top of the *lamberti* Biozone, within the Middle Volgian and at the top of the Ryazanian Stages, for material from the offshore Inner Moray Firth Basin and Viking Graben.

Haplophragmoides kingakensis Tappan, 1955

(Plate 3, Figure 7)

1955 ***Haplophragmoides kingakensis*** Tappan; p. 43, pl. 10, figs. 1-6.
1972 ***Haplophragmoides kingakensis*** Tappan; Norling, p. 43, fig. 13B.
1984 ***Haplophragmoides kingakensis*** Tappan; Riegraf ***et al.***, p. 680, pl. 1, fig. 40.
1989 ***Haplophragmoides*** cf. ***kingakensis*** Tappan; Gregory, p. 182, pl. 1, fig. 1.

Description. Medium-large test that is planispiral, involute and biumbilicate, with a rounded periphery and a final whorl consisting of 5-7 chambers; chambers sub-triangular, greater in breadth, becoming more inflated as added; sutures radial and depressed, sometimes curved at the periphery; test wall finely agglutinated, sometimes medium grained; aperture areal, circular opening on periphery of the final chamber.

Remarks. ***H. kingakensis*** can be distinguished from ***H. canui*** which has a more involute test with more chambers. This is the most common form of ***Haplophragmoides*** in the study area and is generally associated with initial transgressive facies, especially in the Lower Callovian.

Material. 1964 specimens.

Distribution.

63 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.

1300 from Staffin Bay; common throughout, but concentrated in 3 acmes: between the ***macrocephalus*** Biozone and ***athleta*** Biozone, between the ***glosense*** Biozone and ***rosenkrantzi*** Biozone, and finally between the ***cymodoce*** Biozone and ***mutabilis*** Biozone.

551 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.

50 from Helmsdale; ***cymodoce*** Biozone.

Haplophragmoides pygmaeus (Haeusler), 1881

(Plate 3, Figure 8)

1881a ***Rotalina pygmaeus*** Haeusler; p. 40, pl. 2, fig. 69.

1968 ***Haplophragmoides pygmaeus*** (Haeusler); Oesterle, p. 731, figs. 25c, 28d, 29.

Description. Test small, compressed, planispirally coiled, involute, biumbilicate; umbilical region small; periphery rounded and lobulate; 6-8 chambers in final whorl, chambers elongate, sub-triangular and only gradually increase in size as added; sutures curved, constricted and radial; test wall finely agglutinated; aperture is a small areal opening on final chamber.

Remarks. A very common form especially at Brora where it is often the only taxon present. It is distinguished from other ***Haplophragmoides*** species by its small size and curved, constricted sutures.

Material. 1445 specimens.

Distribution.

328 from Staffin Bay; total range from the ***athleta*** Biozone to ***cordatum*** Biozone, being concentrated between the ***athleta*** Biozone and the ***mariae*** Biozone.

57 from Balintore; ***jason*** Biozone-***mariae*** Biozone (***scarburgense*** Sub-biozone).

1060 from Brora; ***calloviense*** Biozone-***athleta*** Biozone, with an acme between the ***calloviense*** Biozone and ***jason*** Biozone.

Family Lituotubidae Loeblich & Tappan, 1984

Genus *Lituotuba* Rhumbler, 1895

Lituotuba sp. A

(Plate 4, Figure 1)

Description. Test is a large, irregularly coiled tube with angular peripheries; proloculus is followed by an unseptated second chamber that is initially coiled in several planes, but which then uncoils in a curvilinear fashion; tube flattened and initially rapidly increases in diameter, but then remains fairly constant as added; test wall coarsely agglutinated;

aperture is a simple, terminal opening.

Remarks. This form can appear superficially similar to ***Ammobaculites fontinensis***, especially in crushed specimens, but can be distinguished by its irregular coiling mode. ***Lituotuba*** sp. A can be differentiated from ***L. irregularis*** whose tube is rounded, of smaller diameter and is much more irregular in its coiling mode, having constrictions produced by tube twisting.

Material. 29 specimens.
Distribution.
12 from Staffin Bay; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***mutabilis*** Biozone.
12 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***tenuiserratum*** Biozone.
5 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

Lituotuba irregularis Tappan, 1955

(Plate 4, Figure 2)

1955 ***Lituotuba irregularis*** Tappan; p. 39, pl. 9, figs. 5-9.
1968 ***Lituotuba irregularis*** Tappan; Welzel, p. 5, pl. 1, fig. 12.
1985 ***Lituotuba irregularis*** Tappan; Riegraf, p. 87, pl. 6, fig. 2.

Description. Test medium-small, irregularly shaped proloculus followed initially by a short, planispirally coiled tube, which then uncoils in a random and haphazard fashion; test wall very finely agglutinated and smooth; aperture is a variably shaped opening at the end of the tube.

Remarks. The uncoiled section is highly irregular in growth sometimes twisting and changing direction rapidly, producing constrictions.

Material. 92 specimens.
Distribution.
80 from Staffin Bay; rare throughout and concentrated between the ***jason*** Biozone and ***vertebrale*** Sub-biozone and between the ***rosenkrantzi*** Biozone and ***mutabilis*** Biozone.
12 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Sub-biozone.

This form has been reported from the Lower and Upper Jurassic of Alaska (Tappan, 1955), Canada (Souaya, 1976) and the Lower Jurassic of Germany (Welzel, 1968 and Riegraf, 1985).

Family Lituolidae de Blainville, 1827

Subfamily Ammomarginulininae Podobina, 1978

Genus *Ammobaculites* Cushman, 1910

Ammobaculites agglutinans (d'Orbigny), 1846

(Plate 4, Figure 3)

1846 ***Spirolina agglutinans*** d'Orbigny; p. 137, pl. 7, figs. 10-12.

1876 ***Lituola agglutinans*** (d'Orbigny); Blake, p. 452, pl. 17, fig. 40.

1922 ***Haplophragmium coprolithiforme*** Schwager; Paalzow, p. 31, pl. 4, fig. 3.

1937 ***Ammobaculites agglutinans*** (d'Orbigny); Bartenstein & Brand p. 186, pl. 4, fig. 14; pl. 5, figs. 7-8; pl. 6, figs. 40a-b; pl. 8, figs. 38a-c; pl. 10, figs. 45a-b; pl. 11a, figs. 19a-b; pl. 11b, figs. 28a-b.

1955 ***Ammobaculites alaskensis*** Tappan; p. 43, pl. 10, figs. 1-10.

1981 ***Ammobaculites agglutinans*** (d'Orbigny); Barnard ***et al.***, p. 388, pl. 1, fig. 2.

1989 ***Ammobaculites agglutinans*** (d'Orbigny); Morris & Coleman, p. 218, pl. 6.3.6, fig. 1.

1989 ***Ammobaculites agglutinans*** (d'Orbigny); Gregory, p. 182, pl. 1, fig. 2.

Description. Small to medium test; initial evolute and biumbilicate planispire of 3-8 chambers in 1-1$^1/_2$ whorls is followed by a well developed, rectilinear section of 8 chambers; chambers sub-rectangular, sometimes inflated; proloculus obscured; sutures indistinct-distinct, depressed and straight; test coarsely agglutinated; aperture is terminal, central to peripheral and is either flush or produced on a short neck.

Remarks. This Jurassic form appears to be conspecific with Tertiary examples described by d'Orbigny (1846), thereby invalidating Tappan's (1955) contention that Jurassic forms should be assigned to *A. alaskensis* Tappan. Variation is mainly in the size of the coil, number of chambers in the uniserial portion and grain size of the agglutinated material. It can be distinguished from *A. fontinensis* by its more regularly defined linear portion and a smaller initial coil.

Material. 380 specimens.

Distribution.

243 from Staffin Bay; common throughout, concentrated between the ***lamberti*** Biozone to ***cordatum*** Sub-biozone and between the ***rosenkrantzi*** Biozone and ***mutabilis*** Biozone.

51 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***tenuiserratum*** Sub-biozone.

35 from Brora; ***calloviense*** Biozone-***lamberti*** Biozone (***henrici*** Sub-biozone).

48 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.

3 from Helmsdale; ***cymodoce*** Biozone.

This is commonly reported from the Bathonian-Oxfordian interval of the UK.

Ammobaculites coprolithiformis (Schwager), 1867

(Plate 4, Figures 4-5)

1867 ***Haplophragmium coprolithiformis*** Schwager; p. 654, pl. 34, fig. 3.

1941 ***Haplophragmium aequale*** (Roemer); Frentzen, p. 365, pl. 7, figs. 6-8.

1952 ***Haplophragmium aequale*** (Roemer); Bartenstein p. 325, pl. 1, figs. 2, 11; pl. 2, figs. 17-26; pl. 3, figs. 1-6; pl. 6, figs. 6-8.

1953 ***Ammobaculites suprajurassicum*** (Schwager); Barnard, p. 184, text-fig. a, figs. 2a-b.

1960 ***Haplophragmium aequale*** (Roemer); Lutze, p. 438, pl. 26, figs. 1-2, 5-6.

1965 ***Ammobaculites coprolithiformis*** (Schwager); Gordon, p. 833, text-figs. 2-3, figs. 25-28.

1970 ***Ammobaculites infrajurensis*** (Terquem); Garbowska, p. 47, fig. 7.

1970 ***Ammobaculites braunsteini*** Cushman & Applard; Garbowska, p. 49, fig. 9.

1971 ***Ammobaculites coprolithiformis*** (Schwager); Wernli, p. 310, pl. 11, figs. 6-8; pl. 1, fig. 16.

1981 ***Ammobaculites coprolithiformis*** (Schwager); Barnard ***et al.***, p. 389, pl. 1, fig. 9.

1981 ***Ammobaculites coprolithiformis*** (Schwager) form A; Barnard ***et al.***, p. 389, pl. 1, figs. 3-4, text-fig. 4.

1989 ***Ammobaculites coprolithiformis*** (Schwager); Morris & Coleman, p. 218, pl. 6.3.6, fig. 2.

Description. Very large test, initial section is a large, involute-evolute planispire of 2-6 chambers followed by a rectilinear to curvilinear series of up to 6 chambers; chambers globular becoming pyriform or conical, final chamber is extended distally to a large neck; proloculus large and spherical; sutures distinct, depressed and arcuate-oblique; test wall finely-coarsely agglutinated; aperture is a circular opening that is always produced on a centrally placed neck.

Remarks. This highly variable form has previously been assigned to many taxa and variation occurs particularly in the size of the initial coil and in the curvature of the uniserial section, which can be curvilinear to rectilinear. The chambers also vary from globular to flattened in cross-section. Garbowska (1970) assigned tightly coiled forms to ***A. braunsteini*** and loosely coiled forms to ***A. infrajurensis***.

Within the material from Brora were numerous examples of juvenile forms that consisted of 3-4 chambers in a tightly coiled ball. ***A. coprolithiformis*** can be distinguished from ***A. agglutinans*** and ***A. fontinensis*** by a lack of a biumbilicate planispire, and its pyriform chambers.

Material. 181 specimens.

Distribution.
2 from Staffin Bay; *mariae* Biozone-*cordatum* Biozone.
179 from Balintore; only recovered from the *cordatum* Sub-biozone.

This form has a British range from the ***murchisonae*** Biozone (Morris & Coleman, 1989) to the ***mutabilis*** Biozone and is particularly prevalent in the shallow water deposits developed during the ***athleta*** Biozone to ***cordatum*** Biozone in southern England (Barnard ***et al.***, 1981). It has also been recorded from offshore North Sea material by Partington ***et al.*** (1993a, b), with final acme appearances within the ***lamberti*** and ***cordatum*** Biozones.

Ammobaculites deceptoria (Haeusler), 1890
(Plate 4, Figure 6)

1890 ***Bigeneria deceptoria*** Haeusler; p. 74, pl. 12, figs. 8-13.
1944 ***Bigeneria deceptoria*** Haeusler; Frentzen, p. 336.
1960 ***Haplophragmium subaequale*** (Mjatluik); Lutze, p. 439, pl. 26, figs. 3-4, 7, 9, 15; pl. 27, fig. 3.
1960 ***Haplophragmium*** cf. ***subaequale*** (Mjatluik); Lutze, p. 439, pl. 26, fig. 8.
1960 ***Ammobaculites*** cf. ***helveto-jurassicus*** (Haeusler); Bielecka, p. 114, pl. 1, fig. 4.
1965 ***Ammobaculites*** cf. ***reophaciformis*** Cushman; Gordon, p. 834, text-fig. 3, fig. 12.
1967 ***Ammobaculites*** cf. ***pictonicus*** (Berthelin); Gordon, p. 449, pl. 1, fig. 18.
1970 ***Ammobaculites suprajurassicus*** (Schwager); Winter, p. 8, pl. 2, fig. 36.

Description. Medium-large agglutinated test, with an initial evolute planispire of 2-3 chambers, the coil of which is never greater than the width of later chambers; planispire succeeded by up to 6 chambers in a straight rectilinear series; proloculus large, spherical; chambers globular to sub-rectangular, regularly increasing in width and height as added, final chamber pyriform; sutures very distinct, depressed, straight-oblique; test wall composed of medium-fine grained material; aperture circular opening on a short, squat neck.

Remarks. ***A. deceptoria*** is a remarkably consistent form with a very regular rectilinear series. The initial coil is never composed of more than three chambers. It can be distinguished from ***A. agglutinans*** and ***A. fontinensis*** by its much smaller planispire, and from ***A. vetusta*** by its straight, uniserial section.

Material. 362 specimens.
Distribution.
248 from Staffin Bay; rare throughout the section, common within the jason Biozone and between the ***serratum-regulare*** Biozones.

82 from Balintore; ***cordatum*** Sub-biozone-***tenuiserratum*** Sub-biozone.
32 from Brora; ***jason*** Biozone-***lamberti*** Biozone (***henrici*** Sub-biozone).

Morris & Coleman (1989) and Morris & Dyer (1990) reported this form to be limited to the Bathonian to Kimmeridgian interval in the offshore North Sea Heather Formation, with acmes in the Callovian to Oxfordian. Partington *et al.* (1993a, b) attempt to further delineate its range (but without recourse to ammonite corroboration), to a final appearance within the ***rosenkrantzi*** Biozone.

Ammobaculites fontinensis (Terquem), 1870

(Plate 4, Figure 7)

1870 ***Haplophragmium fontinense*** Terquem; p. 235, pl. 24, figs. 29-30.
1950b ***Ammobaculites fontinensis*** (Terquem); Barnard, p. 4, pl. 1, figs. 1-2.
1955 ***Ammobaculites barrowensis*** Tappan; p. 45, pl. 11, figs. 7-12.
1958 ***Ammobaculites fontinensis*** (Terquem); Said & Barakat, p. 241, pl. 2, fig. 2; pl. 3, fig. 9.
1964 ***Ammobaculites alaskensis*** Tappan; Kristan-Tollman, p. 37, pl. 4, fig. 14.
1989 ***Ammobaculites fontinensis*** (Terquem); Morris & Coleman, p. 218, pl. 6.3.6, fig. 3.

Description. Test variable in size; initial large, biumbilicate and evolute planispire of 1-2$^1/_2$ whorls with up to 8 chambers is followed by a curvilinear portion, with up to 5 chambers; proloculus small, spherical; chambers sub-rectangular to drum shaped, greater in width than height and increase in width as added; test wall coarsely agglutinated; aperture is circular, being marginal-centrally placed, and flush to the test wall.

Remarks. ***Ammobaculites fontinensis*** is a variable form, but the diameter of the planispiral coil is always much greater than the width of the chambers in the uniserial section and this feature allows differentiation from ***A. agglutinans***.

Material. 827 specimens.
Distribution.
5 from Bearreraig Bay; rare throughout.
539 from Staffin Bay; very common, particularly in 2 acmes from the ***jason*** Biozone to ***cordatum*** Biozone and the top ***bukowskii*** Sub-biozone to the ***mutabilis*** Biozone.
97 from Balintore; ***jason*** Biozone-***tenuiserratum*** Biozone, with an acme within the ***mariae*** Biozone.
9 from Brora; only found within the ***athleta*** Biozone.
177 from Eathie Haven; common throughout the section, from the ***baylei*** Biozone to the ***cymodoce*** Biozone.

Ammobaculites vetusta (Terquem & Berthelin), 1875

(Plate 4, Figure 8)

1875 ***Haplophragmium vetustum*** Terquem & Berthelin; p. 53, pl. 4, figs. 16a-d.

1955 ***Ammobaculites vetusta*** (Terquem & Berthelin); Tappan, p. 45, pl. 13, figs. 1-3.

1965 ***Ammobaculites fisheri*** Crespin; Gordon, p. 833, text-fig. 3, figs. 13-15.

1968 ***Ammobaculites vetusta*** (Terquem & Berthelin); Welzel, p. 7, pl. 1, fig. 10.

1972 ***Haplophragmium elongalulum*** Dain; pl. 18, figs. 8-10.

1991 ***Ammobaculites vetusta*** (Terquem & Berthelin); Nagy & Johansen, p. 21, pl. 2, figs. 17-19.

Description. Medium-large, agglutinated test that possesses a small, involute planispire with 4-6 globular chambers, followed by an elongate, parallel sided, rectilinear series of up to 8 chambers; chambers elongate-pyriform, being greatest in height; sutures indistinct, straight to curved; test wall coarsely agglutinated; aperture is a simple, circular opening and is produced on an elongate neck.

Remarks. This is a common species in the Lower Jurassic, with records from Alaska, France, England and Siberia. It is particularly common in Pliensbachian samples from the Lower Jurassic of Allt Leahach, Morvern in NW Scotland (from initial work carried out for this project).

Material. 60 specimens.
Distribution.
19 from Staffin Bay; very rare throughout the section.
3 from Balintore; ***scarburgense*** Sub-biozone.
26 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.
12 from Eathie Haven; ***baylei*** Biozone.

Subfamily Flabellammininae Podobina, 1978

Genus ***Triplasia*** Reuss, 1854
emend. Loeblich & Tappan, 1952

Triplasia acuta Bartenstein & Brand, 1951

(Plate 4, Figure 9)

1951 ***Triplasia acuta*** Bartenstein & Brand ssp. ***acuta*** Bartenstein & Brand; p. 274, pl. 3, fig. 68.

1952 ***Triplasia acuta*** Bartenstein & Brand; Loeblich & Tappan, p. 12, pl. 2, figs. 5a-b.

1952 ***Triplasia bartensteini*** Loeblich & Tappan; p. 8, pl. 1, fig. 9.

1954 ***Flabellamminopsis variablis*** Malecki; p. 118, pl. 3, figs. 3, 11; pl. 4, figs, 4, 6-11.

1955 ***Triplasia kingakensis*** Tappan; p. 46, pl. 13, figs. 4-11.

1967 ***Triplasia bartensteini*** Loeblich & Tappan; Gordon, p. 450, pl. 1, figs. 19-20.
1981 ***Triplasia acuta*** Bartenstein & Brand; Barnard ***et al.***, p. 391, pl. 1, figs. 10-11, text-fig. 5B.
1989 ***Triplasia althoffi*** (Bartenstein); Morris & Coleman, p. 220, pl. 6.3.6, figs. 8-9.

Description. Large tapering agglutinated test, the early stage of 2-3 chambers is planispirally enrolled, with the later section uncoiled in a rectilinear, uniserial section; test angular and triangular in section, with 3 rough peripheral, rounded keels, one of which occupies only the proximal $^1/_2$ to $^1/_3$ of the total test length; chambers curved and broader than high, gradually increase in size as added; sutures depressed and arched distally on all faces of the test; test wall coarsely agglutinated; aperture terminal and produced on a neck at the mid-point of the apertural face.

Remarks. This form appears to be similar to ***T. althoffi*** (Bartenstein) as illustrated by Morris & Coleman (1989) and to ***Frankerina brandi*** as described by Weir (1943). In both cases the illustrations are not clear enough to be certain of their actual affinities.

Material. 12 specimens, only recovered from the ***cordatum*** Biozone (***costicardia*** Sub-biozone-***cordatum*** Sub-biozone) of Balintore.

Family Placopsilinidae Rhumbler, 1913

Subfamily Placopsilininae Rhumbler, 1913

Genus *Placopsilina* d'Orbigny, 1850

Placopsilina argoviensis Haeusler, 1881

(Plate 4, Figure 10)

1881a ***Placopsilina argoviensis*** Haeusler; p. 26, pl. 2, fig. 40.
1944 ***Placopsilina suprajurassica*** Haeusler; Frentzen, p. 38, pl. 5, figs. 1-6, 8-17.
1968 ***Placopsilina argoviensis*** Haeusler; Oesterle, p. 737, figs. 32-33.
1988 ***Sorosphaera argoviensis*** (Haeusler); Riegraf, p. 459, pl. 1, figs. 1-2.

Description. Test attached, small-medium, irregularly curvilinear, generally uniserial, but with the initial stage planispirally coiled; chambers sub-rectangular; sutures depressed, oblique-straight; test coarsely agglutinated; aperture not visible.

Remarks. ***P. argoviensis*** is inevitably found attached to bivalve debris and has a high degree of variation in the axial curvature of the uniserial section. It is very similar to ***P. cenomana*** d'Orbigny, with which it may be conspecific.

Material. 23 specimens.
Distribution.
16 from Staffin Bay; very rare throughout.

7 from Balintore; ***bukowskii*** Sub-biozone-***tenuiserratum*** Sub-biozone.

Superfamily Haplophragmiacea Eimer & Fichert, 1899

Family Ammosphaeroidinidae Cushman, 1927

Subfamily Recurvoidinae Alekeseyohik-Mitskevich, 1973

Genus ***Recurvoides*** Earland, 1934

Recurvoides disputabilis Dain, 1972

(Plate 5, Figure 1)

1972 ***Recurvoides disputabilis*** Dain; p. 55, pl. 10, figs. 6-7; pl. 11, figs. 1-4.

1976 ***Recurvoides*** cf. ***disputabilis disputabilis*** Dain; Souaya, p. 267, pl. 7, fig. 4.

1980 ***Recurvoides disputabilis*** Dain; Løfaldli & Nagy, p. 72, pl. 2, figs. 10-11.

1981 ***Recurvoides*** ? cf. ***disputabilis*** Dain; Brooke & Braun, p. 19, pl. 3, figs. 12-20.

1990a ***Recurvoides disputabilis*** Dain; Nagy ***et al.***, p. 993, pl. 4, figs. 1-4.

1991 ***Recurvoides disputabilis disputabilis*** Dain; Efimova & Mesezhnikov, pl. 39, fig. 9.

Description. Test large, sub-globular to flattened and sub-circular in outline; periphery rounded and slightly lobulate; initially streptospirally enrolled with 5-6 chambers per whorl, later chambers change from trochospiral to roughly planispiral coiling with up to 16 chambers in the final whorl; chambers elongate and narrow, being triangular to sub-rectangular and gradually increase in size as added; sutures depressed, straight and radial; test wall finely agglutinated; aperture located at the base of the final chamber and is a simple slit to circular opening.

Remarks. ***R. disputabilis*** can be distinguished from ***R. sublustris*** which is elongate and ellipsoidal in outline. ***R. pauas*** Dubrouskaya has a more inflated, smaller test with fewer chambers and ***R. obskiensis*** Romanova also has fewer chambers which are more rectangular in shape. Dain (1972) split ***R. disputabilis*** into several subspecies including ***R. disputabilis disputabilis*** and ***R. disputabilis plana***, the latter of which is more flattened. However, these subspecies are difficult to establish from his diagrams as many transitional forms are also illustrated.

Material. 563 specimens.

Distribution.

499 from Staffin Bay; concentrated between the base of the ***glosense*** Biozone to the ***mutabilis*** Biozone.

64 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.

R. disputabilis has been consistently reported from Boreal Upper Oxfordian and Lower Kimmeridgian deposits, e.g. from Svalbard and Spitsbergen by Løfaldli & Nagy (1980, 1983) and Nagy ***et al.*** (1990a); from Alaska by Souaya (1976), Balkwill ***et al.***, (1977) and Brooke & Braun (1981); and from Russia and Western Siberia by Dain

(1972) and Efimova & Mesezhnikov (1991).

Recurvoides sublustris Dain, 1972

(Plate 5, Figure 2)

1972 ***Recurvoides sublustris*** Dain; p. 56, pl. 12, figs. 3-6.
1981 ***Recurvoides*** ? sp. 149 Brooke & Braun; p. 20, pl. 3, figs. 21-32.
1983 ***Recurvoides sublustris*** Dain; Løfaldli & Nagy, p. 101, pl. 2, figs. 3-4.
1989 ***Recurvoides sublustris*** Dain; Morris & Coleman, p. 232, pl. 6.3.2, figs. 7-9.

Description. Test small-medium, asymmetrical, ellipsoidal or ovate in outline with a rounded and lobulate periphery, dorsal side is more evolute with 2-2$^1/_2$ whorls; coiling plane varies with the penultimate whorl coiled at 90° to the final whorl, the coiling style is initially streptospiral with the final whorl of 14-16 chambers coiled planispirally creating a degree of involution of the earliest whorls; sutures thickened, flush to depressed, being straight to curved; test wall agglutinated, composed of fine-medium grained material; aperture present at the base of the final chamber.

Remarks. Variation occurs in the extent of envelopment of the initial whorls by the final planispiral whorl, which can totally obscure the streptospirally coiled section. ***R. sublustris*** can be distinguished from ***R. scherkalyensis*** Levina which has a more distinctive and visible early stage with more chambers exposed.

Material. 196 specimens.
Distribution.
109 from Staffin Bay; total range between the ***macrocephalus*** Biozone to ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone), with an acme between the ***macrocephalus*** Biozone and basal ***athleta*** Biozone.
39 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Sub-biozone, with an acme in the ***mariae*** Biozone.
48 from Brora; ***calloviense*** Biozone-***athleta*** Biozone, concentrated in the ***calloviense*** Biozone.

There have been consistent reports of a first appearance of this form in the Lower Callovian e.g. Brooke & Braun (1981) from Alaska, with acmes developed in the Callovian to Oxfordian interval reported by Morris & Coleman (1989) from the Heather Formation in the North Sea.

Superfamily Spiroplectamminacea Cushman, 1927
Family Spiroplectamminidae Cushman, 1927
Subfamily Spiroplectammininae Cushman, 1927
Genus *Spiroplectammina* Cushman, 1927

Remarks. ***Bolivinopsis*** Yakovlev (1891) appears to be a senior synonym of ***Spiroplectammina***, however, Charnock & Jones (1990, p. 181) consider the former genus to be ***nomen dubium*** as the type species is apparently lost.

Spiroplectammina biformis (Parker & Jones), 1865
(Plate 5, Figure 3)

1865 ***Textularia agglutinans*** d'Orbigny var. ***biformis*** Parker & Jones; p. 370, p. 15, figs. 23a-b.

1937 ***Spiroplectammina biformis*** (Parker & Jones); Bartenstein & Brand, p. 183, pl. 12b, fig. 39.

1958 ***Spiroplectammina biformis*** (Parker & Jones); Said & Barakat, p. 242, pl. 2, fig. 3.

1959 ***Spiroplectammina biformis*** (Parker & Jones); Lloyd, p. 315, pl. 54, fig. 28.

Description. Small tapering agglutinated test, with a very small, evolute planispire of 3-4 globular chambers, followed by a series of biserially arranged chambers; planispiral section is only just greater in diameter than the width of the first 2-3 series of biserially arranged chambers; chambers much broader than high, becoming inflated as added; sutures depressed, straight and oblique; test wall finely arenaceous with much cement; aperture is a circular or crescentic shaped opening at the base of the final chamber.

Remarks. In the UK *S. **biformis*** is only recovered from the Middle to Upper Jurassic, with a definite acme in the Upper Oxfordian-Lower Kimmeridgian (e.g. Lloyd, 1959). *S. **biformis*** can be distinguished from *S. **vicinalis*** Dain, which is much larger and has a more coarsely agglutinated test.

Material. 152 specimens.
Distribution.
29 from Staffin Bay; rare throughout, but concentrated between the top of the ***rosenkrantzi*** Biozone to ***mutabilis*** Biozone.
23 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.
25 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

Spiroplectammina vicinalis Dain, 1967
(Plate 5, Figure 4)

1939 ***Spiroplectammina*** aff. ***biformis*** Myatluik, p. 49, pl. 2, fig. 24a.

1967 ***Spiroplectammina vicinalis*** Dain; p. 94, pl. 7, fig. 5.

1972 ***Spiroplectammina vicinalis*** Dain; Dain, p. 75, pl. 21, figs. 1-4, 9.

Description. Very large, tapering test, initial planispiral whorl is followed by a biserial section with up to 20 chambers; initial, single whorl consists of 5-7 oval-spherical chambers; proloculus where visible is small and spherical; initial biserial section is slightly larger in width than the total planispire diameter; chambers within the biserial section are sub-trapezoidal and greatest in width, increasing rapidly in size as added; septa depressed forming a distinct, zig-zag shaped suture; test wall coarsely agglutinated, but the planispire is finely agglutinated; aperture where visible, is a small interiomarginal opening at the base of the final chamber.

Remarks. Dain (1967, 1972) described microspheric forms with $2^1/_2$-3 whorls in the spiral section, and 13-15 chambers in the biserial portion. ***S. vicinalis*** can be distinguished from ***S. paravicinalis*** Dain by a less trapezoidal test shape and a smaller coil, and from ***G.*** sp. A which has a trochospirally coiled initial section.

Material. 364 specimens.
Distribution.
315 from Staffin Bay; ***glosense*** Biozone-***mutabilis*** Biozone.
49 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.

Dain (1972) indicated that this form was established in the Lower Volgian of the Russian deposits.

Superfamily Trochamminacea Schwager, 1877

Family Trochamminidae Schwager, 1877

Subfamily Trochammininae Schwager, 1877

Genus *Trochammina* Parker & Jones, 1859

Remarks. The subfamilies and genera of Trochamminidae have been recently defined by Brönnimann & Whittaker (1988) based on a revision of Recent Trochamminacea of the Discovery reports. This classification depends on identification of the aperture, with seven types. The most important are; those with a single interiomarginal type with a border resting completely on the first chamber of the final whorl (***Trochammina***); double apertures are characteristic of representatives of ***Deuterammina***, whilst triple apertures typify the genus ***Zavodovskia***.

Preservation of the Jurassic material in the present study, however, often precludes the differentiation of the apertural types and so the simplified generic classification of Loeblich & Tappan (1988) is used here and is based on the definition of a single genus irrespective of apertural type.

Trochammina canningensis Tappan, 1955

(Plate 5, Figure 5)

1955 ***Trochammina canningensis*** Tappan; p. 49, pl. 14, figs. 15-19.

1959 ***Trochammina globigeriniformis*** (Parker & Jones); Cifelli, p. 290, pl. 1, figs. 23-24.

1968 ***Trochammina canningensis*** Tappan; Welzel, p. 7, pl. 1, figs. 13a-b.

1983a ***Trochammina canningensis*** Tappan; Wall, pl. 1, figs. 4-6.
1989 ***Trochammina canningensis*** Tappan; Morris & Coleman, p. 234, pl. 6.3.12, fig. 1.

Description. Small, inflated, high trochospiral test with up to 5 chambers in the final whorl and has a rounded, lobulate periphery; proloculus small and spheroidal, followed by 2-$2^1/_2$ whorls composed of globular chambers that gradually increase in size as added; umbilical area exposed on the ventral side is small; sutures radial, depressed and curved; test wall finely agglutinated; aperture obscured.

Remarks. This is a very common form which occurs in acmes that appear to coincide with the initial phases of transgression in both the Hebrides and Moray Firth Basins during the Lower Callovian, Upper Oxfordian and Kimmeridgian. ***T. canningensis*** is widely distributed between the Lower and Upper Jurassic, being particularly common between the Middle Bathonian to Middle Callovian of the Brent Field (Morris & Coleman, 1989).

Material. 1030 specimens.
Distribution.
500 from Staffin Bay; common between the ***jason*** Biozone to ***bukowskii*** Sub-biozone and between the ***serratum*** Biozone to ***mutabilis*** Biozone.
104 from Balintore; ***jason*** Biozone-***cordatum*** Sub-biozone, with a maximum abundance between the ***jason*** Biozone and the ***mariae*** Biozone (***scarburgense*** Sub-biozone).
285 from Brora; ***calloviense*** Biozone-***lamberti*** Biozone, with an acme between the ***calloviense*** Biozone to ***athleta*** Biozone.
141 from Eathie Haven; common throughout between the ***baylei*** and ***mutabilis*** Biozones.

Trochammina sablei Tappan, 1955

(Plate 5, Figure 6)

1955 ***Trochammina sablei*** Tappan; p. 50, pl. 14, figs. 6-9.
1969 ***Trochammina sablei*** Tappan; Brouwer, p. 26, pl. 1, figs. 26-27.
1981 ***Trochammina*** cf. ***sablei*** Tappan; Brooke & Braun, p. 23, pl. 5, figs. 49-52.
1985 ***Trochammina sablei*** Tappan; Riegraf, p. 99, pl. 6, fig. 21.

Description. Small-medium, discoidal, low trochospiral test, with rounded margins; test coiled in $2^1/_2$ whorls, with 6-8 chambers in the final whorl; chambers crescentic or slightly irregular in development, usually inflated and gradually increase in size as added; sutures depressed and straight to curved; test wall generally finely agglutinated; aperture obscured due to poor preservation of specimens.

Remarks. Variation occurs in the degree of development of the trochospire which is plano-convex in outline, but still low. It can be distinguished from ***T. gryci*** Tappan, which has a more highly spired test, with 8-10 chambers in the final whorl. All Tappan's (1955) specimens were from the Lower Jurassic of Alaska and ***T. sablei*** appears to have been more widely reported from the Lower Jurassic, such as records from Germany by Riegraf (1985) and from other European sites by Brouwer (1969).

Material. 29 specimens.
Distribution. A rare form with 22 specimens recovered from the ***rosenkrantzi*** Biozone to ***baylei*** Biozone at Staffin Bay and 7 from the ***baylei*** Biozone at Eathie Haven. Partington ***et al.*** (1993a, b) record a final appearance within the Middle Volgian for this taxon in North Sea deposits.

Trochammina squamata Jones & Parker, 1860
(Plate 5, Figures 7-8)

1860 ***Trochammina squamata*** Jones & Parker; p. 304.
1937 ***Trochammina squamata*** Jones & Parker; Bartenstein & Brand, p. 190, pl. 6, fig. 41; pl. 11b, fig. 6; pl. 15c, figs. 22a-b.
1959 ***Trochammina squamata*** Jones & Parker; Lloyd, p. 316, pl. 54, fig. 29.
1981 ***Trochammina squamata*** Jones & Parker; Barnard & Shipp, p. 10, pl. 1, figs. 7-8.
1989 ***Trochammina squamata*** Jones & Parker; Morris & Coleman, p. 234, pl. 6.3.12, fig. 14.

Description. Test small-medium and trochospiral, with a loose coil of 14-16 chambers in $2^1/_2$ whorls present on the dorsal side and 6 chambers in the final whorl; initial chambers are sub-globular with later chambers being crescentic, flattened and wedging out towards the periphery; ventral side of the test is flat with a large, circular umbilical/axial depression; sutures are well developed on the dorsal and ventral sides, being curved and depressed; periphery is sometimes keeled or angular; test wall finely agglutinated; aperture where visible is a single, slit like, interiomarginal opening between the test periphery and axial depression.

Remarks. Variation is not particularly great with a very consistent number of chambers developed. This is a very common form and is frequently associated with the initial phases of transgression.

Material. 1202 specimens.
Distribution.
258 from Staffin Bay; common throughout, but concentrated between the ***jason*** Biozone and ***mariae*** Biozone and the ***rosenkrantzi*** Biozone and ***mutabilis*** Biozone.

292 from Balintore; again a common form between the ***jason*** Biozone and ***tenuiserratum*** Biozone, with acmes between the ***jason*** Biozone and ***mariae*** Biozone (***scarburgense*** Sub-biozone) and within the ***cordatum*** Biozone.
644 from Brora; very rarely occurring within the ***calloviense*** Biozone, and is widespread between the ***athleta*** Biozone and ***lamberti*** Biozone.
8 from Eathie Haven between the ***baylei*** and ***mutabilis*** Biozones.

Most records of *T. squamata* from the Jurassic have been from the Middle and Upper Jurassic of Dorset (Lloyd, 1958, 1959), from southern England and France (Barnard *et al.*, 1981; Barnard & Shipp, 1981) and from the North Sea (Morris & Coleman, 1989).

Trochammina topagorukensis Tappan, 1955
(Plate 6, Figures 1-2)

1955 ***Trochammina topagorukensis*** Tappan; p. 51, pl. 14, figs. 10-11.
1968 ***Trochammina*** cf. ***topagorukensis*** Tappan; Oesterle, p. 752.
1976 ***Trochammina topagorukensis*** Tappan; Souaya, p. 275, pl. 6, fig. 2.
1981 ***Trochammina globigeriniformis*** (Parker & Jones); Barnard ***et al.***, p. 394, pl. 1, fig. 12, text-fig. 6c.
1983 ***Trochammina topagorukensis*** Tappan; Løfaldli & Nagy, p. 101, pl. 2, figs. 5-6.

Description. Test small-medium, coiled in a high plano-convex trochospire, periphery is rounded and sub-arcuate; umbilical region is distinct, depressed and quite small; 4-5 chambers are developed in the final whorl; chambers flattened and sub-triangular; sutures distinct, depressed and radial, initially straight, then becoming curved towards the periphery; test wall usually composed of fine-medium grained agglutinated material; aperture where visible is a small interiomarginal slit on the ventral side.

Remarks. As Tappan (1955) indicated, ***T. topagorukensis*** is somewhat similar to ***T. gryci*** Tappan, but the latter form is differentiated by having 8-10 chambers in the final whorl and is larger in size.

Material. 105 specimens.
Distribution. This is generally a rare form, with 73 specimens from the top of the ***rosenkrantzi*** Biozone to ***mutabilis*** Biozone at Staffin Bay, 2 from the ***cordatum*** Sub-biozone at Balintore, 9 from the upper ***athleta*** Biozone at Brora and 21 specimens from the ***baylei*** Biozone at Eathie Haven.

Superfamily Verneuilinacea Cushman, 1911

Family Verneuilinidae Cushman, 1911

Subfamily Verneuilinoidinae Suleymanov, 1973

Genus *Verneuilinoides* Loeblich & Tappan, 1949

Verneuilinoides sp. 2 Morris & Coleman, 1989

(Plate 6, Figure 3)

1989 *Verneuilinoides* sp. 2; Morris & Coleman; p. 234, pl. 6.3.12, figs. 10-12.

Description. Medium sized, regularly tapering triserial test, with a lobulate outline in lateral view; small oval-globular proloculus is followed by up to 5 whorls of globular chambers that gradually increase in size as added; sutures indistinct-distinct curved and depressed; test wall is built up from medium-coarsely grained agglutinated material; aperture where visible appears to be a simple crescentic opening at the base of the final chamber.

Remarks. *V.* sp. 2 can be distinguished from *V. tryphera* and *V. mauritii* which are both more finely agglutinated. The former is also more elongate, with well defined chambers, whilst the latter possesses a greatly inflated, final triserial whorl. *V.* sp. 1, also described by Morris & Coleman (1989), is smaller, more finely agglutinated and has a more regular, narrow outline.

Material. 21 specimens.

Distribution. A very rare form with 6 specimens from throughout the section at Staffin Bay, only 1 from the *athleta* Biozone at Brora and 14 from the *baylei* Biozone at Eathie Haven.

V. sp. 2 has only been reported from the Middle Bathonian to Lower Callovian interval of the lower Heather Formation of the North Sea (Morris & Coleman, 1989).

Verneuilinoides mauritii (Terquem), 1866

(Plate 6, Figure 4)

1866b *Verneuilina mauritii* Terquem; p. 448, pl. 18, figs. 18a-b.

1960 *Verneuilinoides mauritii* (Terquem); Bizon, p. 4, pl. 1, figs. 3a-b, pl. 4, fig. 10.

1979 *Verneuilinoides mauritii* (Terquem); Exton, p. 8, pl. 1, fig. 4.

1989 *Verneuilinoides mauritii* (Terquem); Copestake & Johnson, p. 166, pl. 6.2.1, fig. 14.

Description. Small-medium, distinctly tapering triserial test; chambers sub-globular to globular, initially increasing in size gradually, with the final whorl of 3 chambers being greatly inflated; sutures depressed and curved; test wall is finely agglutinated; aperture is an interiomarginal arch on the final chamber.

Remarks. Variation occurs mainly in the divergence of the peripheries caused by the degree of inflation of the final whorl. This produces noticeably tapering forms.

Material. 42 specimens.
Distribution. 36 specimens were recovered from the Staffin Bay section, with 3 from the ***bukowskii*** Sub-biozone at Balintore and 3 from the ***cymodoce*** Biozone to ***mutabilis*** Biozone at Eathie Haven.

Verneuilinoides tryphera Tappan, 1955

(Plate 6, Figure 5)

1955 ***Verneuilinoides tryphera*** Tappan; p. 42, pl. 11, fig. 16.
1974 ***Verneuilinoides tryphera*** Tappan; Coleman, p. 92, pl. 6, fig. F.
1974 ***Verneuilinoides neocomiensis*** (Mjatluik); Kuznetsova, pl. 1, fig. 6.
1989 ***Verneuilinoides tryphera*** Tappan; Morris & Coleman, p. 234, pl. 6.1.3, fig. 6.

Description. Test small, elongate and triserial with lobulate margins; chambers initially sub-rectangular, becoming increasingly globular as added; sutures distinct and depressed; test wall finely agglutinated with considerable cement; aperture distinct, interiomarginal at the base of the final chamber, and is a large comma shaped opening with an arched lip.

Remarks. This is a distinct form with little observable variation, except in the degree of tapering of the test. ***V. tryphera*** has been reported from the Middle Bathonian to Lower Callovian of the Heather Formation (Morris & Dyer, 1990) and from the lower part of the ***cymodoce*** Biozone at Helmsdale (Gregory, 1986, 1989). The ***mutabilis*** Biozone appears to mark the final appearance of this form.

Material. 156 specimens.
Distribution.
57 from Staffin Bay; ***bukowskii*** Sub-biozone-***mutabilis*** Biozone, with an acme between the ***rosenkrantzi*** Biozone and ***mutabilis*** Biozone.
4 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Biozone.
37 from Brora; ***athleta*** Biozone-***lamberti*** Biozone (***henrici*** Sub-biozone).
31 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.
27 from Helmsdale; ***cymodoce*** Biozone.

Subfamily Verneuilininae Cushman, 1911

Genus *Gaudryina* d'Orbigny 1839

***Gaudryina* sp. A**

(Plate 6, Figure 6)

1987 ***Gaudryina*** sp. 2 Young; p. 216, pl. 6, fig. 4.

Description. Very large, elongate, tapering, and coarsely agglutinated test with lobulate margins; the initial small triserial coil of 1-2 whorls grades into a series of numerous, biserially arranged chambers; chambers small, broader than high, gradually increasing in size as added; sutures depressed, straight and oblique-horizontal; aperture when visible is a small, irregular, basal opening on the final chamber.

Remarks. The megalospheric forms tend to have a larger initial trochospiral portion, but in both generations the width of the triserial section does not generally exceed the width of the following biserial section. This form has only previously been reported from the Flodigarry section on the Isle of Skye (Young, 1987).

Poorly preserved examples of ***G.*** sp. A are particularly difficult to differentiate from ***S. vicinalis***.

Material. 1358 specimens.

Distribution. This form is restricted to the Upper Oxfordian and Lower Kimmeridgian and is extremely common from the Staffin Bay section, accounting for 1354 of the total, being limited in its range between the ***glosense*** Biozone and ***mutabilis*** Biozone with a very distinct acme between the ***cymodoce*** and ***mutabilis*** Biozones. 4 specimens were recovered from the ***mutabilis*** Biozone at Eathie Haven.

Gaudryina* aff. *sherlocki (Bettenstaedt), 1952

(Plate 6, Figure 7)

see 1952 ***Gaudryinella sherlocki*** Bettenstaedt; p. 268, pl. 1, figs. 1-5.

1955 ***Gaudryina milleri*** Tappan; p. 48, pl. 8, figs. 7-8.

1960 ***Gaudryina*** sp. 2 Lutze; p. 447, pl. 27, figs. 6-7.

1976 ***Gaudryina milleri*** Tappan; Souaya, p. 276, pl. 5, fig. 8.

1981 ***Gaudryina sherlocki*** (Bettenstaedt); Barnard ***et al.***, p. 394, pl. 1, fig. 17, text-figs. 6a-b.

1989 ***Gaudryina sherlocki*** (Bettenstaedt); Shipp, p. 252, pl. 6.4.1, fig. 8.

Description. Medium to large agglutinated test, rounded at the base with sub parallel, but lobulate margins; test is initially triserial for 1-2 whorls, and extends for approximately $^1/_3$-$^1/_2$ of the total test length, this is followed by an irregular biserial section; chambers rounded to sub-triangular, which only gradually increase in size as added; sutures depressed, straight and oblique; test wall finely arenaceous; aperture is a crescentic opening at the base of the final chamber.

Remarks. There are some differences between the Scottish material and the Cretaceous taxon described by Bettenstaedt (1952), as the final biserial section is more regular in development in the latter. The taxa outlined in the synonymy above appear to compare more readily to the Scottish material than to the form erected by Bettenstaedt (1952). Therefore, the material recovered here and listed in the synonymy could be adequately contained under ***G. milleri*** Tappan. However, without recourse to the original material, specimens are grouped under *G.* aff. ***sherlocki.***

Material. 223 specimens.
Distribution.
185 from Staffin Bay; rare throughout, but concentrated between the ***athleta*** Biozone and ***cordatum*** Biozone (***bukowskii*** Sub-biozone).
16 from Balintore; lower ***athleta*** Biozone-***cordatum*** Biozone (***cordatum*** Sub-biozone).
22 from Brora; middle ***athleta*** Biozone-***lamberti*** Biozone.

The majority of the records of this form are from the Callovian-Oxfordian interval from the UK (Barnard ***et al.***, 1981; Shipp, 1989), Alaska (Tappan, 1955), Germany (Lutze, 1960 as ***G.*** sp. 2) and France (Guyader, 1968).

Superfamily Textulariacea Ehrenberg, 1838
Family Textulariidae Ehrenberg, 1838
Subfamily Textulariinae Ehrenberg, 1838
Genus ***Textularia*** DeFrance, 1824

Textularia sp. A

(Plate 6, Figure 8)

Description. Small, tapering, flattened, biserial test with lobulate margins; proloculus small and globular, followed by a series of globular chambers that increase systematically in size as added, final chamber is somewhat inflated; test wall finely agglutinated; aperture where visible is a small, crescentic opening at the base of the final chamber.

Remarks. ***T.*** sp. A can be distinguished from ***T. jurassica*** which is much larger, more robust and inflated. ***T. aeroplecta*** is similar in size, but its chambers are sub-rectangular and its periphery is non-lobulate.

Material. 88 specimens.
Distribution. ***T.*** sp. A was recovered from Staffin Bay, with 58 specimens from the ***cordatum*** Biozone (***cordatum*** Sub-biozone) to ***rosenkrantzi*** Biozone and Eathie Haven, with 30 specimens from the ***baylei*** Biozone to ***cymodoce*** Biozone.

Textularia areoplecta Tappan, 1955
(Plate 6, Figure 9)

1955 ***Textularia areoplecta*** Tappan; p. 47, pl. 13, figs. 13-16
1985 ***Textularia areoplecta*** Tappan; Riegraf, p. 100, pl. 6, figs. 16-18.

Description. Small, elongate, compressed and tapering, biserial test with rounded margins that distally become almost parallel sided; initial chambers expand rapidly, then are added with a gradual increase in size, chambers generally greatest in breadth; sutures slightly depressed, oblique and curved; test wall finely agglutinated, giving rise to a smooth surface; aperture where visible is a small slit at the base of the final chamber.

Remarks. Riegraf (1985) indicated a large degree of variation in test outline, from elongate to squat, in his material from the Lower Jurassic of Germany. This morphological variation was not reported by Tappan (1955) for the original material, nor was it observed in specimens from this study. ***T. areoplecta*** can be distinguished from ***T. inversa*** (Terquem), which is larger and has a more elongate test. ***T*** sp. A, described herein, has a more noticeable tapering of the test outline and possesses more globular chambers.

Material. 158 specimens.
Distribution.
99 from Staffin Bay; rare between the ***jason*** Biozone and ***densiplicatum*** Biozone and common between the ***rosenkrantzi*** Biozone and ***cymodoce*** Biozone.
2 from Balintore; ***athleta*** Biozone-***lamberti*** Biozone.
19 from Brora; ***calloviense*** Biozone-***lamberti***Biozone.
38 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.

Textularia jurassica (Gümbel), 1862
(Plate 6, Figure 10)

1862 ***Textilaria jurassica*** Gümbel; p. 228, pl. 4, figs. 17a-b.
1917 ***Textularia (Spiroplecta) jurassica*** (Gümbel); Paalzow, p. 222, pl. 42, figs. 1-2.
1960 ***Textularia jurassica*** (Gümbel); Bielecka, p. 115, pl. 1, fig. 6.
1988 ***Textularopsis jurassica*** (Gümbel); Riegraf, p. 471, pl. 5, figs. 8-11.
1989 ***Textularia jurassica*** (Gümbel); Shipp, p. 252, pl. 6.4.1, fig. 7.

Description. Small to medium, regularly tapering biserial test with a rounded and lobulate periphery; proloculus small and ovoid; chambers globular to sub-rectangular; sutures distinct, depressed, being curved to sub-horizontal; test wall usually coarsely agglutinated; aperture is an interiomarginal, crescentic shaped slit located on the final chamber.

Remarks. ***T. jurassica*** can be distinguished form ***T. areoplecta*** and ***T.*** sp. A by its inflated and rounded test, and by its distinct, lobulate periphery and globular chambers.

Material. 350 specimens.
Distribution.
294 from Staffin Bay; occurs rarely throughout the section, being concentrated within the ***glosense*** Biozone and between the ***rosenkrantzi*** Biozone and ***cymodoce*** Biozone.
2 from Balintore; only from the ***cordatum*** Biozone (***cordatum*** Sub-biozone).
52 from Brora; only recovered from the ***athleta*** Biozone.
2 from Eathie Haven; ***baylei*** Biozone.

This is a very common component of German, Polish and British Middle and Upper Jurassic sequences. Partington ***et al.*** (1993a, b) record an acme final appearance within the ***baylei*** Biozone for this taxon for North Sea Jurassic deposits.

Genus ***Bigenerina*** d'Orbigny, 1826

Bigenerina sp.

(Plate 6, Figure 11)

1967 ***Bigenerina*** sp. Gordon; p. 450, pl. 1, fig. 14.

Description. Test small-medium; initial biserial section is followed by 2-3 irregularly added, uniserial chambers; proloculus large, globular; chambers globular; sutures distinct, curved-oblique; test wall finely agglutinated; aperture is a simple, circular opening that is flush to the test wall.

Remarks. There were too few specimens to make a positive identification, but it is probably similar to a form illustrated by Gordon (1967) from the Callovian of Brora. It is also similar to ***B. arcuata*** Haeusler and to illustrations of this form by Oesterle (1968) and Riegraf ***et al.*** (1984).

Material. 2 specimens from the ***baylei*** Biozone of Staffin Bay.

Family Valvulinidae Berthelin, 1880

Subfamily Valvulininae Berthelin, 1880

Genus ***Valvulina*** d'Orbigny, 1826

?Valvulina sp.

(Plate 7, Figure 1)

Description. Test small-medium, triangular in outline, with a smooth periphery and triserially arranged chambers; chambers sub-triangular which rapidly increase in size as added; sutures smooth; test wall finely agglutinated; aperture obscured, but appears to be a small, slit opening at the base of the final chamber.

Remarks. This form can not be definitely assigned to ***Valvulina*** as the aperture was not preserved sufficiently well to differentiate the presence of a typical, valvuline toothed aperture. There is a similar form in the British Museum (Natural History) type collection, from Gordon's (1967) work at Brora, described as ***Textularia duomortieri*** (Schwager), but again the aperture is not well preserved.

Material. 2 specimens.
Distribution. A rare form with 1 specimen recovered from the ***costicardia*** Sub-biozone at Staffin Bay and the other specimen from the ***tenuiserratum*** Sub-biozone at Balintore.

Suborder Involutinina Hoheneger & Piller, 1977

Family Involutinidae Bütschli, 1880

Subfamily Involutininae Bütschli, 1880

Genus ***Trocholina*** Paalzow, 1922

?Trocholina sp. A

(Plate 7, Figure 2)

Description. Small, smooth, conical test; proloculus followed by a flattened unseptated tube wound in several whorls; there are no visible external features and the aperture was not visible.

Remarks. This form is tentatively assigned to ***Trocholina*** and is somewhat similar to ***T. granulata*** as illustrated by Cordey (1962) for material from Staffin Bay.

Material. 3 specimens, only recovered from the ***lamberti*** Biozone to ***tenuiserratum*** Biozone at Balintore.

Suborder Spirilliniina Hohnegger & Piller, 1975

Family Spirillinidae Reuss & Fritsch, 1861

Genus ***Conicospirillina*** Cushman, 1927

Conicospirillina trochoides (Berthelin), 1879

(Plate 7, Figure 4)

1879 ***Spirillina trochoides*** Berthelin; p. 37, pl. 1, figs. 20-22.

1964 ***Conicospirillina trochoides*** (Berthelin); Loeblich & Tappan, p. 600, text-fig. 475, figs. 5a-c.

1969 ***Conicospirillina pictonia*** (Berthelin); Brouwer, p. 42, pl. 7, fig. 28.

1981 ***Conicospirillina trochoides*** (Berthelin); Copestake & Johnson, p. 100, pl. 6.1.5, figs. 4-5.

1989 ***Conicospirillina*** cf. ***trochoides*** (Berthelin); Morris & Coleman, p. 210, pl. 6.3.2, figs. 7-9.

1989 ***Conicospirillina trochoides*** (Berthelin); Gregory, p. 188, pl. 1, fig. 24.

Description. Planispiral, low, conical domed test; small spherical proloculus is followed by 6-7 whorls of a non-septated, angular tube; spiral suture depressed; surface coarsely perforated; aperture is a simple opening at the end of the tube.

Remarks. The forms illustrated by Copestake & Johnson (1981) possess a single row of pores. However, material from Brora and Kintradwell (Gregory, 1986, 1989) more closely resembles *C.* cf. ***trochoides*** as illustrated by Morris & Coleman (1989), which has a coarsely, irregularly perforate test. As such, this may be a variant or subspecies. It is most common from the shallower water deposits of Kintradwell.

Material. 121 specimens.
4 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Sub-biozone.
117 from Helmsdale; ***cymodoce*** Biozone-***eudoxus*** Biozone.

Genus *Spirillina* Ehrenberg, 1843

Spirillina elongata Bielecka & Pozaryski, 1954

(Plate 7, Figure 3)

1954 ***Spirillina elongata*** Bielecka & Pozaryski; p. 196, pl. 10, fig. 3.
1958 ***Spirillina*** cf. ***elongata*** Bielecka & Pozaryski; Bizon, p. 18.
1980 ***Spirillina elongata*** Bielecka & Pozaryski; Munk, p. 200, pl. 20, fig. 12.
1986 ***Spirillina elongata*** Bielecka & Pozaryski; Stam, p. 125, pl. 6, fig. 11.

Description. Test small, compressed, oval and consists of a single planispirally wound, unseptated tube of 2-4 volutions; tube irregular, with the final whorl greatly inflated; surface in well preserved examples has an ornament of fine pores; aperture is a simple opening at the end of the tube.

Remarks. ***S. elongata*** can be distinguished from ***S. obconica*** Brady which has a more regular whorl development.

Material. 13 specimens.
Distribution. A rare form, with 4 specimens from the ***densiplicatum*** Biozone at Staffin Bay, 8 from the base of the ***mariae*** Biozone to the ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) at Balintore and 1 specimen from the ***cymodoce*** Biozone at Eathie Haven.

Spirillina infima (Strickland), 1846

emend. Barnard, 1952b

(Plate 7, Figure 5)

1846 ***Orbis infimus*** Strickland; p. 30, text-fig. a.
1876 ***Cornuspira infima*** (Strickland); Blake, p. 451, pl. 8, fig. 1.
1936 ***Cornuspira obicula*** (Terquem & Berthelin); Franke, p. 17, pl. 1, fig. 16.

1950a *Spirillina infima* (Strickland); Barnard, p. 376, fig. 1g.
1952b *Spirillina infima* (Strickland); Barnard, p. 905, text-figs. 1-3.
1989 *Spirillina infima* (Strickland); Morris & Coleman, p. 216, pl. 6.3.5, fig. 11.

Description. Test small-medium, non-septated, evolute and biconcave, planispiral tube; tube wound into 4-6 rounded whorls, last whorl can be greatly inflated and slightly involute; spiral suture initially indistinct, eventually becoming depressed; test wall coarsely perforated; aperture is a simple opening at the end of the tube.

Remarks. Confusion existed as to the exact generic position of the holotype, which had been assigned to ***Ammodiscus*** and ***Cornuspira*** by various authors. Barnard (1952b) studied the holotype, which conformed to ***Spirillina*** and he also nominated a lectotype which differs from some of the Scottish material in having a finely perforated surface. ***S. infima*** can be distinguished from ***S. tenuissima*** by its smaller size, lower number of whorls and inflated final whorl.

Material. 398 specimens.
Distribution.
6 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
76 from Staffin Bay; occurs sporadically from the base of the ***mariae*** Biozone to the ***cymodoce*** Biozone.
61 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.
3 from Brora; only from the ***jason*** Biozone.
32 from Eathie Haven; ***cymodoce*** Biozone-***mutabilis*** Biozone.
220 from Helmsdale; ***cymodoce*** Biozone- ***mutabilis*** Biozone.

Spirillina tenuissima Gümbel, 1862
(Plate 7, Figure 6)

1862 ***Spirillina tenuissima*** Gümbel; p. 214, pl. 4, fig. 12.
1884 ***Spirillina crassa*** (Kübler & Zwingli); Jones, p. 770, pl. 34, fig. 13.
1953 ***Spirillina tenuissima*** Gümbel; Barnard, p. 492, pl. 3.
1981 ***Spirillina tenuissima*** Gümbel; Barnard *et al.*, p. 428, pl. 4, figs. 4, 8.
1989 ***Spirillina tenuissima*** Gümbel; Gregory, p. 188, pl. 1, fig. 23.

Description. Test medium-large, arranged in an evolute to slightly involute planispiral, flattened tube; small, spherical proloculus is followed by up to 10 whorls that gradually increase in diameter as added; sutural spiral is distinct and depressed; surface marked by distinct and regularly arranged perforations that parallel the spiral suture; aperture is a simple opening at the end of the tube.

Remarks. Several authors have assigned this form to ***S. numismallis*** (e.g. Exton, 1979), as they contended that the holotype of ***S. tenuissima*** was not a true spirillinid and was an agglutinated form that belonged to ***Ammodiscus***. This issue had already been resolved by Seibold & Seibold (1955) who indicated that the generic position of ***S. tenuissima*** was not in doubt. ***S. tenuissima*** can be distinguished from ***A. siliceus*** to which it bears a passing resemblance, by the presence of perforations, and from ***S. infima*** which is smaller and has more irregularly arranged perforations. Gregory (1986, 1989) recovered ***S. tenuissima*** in great numbers from the hypothesised shallow water environment at Helmsdale. It generally occurs in 'floods' with ***S. infima*** and appears to be indicative of shallow water conditions.

Material. 1226 specimens.
Distribution.
259 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone, with an acme within the ***discites*** Biozone.
61 from Staffin Bay; ***mariae*** Biozone-***tenuiserratum*** Biozone.
135 from Balintore; common only from the base of the ***mariae*** Biozone to the ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
6 from Brora; ***calloviense*** Biozone-***athleta*** Biozone.
83 from Eathie Haven from the ***cymodoce*** to ***mutabilis*** Biozones.
722 from Helmsdale; ***cymodoce*** Biozone- ***mutabilis*** Biozone.

Suborder Miliolina Delage & Hérouard, 1896
Superfamily Cornuspiracea Schultze, 1854
Family Cornuspiridae Schultze, 1854
Subfamily Cornuspirinae Schultze, 1854
Genus ***Cornuspira*** Schultze, 1854
Cornuspira eichbergensis Kübler & Zwingli, 1870
(Plate 7, Figure 7)

1870 ***Cornuspira eichbergensis*** Kübler & Zwingli; p. 17, 24, 28, pl. 2, fig. 2; pl. 3, fig. 2; pl. 4, fig. 2.
1960 ***Cornuspira eichbergensis*** Kübler & Zwingli; Lutze, p. 493, pl. 33, fig. 5.
1989 ***Cornuspira eichbergensis*** Kübler & Zwingli; Gregory, p. 183, pl. 1, fig. 5.
1989 ***Cornuspira eichbergensis*** Kübler & Zwingli; Shipp, p. 254, pl. 6.4.1, fig. 9.

Description. Large ovate, biconcave and planispiral test that can be free or attached; test wound as a single, unseptated, evolute tube; large, spherical proloculus is followed by 8-10 whorls, whorl section rounded and is also twisted in places to give constrictions; spiral suture distinct and depressed; test wall calcareous, porcellaneous and imperforate; aperture is a simple, terminal opening.

Remarks. ***C. eichbergensis*** is a large form, that can be distinguished from ***C. liasina*** by its rounded, inflated whorls, and characteristic constrictions, and from *S. tenuissima* by its porcellaneous, imperforate test.

Material. 5 specimens.
Distribution. A very rare form, with 1 specimen from the ***baylei*** Biozone at Staffin Bay and 4 from the ***cymodoce-mutabilis*** Biozones at Helmsdale. It has been previously found in the UK from the ***athleta*** Biozone to ***cordatum*** Biozone at Blackhead (Shipp, 1989).

Cornuspira liasina Terquem, 1866
(Plate 8, Figure 1)

1866b ***Cornuspira liasina*** Terquem; p. 474, pl. 19, figs. 4a-b.
1936 ***Cornuspira liasina*** Terquem; Franke, p. 16, pl. 1, fig. 15.
1937 ***Cornuspira orbicula*** Bartenstein & Brand; p. 137, pl. 1a, figs. 3a-b; pl. 1b, fig. 3; pl. 2a, figs. 3a-b; pl. 2b, fig. 5; pl. 3, fig. 14; pl. 4, fig. 9; pl. 5, fig. 7; pl. 6, figs. 6a-b; pl. 8, figs. 7a-b; pl. 10, figs. 6a-b; pl. 12a, figs. 2a-b; pl. 12b, fig. 1; pl. 14c, fig. 2.
1968 ***Cyclogryra liasina*** (Terquem); Welzel, p. 7, pl. 1, fig. 14.
1989 ***Cornuspira liasina*** Terquem; Morris & Coleman, p. 221, pl. 6.3.6, fig. 10.

Description. Test small-medium, biumbilicate, discoidal and slightly involute planispire; large spheroidal proloculus followed by up to 12 whorls of a single, rounded, unseptated tube; spiral suture distinct, depressed; test wall imperforate and porcellaneous; aperture not visible.

Remarks. This is a rare species that can be distinguished from ***C. eichbergensis*** by being much smaller and having a greater number of whorls that also do not possess constrictions.

Material. 8 specimens.
Distribution. Only recovered in small numbers, with 1 specimen from the ***discites*** Biozone at Bearreraig Bay, 5 specimens within the ***cordatum*** Biozone (***bukowskii*** Sub-biozone-***cordatum*** Sub-biozone) at Staffin Bay and 2 from the ***mariae*** Biozone-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) at Balintore.

Family Nubeculariidae Jones, 1875
Subfamily Nubeculinellinae Avnimelech & Reiss, 1954
Genus ***Nubeculinella*** Cushman, 1930
Nubeculinella tibia (Jones & Parker), 1860
(Plate 8, Figures 2-3)

1860 ***Nubecularia lucifuga*** DeFrance var. ***tibia*** Jones & Parker; p. 455, pl. 20, fig.

48.

1962 ***Nubeculinella tibia*** (Jones & Parker); Adams, p. 164, pl. 23, figs. 4-5, 10-13; text-figs. 1e-g.

1968 ***Nodobacularia tibia*** (Jones & Parker); Welzel, p. 10, pl. 1, fig. 15.

1981 ***Nubeculinella tibia*** (Jones & Parker) var. ***bubifera*** (Paalzow); Barnard ***et al.***, p. 396, pl. 1, fig. 21.

1989 ***Nubeculinella bigoti*** Cushman; Shipp, p. 254, pl. 6.4.1, fig. 12.

Description. Attached, elongate and narrow test, with an initially tight planispiral coil of 1-2 chambers followed by a rectilinear to curvilinear series of up to 7 chambers; chambers elongate, being widest proximally and tapering distally to an elongate neck; sutures constricted and horizontal; test wall smooth, porcellaneous and imperforate; aperture is a simple, terminal opening.

Remarks. This is an extremely common component of Oxford Clay deposits within the UK as recorded by Barnard *et al.* (1981). In their study, as is the case with the Scottish material, it is usually preserved without the initial coiled section (as in Plate 8, Figure 2). It can be distinguished from *N. bigoti* Cushman, which has more robust chambers.

Material. 1194 specimens.
Distribution.
849 from Staffin Bay; an extremely common component of the Dunans Clay Formation (Oxford Clay equivalent) occurring between the ***athleta*** Biozone and ***tenuiserratum*** Biozone (***blakei*** Biozone).
344 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone), with an acme between the ***athleta*** Biozone and ***cordatum*** Biozone (***bukowskii*** Sub-biozone).
1 from Brora; only from the ***lamberti*** Biozone.

Subfamily Nubeculariinae Jones, 1875

Genus *Nubecularia* DeFrance, 1825

Nubecularia infraoolithica (Terquem), 1870

(Plate 8, Figure 4)

1870b ***Webbina infraoolithica*** Terquem; p. 271, pl. 29, figs. 19-23.

1937 ***Nubecularia infraoolithica*** (Terquem); Bartenstein & Brand, p. 181, pl. 6, figs. 38a-c; pl. 8, figs. 35a-f; pl. 14b, figs. 18a-b; pl. 14c, fig. 1; pl. 15c, figs. 5a-d.

1960 ***Nubeculinella infraoolithica*** (Terquem); Bielecka, p. 120, pl. 2, fig. 14.

1962 ***Nubeculinella*** sp. Adams; p. 166.

1964 ***Nubeculinella infraoolithica*** (Terquem); Kristan-Tollman, p. 54, pl. 8, figs. 16-23; pl. 9, fig. 1a.

Description. Test attached, porcellaneous and imperforate; test form irregular, initially coiled in a haphazard planispire, this section is often missing; remaining chambers arranged in a rectilinear to irregular series depending upon the attachment surface; chambers flattened, irregular and generally rectangular in shape; sutures irregular, flush-depressed; test surface smooth; aperture is a simple, terminal opening.

Remarks. *N.* ***infraoolithica*** can be distinguished from *N.* ***tibia*** which has a tightly coiled initial section. However, in the absence of this feature *N.* ***tibia*** can be defined by its more regular and tubular chambers.

Material. 149 specimens.
Distribution. Most specimens, 104 were recovered from the ***concavum*** Biozone-***discites*** Biozone at Bearreraig Bay, with 12 from the ***lamberti*** Biozone to ***cymodoce*** Biozone at Staffin Bay, 19 from the ***lamberti*** Biozone to ***tenuiserratum*** Biozone at Balintore and 14 from the ***athleta*** Biozone at Brora.

Nubecularia triloculina Dam, 1950

(Plate 8, Figure 5)

1860 ***Nubecularia lucifuga*** DeFrance; Jones & Parker, p. 455, pl. 20, figs. 52-56.
1950 ***Nubecularia triloculina*** Dam; p. 19, pl. 1, fig. 22.
1950b ***Calcitornella woodi*** Barnard; p. 6, pl. 1, figs. 1a-b, 3-4.
1962 ***Nubecularia triloculina*** Dam; Adams, p. 160, pl. 21, figs. 7-11; text-figs. 1a-c.

Description. Small-medium, porcellaneous, imperforate and smooth test, that is initially tightly coiled and becomes uncoiled, margins carinate; spherical proloculus followed by a second chamber of 1-$1^1/_2$ whorls in length, later chambers irregularly developed, with 2-4 per whorl that sometimes cross earlier whorls, final chambers uncoiled in an occasionally meandering and curvilinear series, final chamber distally extended and tapers to an elongate neck, all chambers elongate and tubular in shape; sutures indistinguishable; aperture is a terminal, simple opening with a lip.

Remarks. Dam (1950) indicated that the form was incorrectly nominated by Jones & Parker (1860) as ***Nubecularia lucifuga***, and so proposed this new name. Adams (1962) indicated that attached forms were present in his material, but no such specimens were recovered from the Scottish sections.

Material. 31 specimens.
Distribution. A rare species with 26 specimens from the Lower to Middle Oxfordian (base of the ***cordatum*** Biozone to the top of the ***tenuiserratum*** Biozone) of Staffin Bay, and 5 specimens from the ***lamberti*** Biozone (***lamberti*** Sub-biozone) at Balintore.

Family Ophthalmidiidae Wiesner, 1920

Genus *Ophthalmidium* Kübler & Zwingli, 1870

emend. Macfadyen, 1939

Ophthalmidium sp. A

(Plate 8, Figure 7)

Description. Test ovate in outline, small-medium in size and bilaterally symmetrical and planispirally enrolled, being evolute; test compressed with rounded margins and many chambers visible on the external surface; chambers arranged 2 per whorl and are regularly tubular, narrow and constant in diameter; sutures depressed, curved with very little flange material separating the chambers; surface smooth, imperforate and porcellaneous; aperture is a circular opening at the distal end of the final chamber.

Remarks. ***O.*** sp. A is characterised by the consistent and thin diameter of its chambers and as such is similar to ***O. strictum*** Copestake as described in his PhD thesis (Copestake, 1978). However, this latter form is more circular in outline and the chambers taper distally.

Material. 408 specimens. This species is an exceptionally common component of only the Aalenian and Bajocian deposits of Bearreraig Bay and is restricted to the top ***concavum*** Biozone to ***discites*** Biozone.

Ophthalmidium sp. B

(Plate 8, Figure 6)

Description. Very small, elongate, narrow, compressed and planispirally enrolled, evolute test with a rounded periphery and up to 6 chambers visible in the external view; there are 2 chambers per whorl, with the final 2 chambers dominating, producing a bilateral symmetry; chambers very narrow and gently curved tubes that are slightly wider proximally and taper distally to a long, thin, tubular neck that is approximately $^1/_2$ the length of the entire test; sutures depressed and curved, with no flange material present between the chambers; test wall porcellaneous and imperforate; aperture produced at the terminal end of a long thin tube and is a circular opening, surrounded by a small phialine lip.

Remarks. The main morphological variation is in the length of the tubular neck, and this form is always characterised by a distinct thin, elongate test.

Material. 19 specimens.

Distribution. 16 specimens were recorded from the ***athleta*** Biozone to ***cordatum*** Biozone (***costicardia*** Sub-biozone) of Staffin Bay and 3 from the ***lamberti*** Sub-biozone at Balintore.

Ophthalmidium sp. C

(Plate 8, Figure 8)

Description. Test large, asymmetrical to bilaterally symmetrical, compressed and planispirally enrolled and to a certain extent involute, with 4-5 chambers visible on the external surface, the periphery is marked by a broad keeled area; final 2 chambers dominate and are $^1/_2$ a whorl in length, being much broader proximally, with a narrow, central portion and are expanded distally; the typically compressed chambers are separated by a wide flange of imperforate material; sutures indistinct and depressed; test surface smooth, porcellaneous and imperforate; aperture is a simple circular opening at the distal end of the final chamber.

Remarks. There is some variation in the degree of involution of the initial chambers, with the final 2 chambers always flattened and sometimes irregular, possibly reflecting an original attachment surface.

Material. 409 specimens.
Distribution. Only recovered from the Staffin Bay section, being restricted to the ***cordatum*** Biozone (***bukowskii*** Sub-biozone) to ***tenuiserratum*** Biozone (***bukowskii*** Sub-biozone), with an acme in the ***cordatum*** Biozone, between the ***bukowskii*** Sub-biozone and ***costicardia*** Sub-biozone.

Ophthalmidium birmenstorfense Kübler & Zwingli, 1870

(Plate 8, Figure 9)

1870 ***Ophthalmidium birmenstorfense*** Kübler & Zwingli, p. 31, pl. 3, fig. 46.
1962 ***Ophthalmidium*** cf. ***birmenstorfense*** Kübler & Zwingli; Cordey, p. 392, pl. 48, fig. 38, text-figs. 45-56.
1970 ***Ophthalmidium*** cf. ***stuifense*** (Paalzow); Winter, p. 14, pl. 2, fig. 52.
1981 ***Ophthalmidium birmenstorfense*** Kübler & Zwingli; Barnard ***et al.***, p. 400, pl. 1, fig. 18, text-figs. 9C, 1-10.

Description. Elongate, narrow, flattened and blade like test that is closely planispirally coiled, with sharp and carinate margins; final 2 chambers envelop and obscure the initial chambers; chambers flattened, being widest proximally and taper distally to give an irregular bilateral symmetry; sutures indistinct and irregular; test wall porcellaneous and imperforate; aperture is a circular, flush opening at the distal end of the chamber.

Remarks. The test morphology of ***O. birmenstorfense*** is highly variable and irregular, with the final chambers being twisted and flattened as if reflecting an attachment surface. It can be distinguished from ***O. milioliniforme*** whose chamber development is regular, is not as closely coiled, has up to 4 chambers visible and it is rounded in section. Barnard ***et al.*** (1981) recovered forms from the ***athleta*** Biozone to ***cordatum*** Biozone of the

English Oxford Clay that they tentatively assigned to ***O. birmenstorfense***, but which compare well with this and the original material of Kübler & Zwingli (1870).

Material. 339 specimens.
Distribution.
324 from Staffin Bay; total range from the athleta Biozone to top ***tenuiserratum*** Biozone, with an acme within the ***cordatum*** Biozone, between the ***bukowskii*** Sub-biozone and ***costicardia*** Sub-biozone.
15 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).

Ophthalmidium carinatum (Kübler & Zwingli), 1866
emend. Wood, 1947
(Plate 8, Figure 10)

1866 ***Oolina carinata*** Kübler & Zwingli; p. 14, pl. 2, fig. 19.
1947 ***Ophthalmidium carinatum*** (Kübler & Zwingli); Wood, p. 462, pl. 29, figs. e-h; pl. 30, figs. 2-3.
1985 ***Ophthalmidium carinatum*** (Kübler & Zwingli); Riegraf, p. 102, pl. 6, fig. 37.
1989 ***Ophthalmidium carinatum*** (Kübler & Zwingli); Morris & Coleman, p. 221, pl. 6.3.6, fig. 13.

Description. Test oval, flattened, bilaterally symmetrical and planispirally coiled; final 2 chambers can be somewhat involute with a total of 6 chambers visible; chambers elongate, curved, $^1/_2$ a whorl in length and greatly wider proximally and tapering distally; sutures depressed and curved; test wall structure imperforate, porcellaneous and smooth; aperture produced on a thin neck, and is a simple circular opening, with or without a lip.

Remarks. Pazdrowa (1957, 1958a, 1972 for illustration) split ***O. carinatum*** into several subspecies, based on a biometric analysis. ***O. carinatum marginata*** appears to be similar to ***O. purtonensis,*** with its distinct, keeled periphery and flattened test morphology. The majority of forms from the Scottish Callovian-Oxfordian sections are comparable to ***O. carinatum terquemi*** (as in the description above), whilst ***O. carinatum agglutinans***, in which the chambers are not so broad proximally, is typical of the forms recovered from the Aalenian and Bajocian deposits of Bearreraig Bay.

Material. 1924 specimens.
Distribution.
1034 from Bearreraig Bay; extremely common, and the most important component of the fauna, being present in the ***concavum*** and ***discites*** Biozones.
618 from Staffin Bay; very common between the ***athleta*** Biozone and ***tenuiserratum*** Biozone (***blakei*** Sub-biozone).

254 from Balintore; total range is between the ***athleta*** Biozone and ***tenuiserratum*** Biozone, with acmes between the ***athleta*** Biozone and ***bukowskii*** Sub-biozone and within the ***tenuiserratum*** Biozone.

18 from Brora; ***athleta*** Biozone-*lamberti* Biozone (***henrici*** Sub-biozone).

Ophthalmidium liasicum (Kübler & Zwingli), 1866

(Plate 8, Figure 11)

1866 ***Oolina liasica*** Kübler & Zwingli; p. 11, pl. 1, fig. 24.

1870 ***Ophthalmidium liasicum*** Kübler & Zwingli; p. 46.

1908 ***Ophthalmidium liasicum*** (Kübler & Zwingli); Issler, p. 45, pl. 1, figs. 26-29.

1947 ***Ophthalmidium liasicum*** (Kübler & Zwingli); Wood, p. 461, pl. 26, fig. a; pl. 30, fig. 1.

1947 ***Ophthalmidium liasicum*** (Kübler & Zwingli); Wood & Barnard, p. 84, fig. 1.

1989 ***Ophthalmidium liasicum*** (Kübler & Zwingli); Copestake & Johnson, p. 167, pl. 6.2.1, fig. 22.

Description. Small, discoidal to circular, compressed and planispirally coiled test, with an angular periphery; chambers long, thin and tubular, usually $^3/_4$ of a whorl in length, final chambers are $^1/_2$ a whorl in length; whorls joined by a wide flange of imperforate test; sutures indistinct; test wall imperforate and porcellaneous; aperture is a simple opening at the distal end of the chamber.

Material. 143 specimens.

Distribution. This form is only common within the Aalenian to Bajocian section at Bearreraig Bay with 133 specimens from the ***concavum*** Biozone-***discites*** Biozone, and 1 specimen from the ***cordatum*** Biozone (***cordatum*** Sub-biozone) at Staffin Bay, with 9 from the ***mariae*** Biozone-***tenuiserratum*** Biozone at Balintore.

The majority of previous occurrences are from within the Lower Jurassic of Germany, Riegraf (1985), Issler (1908) and of the UK (Copestake & Johnson, 1989 and Wood & Barnard, 1947).

Ophthalmidium milioliniforme (Paalzow), 1932

(Plate 8, Figure 12)

1932 ***Spirophthalmidium milioliniforme*** Paalzow; p. 100, pl. 5, figs. 15-19.

1941 ***Spirophthalmidium milioliniforme*** Paalzow; Frentzen, p. 360.

1960 ***Ophthalmidium milioliniforme*** (Paalzow); Seibold & Seibold, p. 341, text-figs. 4r-t.

1970 ***Ophthalmidium milioliniforme*** (Paalzow); Winter, p. 13, pl. 2, fig. 50.

1970 ***Ophthalmidium milioliniforme*** (Paalzow); Garbowska, p. 49, fig. 10.

Description. Elongate, fusiform, porcellaneous and imperforate test with 3-4 chambers visible in an involute planispire; test rounded in cross section with rounded peripheries; chambers are approximately $^1/_2$ a turn in length, being broadest proximally and rapidly tapering to a thin, elongate tube that is extended to a long, distal, tubular neck; sutures depressed and curved; aperture circular opening at the end of the elongate neck.

Remarks. ***O. milioliforme*** is similar to ***O. birmenstorfense*** but the latter has a much greater range of morphological irregularities and is flattened in section.

Material. 448 specimens.
Distribution. This form is commonest at Staffin Bay, with 305 specimens that range from the ***athleta*** Biozone to ***tenuiserratum*** Biozone (***bukowskii*** Sub-biozone), with acmes between the ***athleta*** Biozone and ***cordatum*** Biozone and within the ***tenuiserratum*** Biozone. The remaining 143 specimens were recovered from the Balintore section, with a total range from the ***lamberti*** Biozone to ***tenuiserratum*** Biozone and an acme in the ***tenuiserratum*** Biozone.

Ophthalmidium purtonensis Barnard ***et al.***, 1981

(Plate 9, Figure 1)

1981 ***Ophthalmidium purtonensis*** Barnard ***et al.***; p. 399, pl. 1, figs. 19, 26; text-figs. 9b, 1-5, 26.
1983 ***O. dyeri*** Medd; p. 231, pl. 3, figs. 8-10, 12-14.

Description. Porcellaneous, imperforate and compressed test arranged in an evolute, elongate planispire; 4-5 chambers are visible on the external surface, but the final 2 chambers dominate; the periphery is angular, with a thin keel developed; chambers approximately $^1/_2$ a whorl in length, being much wider proximally and tapering rapidly to a tube of constant diameter that is extended distally on the final chamber to an extremely elongate, tubular neck; sutures depressed and curved; aperture is a simple opening at the end of the tubular neck, surmounted by a slightly raised lip.

Remarks. ***O. dyeri*** as illustrated by Medd (1983) conforms exactly to the description given by Barnard ***et al.*** (1981) and so is included as a junior synonym.

Material. 173 specimens.
Distribution. 163 specimens were recovered from the ***cordatum*** Biozone to ***tenuiserratum*** Biozone of Staffin Bay, with acmes in the ***cordatum*** Biozone (***bukowskii*** Sub-biozone to ***cordatum*** Sub-biozone) and in the ***densiplicatum*** Biozone. 10 specimens were found between the ***mariae*** Biozone (***praecordatum*** Sub-biozone) and ***cordatum*** Biozone(***bukowskii*** Sub-biozone).

This form was originally recorded by Barnard ***et al.*** (1981) from several sites from the English Oxford Clay and its range appears to be remarkably consistent, being generally confined to the ***cordatum*** Biozone here with a first appearance in the ***mariae*** Biozone (***praecordatum*** Sub-biozone) in the English Oxford Clay.

Ophthalmidium strumosum (Gümbel), 1862

(Plate 9, Figure 2)

1862 ***Guttulina strumosa*** Gümbel; p. 227, pl. 4, figs. 13-14.

1965 ***Ophthalmidium strumosum*** (Gümbel); Gordon, p. 838, text-figs. 4, 8-10.

1983 ***Ophthalmidium strumosum*** (Gümbel); Kalia & Chowdhury, p. 231, pl. 1, fig. 7.

1989 ***Ophthalmidium strumosum*** (Gümbel); Morris & Coleman, p. 221, pl. 6.3.6, fig. 14.

Description. Test large, elongate, compressed and bilaterally symmetrical, being coiled in an evolute planispire with up to 7 chambers visible; chambers $^1/_2$ a whorl in length and tubular in form, being slightly wider proximally and taper distally; sutures depressed and curved; test wall porcellaneous and imperforate, generally smooth, but can sometimes be rough in texture; aperture simple opening at the terminal end of the neck.

Remarks. Morphological variation is strongest in the degree of asymmetry in the coiling which can produce an arcuate test in outline. ***O. strumosum*** can be distinguished from ***O. carinatum***, which has broader, and fewer externally visible chambers.

Material. 36 specimens.
Distribution. A rare form that is restricted to the Upper Callovian to Middle Oxfordian, with 19 specimens from between the ***athleta*** Biozone and ***densiplicatum*** Biozone at Staffin Bay, 11 between the ***athleta*** Biozone and ***lamberti*** Biozone at Balintore and 6 specimens from the ***athleta*** Biozone at Brora.

Superfamily Miliolacea Ehrenberg, 1839

Family Spiroloculinidae Wiesner, 1920

Genus '***Duoplanum***' Copestake, 1978

Remarks. '***Duoplanum***' was designated as an unavailable generic name by Loeblich & Tappan (1988), as in their opinion Copestake & Johnson (1984) and Haynes (1981) erected this form without a description of a species. However, Copestake (1978) described '***Duoplanum***' and two new species in his, as yet, unpublished PhD thesis.

Forms included in this genus have chambers arranged in 2-3 mutually perpendicular planes, and change rapidly between planes. Copestake (1978) considered '***Duoplanum***' to be ancestral to ***Spiroloculina*** and so it is included here under the Family Spiroloculinidae. Since these forms are sufficiently different to ***Spiroloculina***, in having irregular coiling and no apertural tooth plate present, they must be included in a new genus. As there are no similar forms described in Loeblich & Tappan's (1988) classification the name '***Duoplanum***' is used here; this will assist later allocation when a new name is selected.

'*Duoplanum*' sp. A

(Plate 9, Figures 3-4)

Description. Test small, oblate, narrow and symmetrical with rounded peripheries; chambers narrow, tubular and curved, being $^1/_2$ a whorl in length and 3-4 chambers visible on the external surface; chambers arranged in 2 mutually perpendicular planes; sutures depressed, irregular to curved; test surface finely pitted, porcellaneous and imperforate; aperture is a simple, circular opening at the distal end of the final chamber.

Remarks. Variation occurs in the degree of asymmetry, producing a bowed test outline. '***D***'. sp. A can be distinguished from '***D***'. ***laevis*** Copestake which has a carinated margin, and from '***D***'. ***inaequalis*** Copestake which is more asymmetrical and has a coarsely rugose test surface.

Material. 58 specimens.
Distribution. Restricted to the Staffin Bay and Balintore sections, with 40 specimens from the ***athleta*** Biozone to ***tenuiserratum*** Biozone at the former and 18 from the ***tenuiserratum*** Sub-biozone at the latter section.

Genus *Palaeomiliolina* Antonova, 1959

Palaeomiliolina czestochowiensis (Pazdrowa), 1959

(Plate 9, Figure 5)

1959 ***Miliolina czestochowiensis*** Pazdrowa; p. 360, pl. 23, figs. 1-5, 9-10.
1972 ***Palaeomiliolina czestochowiensis*** (Pazdrowa); Pazdrowa, pl. 23, fig. 9.
1988 ***Palaeomiliolina czestochowiensis*** (Pazdrowa); Bielecka ***et al.***, p. 99, pl. 15, figs. 14-15.

Description. Small to medium sized, ovate test with angular peripheries; initial chambers arranged in a quinqueloculine coiling mode of several planes, the final 2 chambers are coiled in an involute, planispire that only allows 3-6 chambers to be viewed on the external surface; chambers sub-triangular in section, elongate and curved; sutures indistinct, depressed and curved; test wall porcellaneous and imperforate, but the surface is rough in most specimens; aperture is circular and terminal, sometimes surrounded by a small lip.

Remarks. ***P. czestochowiensis*** has not been previously recorded from the UK and has only been found in the Upper Bajocian to Upper Bathonian interval of Poland (Pazdrowa, 1959, 1972; Bielecka ***et al.***, 1988). It appears to be similar to ***Massilina dorsetensis*** Cifelli, but Cifelli (1959) indicated that the quinqueloculine coiling mode was sustained throughout. ***P. czestochowiensis*** can be distinguished from ***P. rawiensis*** by its angular margins and rough surface.

Material. 137 specimens.
Distribution. This form was only recovered from the Lower Bajocian of Bearreraig Bay and as such extends the biostratigraphical range that other Polish workers have nominated. It first appears in the Skye section after ***P. rawiensis*** and has an acme in the ***discites*** Biozone.

Palaeomiliolina rawiensis (Pazdrowa), 1959

(Plate 9, Figure 6)

1959 ***Miliolina rawiensis*** Pazdrowa; p. 367, pl. 23, figs. 6-8; pl. 24, figs. 6-9.
1972 ***Palaeomiliolina rawiensis*** (Pazdrowa); Pazdrowa, pl. 23, fig. 8.
1988 ***Palaeomiliolina rawiensis*** (Pazdrowa); Bielecka *et al.*, p. 100, pl. 15, fig. 20.

Description. Small-medium, oblate to fusiform test in outline, that is rounded in section; initial chambers involved in coiling in several planes, with the final 2 chambers coiled planispirally and obscuring the initial chambers so that only 3-4 chambers are visible on the external surface; chambers rounded and longitudinally elongate and are widest proximally; sutures flush; test wall porcellaneous, imperforate and smooth; aperture is a terminal, circular opening.

Remarks. ***P. difficilis*** (Wisniowski) and ***P. michalskii*** (Wisniowski), both of which were recovered from the Lower Callovian to Oxfordian of Poland, can be distinguished from ***P. rawiensis*** by being more narrow and elongate. ***P. czestochowiensis*** also has angular margins and is characterised by its rough surface texture.

Material. 541 specimens.
Distribution. ***P. rawiensis*** is restricted to the Aalenian and Bajocian (top ***concavum*** Biozone and lower ***discites*** Biozone) at Bearreraig Bay and as such appears before, and has a shorter range than ***P. czestochowiensis*** at the same locality. Both these forms are the first recorded instances outside the Polish Bajocian and Bathonian. This may be explained by the fact that the initial quinqueloculine coiling is often obscured by the final chambers and gives an external appearance that is similar to some forms of ***Ophthalmidium***, such as inflated specimens of ***O. carinatum***.

Suborder Lagenina Delage & Hérouard, 1896

Family Robuloididae Reiss, 1963

Genus *Falsopalmula* Bartenstein, 1948

Falsopalmula deslongchampsi (Terquem), 1863

(Plate 9, Figure 7)

1863 ***Flabellina deslongchampsi*** Terquem; p. 216, pl. 10, fig. 13.
1932 ***Flabellina deslongchampsi*** Terquem; Paalzow, p. 132, pl. 9, fig. 26.
1948 ***Flabellina deslongchampsi*** Terquem; Bartenstein, p. 130, pl. 1, figs. 6-7; pl. 2, fig. 10.
1970 ***Lenticulina (Falsopalmula) deslongchampsi*** Terquem; Groiss, p. 63.
1970 ***Palmula deslongchampsi*** (Terquem); Garbowska, p. 68, fig. 40.
1989 ***Palmula deslongchampsi*** Terquem; Morris & Coleman, p. 224, pl. 6.3.8, fig. 1.

Description. Test palmate, large to medium in size; initial involute-evolute planispiral coil of 3-5, small chambers is followed and embraced by up to 7 initially arcuate then chevron shaped chambers, which are much greater in width than height; periphery irregular and lobate; sutures distinct, depressed to raised, cord like and chevron shaped; surface ornamentation consists of a series of irregularly placed, coarse perforations; aperture is central, radiate and raised on a short neck.

Remarks. The initially coiled section is a point of weakness, and many forms are found lacking this juvenile feature. Variation exists in the degree and extent of this coiling and the number of chambers in the frondiculine section.

Material. 27 specimens.

Distribution. The majority of forms, 23, were from the ***concavum*** Biozone-***discites*** Biozone at Bearreraig Bay, with 3 specimens from the ***cordatum*** Biozone to ***densiplicatum*** Biozone of Staffin Bay and 1 from the ***cordatum*** Biozone (***bukowskii*** Sub-biozone) at Balintore.

F. deslongchampsi initially appears at the base of the Toarcian in Europe, and is an important biostratigraphical form in the Aalenian to Bajocian, with a final appearance in the ***densiplicatum*** Biozone.

Superfamily Nodosariacea Ehrenberg, 1838

Family Nodosariidae Ehrenberg, 1838

Subfamily Nodosariinae Ehrenberg, 1838

Genus ***Dentalina*** Risso, 1826

Dentalina cuneiformis Terquem, 1870

(Plate 9, Figure 8)

1870b ***Dentalina cuneiformis*** Terquem; p. 257, pl. 26, figs. 24-25.
1958 ***Dentalina*** cf. ***cuneiformis*** Terquem; Lloyd, p. 282, pl. 28, figs 8a-c.
1985 ***Dentalina cuneiformis*** Terquem; Riegraf, p.117.

Description. Small, very arcuate, uniserial test with up to 6 chambers; proloculus small, ovate and aplicate; chambers greater in length than height and barrel shaped, increasing gradually in size as added; sutures flush, becoming depressed distally and are straight to oblique; test surface smooth; aperture marginal, produced on a short neck.

Remarks. A distinct form by virtue of its extremely arched test and small size.

Material. 15 specimens.
Distribution.
7 from Staffin Bay; ***lamberti*** Sub-biozone-***tenuiserratum*** Sub-biozone.
2 from Balintore; ***lamberti*** Sub-biozone-***cordatum*** Sub-biozone.
6 from Brora; Upper ***athleta*** Biozone.

Dentalina exilis Franke, 1936

(Plate 9, Figure 9)

1936 ***Dentalina exilis*** Franke; p. 31, pl. 2, fig. 25.
1955 ***Dentalina exilis*** Franke; Tappan, p. 66, pl. 23, figs. 5-7.
1970 ***Dentalina exilis*** Franke; Ruget & Sigal, p. 97, pl. 5, figs. 1-8.
1976 ***Dentalina*** cf. ***exilis*** Franke; Souaya, p. 278, pl. 9, fig. 6.

Description. Test uniserial, slender, long and slightly arcuate with up to 8 chambers; proloculus spherical and somewhat larger than the subsequent 2-3 chambers; chambers initially equiant, becoming increasingly longer as added; sutures very distinct, depressed and are straight-slightly oblique; aperture is radiate, terminal, being peripheral to central and is produced on a short neck.

Remarks. ***D. exilis*** can be distinguished from ***D. sinemurensis*** which is more robust. Most recorded cases of this form come from the Lower Jurassic of Europe.

Material. 40 specimens.
Distribution.
35 from Staffin Bay; a rare form ranging from the ***athleta*** Biozone-***tenuiserratum*** Biozone (***bukowskii*** Sub-biozone).
5 from Balintore; only from the ***lamberti*** Sub-biozone.

Dentalina guembeli Schwager, 1865

(Plate 9, Figure 10)

1865 ***Dentalina guembeli*** Schwager; p. 101, pl. 2, fig. 20.
1886 ***Dentalina guembeli*** Schwager; Deecke, p. 308, pl. 1, fig. 14.
1950a ***Dentalina ectadia*** Loeblich & Tappan; p. 47, pl. 13, figs. 3-5.
1952a ***Dentalina guembeli*** Schwager; Barnard, p. 346, fig. A7.
1990 ***Dentalina guembeli*** Schwager; Quilty, p. 360, pl. 2, figs. 21-22.

Description. Small-medium sized, squat, arcuate and uniserial test with up to 5 chambers; one margin is lobulate, whilst the opposite is convex; proloculus large, spherical-ellipsoidal, aplicate, and is similar in size or greater than succeeding chambers; chambers sub-rectangular, slightly longer than wide; sutures very distinct, constricted, straight; test surface smooth; aperture is terminal, marginal, radiate and produced on a short neck.

Remarks. A highly variable and rare form which has a widely reported Jurassic range.

Material. 3 specimens, with 1 specimen from the ***athleta*** Biozone at Staffin Bay and 2 from the ***discites*** Biozone at Bearreraig Bay.

Dentalina integra (Kübler & Zwingli), 1870

(Plate 9, Figure 11)

1870 ***Vaginulina integra*** Kübler & Zwingli, p. 5, pl. 1, fig. 1.
1875 ***Cristellaria dentaliniformis*** Terquem & Berthelin, p. 43, pl. 3, figs. 19a-c.
1922 ***Dentalina pauperata*** d'Orbigny; Paalzow, p. 17, pl. 2, figs. 6-7.
1936 ***Dentalina integra*** (Kübler & Zwingli); Franke, p. 33, pl. 3, figs. 2a-b.
1968 ***Dentalina integra*** (Kübler & Zwingli); Welzel, p. 27, pl. 1, fig. 57.
1980 ***Dentalina integra*** (Kübler & Zwingli); Munk, p. 191, pl. 19, fig. 21.
1985 ***Dentalina dentaliniformis*** Terquem & Berthelin; Riegraf, p. 112, pl. 7, figs. 53-54.

Description. Medium to large, uniserial and straight to slightly arcuate test with up to 5 chambers; proloculus ellipsoidal, aplicate; chambers equiant, barrel shaped; sutures flush, being straight to slightly curved; test surface smooth, aperture is peripheral and flush to the test wall.

Remarks. This form was also described as ***Cristellaria dentaliniformis*** by Terquem & Berthelin (1875), but ***D. integra*** (Kübler & Zwingli) was illustrated and described in 1870 and so takes priority.

Material. 29 specimens.
Distribution. This form is restricted between the ***lamberti*** Biozone to ***tenuiserratum***

Sub-biozone, with 9 specimens from Staffin Bay and 20 from Balintore.

Dentalina intorta Terquem, 1870

(Plate 10, Figure 1)

1870b ***Dentalina intorta*** Terquem; p. 262, pl. 2, figs. 26-34.
1959 ***Dentalina intorta*** Terquem; Cifelli, p. 308, pl. 4, figs. 16-19.
1978 ***Dentalina intorta*** Terquem; Munk, p. 41, pl. 2, fig. 3.
1989 ***Dentalina intorta*** Terquem; Morris & Coleman, p. 222, pl. 6. 3.7, fig. 7.

Description. Test large-medium, compressed, arcuate and uniserial with up to 6 chambers; proloculus elongate, aplicate, and can be embraced by the initial, succeeding chamber; chambers initially equiant, but rapidly increase in height as added; sutures depressed, very oblique; final chamber spindle shaped and produced to a tapering point; aperture small and radiate, at the end of the neck.

Material. 11 specimens, only recovered between the ***concavum*** Biozone and ***discites*** Biozone at Bearreraig Bay.

Dentalina propinqua Terquem, 1870

(Plate 10, Figure 2)

1870b ***Dentalina propinqua*** Terquem; p. 263, pl. 28, figs. 1-2.
1959 ***Dentalina propinqua*** Terquem; Cifelli, p. 311, pl. 4, figs. 4-6.
1976 ***Dentalina propinqua*** Terquem; Ruget, p. 532, pl. 8, fig. 5.
1981 ***Nodosaria propinqua*** Terquem; Barnard & Shipp, p. 10, pl. 2, figs. 18-19.
1985 ***Dentalina propinqua*** Terquem; Riegraf, p. 114, pl. 7, figs. 49-50.

Description. Large, uniserial and arcuate test of 6 chambers; proloculus small, oval and teat-like with a distal sutural constriction; chambers equiant, final chamber inflated, constricted proximally; sutures oblique to horizontal, flush, but constricted in the final chamber; test wall smooth; aperture is a terminal, flush, circular opening.

Remarks. Both Cifelli (1959) and Barnard & Shipp (1981) considered ***D. propinqua*** to be a transitional form between ***Dentalina*** and ***Nodosaria***. Cifelli considered it best placed within the former, whilst Barnard & Shipp chose the latter. The single specimen from Bearreraig Bay conforms more closely to ***Dentalina***.

Material. 1 specimen from the ***discites*** Biozone at Bearreraig Bay.

Dentalina pseudocommunis Franke, 1936

(Plate 10, Figure 3)

1936 ***Dentalina pseudocommunis*** Franke; p. 30, pl. 2, figs. 20a-b.
1950a ***Dentalina pseudocommunis*** Franke; Barnard, p. 364, fig. 5K.
1981 ***Dentalina pseudocommunis*** Franke; Barnard ***et al.***, p. 406, pl. 2, fig. 2.
1989 ***Dentalina pseudocommunis*** Franke; Morris & Coleman, p. 222, pl. 6.3.7, fig. 5.

Description. Test large-very large, slender, arcuate and uniserial with up to 12 chambers; proloculus small, spheroidal; chambers initially equiant, becoming marginally greater in height as added, final chamber inflated; sutures distinct, straight and oblique; a radiate aperture is present on a prominent neck.

Material. 511 specimens.
Distribution.
107 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
149 from Staffin Bay; an ubiquitous form, from the ***athleta*** Biozone-***cymodoce*** Biozone.
22 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.
221 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.
9 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.
3 from Helmsdale; ***cymodoce*** Biozone.

D. pseudocommunis is a widely reported Jurassic species, being especially common in the Middle and Upper Jurassic of England, Scotland, continental Europe and Alaska.

Dentalina pseudocruata Seibold & Seibold, 1960

(Plate 10, Figure 4)

1960 ***Dentalina pseudocruata*** Seibold & Seibold; p. 30 text-fig. 60.
1987 ***Dentalina pseudocruata*** Seibold & Seibold; Young, p. 254, pl. 11, fig. 10.

Description. Small, pupae shaped, uniserial test with up to 4 chambers; ellipsoidal proloculus, that is sometimes aplicate, subsequent chambers barrel-shaped; margins rounded, curved; initial sutures flush, becoming depressed distally, horizontal; test surface smooth; aperture central and flush with test wall.

Remarks. This material agrees well with the description of Seibold & Seibold (1960) from the Oxfordian of western Germany. ***D. pseudocruata*** is not a widely reported form, with its only other occurrence being from the ***rosenkrantzi*** Biozone of England (Young, 1987 .

Material. 6 specimens, with 4 from the ***praecordatum*** Sub-biozone-***densiplicatum*** Biozone of Staffin Bay and 2 from the ***athleta -mariae*** Biozones at Balintore.

Dentalina sinemurensis Terquem, 1866

(Plate 10, Figure 5)

1866a ***Dentalina sinemurensis*** Terquem; p. 405, pl. 15, fig. 6.

1936 ***Dentalina sinemurensis*** Terquem; Franke, p. 31, pl. 2, figs. 23a-b.

1970 ***Dentalina sinemurensis*** Terquem; Winter, p. 23, pl. 3, fig. 83.

1979 ***Dentalina sinemurensis*** Terquem; Exton, p. 25, pl. 6, fig. 10.

Description. Test large, elongate, smooth and gently arcuate with up to 6 chambers; proloculus large, spherical and equal in size to subsequent chambers; chambers greatest in height, with no discernible change in size as added; sutures produced as horizontal constrictions between chambers; aperture terminal, central and radiate.

Remarks. ***D. sinemurensis*** can be distinguished from most species of ***Dentalina*** by its equiant chambers, large spherical proloculus and constricted sutures. It would appear to be more common within Lower Jurassic with records including Germany, France and Portugal. It is also an important component of the Hettangian-Sinemurian section at Morvern (unpublished, this work).

Material. 33 specimens.

Distribution.

31 from Staffin Bay ; occurs throughout the section and is rare.

2 from Balintore; only found within the ***mariae*** Biozone (***scarburgense*** Sub-biozone).

Dentalina tenuistriata Terquem, 1866

(Plate 10, Figure 6)

1866a ***Dentalina tenuistriata*** Terquem; p. 405, pl. 15, fig. 5.

1955 ***Dentalina tenuistriata*** Terquem; Tappan, p. 67, pl. 23, figs. 8-13.

1965 ***Dentalina tenuistriata*** Terquem; Hanzlikova, p. 66, pl. 9, fig. 4.

1968 ***Dentalina*** sp.; Welzel, p. 30, pl. 3, fig. 27.

1989 ***Dentalina tenuistriata*** Terquem; Copestake & Johnson, p. 171, pl. 6.2.2., fig. 12.

Description. Large, slender, fragile, arcuate, uniserial test; proloculus ovate, followed by up to 5 chambers that are greatest in height, and only increase in height as added; sutures distinct, horizontal and depressed; ornament consists of numerous, fine longitudinal ribs that do not cross the sutures; aperture is terminal, central-peripheral, radiate, being either flush or produced on a short neck.

Remarks. ***D. tenuistriata*** is a common and useful biostratigraphical indicator for the Pliensbachian of the UK (Copestake & Johnson, 1989), becoming rarer in the Middle and Upper Jurassic (Hanzlikova, 1965).

Material. 6 specimens, with 5 from the ***athleta*** Biozone-***densiplicatum*** Biozone of Staffin Bay and 1 specimen from the ***athleta*** Biozone at Balintore.

Dentalina torta Terquem, 1858

(Plate 10, Figure 7)

1858 ***Dentalina torta*** Terquem; p. 599, pl. 2, figs. 6a-b.
1936 ***Dentalina torta*** Terquem; Franke, p. 27, pl. 2, figs. 9a-b.
1959 ***Dentalina torta*** Terquem; Cifelli, p. 312, pl. 4, fig. 9.
1981 ***Dentalina torta*** Terquem; Barnard ***et al.***, p. 406, pl. 2, fig. 2.

Description. A very large, arcuate, uniserial test that is rounded in section and has up to 8 chambers; margins rounded and smooth; proloculus pear shaped to oval, and sometimes bears a basal spine, proloculus enveloped by succeeding chamber; chambers eqiuant and drum shaped, final chambers bulbous and produced distally to form a neck; sutures horizontal, initially flush becoming distinct and depressed; surface smooth; aperture is radiate, central, being flush or produced on a short neck.

Remarks. ***D. torta*** can be distinguished from ***D. intorta*** which Cifelli (1959) considered to be a variant of ***D. torta***, as it is compressed and has oblique sutures. ***D. tortilis*** has a more robust, aplicate proloculus and more elongate chambers.

Material. 69 specimens.
Distribution.
38 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
26 from Staffin Bay; ***athleta*** Biozone-***cordatum*** Biozone (***costicardia*** Sub-biozone).
5 from Balintore; ***lamberti*** Biozone-***cordatum*** Biozone.

D. torta is a common form from the Lower and Middle Jurassic of England and Scotland (Cifelli, 1959; Barnard ***et al.***, 1981; Cordey, 1962) and Europe (Terquem, 1858; Franke, 1936).

Dentalina tortilis Franke, 1936

(Plate 10, Figure 8)

1936 ***Dentalina tortilis*** Franke; p. 29, pl. 2, figs. 19a-b.
1955 ***Dentalina tortilis*** Franke; Tappan, p. 68, p. 121, figs. 23-25.
1970 ***Dentalina tortilis*** Franke; Winter, p. 23, pl. 3, fig. 85.
1979 ***Dentalina tortilis*** Franke; Exton, p. 30, pl. 4, fig. 4.

Description. Large robust, curved to straight, uniserial test with up to 6 chambers; proloculus oval and noticeably aplicate; chambers elongate, being greatest in length, the chambers only increase in length as added; sutures distinct, depressed, being horizontal to slightly oblique; aperture is marginal, radiate and produced on a short neck.

Material. 35 specimens, 32 of which came from the ***athleta*** Biozone at Brora, with the remainder from the ***cordatum*** Biozone-***tenuiserratum*** Biozone at Staffin Bay

Dentalina varians Terquem, 1866

(Plate 10, Figure 9)

1866b ***Dentalina varians*** Terquem; p. 485, pl. 19, figs. 26-27.
1936 ***Dentalina varians*** Terquem; Franke, p. 26, pl. 2, fig. 6.
1985 ***Dentalina varians*** Terquem; Riegraf, p. 114, pl. 7, figs. 43-44.

Description. Small-medium, straight to arcuate, uniserial test of up to 6 chambers; peripheries distinct, one being lobulate, whilst the opposite is straight to convex and smooth; proloculus large, elongate, but not aplicate; chambers sub-rectangular, greatest dimension is their height, gradually increasing in size as added, final chambers slightly inflated; sutures depressed, horizontal; surface smooth; aperture radiate, being located marginally and produced on an elongate, narrow neck.

Material. 51 specimens, 33 of which came from the ***athleta*** Biozone-***tenuiserratum*** Biozone at Staffin Bay and 18 from the ***lamberti*** Biozone (***lamberti*** Sub-biozone)-***cordatum*** Biozone (***cordatum*** Sub-biozone) at Balintore.

Dentalina ventricosa Franke, 1936

(Plate 10, Figure 10)

1936 ***Dentalina ventricosa*** Franke; p. 33, pl. 3, figs. 1a-b.
1979 ***Dentalina ventricosa*** Franke; Exton, p. 30, pl. 5, fig. 8.

Description. Small-medium, broad, compressed and arcuate uniserial test of up to 6 chambers; periphery straight to lobulate; proloculus irregular, sub-ovoid with a small, blunt basal spine; chambers initially much broader than high, final chamber spindle shaped and tapering distally; sutures depressed, becoming more oblique distally; aperture small and radiate.

Remarks. ***D. ventricosa*** can be distinguished from most forms of ***Dentalina*** by its extremely compressed test. It may indeed represent the end member in a variation series based on the degree of compression from ***D. torta*** to ***D. intorta*** to ***D. ventricosa.***

Material. 36 specimens.

Distribution. A rare form with 34 specimens occurring sporadically in the Staffin Bay section from the ***athleta*** Biozone to ***baylei*** Biozone, but is generally concentrated between the ***athleta*** Biozone to ***cordatum*** Biozone. 2 specimens were recovered from the ***lamberti*** Biozone-***mariae*** Biozone at Balintore.

Genus *Nodosaria* Lamark, 1812

Nodosaria sp. A

(Plate 10, Figure 11)

Description. Large-medium, uniserial test with lobulate margins and up to 3 chambers; proloculus variable in size from small to large, always globular and followed by elongate chambers that are much longer than wide and increase in size only gradually; sutures constricted and horizontal; ornament consists of 8-10 robust, continuous, blade-like ribs that converge distally to form an apertural collar; aperture radiate, surrounded by a thick notched apertural collar.

Remarks. This form is similar to ***N. dispar***, except it possesses elongate chambers and blade-like ribs. ***N. rara*** Franke is also similar, but has equiant chambers and coarser, flatter ribbing.

Material. 11 specimens.
Distribution. A rare form restricted to 7 specimens from the ***athleta*** Biozone to ***lamberti*** Biozone at Staffin Bay, and 4 from the ***athleta*** Biozone to ***lamberti*** Biozone at Balintore.

Nodosaria apheilolocula Tappan, 1955

(Plate 10, Figure 13)

1875 ***Nodosaria incerta*** Terquem & Berthelin; p. 18, pl. 1, fig. 15.
1937 ***Nodosaria hirsula*** d'Orbigny; Bartenstein & Brand, p. 145, pl. 4, figs. 39a-b; pl. 5, fig. 26.
1955 ***Nodosaria apheilolocula*** Tappan; p. 68, pl. 24, figs. 6-7.
1984 ***Nodosaria apheilolocula*** Tappan; Riegraf ***et al.***, p. 681, pl. 5, fig. 130.
1989 ***Nodosaria apheilolocula*** Tappan; Hornibrook ***et al.***, p. 43, pl. 9, fig. 19.

Description. Test large, originally uniserial; chambers large, globular and connected by a thin, fragile stolon; proloculus large, globular and aplicate; test surface hispid; aperture is located at the end of a long thin neck and is a simple circular opening with a crenulated apertural collar.

Remarks. The Scottish forms compare well with Tappan's (1955) original description of specimens from the Lower Jurassic, some, however, are larger than the holotype. Only single chambers were observed, but broken necks distally and proximally indicate that this was originally a multilocular test. *N.* ***incerta*** Terquem & Berthelin is included in the synonymy as the name was preoccupied and Bartenstein & Brand (1937) incorrectly assigned forms to *N.* ***hirsula*** which is more coarsely hispid.

Material. 26 specimens, recovered only from the ***athleta*** Biozone to ***cymodoce*** Biozone at Staffin Bay, and being concentrated within the ***athleta*** Biozone and ***cordatum*** Biozone (***bukowskii*** Sub-biozone).

Nodosaria berthelini Tappan, 1955

(Plate 11, Figure 1)

1955 ***Nodosaria berthelini*** Tappan; p. 69, pl. 25, figs. 13-16.

Description. Test small, elongate, uniserial and tapers both distally and proximally; proloculus small and aplicate, followed by 6-8 chambers; sutures not visible on the test surface; surface ornament consists of several thin, discontinuous, longitudinal ribs that also taper distally and proximally and die out on the distal portion of the test.

Remarks. Tappan (1955) considered this form identical to ***D. paucicosta*** Terquem as figured by Terquem & Berthelin (1875). This did not compare with the original description of Terquem (1866a), hence this new species was created to accommodate these forms. Only microspheric examples were recovered, which were typified by a distinctly tapering test.

Material. 2 specimens.
Distribution. An extremely rare form from the ***athleta*** Biozone, with 1 specimen from Staffin Bay and 1 from Brora.

This form has only previously been reported from the Lias of France (Terquem & Berthelin, 1875), from the Lower Kimmeridgian of Dorset (Young, 1987) and from the Pliensbachian of Alaska (Tappan, 1955).

Nodosaria corallina Gümbel, 1862

(Plate 11, Figure 2)

1862 ***Nodosaria corallina*** Gümbel; p. 218, pl. 3, figs. 10a-b.
1955 ***Nodosaria corallina*** Gümbel; Seibold & Seibold, p. 113, pl. 13, figs. 10a-b, text-figs. 2k, c.
1962 ***Nodosaria*** cf. ***hortensis*** Terquem; Cordey, p. 380, pl. 47, fig. 25.
1981 ***Nodosaria corallina*** Gümbel; Barnard ***et al.***, p. 405, pl. 1, fig. 22.

Description. Medium-large, uniserial, arcuate-straight test with up to 4 chambers; proloculus not present in this material; chambers elongate, sub-rectangular and consistently longer than broad and retain the same dimensions as added; sutures constricted, horizontal; ornament of 8-10 low, broad, continuous, longitudinal ribs that converge distally to form an apertural collar, aperture is flush or slightly raised and radiate.

Remarks. *N. **corallina*** can be distinguished from *N. **hortensis*** and *N. **fontinensis***, which are more robust and have globular chambers.

Material. 2 specimens.
Distribution. A rare form with 1 specimen from the ***densiplicatum*** Biozone at Staffin Bay and 1 from the ***lamberti*** Biozone (***lamberti*** Sub-biozone) at Balintore.

Nodosaria dispar Franke, 1936

(Plate 11, Figure 3)

1936 *Nodosaria dispar* Franke; p. 39, pl. 4, figs. 18a-d.
1972 *Nodosaria dispar* Franke; Norling, p. 47, figs. 18a, 19b.
1982 *Nodosaria dispar* Franke; Ruget, p. 73, pl. 2, fig. 21.
1983 *Nodosaria dispar* Franke; Kalia & Chowdhury, p. 232, pl. 2, fig. 1.

Description. Large, robust, uniserial test with 2-3 chambers; proloculus large, spherical, sometimes aplicate and generally greater than the subsequent chambers; chambers globular to pear shaped and taper distally; sutures depressed, curved; ornament consists of 8-12 coarse, blade like, longitudinal ribs that are continuous over sutures; aperture is radiate and centrally placed, with all the ribs converging to form a notched apertural collar.

Remarks. *N. **dispar*** was only recovered with 2-3 chambers and the proloculus was always larger than the chambers. It can be distinguished from *N. **fontinensis*** by its continuous ribbing and from *N. **metensis*** which has more ribs that are also finer.

Material. 20 specimens.
Distribution.
10 from Staffin Bay; ***mariae*** Biozone-***baylei*** Biozone.
3 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Biozone.
7 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

Nodosaria elongata (Ehrenberg), 1844

(Plate 10, Figure 12)

1844 *Miliola elongata* Ehrenberg, p. 284.
1961 *Nodosaria elongata* (Ehrenberg); Pietrzenik, p. 58, pl. 4, fig. 9.
1968 *Nodosaria elongata* (Ehrenberg); Welzel, p. 12, pl. 1, fig. 20.

Description. Test medium to large, slender and rectilinear with up to 7 chambers, and a lobulate periphery; proloculus ellipsoidal and aplicate; chambers sub-rectangular, being very elongate and increase in length more rapidly as added, final chamber tapers distally to the apertural region; sutures depressed and horizontal; aperture radiate and produced on a short neck.

Remarks. This form is superficially similar to ***D. nodigera*** (Terquem & Berthelin) which is, however, arcuate along its growth axis.

Material. 4 specimens, only recovered from Eathie Haven.

Nodosaria fontinensis Terquem, 1870

(Plate 11, Figure 4)

1870b ***Nodosaria fontinensis*** Terquem; p. 251, pl. 26, figs. 1-5.
1960 ***Nodosaria fontinensis*** Terquem; Bielecka, p. 133, pl. 5, fig. 38.
1989 ***Nodosaria metensis*** Terquem; Morris & Coleman, p. 216, pl. 6.3.5, fig. 4.
1989 ***Nodosaria fontinensis*** Terquem; Gregory, p. 184, pl. 1, fig. 8.
1990 ***Nodosaria mutabilis*** Terquem; Quilty, p. 361, pl. 3, fig. 4.

Description. Test large and uniserial, with 4-8 chambers; proloculus spherical and sometimes aplicate; chambers globular, but higher than wide; sutures strongly depressed and constricted; ornament consists of 8-12 coarse, sharp ribs that taper proximally and do not cross sutures; aperture where visible is radiate, terminal and produced on a short neck.

Remarks. Morphological variation is reflected by irregular chamber development and in the rib number which accounts for the large numbers of incorrect assignments as detailed in the synonymy lists of Copestake (1978). ***N. fontinensis*** can be distinguished from ***N. dispar*** which is more robust, and has a proloculus which is larger than its remaining chambers.

Material. 209 specimens.
Distribution.
148 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
16 from Staffin Bay; a rare form with a total range from the ***athleta*** Biozone to ***tenuiserratum*** Biozone.
13 from Balintore; only recovered from the ***tenuiserratum*** Sub-biozone.
2 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.
4 from Eathie Haven; ***cymodoce*** Biozone only.
26 from Helmsdale; ***cymodoce-eudoxus*** Biozones.

This is a distinct form being commonest in the Lower and Middle Jurassic of Europe, Africa and the UK, but does occur in the Upper Jurassic (e.g. Morris & Coleman, 1989 and Gregory, 1989).

Nodosaria hortensis Terquem, 1866

(Plate 11, Figure 5)

1866b ***Nodosaria hortensis*** Terquem; p. 476, pl. 19, fig. 13.
1960 ***Nodosaria hortensis*** Terquem; Bielecka, p. 133, pl. 5, fig. 39.
1979 ***Nodosaria hortensis*** Terquem; Exton, p. 13, pl. 1, fig. 8.
1989 ***Nodosaria hortensis*** Terquem; Morris & Coleman, p. 228, pl. 6.3.9, fig. 3.

Description. Small-medium, uniserial and distally tapering test of up to 8 chambers; proloculus large, globular and followed by small, equiant chambers; sutures distinct to indistinct, being depressed and horizontal; ornament consists of 6-8 fine, longitudinal ribs that are not always continuous to the aperture; aperture is radiate, central and produced on a short neck.

Remarks. The main variations are in the chamber form, which ranges from elongate to globular, and in the number of ribs. It is similar to *N. dispar* with its tapering test, but differs in being smaller in size and *N. dispar* has much coarser ribbing.

Material. 46 specimens.
Distribution. This form is commonest in the Middle Jurassic section of Bearreraig Bay, with 39 specimens from the ***concavum*** Biozone to ***discites*** Biozone. 5 specimens were recovered from the ***cordatum*** Biozone to ***tenuiserratum*** Biozone of Staffin Bay and 2 from the ***athleta*** Biozone at Brora.

Nodosaria metensis Terquem, 1863

(Plate 11, Figure 6)

1863 ***Nodosaria metensis*** Terquem; p. 167, pl. 7, figs. 5a-b.
1936 ***Nodosaria metensis*** Terquem; Franke, p. 47, pl. 4, figs. 15a-c.
1950a ***Nodosaria metensis*** Terquem var. ***robusta*** Barnard; p. 356, fig. 3.
1950a ***Nodosaria amphigya*** Loeblich & Tappan; p. 49, pl. 13, figs. 15-16.
1989 ***Nodosaria metensis*** Terquem; Copestake & Johnson, p. 182, pl. 6.2.5, fig. 14.

Description. Small to medium test with up to 4 robust chambers; proloculus is large, globular to elongate and is succeeded by distally elongate chambers which decrease in size as added; sutures distinct, depressed and curved; ornament distinct with up to 20 fine, continuous, longitudinal ribs; aperture where visible is radiate and produced on a short neck, with a thin notched apertural collar.

Remarks. The variation in size of the Scottish material was such that it included the larger examples that Barnard (1950a) described as a new variety. Most of the specimens from Bearreraig Bay possessed numerous ribs, usually more than 14. Copestake & Johnson

(1989) noted that forms from the Lower Jurassic had a greater degree of variation in rib number, ranging from 8 to 23.

Material. 28 specimens.
Distribution. This form was only recovered from the Aalenian and Bajocian of Bearreraig Bay, which confirms the final appearance of this form in the Bajocian as reported by Copestake & Johnson (1989). *N. metensis* is a common component of British and European Hettangian to Bajocian faunas and is often associated with *N. hortensis* and *N. fontinensis*.

Nodosaria minuta Cordey, 1962
(Plate 11, Figure 7)

1890 ***Nodosaria (Dentalina) multicostata*** Wisniowski; p. 196, pl. 8, fig. 44.
1962 ***Nodosaria minuta*** Cordey; p. 390, pl. 47, fig. 27.

Description. Very small, uniserial and parallel sided test with up to 5 chambers; proloculus large, rectangular and aplicate; chambers rectangular to generally equiant; sutures flush to slightly depressed and horizontal; ornament consists of 8-10 narrow, sharp, continuous longitudinal to slightly oblique ribs that converge distally to form an apertural collar; aperture is radiate and sometimes produced on a short neck.

Remarks. This form was renamed by Cordey (1962) as he established that Wisniowski (1890) had incorrectly nominated *N. multicostata* as a new form when the name had already been used by d'Orbigny (1840). It can be distinguished from other costate forms by its small size and poorly defined sutures.

Material. 90 specimens.
Distribution.
67 from Staffin Bay; total range occurs between the ***athleta*** Biozone and ***densiplicatum*** Biozone, with an acme between the ***athleta*** Biozone and ***lamberti*** Biozone.
23 from Balintore; total range ***athleta*** Biozone to ***mariae*** Biozone, with an acme between the ***athleta*** Biozone and ***lamberti*** Biozone.

This form appears to be restricted in its range between the ***athleta*** Biozone and ***densiplicatum*** Biozone, with a well established acme towards the base of its range.

Nodosaria nitidana Bartenstein & Brand, 1937
(Plate 11, Figure 8)

1870a ***Nodosaria nitida*** Terquem; p. 436, pl. 5, fig. 11.
1937 ***Nodosaria nitidana*** Bartenstein & Brand; p. 143, pl. 2b, fig. 22; pl. 4, fig. 32; pl. 5, fig. 27.
1955 ***Nodosaria nitidana*** Bartenstein & Brand, 1937; Seibold & Seibold, p. 116, pl.

13, fig. 13; text-figs. 2h-i.
1979 *Nodosaria nitidana* Bartenstein & Brand, 1937; Ruget, p. 117, pl. 16, figs. 1-8.
1984 *Pseudonodosaria nitidana* Brand; Riegraf *et al.*, p. 686, pl. 1, fig. 36.

Description. Test large, rounded, with a lobulate margin and uniserial with up to 7 chambers; proloculus oblate and is followed by chambers that are generally broader than high and gradually increase in width as added, final chamber slightly inflated; sutures marked, being depressed and straight; surface smooth; aperture radiate and produced on a short neck.

Material. 31 specimens.
Distribution. A rare form with 15 specimens restricted between the ***athleta*** to ***cordatum*** Biozones at Staffin Bay, 2 specimens from the ***athleta*** Biozone to ***tenuiserratum*** Biozone of Balintore and 14 from the ***athleta*** Biozone at Brora.

Nodosaria opalini Bartenstein & Brand, 1937

(Plate 11, Figure 9)

1937 *Nodosaria opalini* Bartenstein & Brand; p. 147, pl. 8, figs. 13a-b; pl. 10, figs. 18a-b.
1958 *Nodosaria opalini* Bartenstein & Brand; Said & Barakat, p. 255, pl. 2, fig. 26.
1989 *Nodosaria opalini* Bartenstein & Brand; Morris & Coleman, p. 228, pl. 6.3.9, fig. 5.
1991 *Nodosaria opalini* Bartenstein & Brand; Gregory, p. 89, pl. 1, fig. 8.

Description. Robust, parallel sided, uniserial test with up to 6 chambers; chambers sub-rectangular and generally equal in height and width, increasing gradually in size as added, final chamber is inflated and produced distally to form a short neck; sutures depressed and horizontal; ornament consists of numerous, evenly spaced and slightly curved, longitudinal ribs that are continuous over sutures, with several terminating distally on the final chamber; aperture is small, radiate and produced on a central, short neck.

Material. 65 specimens.
Distribution. This form is commonest from the Aalenian and Bajocian deposits at Bearreraig Bay, with 61 specimens from the ***concavum*** Biozone to ***discites*** Biozone. 4 specimens were recovered between the ***athleta*** Biozone and ***cordatum*** Biozone (***bukowskii*** Sub-biozone) of Staffin Bay.

Nodosaria pectinata (Terquem), 1870

(Plate 11, Figure 10)

1870b *Dentalina pectinata* Terquem; p. 310, pl. 15, fig. 6.
1989 *Nodosaria pectinata* (Terquem); Morris & Coleman, p. 228, pl. 6.3.9, fig. 7.

1991 *Nodosaria pectinata* (Terquem); Gregory, p. 90, pl. 1, fig. 9.

Description. Uniserial, tapering test with up to 6 chambers; proloculus small, spheroidal and is sometimes aplicate; chambers sub-rectangular, being higher than broad, but increase more rapidly in breadth as added; sutures indistinct, flush, straight and obscured by the ornament; ornament consists of up to 16 sharp, continuous ribs that diverge from the proloculus and are continuous over the sutures; aperture central, radiate and flush.

Material. 25 specimens.
Distribution. A rare form most common in the Aalenian-Bajocian of Bearreraig Bay, with 22 specimens from the ***concavum*** Biozone and lower ***discites*** Biozone. The remaining 3 specimens were retrieved from the ***athleta*** Biozone to ***lamberti*** Biozone at Staffin Bay.

Nodosaria procera Franke, 1936
(Plate 11, Figure 11)

1865 ***Nodosaria raphanistrum*** (Linné); Brady, p. 106, pl. 1, fig. 7.
1936 ***Nodosaria procera*** Franke; p. 51, pl. 5, fig. 3.
1969 ***Nodosaria procera*** Franke; Brouwer, p. 28, pl. 3, fig. 16.

Description. Slender, elongate, tapering and flattened, uniserial test with up to 9 chambers; proloculus small and aplicate; chambers sub-rectangular and are much greater in length, increasing more rapidly in length as added; sutures depressed, straight to arcuate; ornament consists of numerous thin, longitudinal ribs which are not always continuous over sutures; aperture is radiate, central and produced on a short neck.

Remarks. This form is more slender and flattened than *N. **raphanistriformis.***

Material. 2 specimens.
Distribution. A very rare from found only in the ***athleta*** Biozone at Staffin Bay and Balintore.

Nodosaria raphanistriformis (Gümbel), 1862
(Plate 11, Figure 12)

1862 ***Dentalina raphanistriformis*** Gümbel; p. 219, pl. 3, figs. 12a-b.
1960 ***Nodosaria raphanistriformis*** (Gümbel); Bielecka, p. 136, pl. 5, fig. 44.
1982 ***Nodosaria*** cf. ***raphanistriformis*** (Gümbel); Enay ***et al.***, p. 752, pl. 3, fig. 20.
1989 ***Nodosaria*** aff. ***raphanistriformis*** (Gümbel); Gregory, p. 184, pl. 1, fig. 7.
1989 ***Nodosaria raphanistriformis*** (Gümbel); Hornibrook ***et al.***, p. 44, fig. 9:20.

Description. Test uniserial, with a lobulate periphery and 3-8 chambers; large spherical proloculus, that is occasionally larger than the following chambers; chambers equiant and generally similar in size; sutures distinct, depressed and horizontal, sometimes associated with a secondary proximal constriction; ornament consists of up to 26 closely and evenly spaced cord-like ribs, that taper both distally and proximally; aperture is a simple, circular opening that is flush to slightly protruding.

Remarks. There are some differences to the description and illustrations of Terquem (1862) in which the ribs are more numerous and not as well defined

Material. 197 specimens.
Distribution.
11 from Bearreraig Bay; top ***concavum*** Biozone-***discites*** Biozone.
4 from Staffin Bay; ***cordatum*** Biozone (***costicardia*** Sub-biozone)-***densiplicatum*** Biozone (***vertebrale*** Sub-biozone).
2 from Balintore; ***lamberti*** Sub-biozone.
12 from Eathie Haven; ***cymodoce*** Biozone-***mutabilis*** Biozone.
168 from Helmsdale; ***cymodoce-eudoxus*** Biozones.

Nodosaria regularis Terquem, 1862
(Plate 11, Figure 13)

1862 *Nodosaria regularis* Terquem; p. 436, pl. 5, fig. 12.
1936 *Nodosaria germanica* Franke; p. 41, pl. 3, figs. 18a-b.
1955 *Nodosaria regularis* Terquem; Tappan, p. 72, pl. 26, figs. 7-9.
1979 *Nodosaria regularis* Terquem; Exton, p. 16, pl. 8, fig. 7.

Description. Large, uniserial test, with up to 5 similarly sized, globular, bead-like chambers that are generally higher than broad and connected by short necks; sutures straight and very constricted; test surface smooth to slightly hispid; aperture is a large, circular opening, or can be radiate and produced on a short neck.

Remarks. The Scottish material tends to be several times larger than the description given by Terquem (1862) and, as such bears more of a resemblance to *N.* ***regularis*** Terquem ssp. A Copestake & Johnson, which is restricted to the Toarcian to Upper Bajocian and is used as a zonal marker for the Upper Toarcian. If the Scottish material is the same, then obviously the upper extent will have to be extended. *N.* ***regularis*** can be distinguished from *N.* ***apheilolocula*** which has much thinner stolons and a more coarsely hispid surface.

Material. 41 specimens.
Distribution.
1 from Bearreraig Bay; ***concavum*** Biozone only.

19 from Staffin Bay; very rare throughout, with a total range from the ***athleta*** Biozone to ***tenuiserratum*** Biozone.
21 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.

Nodosaria simplex (Terquem), 1858

(Plate 12, Figure 1)

1858 ***Dentalina simplex*** Terquem; p. 39, pl. 2, fig. 5.
1936 ***Nodosaria simplex*** (Terquem); Franke, p. 44, pl. 4, fig. 6.
1968 ***Nodosaria simplex*** (Terquem) ***tenuissima*** Franke; Welzel, p. 13, pl. 1, fig. 22.
1984 ***Nodosaria simplex*** (Terquem); Riegraf ***et al.***, p. 682, pl. 5, fig. 128.

Description. Small-medium, rectilinear test with lobulate margins and up to 7 chambers; proloculus small and spherical; chambers sub-rectangular to elongate and parallel sided, being greatest in height and increasing more rapidly in length as added, final chamber particularly elongate, and tapers distally; sutures distinct and constricted; test surface smooth; aperture radiate and produced on a short neck.

Remarks. ***N. simplex*** can be distinguished from ***N. nitidana*** which has broader chambers and less distinct sutures.

Material. 101 specimens.
Distribution.
2 from Bearreraig Bay; only found in the ***concavum*** Biozone.
65 from Staffin Bay; fairly common between the ***athleta*** Biozone and ***tenuiserratum*** Biozone (***bukowskii*** Sub-biozone).
34 from Balintore; total range from the ***athleta*** Biozone to ***tenuiserratum*** Biozone, with an acme between the ***athleta*** Biozone and ***mariae*** Biozone (***scarburgense*** Sub-biozone).

Nodosaria sphingothalamus Loeblich & Tappan, 1950

(Plate 12, Figure 2)

1950b ***Nodosaria sphingothalamus*** Loeblich & Tappan; p. 11, pl. 1, fig. 34.
1976 ***Nodosaria*** cf. ***sphingothalamus*** Loeblich & Tappan; Souaya, p. 277, pl. 9, fig. 11.

Description. Large, uniserial test with up to 4 chambers; proloculus large and is globular to drum-shaped; chambers elongate and spindle shaped, increasing in length as added, and are widest distally; sutures distinct, constricted and horizontal; ornament consists of numerous fine, evenly spaced, longitudinal ribs which are continuous over sutures; aperture not visible in this material.

Remarks. This is a rare form that, none the less, compares well with the description of Loeblich & Tappan (1950b) for material from the Middle and Upper Jurassic of North America, and is identical to the Upper Jurassic forms illustrated by Souaya (1976) from Alaska. ***N. sphingothalamus*** can be distinguished from ***N. raphanistriformis*** which has fewer ribs that are also more cord-like and has chambers that are more equiant in dimension.

Material. 4 specimens.
Distribution. Only recovered from the Upper Callovian deposits of Staffin Bay and Brora, with 3 specimens from the ***athleta*** Biozone to ***lamberti*** Biozone from the former and 1 specimen from the ***athleta*** Biozone at the latter.

Genus ***Pseudonodosaria*** Boomgaart, 1949

Pseudonodosaria sp. A

(Plate 12, Figure 3)

Description. Large, robust, tapering uniserial test which is rounded in cross section; proloculus oblate and small; chambers sub-rectangular, and wide, increasing more rapidly in width as added, final chamber inflated and tapers sharply distally to an apertural collar; sutures flush, straight and horizontal, with no surface expression; test wall thick, surface smooth; aperture is large, radiate and produced on a short neck.

Remarks. ***P.*** sp. A is similar to ***P. brandi*** (Tappan) as illustrated by Dain (1972, pl. 14, figs. 1-2 and 6 only), except this form has well developed and depressed, horizontal sutures.

Material. 2 specimens.
Distribution. Only found in the Staffin Bay section within the ***tenuiserratum*** Biozone and ***baylei*** Biozone.

Pseudonodosaria annulifera (Frentzen), 1941

(Plate 12, Figure 4)

1941 ***Nodosaria annulifera*** Frentzen; p. 316, pl. 2, figs. 20-21.
1968 ***Nodosaria annulifera*** Frentzen; Welzel, p. 13, pl. 1, fig. 23.
1985 ***Nodosaria annulifera*** Frentzen; Riegraf, p. 108, pl. 10, fig. 25.

Description. Test large and rectilinear with roughly parallel, but lobulate sides and has up to 6 chambers; proloculus large and spherical; chambers sub-rectangular, broader than high and gradually increasing in width as added; sutures depressed, straight and horizontal; surface of test smooth, proximal portion of chambers marked by a horizontal constriction; aperture where present is radiate, central and extended on a squat test.

Remarks. Most of the specimens recovered were crushed giving a flattened appearance to the test. It can be distinguished from ***P. dubia*** and ***P. vulgata*** by its larger proloculus and more regular chamber size increase.

Material. 22 specimens.
Distribution.
8 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
3 from Staffin Bay; ***cordatum*** Biozone (***costicardia*** Sub-biozone-***cordatum*** Sub-biozone).
7 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Biozone.
4 from Brora; only from the upper part of the ***athleta*** Biozone.

Pseudonodosaria douglasi Weir, (1943)

(Plate 12, Figure 6)

1943 ***Pseudoglandulina douglasi*** Weir; p. 143, figs. 13a-b.
1952a ***Pseudoglandulina radiata*** Barnard; p. 347, text-fig. A2.
1960 ***Rectoglandulina costata obtus*** (Wisniowski); Lutze, p. 482, pl. 29, fig. 10a-b.
1981 ***Pseudonodosaria radiata*** (Barnard); Barnard ***et al.***, p. 411, pl. 3, fig. 7.
1989 ***Pseudonodosaria radiata*** (Barnard); Shipp, p. 259, pl. 6.4.3, figs. 1-2.

Description. Large robust, rounded and uniserial test with up to 6 chambers; proloculus large, oval to rounded; chambers globular to sub-rectangular, equiant and increasing gradually in all dimensions as added, giving lobulate peripheries; sutures depressed and horizontal; ornament distinct with up to 16 striations/ribs arranged obliquely and twisted like internal rifle barrel grooves, ribs not continuous and terminate before the apertural end of the final chamber; aperture flush and produced on a short squat neck.

Remarks. This species was originally described by Weir (1943) who collected it from the ***mariae*** Biozone of the Oxford Clay from Dorset and Gristhorpe. Barnard (1952a) appears not to have seen this publication and subsequently named this form ***P. radiata*** which has come into common use. However, Weir's species description has priority, and so the many forms incorrectly attributed to ***P. radiata*** are listed in the synonymy. This form is similar to ***Pseudoglandulina striata*** Hagenmayer illustrated in Bach ***et al.*** (1959), except ***P. douglasi*** has fewer ribs which are also more distinct.

Material. 4 specimens.
Distribution. Only recovered from the ***cordatum*** Biozone (***bukowskii*** Sub-biozone-***costicardia*** Sub-biozone) at Staffin Bay. In greater numbers this form could be useful as a biostratigraphical marker as it is restricted to the ***mariae*** Biozone-***cordatum*** Biozone in the British Isles (Weir, 1943; Barnard, 1952; Barnard ***et al.***, 1981; Shipp, 1989) and

Germany (Lutze, 1960).

Pseudonodosaria dubia (Terquem), 1870
(Plate 12, Figure 5)

1870b ***Glandulina dubia*** Terquem; p. 240, pl. 25, figs. 10-11.
1936 ***Glandulina dubia*** Terquem; Franke, p. 56, pl. 5, fig. 16.
1957 ***Pseudoglandulina vulgata*** (Bornemann) var. ***irregularis*** (Franke); Nørvang, p. 360, fig. 86.
1972 ***Pseudonodosaria*** ex gr. ***vulgata*** (Bornemann); Norling, p. 86, only fig. 46B (not 46A or 46C).
1985 ***Pseudonodosaria dubia*** (Terquem); Riegraf, p. 109, pl. 10, fig. 26.

Description. Small-medium sized, uniserial and tapering test with up to 6 chambers; proloculus small, oval to sub-rectangular; chambers sub-rectangular, becoming consistently greater in height than width as added, final chamber inflated; sutures depressed and straight; test surface smooth; aperture is small, radiate and centrally placed on a small elongate neck.

Remarks. This form is considered to be sufficiently consistent and regular in its chamber development to be separated from the ***P. vulgata*** group, in which some authors such as Macfadyen (1941) and Norling (1972) have placed ***P. dubia***.

Material. 20 specimens.
Distribution. This is a rare form with 11 specimens from the ***lamberti*** Biozone to ***tenuiserratum*** Biozone at Staffin Bay, 5 from the ***athleta*** Biozone-***mariae*** Biozone at Balintore and 4 from the ***athleta*** Biozone at Brora.

Pseudonodosaria vulgata (Bornemann), 1854
(Plate 12, Figure 7)

1854 ***Glandulina vulgata*** Bornemann; p. 31, pl. 2, figs. 1a-b, 2.
1950a ***Pseudoglandulina oviformis*** (Terquem); Barnard, p. 365, fig. 6h.
1952a ***Pseudoglanudulina vulgata*** (Bornemann); Barnard, p. 365, fig. 4c.
1956 ***Pseudonodosaria vulgata*** (Bornemann); Seibold & Seibold, p. 139, text-figs. 6m-n, r-t.
1967 ***Pseudonodosaria sowerbyi*** (Schwager); Gordon, p. 453, pl. 4, figs. 10-11.
1972 ***Pseudonodosaria*** ex gr. ***vulgata*** (Bornemann); Norling, p. 86, figs. 46A, C (not B).
1989 ***Pseudonodosaria vulgata*** (Bornemann); Gregory, p. 186, pl. 1, figs. 17.

Description. Test medium-large, compressed to rounded in section, uniserial; small, sometimes aplicate, oval proloculus is followed by 4-5 sub-rectangular chambers which are inconsistent in size; sutures flush-depressed and straight; surface smooth, although sometimes can be pitted; aperture is central, radiate and is flush or raised on a short neck.

Remarks. Due to a great degree of morphological variation in chamber size, which is a product of fluctuating growth rate, ***P. vulgata*** has given rise to many varieties and species. Norling (1972) placed all these forms under ***P. vulgata*** for which he provides an extensive synonymy list, which includes for example, tapering forms previously assigned to ***P. pupa*** and rounded forms assigned to ***P. oviformis.***

Material. 164 specimens.
Distribution.
15 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
6 from Staffin Bay; ***cordatum*** Biozone-***cymodoce*** Biozone.
4 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Biozone.
20 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.
120 from Helmsdale; ***cymodoce-mutabilis*** Biozones.

Pseudonodosaria vulgata (Bornemann), 1854 ssp. A

(Plate 12, Figure 8)

Description. Medium-large, compressed, uniserial test with up to 6 chambers and peripheries which are divergent, rounded, and irregularly lobulate; proloculus is large and spherical; chambers broad and arcuate, increasing irregularly in size as added, final chamber inflated; sutures constricted, arcuate; ornament consists of numerous, regularly spaced, fine striations which fade both distally and proximally and do not cross the sutures, some chambers marked by a secondary horizontal, basal constriction; aperture is radiate and central, being flush or slightly extended on a short neck.

Remarks. Morphological variation occurs mainly in aberrant chamber development which is the same as that for the ***P. vulgata*** group. Copestake (1978) included striated forms within his diagnosis of ***P. vulgata.*** It is concluded that whilst the differences in gross morphology are not sufficient for nomination to species level they are distinct enough to allow the differentiation of a 'new' subspecies to include such striated forms. Franke (1936) indicated he had found a similar striated species, nominated as ***Glandulina vulgata*** form ***tenuistriata***, but unfortunately it was not illustrated. ***P. striata*** Hagenmeyer reported from the Lias by Bach ***et al.*** 1959 is similar, but has continuous and oblique striae.

Material. 9 specimens, only recovered from the ***cordatum*** Biozone (***costicardia*** Sub-biozone) to ***rosenkrantzi*** Biozone at Staffin Bay.

Subfamily Linguliniinae Loeblich & Tappan, 1961

Genus *Lingulina* d'Orbigny, 1826

Remarks. Loeblich & Tappan (1988) split ***Lingulina*** into several genera based on the presence or absence of ornamentation and whether the test was non-lamellar. This latter feature is difficult to ascertain in Jurassic forms which must have undergone some form of diagenesis that would destroy such test laminations. So, ***Paralingulina*** Gerke, represented by non-lamellar, ribbed forms, ***Lingulonodosaria*** Silvestri represented by ribbed forms and ***Lingulina*** are all grouped under the single genus ***Lingulina*** for this study.

Lingulina longiscata (Terquem), 1870

(Plate 12, Figure 9)

1870b ***Frondicularia longiscata*** Terquem; p. 318, pl. 22, figs. 23-24.

1937 ***Frondicularia nodosaria*** Terquem; Bartenstein & Brand, p. 155, pl. 12a, fig. 6; pl. 13, fig. 14; pl. 15a, fig. 21.

1950b ***Lingulina nodosaria*** (Terquem); Barnard, p. 29, text-fig. 16.

1967 ***Lingulina longiscata*** (Terquem); Gordon, p. 456, pl. 3, fig. 10.

1989 ***Lingulina longiscata*** (Terquem); Gregory, p. 187, pl. 1, fig. 20.

Description. Test large, compressed and uniserial; proloculus spherical and large, followed by 5-7 arcuate to chevron shaped chambers; sutures distinct and are occasionally associated with basal constrictions; ornament consists of numerous fine, evenly spaced ribs that converge to the central distal area and are not continuous over the sutures; aperture is a terminal, elongate slit that is flush or slightly protruding and is surrounded by a thin lip.

Remarks. ***L. longiscata*** is similar to some striated frondicularids as illustrated by Barnard (1957) for material from the Lower Lias. However, it can be distinguished by its elongate apertural slit. Variation occurs in the number and thickness of the ribs.

Material. 18 specimens.
Distribution. A rare form with;
3 from Bearreraig Bay.
5 from Staffin Bay; ***athleta*** Biozone to ***cordatum*** Biozone.
1 from Balintore; ***lamberti*** Biozone.
9 from Helmsdale; ***cymodoce*** Biozone.

Lingulina tenera Bornemann, 1854

(Plate 12, Figure 10)

1854 ***Lingulina tenera*** Bornemann; p. 38, pl. 3, fig. 24.

1957 ***Geinitzina tenera*** (Bornemann) ssp. ***tenera*** (Bornemann); Nørvang, p. 58, figs.

18-23.

1968 ***Lingulina tenera*** Bornemann; Welzel, p. 36, pl. 2, fig. 19.

1982 ***Lingulina tenera*** Bornemann; Ruget, p. 72, pl. 4, fig. 4.

1989 ***Lingulina tenera*** Bornemann; Hornibrook ***et al.***, p. 43, figs. 9:18a-b.

Description. Test small-medium, uniserial, compressed and quadrate in section with a median sulcus; a small, possibly aplicate proloculus is followed by 8 chambers; chambers arcuate-chevron shaped; final chamber constricted; sutures flush or slightly raised; ornament consists of a carinate margin, a median sulcus and 2 strong, continuous ribs emanating from the proloculus; aperture is a slit like opening that is either flush or slightly raised.

Remarks. This single specimen bears some resemblance to ***L. tenera occidentalis*** (Berthelin) with its raised ribs, but is probably most similar to ***L. tenera tenera.***

Material. 1 specimen from the *discites* Biozone at Bearreraig Bay.

Distribution. ***Lingulina tenera*** is a very rare form in the Middle or Upper Jurassic and this is the first recorded instance from the British Bajocian. The ***Lingulina tenera*** plexus has been established as one of the most useful foraminiferal biostratigraphical indicators for the Lower Jurassic (e.g. Barnard, 1956, 1963; Copestake & Johnson, 1981, 1984, 1989).

This plexus is an extremely important component of the Lower Jurassic sections at Morvern, Mull, Raasay and Skye with ***L. tenera tenera, L. tenera pupa, L. tenera subprismatica,*** and ***L. tenera collonoti*** all being present and agree well with the biozonation scheme erected by Copestake & Johnson (1984, 1989), defining the Sinemurian particularly well.

Subfamily Frondiculariinae Reuss, 1860

Genus *Frondicularia* DeFrance, 1826

Frondicularia franconica Gümbel, 1862

(Plate 12, Figure 11)

1862 ***Frondicularia franconica*** Gümbel; p. 219, pl. 3, figs. 13a-c.

1870b ***Frondicularia spissa*** Terquem; p. 317, pl. 22, fig. 10.

1937 ***Frondicularia spissa*** Terquem; Bartenstein & Brand, p. 153, pl. 13, figs. 13a-b; pl. 14c, fig. 8.

1952a ***Frondicularia franconica*** Gümbel; Barnard, p. 340, text-fig. A1.

1960 ***Frondicularia hathra*** Loeblich & Tappan; Wall, p. 91, pl. 13, figs. 1-5.

1960 ***Frondicularia glanduloides*** Bielecka; p. 140, pl. 7, fig. 54.

1981 ***Frondicularia franconica*** Gümbel; Barnard ***et al.***, p. 406, pl. 2, text-fig. 13.

1989 ***Frondicularia franconica*** Gümbel; Morris & Coleman, p. 224, pl. 6.3.8, fig. 3.

Description. Test medium-large, elongate and uniserial, with a rounded, un-keeled and irregularly lobulate periphery; proloculus large, oval-spherical, sometimes aplicate and is followed by 5-8 chambers which are chevron shaped or arcuate and very variable in size; sutures depressed; aperture is terminal, central and radiate, placed on a short neck.

Remarks. As a result of irregular chamber growth, this is a highly variable form.

Material. 85 specimens.
Distribution.
33 from Bearreraig Bay; top ***concavum*** Biozone-***discites*** Biozone.
13 from Staffin Bay; ***cordatum*** Biozone-***densiplicatum*** Biozone.
3 from Balintore; ***lamberti*** Biozone (***lamberti*** Sub-biozone).
21 from Brora; ***calloviense*** Biozone-***lamberti*** Biozone.
15 from Helmsdale; ***cymodoce*** Biozone.

Frondicularia kuldharensis Kalia & Chowdhury, 1983

(Plate 13, Figure 1)

1983 ***Frondicularia kuldharensis*** Kalia & Chowdhury; p. 234, pl. 3, figs. 15-16.

Description. Test large, palmate and very compressed with angular and irregular margins; large, globular proloculus is followed by numerous low, broad arched-chevron shaped chambers, which increase rapidly in width as added; sutures flush to slightly depressed; surface smooth; aperture radiate, central and either flush or mounted on a short neck.

Remarks. The Scottish material agrees well with the description of Kalia & Chowdhury (1983) for specimens from the Callovian of Rajasthan. This is the first recorded occurrence outside of India.

Material. 4 specimens. A rare form that was only recovered from the ***cordatum*** Biozone (***costicardia*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) of Balintore

Frondicularia laevissima Terquem, 1866

(Plate 13, Figure 2)

1866b ***Frondicularia laevissima*** Terquem; p. 48, pl. 19, fig. 19.
1935 ***Frondicularia laevissima*** Terquem; Macfadyen, p. 11, pl. 1, figs. 6a-b.
1968 ***Lingulina lanceolata*** (Haeusler); Welzel, p. 35, pl. 2, fig. 17.

Description. Compressed, narrow uniserial test with up to 8 chambers and lobulate margins; proloculus large and spheroidal; chambers sub-globular to chevron shaped and marginally greater in width, gradually increasing with size as added; aperture is central, terminal and radiate.

Remarks. This form is assigned to ***Frondicularia*** as it possesses a radiate aperture, and not a slit like aperture that is a characteristic of ***Lingulina***. This form may have been incorrectly attributed to ***Lingulina*** by Barnard (1956, p. 39) and Bielecka (1960, p. 137), but their figures are inconclusive.

Material. 17 specimens.
Distribution. A rare form with 6 specimens from the ***discites*** Biozone at Bearreraig Bay, 2 from Staffin Bay and 9 from the ***mariae*** Biozone to ***tenuiserratum*** Biozone of Balintore.

Frondicularia lignaria Terquem, 1866

(Plate 13, Figure 3)

1866b ***Frondicularia lignaria*** Terquem; p. 480, pl. 19, fig. 14.
1936 ***Frondicularia lignaria*** Terquem; Franke, p. 65, pl. 6, fig. 21.
1958 ***Frondicularia lignaria*** Terquem; Said & Barakat, p. 262, pl. 1, fig. 38.
1989 ***Frondicularia lignaria*** Terquem; Morris & Coleman, p. 212, pl. 6.3.3, fig. 2; p. 224, pl. 6.3.8, fig. 5.

Description. Test compressed and uniserial with up to 8 chambers; margins straight, angular and nearly parallel sided; proloculus spherical, chambers arcuate, being broader than high, and increase regularly as added; sutures depressed, curved and often marked by low, sutural ribs; aperture is radiate, central and terminal.

Remarks. ***F. lignaria*** can be distinguished from ***F. franconica***, which is more inflated and has irregular chamber development, and from ***F. oolithica*** which has no surface markings and is also inflated.

Material. 11 specimens.
Distribution. 9 specimens from the ***athleta*** Biozone to ***lamberti*** Biozone of Brora and 2 from the ***cordatum*** Sub-biozone of Staffin Bay.

Frondicularia moelleri Uhlig, 1883

(Plate 13, Figure 5)

1883 ***Frondicularia moelleri*** Uhlig; p. 758, pl. 9, figs. 12-15.
1954 ***Flabellinella moelleri*** (Uhlig); Bielecka & Pozaryski, p. 48, pl. 7, fig. 31.
1958 ***Frondicularia moelleri*** Uhlig; Bizon, p. 16.
1970 ***Frondicularia nikitini*** Uhlig; Winter, p. 25, pl. 3, fig. 89.
1981 ***Frondicularia moelleri*** Uhlig; Barnard *et al.*, p. 408, pl. 2, figs. 12-13.
1989 ***Frondicularia moelleri*** Uhlig; Gregory, p. 185, pl. 1, fig. 14.

Description. Test large, quadrate, compressed and uniserial; a large spherical, sometimes aplicate proloculus is followed by 5-6 chevron shaped chambers which are broader than high; sutures distinct and depressed; ornament consists of coarse, discontinuous, oblique to longitudinal ribs, some of which are continuous over several chambers; aperture where visible is radiate and produced on a neck with a thick, notched apertural collar.

Remarks. ***F. moelleri*** can be distinguished from ***F. nikitini***, which possesses more numerous, very regular and finer ribs that do not cross sutures.

Material. 12 specimens.
Distribution. A rare from, which is restricted to the Callovian and Oxfordian, with 4 specimens recovered from the ***mariae*** Biozone to ***densiplicatum*** Biozone at Staffin Bay, 3 from the ***lamberti*** Sub-biozone of Balintore and 5 from the ***cymodoce*** Biozone at Helmsdale.

Frondicularia nikitini Uhlig, 1883
(Plate 13, Figure 6)

1883 ***Frondicularia nikitini*** Uhlig; p. 758, pl. 9, figs. 10-11.
1937 ***Flabellina moelleri*** Bartenstein & Brand; p. 169, pl. 15a, fig. 27; pl. 15c, fig. 13.
1950 ***Frondicularia spatha*** Lalicker; p. 17, pl. 3, figs. 6a-d.
1960 ***Frondicularia nikitini*** Uhlig; Lutze, p. 466, pl. 31, figs. 1-6, 8.
1978 ***Frondicularia nikitini*** Uhlig; Munk, p. 42, pl. 2, fig. 9, text-fig. 17.
1989 ***Citharinella nikitini*** (Uhlig); Morris & Coleman, p. 222, pl. 6.3.7, fig. 2.
1989 ***Frondicularia nikitini*** Uhlig; Shipp, p. 256, pl. 6.4.2, fig. 5.

Description. Large, uniserial test; proloculus oval-spherical and unornamented, followed by 5-8 chambers; proximal chambers arcuate, distal ones chevron shaped, chambers only increase in width as added; sutures distinct, depressed and arcuate-chevron shaped; ornament consists of up to 26 numerous, fine, regularly spaced and curved ribs that are not continuous over the sutures; aperture is centrally placed, radiate and produced on a small neck.

Remarks. Variation occurs in the ornament, with differences in the number of ribs present. The development of typical frondiculine chambers is sometimes postponed until the fourth or fifth chamber.

Material. 29 specimens.
Distribution.
13 from Staffin Bay; ***lamberti*** Sub-biozone-***cymodoce*** Biozone.

2 from Balintore; ***athleta*** Biozone-***lamberti*** Biozone.
14 from Brora; ***athleta*** Biozone-***lamberti*** Biozone (***henrici*** Sub-biozone).

F. nikitini has been widely reported from the Middle to Upper Jurassic of Europe, but seems to be generally restricted between the Callovian and Lower Oxfordian from the ***jason*** Biozone to ***mariae*** Biozone. Morris & Coleman (1989) indicated its common occurrence within the Upper Callovian, from the ***athleta*** Biozone to ***lamberti*** Biozone. Cordey's (1962) restricted range (from the ***lamberti*** to ***mariae*** biozones of the Staffin Bay section, which was apparently caused by limited sampling), which correlates well with the present work. Munk (1978) recovered ***F. nikitini*** from the ***jason*** Biozone to ***athleta*** Biozone of southern Germany.

Frondicularia oolithica Terquem, 1870

(Plate 13, Figure 4)

1870b ***Frondicularia oolithica*** Terquem; p. 230, pl. 23, figs. 1-5.
1989 ***Frondicularia oolithica*** Terquem; Morris & Coleman, p. 212, pl. 6.3.3, figs. 4-6.
1991 ***Frondicularia oolithica*** Terquem; Gregory, p. 90, pl. 1, fig. 10.

Description. Large, compressed, uniserial test of up to 6 chambers, with angular and sharp peripheries; proloculus small and ellipsoidal; chambers arcuate to chevron shaped and broader than high, increasing more rapidly in width as added, final chamber tapers distally to a short neck; sutures flush, chevron shaped; surface smooth; aperture is radiate, central and produced on a short neck.

Remarks. ***F. oolithica*** can be distinguished from ***F. franconica*** which has irregular chamber development, whilst the peripheries of the former are non-lobulate

Material. 26 specimens.
Distribution.
23 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
1 from Staffin Bay; ***cymodoce*** Biozone.
2 from Balintore; ***bukowskii*** Sub-biozone.

Genus *Tristix* Macfadyen, 1941
emend. Loeblich & Tappan, 1952

Tristix oolithica (Terquem), 1866

(Plate 13, Figure 7)

1866a ***Tritaxia oolithica*** Terquem; p. 60, pl. 7, figs. 5a-b.
1932 ***Rhabdogonium suprajurassica*** Paalzow; p. 125, pl. 9, fig. 7.
1933 ***Dentalinopsis oolithica*** (Terquem); Wickenden, p. 167, pl. 2, figs. 6a-d.
1950a ***Tristix alcima*** Loeblich & Tappan; p. 52, pl. 14, fig. 6.

1954 ***Tristix somaliensis*** (Macfadyen); Bielecka & Pozaryski, p. 61, pl. 9, figs. 45a-c.

1962 ***Tristix oolithica*** (Terquem); Gordon, p. 530, text-fig. 2, fig. 9.

1976 ***Tristix wapellensis*** Wall; Souaya, p. 281, pl. 7, fig. 10.

1990 ***Tristix oolithica*** (Terquem); Quilty, p. 361, pl. 3, figs. 25-26.

Description. Test small-medium and uniserial, with up to 8 chambers; test outline is triangular and distinctly tapering, with 3 keeled margins; proloculus spherical; chambers triangular, being greater in width than height and rapidly increase in size as added to give the tapered test; sutures strongly depressed and curved; aperture is radiate, terminal and produced on a short neck.

Remarks. This is a distinctive form, which has often been nominated as a new species; these are collected in the synonymy above.

Material. 6 specimens.

Distribution. A rare from with 2 specimens from the ***cordatum*** Biozone to ***tenuiserratum*** Biozone at Staffin Bay, 2 from the ***lamberti*** Biozone to ***cordatum*** Biozone at Balintore and 2 from the ***athleta*** Biozone at Brora.

This form is widely reported from the Aalenian to Oxfordian of the UK, America, France, Australia and Alasaka.

Tristix reesidei Loeblich & Tappan, 1950

(Plate 13, Figure 8)

1950a ***Tristix reesidei*** Loeblich & Tappan; p. 53, pl. 14, figs. 1-5.

1953 ***Tristix triangularis*** Barnard; p. 190, fig. 45.

1959 ***Tristix suprajurassica*** (Paalzow); Cifelli, p. 317, pl. 5, fig. 12.

1960 ***Tristix acutangulus*** (Reuss); Lutze, p. 475, pl. 29, fig. 1.

1970 ***Tristix somaliensis*** (Macfadyen); Garbowska, p. 78, fig. 54.

1981 ***Tristix triangularis*** Barnard; Barnard ***et al.***, p. 427, pl. 3, fig. 19.

1989 ***Tristix triangularis*** Barnard; Shipp, p. 260, pl. 6.4.3, figs. 5-6.

Description. Test medium-large, narrow, elongate and triangular in section with 10 chambers, the outline tapers out slightly from the proloculus and then becomes parallel sided, test edges are keeled; proloculus and chambers triangular in shape, broader than high and generally not increasing in size as added; sutures slightly depressed and arch towards the aperture, emphasising the triangular nature of the chambers; aperture is terminal, radiate and mounted on a short neck.

Remarks. All the recovered specimens were triangular in outline and can be distinguished from *T. oolithica* which tapers more dramatically due to chamber inflation. This form is commonly assigned to ***T. triangularis*** Barnard (1953), but a form nominated as ***T. reesidei*** by Loeblich & Tappan (1950a) is identical and therefore has priority.

Material. 5 specimens.
Distribution. A very rare form with 2 specimens from the ***lamberti*** Sub-biozone-***bukowskii*** Sub-biozone at Staffin Bay and 3 from the ***cordatum*** Biozone (***cordatum*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) at Balintore.

So far this taxon has only been found from the Bathonian to Kimmeridgian and appears to be commonest from the Oxfordian to Kimmeridgian interval of the UK (Dorset and the Midlands), Germany, America and Poland.

Family Vaginulinidae Reuss, 1860

Subfamily Lenticulininae Chapman, Parr & Collins, 1934

Genus ***Lenticulina*** Lamark, 1804

Lenticulina brevispira (Wisniowski), 1890

(Plate 13, Figure 9)

1890 ***Cristellaria brevispira*** Wisniowski; p. 22, pl. 10, figs. 6a-b.
1962 ***Lenticulina*** cf. ***brevispira*** (Wisniowski); Cordey, p. 378, pl. 46, fig. 2.
1976 ***Marginulina breviformis*** (Terquem & Berthelin); Souaya, p. 279, pl. 9, fig. 7.
1981 ***Lenticulina brevispira*** (Wisniowski); Barnard ***et al.***, p. 411, pl. 2, fig. 26, text-fig. 18.

Description. Medium-large, lenticuline test which is arranged in a loose, evolute planispire of 8-12 chambers; test compressed to inflated in cross-section with a distinct, sharp keel on the dorsal margin; proloculus small, oval and enveloped by some of the subsequent chambers; chambers inflated and broader than high, and gradually increase in height as added; sutures distinct, depressed to constricted, curved to slightly kinked and extend only over two thirds of the test, not reaching the dorsal margin; surface is usually smooth, but there are occasional hispid areas; aperture is radiate, marginal and produced on a short neck.

Remarks. Variation is expressed mainly in the degree of coiling, which is roughly the same as shown by Barnard (1960) for the variation in ***Lenticulina varians***.

Material. 68 specimens.
Distribution.
42 from Staffin Bay; ***athleta*** Biozone-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
7 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Biozone.
19 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

Lenticulina chicheryi Payard, 1947

(Plate 13, Figure 10)

1947 ***Lenticulina chicheryi*** Payard; p. 108, pl. 6, figs. 18-19.
1979 ***Palmula chicheryi*** (Payard); Exton, p. 42, pl. 6, figs. 3-4.
1982 ***Lenticulina chicheryi*** Payard; Rugét, p. 63, pl. 3, figs. 1-15, 18, 20-21.
1985 ***Lenticulina chicheryi*** Payard; Riegraf, p. 121, pl. 9, fig. 1.

Description. Large, robust, lenticuline test, which is arranged in an involute to evolute planispiral coil of up to 8 chambers; periphery angular and unevenly carinate; chambers broader than high and gradually increase in size as added; sutures distinctly depressed, curved and pinch the chambers between into low, broad, limbate ribs that coalesce umbilically; aperture is marginal, radiate and placed on a short neck.

Material. 12 specimens.
Distribution. Only 7 specimens were recovered from the ***mariae*** Biozone to ***cordatum*** Biozone at Staffin Bay, with 5 specimens from the ***athleta*** Biozone at Brora.

L. chicheryi has not been reported previously from the Callovian to Oxfordian in the UK, and has only been found in Toarcian or older sediments elsewhere.

Lenticulina dictyodes (Deeke), 1884

(Plate 14, Figure 1)

1884 ***Cristellaria dictyodes*** Deeke; p. 48, pl. 2, figs. 9a-b.
1962 ***Lenticulina (Planularia) dictyodes*** (Deeke); Brand & Fahrion, p. 155, pl. 20, fig. 35.
1978 ***Lenticulina (Astacolus) dictyodes*** (Deeke); Munk, p. 44, pl. 4, figs. 1, 3.
1989 ***Lenticulina dictyodes*** (Deeke); Morris & Coleman, p. 226, pl. 6.3.9, fig. 7.
1991 ***Lenticulina dictyodes*** (Deeke); Gregory, p. 89, pl. 1, fig. 4

Description. Compressed, medium to small test with up to 8 chambers arranged in a loose lenticuline coil and has an angular periphery; test initially planispirally coiled and becomes uncoiled in a short, curvilinear series; chambers broad, and sub-triangular, gradually increasing in size as added; sutures flush and obscured by the ornament; ornament is regular, reticulate and mesh like, covering the entire test; aperture is marginal, radiate and produced on a short neck.

Remarks. ***L. dictyodes*** can be distinguished from ***L. d'orbigny***, which has a much more irregular and closely spaced reticulate meshwork.

Material. 11 specimens.
Distribution. A rare form, with the majority of the specimens recovered from the ***concavum*** Biozone-***discites*** Biozone at Bearreraig Bay, and 2 specimens from the

athleta Biozone at Brora.

L. dictyodes has a consistent first appearance in the Aalenian to Bajocian (Morris & Coleman, 1989; Gregory, 1990, 1991).

Lenticulina d'orbigny (Roemer), 1839

(Plate 14, Figure 2)

1839 ***Peneroplis d'orbigny*** Roemer; p. 47, pl. 20, fig. 31.
1936 ***Cristellaria d'orbigny*** (Roemer); Franke, p. 118, pl. 12, fig. 4.
1964 ***Lenticulina d'orbigny*** (Roemer); Barbieri, pl. 58, fig. 5.
1973 ***Astacolus d'orbigny*** (Roemer); Ruget, p. 119, pl. 8, fig. 9.
1982 ***Lenticulina d'orbigny*** (Roemer); Ruget, p. 62, pl. 4, figs. 8-10, 15-16.
1989 ***Astacolus*** aff. ***d'orbigny*** (Roemer); Hornibrook *et al.*, p. 41, figs. 9-15.
1989 ***Lenticulina d'orbigny*** (Roemer); Morris & Coleman, p. 212, pl. 6.3.3, figs. 8-9.

Description. Compressed, loose lenticuline test with an initial coil of 2-4 chambers followed by an uncoiled section; periphery angular; 6 chambers are present in the figured specimen and they are broader than high; sutures curved, flush; ornament initially consists of a regularly reticulate meshwork which distally becomes a series of longitudinal spars, connected randomly by a succession of transverse bars; aperture not present.

Remarks. It appears reasonable to suppose that there exists an evolutionary linkage between *L. d'orbigny* and *L. dictyodes*, the latter of which possesses a very similar but more regular ornamental meshwork.

Material. 1 specimen from the *discites* Biozone at Bearreraig Bay.
Distribution. Even though only 1 specimen was recovered its presence is indicative of the consistent wide ranging final appearance of this form in the basal *discites* Biozone of the Bajocian. There are no European records of younger occurrences (Morris & Coleman, 1989; Copestake & Johnson, 1989) and the total range appears to be from the Toarcian to Bajocian.

Lenticulina ectypa (Loeblich & Tappan), 1950

(Plate 14, Figure 5)

1950b ***Astacolus ectypus*** Loeblich & Tappan; p. 17, pl. 1, fig. 10.
1967 ***Lenticulina quenstedti*** (Gümbel); Gordon, p. 451, only fig. 8.
1976 ***Astacolus ectypus*** Loeblich & Tappan; Souaya, p. 277, pl. 7, fig. 11.
1981 ***Lenticulina ectypa*** (Loeblich & Tappan); Barnard *et al.*, p. 412, pl. 2, fig. 19.
1989 ***Lenticulina ectypa*** (Loeblich & Tappan); Shipp, p. 256, pl. 6.4.2, fig. 7.
1989 ***Lenticulina ectypa*** (Loeblich & Tappan); Morris & Coleman, p. 228, pl. 6.3.9, fig. 2.

Description. Medium sized, compressed, lenticuline test with up to 8 chambers; margins are keeled and the lateral cross-section is deeply incised by sutures; proloculus small, spherical and enveloped by 3-4 chambers in the initial coil; chambers sub-triangular, broader than high; sutures deeply incised, curved and marked by median, continuous ribs which are connected proximally to form a central spiral suture, these sutural ribs do not extend as far as the peripheral margins; aperture is peripheral, radiate and produced on a short neck.

Remarks. This form is distinguished from *L. ectypa* spp. ***costata***, which possesses secondary distal ribs, and from ***L. quenstedti***, which does not have the deeply incised, sutural pattern in cross-section.

Material. 190 specimens.
Distribution.
47 from Staffin Bay; total range extends from the ***athleta*** Biozone to the ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone), with an acme between the ***densiplicatum*** Biozone and ***tenuiserratum*** Biozone (***blakei*** Sub-biozone).
110 from Brora; total range from the ***athleta*** Biozone to ***lamberti*** Biozone.
33 from Balintore; two distinct acmes between the ***athleta*** Biozone and ***lamberti*** Biozone and between the ***densiplicatum*** Biozone and ***tenuiserratum*** Biozone, with the latter being more prominent.

This is an important biozonal form that has consistently reported first appearances in the Lower and Middle Callovian, with acmes developed in the Oxfordian (e.g. Shipp, 1989; Morris & Coleman, 1989; Barnard ***et al.***, 1981). Partington ***et al.*** (1993a, b) record a final appearance (without recourse to direct ammonite biozonal corroboration), within the Late Oxfordian for North Sea Jurassic deposits.

Lenticulina ectypa (Loeblich & Tappan) ssp. ***costata*** Cordey, 1962
(Plate 14, Figure 4)

1960 ***Lenticulina (Lenticulina)*** cf. ***ectypa*** Loeblich & Tappan; Lutze; p. 412, fig. 11a.
1962 ***Lenticulina ectypa*** (Loeblich & Tappan) ssp. ***costata*** Cordey; p. 379, pl. 36, fig. 5, text-fig. 3.
1983 ***Lenticulina ectypa*** (Loeblich & Tappan) ssp. ***costata*** Cordey; Medd, p. 233, pl. 3, figs. 4-5.
1989 ***Lenticulina ectypa*** (Loeblich & Tappan) ssp. ***costata*** Cordey; Shipp, p. 258, pl. 6.4.2, fig. 8.
1991 ***Lenticulina ectypa*** (Loeblich & Tappan) ssp. ***costata*** Cordey; Efimova & Mesezhnikov, pl. 26, fig. 12.

Description. Medium to large, compressed test of up to 10 chambers coiled in a loose lenticuline fashion, dorsal and ventral margins are sharply keeled, cross-section deeply incised by sutures; first 4-5 chambers are involved in an involute coil, remaining chambers uncoiled in a curvilinear series; proloculus small, spherical and enveloped by following chambers; chambers sub-triangular, being broader than high, gradually increasing in size as added; sutures deeply incised and curved; ornament consists of sharp median sutural ribs and up to 3 secondary ribs which emerge from the main sutural ribs and are produced distally, but do not cross the sutures; initial primary ribs are joined proximally to form an irregular spiral suture, and do not reach the peripheral margins; aperture is peripheral and radiate, with the keels and some of the secondary ribs joining to form an apertural collar.

Remarks. This subspecies is distinguished from ***L. ectypa*** by the presence of the secondary ribs, and from similar, ribbed lenticulines by its deeply incised cross-section.

Material. 99 specimens.
Distribution. This form is restricted to the Upper Callovian and Middle Oxfordian, with 23 specimens from Staffin Bay, with a total range from the ***lamberti*** Biozone (***lamberti*** Sub-biozone) to ***tenuiserratum*** Biozone (***blakei*** Sub-biozone).
36 specimens were recovered from the ***athleta*** Biozone of Brora.
20 specimens came from Balintore, with a similar total range as at Staffin Bay, and an acme in the ***tenuiserratum*** Sub-biozone.

Previous records of ***L. ectypa*** ssp. ***costata*** show it to be restricted to the Upper Callovian and Oxfordian (Wernli & Septfontaine, 1971; Medd, 1983; Cordey, 1962), with acmes developed in the ***tenuiserratum*** Biozone (Shipp, 1989; Efimova & Mesezhnikov, 1991). Partington ***et al.*** (1993a, b) record a final appearance for this taxon within the ***serratum*** Biozone. Direct corroborative evidence from ammonite dating is, however, lacking for this material from North Sea Jurassic deposits.

Lenticulina exgaleata Dieni, 1985

(Plate 14, Figure 3)

1870a ***Cristellaria galeata*** Terquem; p. 444, pl. 16, figs. 15a-b.
1973 ***Lenticulina galeata*** (Terquem); Ruget, p. 517, pl. 1, figs. 1-3, 6.
1985 ***Lenticulina exgaleata*** Dieni; p. 343.
1989 ***Lenticulina exgaleata*** Dieni; Morris & Coleman, p. 226, pl. 6.3.8, figs. 8-9.

Description. Medium to large, lenticuline, biconvex test with 6-10 chambers and an irregularly keeled, dorsal periphery; proloculus spherical and encompassed by 3-4 chambers in a coil, with the remaining chambers involved in a curvilinear series; chambers sub-triangular, being broader than high; sutures represented by coarse, cord like sutural ribs, which are occasionally nodose and diverge from a central umbilical point and extend to the peripheral margins; aperture is radiate, peripheral and extended on a short neck.

Remarks. A new name for this commonly reported form was suggested by Dieni (1985) because, apparently, the name ***Cristellaria galeata*** Terquem (1870) was already occupied by ***Cristellaria galeata*** Reuss (1851, p. 66) and is therefore a homonym. However, it must be stated that this new name has yet to be ratified by the Committee for Zoological Nomenclature.

L. exgaleata is a distinctive form that can be distinguished from ***L. quenstedti***, which has a central circular ridge that connects the sutural ribs proximally, and from ***L. volubilis***, which has more irregular and nodose sutural ribs. However, these forms are very similar and may represent an evolutionary sequence with an hypothesised lineage from ***L. quenstedti-L. exgaleata-L.volubilis***. This is based on the first appearances from the literature and from the material collected for this study.

L. exgaleata can be distinguished from both ***L. ectypa*** and ***L. ectypa*** ssp. ***costata***, which have deeply incised sections and sutural ribs that do not extend as far as the peripheral margins.

Material. 161 specimens.

Distribution.

148 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone, with an acme in the ***discites*** Biozone.

4 from Staffin Bay; very rare ranging from the ***athleta*** Biozone to ***densiplicatum*** Biozone.

9 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

This form is most commonly reported from the Aalenian to Callovian from the UK, by Coleman (1979, 1980) and Penn (1982) and from the Bathonian of France by Ruget (1973) and the Upper Bathonian of Sardinia by Dieni (1985) and Dieni & Massari (1985).

Lenticulina gottingensis (Bornemann), 1854

(Plate 14, Figure 6)

1854 ***Robulina gottingensis*** Bornemann; p. 43, pl. 4, figs. 40-41.

1936 ***Cristellaria (Lenticulina) gottingensis*** (Bornemann); Franke, p. 116, pl. 11, fig. 22.

1957 ***Lenticulina gottingensis*** (Bornemann); Nørvang, p. 382, fig. 168.

1984 ***Lenticulina gottingensis*** (Bornemann); Riegraf ***et al.***, p. 684, pl. 6, fig. 159.

Description. Small-medium, robust, compressed lenticuline test, which is involute with up to 10 chambers in the final whorl and a keeled margin; chambers higher than broad and gradually increase in size as added; sutures flush-slightly limbate, curved; surface smooth; aperture is radiate and located on the dorsal margin, being produced on a short neck.

Material. 36 specimens.

Distribution. 18 specimens were recovered from the ***discites*** Biozone-***concavum*** Biozone of Bearreraig Bay, with 16 from the ***athleta*** Biozone to ***tenuiserratum*** Biozone at Staffin Bay and 2 from the ***mariae*** Biozone to ***densiplicatum*** Biozone at Balintore.

Lenticulina major (Bornemann), 1854

(Plate 14, Figure 7)

1854 ***Cristellaria major*** Bornemann, p. 40, pl. 4, fig. 31.
1936 ***Cristellaria (Astacolus) major*** Bornemann; Franke, p. 101, pl. 9, fig. 36.
1960 ***Lenticulina (Astacolus) major*** (Bornemann); Lutze, p. 453, pl. 28, fig. 5; text-fig. 12, figs. a-g.
1962 ***Lenticulina major*** (Bornemann); Cordey, p. 379, pl. 46, fig. 3, text-figs 4-9.
1989 ***Lenticulina major*** (Bornemann); Morris & Coleman, p. 226, pl. 6.3.9, fig. 11.

Description. Very large, loosely coiled, lenticuline test with up to 14 chambers; large, ovate proloculus is partly enclosed by later chambers of the initial coil; chambers sub-triangular, broader than high, increasing gradually in size as added; sutures distinct, depressed, producing pinched and raised, arcuate ridges that mark the presence of chambers; aperture is radiate and located on the distal, peripheral margin.

Remarks. Morphological variation occurs in the degree of uncoiling of the final chambers and there is distinctive differentiation into megalospheric and microspheric generations.

Material. 114 specimens.

Distribution.

4 from Bearreraig Bay; ***discites*** Biozone only.

84 from Staffin Bay; ***cordatum*** Biozone-***tenuiserratum*** Biozone with an acme of abundance between the ***costicardia*** Sub-biozone and ***vertebrale*** Sub-biozone.

26 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).

Lenticulina muensteri (Roemer), 1839

(Plate 14, Figure 8)

1839 ***Robulina munsteri*** Roemer; p. 48, pl. 20, fig. 29.
1867 ***Cristellaria vulgaris*** Schwager; p. 461, pl. 34, fig. 19.
1937 ***Cristellaria munsteri*** (Roemer); Bartenstein & Brand, p. 174, pl. 15c, figs. 19a-c.
1960 ***Lenticulina (Lenticulina) muensteri*** (Roemer); Lutze, p. 448, pl. 10, figs a-e.
1989 ***Lenticulina muensteri*** (Roemer); Morris & Coleman, p. 214, pl. 6.3.4, figs. 1-4.

Description. Large biconvex and involute, lenticuline test that is planispirally coiled with a total of up to 20 chambers which are greater in width and increase gradually in size as added; periphery is angular or keeled; sutures flush to limbate and arcuate; test surface is smooth, but the test is biumbonate, with a large boss covering up to a $^1/_4$ of the test; aperture is areal and radiate.

Remarks. ***L. muensteri*** can be distinguished from ***L. matutina*** (d'Orbigny), which is smaller and does not have umbilical bosses. Variation generally relates to the degree of involution and sutural development, producing smooth to ribbed forms.

Material. 670 specimens.
Distribution.
356 from Staffin Bay, common throughout the section with several acmes; between the ***athleta*** Biozone and ***lamberti*** Biozone, within the ***cordatum*** Biozone and within the ***tenuiserratum*** Biozone.
156 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Biozone.
142 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.
16 from Eathie Haven; ***baylei*** Biozone.

This is any extremely common form and is long ranging, reported from the Lower Jurassic to Cretaceous of Australia, Europe, Africa and North and South America.

Lenticulina polygonata (Franke), 1936
(Plate 14, Figure 9)

1936 ***Cristellaria (Lenticulina) polygonata*** Franke; p. 118, pl. 12, figs. 1-2.
1957 ***Lenticulina polygonata*** (Franke); Nørvang, p. 383, fig. 179.
1964 ***Lenticulina (Lenticulina) gottingensis polygonata*** (Franke); Kristan-Tollman, p. 108, pl. 19, fig. 12; pl. 21, fig. 8.
1968 ***Lenticulina muensteri polygonata*** (Franke); Welzel, p. 42, pl. 2, fig. 38.
1975 ***Lenticulina polygonata*** (Franke); Jendryka-Fuglewicz, p. 137, pl. 2, figs. 7-8.
1984 ***Lenticulina polygonata*** (Franke); Riegraf ***et al.***, p. 685, pl. 1, fig. 23.

Description. Medium-large, biconvex and involute, lenticuline test of 1-1$^1/_2$ whorls; periphery is polygonal to irregular and is usually angular; chambers triangular, gradually increasing in size as added; sutures indistinct, flush or slightly raised; aperture is distinct, marginal, radiate and produced on a short neck.

Remarks. A rare form which can be differentiated from ***L. muensteri*** by its polygonal outline and normally featureless test. Many authors have placed ***L. muensteri, L. polygonata***, and ***L. gottingensis*** into the same group. Indeed, this may be the case with each form representing the extreme in morphological features. However, in this study there were too few specimens of the two latter species to establish whether transitional forms exist here.

Material. 11 specimens.
Distribution. A rare species with 9 specimens from the ***athleta*** Biozone to ***densiplicatum*** Biozone at Staffin Bay, 1 specimen from the ***scarburgense*** Sub-biozone at Balintore and 1 from the ***athleta*** Biozone at Brora.

Lenticulina quenstedti (Gümbel), 1862

(Plate 15, Figure 1)

1862 ***Cristellaria quenstedti*** Gümbel; p. 226, pl. 4, figs. 2a-b.
1890 ***Cristellaria polonica*** Wisniowski; p. 222, pl. 10, figs. 3a-c.
1935 ***Cristellaria quenstedti*** Gümbel; Macfadyen, p. 14, pl. 1, figs. 13a-b.
1958 ***Lenticulina polonica*** var. 1 Bizon; p. 12, pl. 4, figs. 1-2.
1971 ***Lenticulina quenstedti*** (Gümbel); Wernli, p. 322, pl. 4, figs. 14, 21, 23, 25, 27, 28; pl. 10, fig. 1.
1987 ***Lenticulina quenstedti*** (Gümbel); Williamson, p. 58, pl. 1, fig. 14.
1989 ***Lenticulina quenstedti*** (Gümbel); Shipp, p. 258, pl. 6.4.2, fig. 13.

Description. Large, robust, inflated, biconvex and tightly to loosely coiled, involute lenticuline test, with up to 10 chambers and an angular periphery which is sometimes keeled; chambers sub-triangular, broader than high and gradually increase in size as added; sutures slightly depressed and marked by coarse, curved, sutural ribs that are joined centrally to form a circular umbilical ridge; aperture is radiate and produced on a neck, with the sutural ribs sometimes converging to form an apertural collar.

Remarks. The main morphological variation is in the ribs, which can be irregular in development and sometimes kink prior to curving to the periphery. ***C. polonica*** from Polish Middle Jurassic deposits is considered to be a junior synonym. ***L. quenstedti*** appears to intergrade with ***L. exgaleata***, especially where there are many specimens for comparison, as at Bearreraig Bay.

Material. 153 specimens.
Distribution.
87 from Bearreraig Bay; top ***concavum*** Biozone-***discites*** Biozone.
52 from Staffin Bay; ***lamberti*** Biozone-***tenuiserratum*** Sub-biozone with an acme in the ***densiplicatum*** Biozone.
14 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Biozone.

L. quenstedti is a widely reported with its first appearance in the top ***concavum*** Biozone in the UK by Gregory (1990, 1991), Coleman (1979, 1980) and Penn (1982); from France and Switzerland by Wernli & Septfontaine (1971); from Poland by Bielecka

(1960) and Garbowska (1970) and from Svalbard by Nagy *et al.* (1983). Other workers use its final appearance in the Oxfordian and Kimmeridgian as a biozonal marker, e.g. Stam (1986), Williamson (1987) and Ascoli (1984) for Canadian sediments. Other Upper Jurassic records include those from India by Said & Barakat (1958) and Kalia & Chowdhury (1983), from Germany by Munk (1978, 1980) and Somalia by Macfadyen (1935).

Lenticulina subalata (Reuss), 1854

(Plate 15, Figure 2)

1854 ***Cristellaria subalata*** Reuss; p. 68, pl. 125, figs. 13a-b.
1936 ***Cristellaria subalata*** Reuss; Franke, p. 115, pl. 11, fig. 9.
1960 ***Lenticulina (Lenticulina) subalata*** (Reuss); Lutze, p. 451.
1989 ***Lenticulina subalata*** (Reuss); Morris & Coleman, p. 226, pl. 6.3.8, fig. 13.

Description. Test free, smooth and lenticular, being biumbonate and planispirally enrolled, with the last 3-4 chambers forming an uncoiled curvilinear series; periphery is angular and sometimes keeled; chambers sub-triangular and are broader than high and only gradually increase in size as added; sutures curved, strongly elevated and converge to form a raised, umbilical boss; aperture is radiate, being located on the dorsal peripheral margin and is produced on a short neck.

Remarks. The morphological variation of ***L. subalata*** was adequately covered by Bhalla & Abbas (1975) from Upper Jurassic material of the Kutch, India. However, their variation range appears to include several separate lenticuline species including ***L. muensteri*** and ***L. matutina.***

Material. 216 specimens.
Distribution.
148 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
31 from Staffin Bay; ***athleta*** Biozone-***tenuiserratum*** Biozone.
15 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
22 from Brora; only from the ***athleta*** Biozone.

Lenticulina varians (Bornemann), 1854

(Plate 15, Figure 3)

1854 ***Lenticulina varians*** Bornemann; p. 41, pl. 4, figs. 32-34.
1936 ***Cristellaria (Lenticulina) varians*** (Bornemann) ***recta*** Franke; p. 113, pl. 11, fig. 12.
1964 ***Lenticulina (Lenticulina) varians varians*** (Bornemann); Kristan-Tollman, p. 112, pl. 26, fig. 10.

1965 ***Lenticulina (Lenticulina) varians*** (Bornemann); Hanzlikova, p. 75, pl. 4, fig. 5.

1989 ***Lenticulina varians*** (Bornemann); Morris & Coleman, p. 214, pl. 6.3.4, figs. 5-6.

Description. Test variable, small-medium in size, lenticuline and is flattened to globular with a rounded periphery and no keel; initial coiled section is involute, with up to 6 chambers, remaining chambers are involved in a curvilinear section; proloculus is small and oval; chambers broader than high and sub-triangular in shape; sutures distinct to indistinct, flush to limbate and arcuate; aperture is peripheral, radiate and produced on a short neck.

Remarks. This is an exceedingly common form with a large degree of morphological variation related to test size and amount of uncoiling, ranging from loosely coiled to tightly coiled, involute forms. The former tend to be encountered more frequently. ***L. varians*** can be distinguished from ***L. subalata*** and ***L muensteri***, which both possess limbate sutures and umbilical bosses. ***L. polygonata*** has a distinct angular and polygonal periphery.

Material. 2553 specimens.
Distribution.
240 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
995 from Staffin Bay; very common throughout the sections, with an acme between the ***cordatum*** Biozone (***costicardia*** Sub-biozone) and ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
478 from Balintore; total range between the ***athleta*** Biozone and ***tenuiserratum*** Biozone.
631 from Brora; ***calloviense*** Biozone-***lamberti*** Biozone, being most abundant between the ***athleta*** Biozone and ***lamberti*** Biozone.
29 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.
280 from Helmsdale; ***cymodoce*** Biozone to ***mutabilis*** Biozone.

Lenticulina volubilis Dain, 1958
(Plate 15, Figure 4)

1958 ***Lenticulina (Astacolus) volubilis*** Dain; p. 37, pl. 6, figs. 7-12.

1969 ***Lenticulina (Astacolus) volubilis*** Dain; Bielecka & Styk, p. 524, pl. 52, figs. 5-8.

1978 ***Lenticulina (Astacolus) volubilis*** Dain; Munk, p. 45, pl. 3, figs. 2, 9; pl. 4, figs. 7, 9-10.

1988 ***Astacolus volubilis*** Dain; Bielecka ***et al.***, p. 102, pl. 24, fig. 12.

1989 ***Lenticulina volubilis*** Dain; Morris & Coleman, p. 226, pl. 6.3.8, fig. 16

Description. Large, compressed, loosely coiled lenticuline test with up to 12 chambers; peripheries are irregularly keeled to angular; chambers sub-triangular, broader than high and gradually increase in size as added; sutures slightly depressed with median, sutural ribs present; sutural ribs continuous to discontinuous and nodose, with all ribs emanating from a central, umbilical point; aperture is marginal, radiate and situated at the end of a short neck.

Remarks. This is a distinctive form which can be distinguished from the very similar ***L. quenstedti***, which has more continuous and regular ribs, forming an umbilical ring and from ***L. ectypa***, which has a deeply incised section.

Material. 30 specimens.

Distribution. This is a rare form, which is most common within the Middle Jurassic of the Scottish sections, with 20 specimens from Bearreraig Bay, between the top ***concavum*** Biozone to ***discites*** Biozone (most common in the ***discites*** Biozone). 6 specimens came from Staffin Bay, with a total range from the ***athleta*** Biozone to ***densiplicatum*** Biozone, but mainly from the ***vertebrale*** Sub-biozone. 2 specimens were recovered from Balintore, between the ***cordatum*** Biozone and ***tenuiserratum*** Biozone, with 2 specimens restricted to the upper ***athleta*** Biozone of Brora.

L. volubilis has only previously been reported from the Upper Bajocian to Late Bathonian in the UK (Coleman, 1979, 1980; Penn, 1982) and from similarly aged deposits in Poland (Bielecka & Styk, 1969; Bielecka ***et al.*** (1988) and from the Bathonian of Russia by Dain (1958). The Scottish material provides the earliest records of this taxon from the Aalenian/Bajocian boundary at Bearreraig Bay.

Genus ***Saracenaria*** deFrance, 1824

Saracenaria oxfordiana Tappan, 1955

(Plate 15, Figure 5)

1952a ***Saracenella triquetra*** (Gümbel); Barnard, p. 343, fig. b2.

1955 ***Saracenaria oxfordiana*** Tappan; p. 64, pl. 26, fig. 27.

1965 ***Saracenaria oxfordiana*** Tappan; Gordon, p. 851, text-fig. g, figs. 26-27.

1978 ***Lenticulina (Saracenaria) triquetra*** (Gümbel); Munk, p. 14, pl. 2, fig. 6; pl. 6, fig. 9.

1989 ***Saracenaria oxfordiana*** Tappan; Morris & Coleman, p. 229, pl. 6.3.9, fig. 15.

Description. Test small-medium, with an initial planispire of 4-7 chambers, which is followed by a later uncoiled, curvilinear section of up to 6 chambers; test triangular in section, with a keeled periphery, these keels join distally to form a notched, apertural collar; sutures depressed and curved proximally at the keels; test surface smooth; aperture is peripheral, radiate and produced on a short neck.

Material. 11 specimens, only recovered from the ***athleta*** Biozone to ***mariae*** Biozone at Staffin Bay.

Subfamily Marginulininae Wedekind, 1937

Genus *Marginulina* d'Orbigny, 1826

Marginulina sp. A

(Plate 15, Figure 6)

1865 *Cristellaria* sp. Schwager; pl. 5, fig. 17.

Description. Elongate, rounded test arranged in an initial, loose planispire of 2-3 small, globular chambers, which is followed by a curvilinear series of up to 4 chambers; margins lobulate and marked by sutural constrictions; chambers globular, being roughly similar in size, final chamber is extended distally to form an elongate, thin neck; sutures depressed, horizontal and straight; surface ornament is finely hispid; aperture is a simple circular, opening at the end of the long, thin, tubular neck.

Remarks. The only identical form found after an extensive literature search was an unnamed and undescribed taxon by Schwager (1865) as *Cristellaria* sp.

M. sp. A is similar to ***M. insecta*** Paalzow, except that the latter's initial coil is much larger and its test surface more coarsely hispid. It also shows some similarities to ***M. ridica*** Lalicker and ***M. rete*** Ruget & Sigal both of which are more coarsely hispid, whilst the former does not posses an elongate apertural neck and the latter has 6-7 chambers in the initial planispire.

Morphological variation in *M.* sp. A is related to the size of the loose, planispiral coil which is smaller in the microspheric generation.

Material. 9 specimens.
Distribution. A rare* form, with 6 specimens from the ***lamberti*** Biozone to ***densiplicatum*** Biozone of Staffin Bay, 1 from the ***athleta*** Biozone at Balintore and 2 specimens also from the *athleta* Biozone at Brora.

Marginulina batrakiensis (Myatluik), 1939

(Plate 15, Figure 7)

1939 ***Cristellaria batrakiensis*** Myatluik; p. 61, pl. 74, figs. 52-53.
1950a ***Marginulinopsis coelate*** Loeblich & Tappan; p. 46, pl. 12, figs. 10a-b.
1962 ***Marginulina batrakiensis*** (Myatluik); Cordey, p. 383, pl. 46, fig. 7.
1965 ***Marginulina oxfordiana*** Gordon; p. 842, text-fig. 6, figs. 28-31.
1967 ***Marginulina batrakiensis*** (Myatluik); Gordon, p. 452, pl. 4, figs. 24-25.
1978 ***Marginulina haynesi*** Bhalla & Abbas; p. 182, pl. 7, figs. 5-6; pl. 11, figs. 7-9.
1981 ***Marginulina batrakiensis*** (Myatluik); Barnard ***et al.***, p. 418, pl., 2, fig. 31.

1983 ***Marginulina batrakiensis*** (Myatluik); Kalia & Chowdhury, p. 235, pl. 5, figs. 4-5.

Description. Small-medium, elongate, rounded and uniserial test with up to 8 chambers; small, initial, evolute coil of 2-3 ovoid chambers; periphery is rounded and lobulate; coil followed by a long rectilinear series of chambers; chambers initially broader than high, but increase more rapidly in length as added, final chamber extended to a long thin neck; sutures constricted, becoming more oblique distally; ornament distinct and consists of abundant, regularly spaced, fine and continuous, longitudinal ribs that converge to the base of the apertural neck; aperture is radiate or a circular opening at the end of the long neck.

Remarks. This form is similar to ***M. sculptilis*** (Schwager) except that ***M. batrakiensis*** has more numerous and continuous ribbing. Variation is restricted to occasional bifurcation of the ribs in distal portions of the test.

Material. 85 specimens.
Distribution.
76 from Staffin Bay; from the ***athleta*** Biozone to ***densiplicatum*** Biozone, with an acme of abundance between the ***mariae*** Biozone-***cordatum*** Biozone (***bukowskii*** Sub-biozone).
3 from Balintore ***cordatum*** Biozone (***bukowskii*** Sub-biozone-***costicardia*** Sub-biozone).
6 from Brora; range limited to the ***athleta*** Biozone.

M. batrakiensis is a widely reported form, being restricted to the Callovian-Oxfordian interval and was originally described from the Callovian of Siberia (Myatluik, 1939). There are many junior synonyms; as ***M. coelate*** from the Oxfordian of North America (Loeblich & Tappan, 1950a); as ***M. haynesi*** from the Callovian of India (Bhalla & Abbas, 1978) and as ***M. oxfordiana*** from the ***mariae*** Biozone-***cordatum*** Biozone of England (Gordon, 1965). It has also been reported from the Middle Oxfordian of Dorset (Barnard ***et al.***, 1981).

Marginulina costata (Batsch), 1791

(Plate 15, Figure 8)

1791 ***Nautilus (Orthoceras) costatus*** Batsch; pl. 3, figs. 1-3.
1864 ***Marginulina radiata*** Terquem; p. 410, pl. 9, figs. 10a-b.
1950a ***Vaginulinopsis ectypa*** Loeblich & Tappan; p. 46, pl. 12, figs. 17a-b-20.
1950b ***Marginulinopsis phragmites*** Loeblich & Tappan; p. 9, pl. 1, figs. 22-23b, text-fig. 1.
1955 ***Marginulinopsis phragmites*** Loeblich & Tappan; Tappan, p. 64, pl. 17, fig. 18.

1960 ***Marginulinopsis radiata*** (Terquem); Bielecka, p. 4, fig. 29.
1965 ***Marginulina sculptilis*** (Schwager); Gordon, p. 842, text-fig. 6, figs. 23-25.
1981 ***Marginulina radiata*** Terquem; Barnard & Shipp, p. 13, pl. 2, figs. 3-4.
1989 ***Marginulina costata*** (Batsch); Shipp, p. 259, pl. 6.4.2, fig. 19

Description. Large, compressed test which consists of a loose, planispire of 3-4 chambers, followed by a curvilinear series of 4-6 chambers; dorsal periphery is keeled; chambers broader than high, and gradually increase as added, final chamber extended to a long, compressed neck; sutures flush and oblique; ornament consist of up to 12 regularly spaced, sharp and continuous ribs, which are notable for being parallel to the growth axis and all tend to fade distally on the final chamber, before the aperture; aperture is marginal and radiate, but sometimes can be a simple, circular opening at the end of the apertural neck.

Remarks. ***M. radiata*** Terquem is considered here to be a junior synonym of ***M. costata***, as are ***Marginulinopsis phragmites*** Loeblich & Tappan and ***Vaginulinopsis ectypa*** Loeblich & Tappan, both of which were recovered from the Middle and Upper Jurassic of North America.

Material. 36 specimens.
Distribution. This form was restricted to the Lower and Middle Oxfordian, 18 specimens came from the ***cordatum*** Biozone (***costicardia*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) at Staffin Bay, with 18 from the ***densiplicatum-tenuiserratum*** Biozones (***tenuiserratum*** Sub-biozone) of Balintore.

Marginulina epicharis (Loeblich & Tappan), 1950
(Plate 15, Figure 9)

1950a ***Vaginulinopsis epicharis*** Loeblich & Tappan, p. 47, pl. 12, figs. 21-23b.
1967 ***Marginulina epicharis*** (Loeblich & Tappan); Gordon, p. 452, pl. 2, figs. 14-15.
1983 ***Vaginulinopsis epicharis*** Loeblich & Tappan; Kalia & Chowdhury, p. 238, pl. 5, figs. 18-19; pl. 6, fig. 1.

Description. Large, elongate, thin, compressed and uniserial test of up to 9 chambers with a small initial coil and a rounded periphery; dorsal periphery is lobulate, whilst the ventral one is arcuate; small, ovate proloculus is enveloped by the following 2-3 chambers in the coil and the remaining 6-7 chambers are added in a rectilinear series; chambers initially broader than high and rapidly increase only in height as added, final chamber pyriform with a long, thin, distal neck; sutures depressed, straight to slightly arcuate; test surface is smooth; aperture is radiate and located on an extended neck.

Material. 8 specimens from the ***athleta*** Biozone to ***tenuiserratum*** Biozone of Staffin

Bay.

Marginulina irregularis Gümbel, 1862

(Plate 15, Figure 10)

1862 ***Marginulina irregularis*** Gümbel; p. 220, pl. 3, figs. 15-18.
1967 ***Marginulina irregularis*** Gümbel; Gordon, p. 452, pl. 2, fig. 11.
1983 ***Marginulina irregularis*** Gümbel; Kalia & Chowdhury, p. 236, pl. 5, figs. 6-7.

Description. Large, loosely, planispirally coiled and inflated test with up to 6 chambers and a rounded, lobulate periphery; the initial coil has 3-4 globular and enveloping chambers; chambers globular; sutures depressed, initially curved, becoming straight and oblique distally; test surface is smooth, except for the base of the coiled section which is faintly hispid; aperture is only slightly radiate and is placed on a short neck, with a phialine neck.

Remarks. This form was previously reported from the UK, by Gordon (1967) from the Brora Brick Clay Pits which have been filled in.

Material. 7 specimens, only recovered from the ***mariae*** Biozone (***praecordatum*** Sub-biozone)-***tenuiserratum*** Biozone (***blakei*** Sub-biozone) of Staffin Bay.

Subfamily Vaginulininae Reuss, 1860

Genus *Citharina* d'Orbigny, 1839

Citharina colliezi (Terquem), 1866

(Plate 16, Figure 1)

1866a ***Marginulina colliezi*** Terquem; p. 430, pl. 17, fig. 10.
1917 ***Vaginulina flabelloides*** Terquem; Paalzow, p. 236, pl. 45, figs. 8-9.
1950a ***Citharina colliezi*** (Terquem); Barnard, p. 14, pl. 3, fig. 1.
1971 ***Citharina colliezi*** (Terquem); Wernli, p. 316, pl. 2, figs. 13-17; pl. 3, figs. 1-2.
1971 ***Citharina colliezi -heteropleura*** Wernli; p. 317, pl. 2, figs. 23-26.
1989 ***Citharina*** cf. ***colliezi*** (Terquem); Gregory, p. 184, pl. 1, fig. 10.

Description. Test large, compressed, uniserial and curved to rectilinear, with 8-10 chambers; dorsal margin straight and sometimes carinate, whilst the ventral margin is curved; chambers broader than wide, gradually increase in size as added; proloculus small, ovate and enveloped by the first 2-3 chambers; sutures depressed, oblique and arcuate; ornament consists of numerous, short and regularly spaced, curved ribs which are oblique to dorsal margin and do not cross sutures; aperture is peripheral and radiate.

Remarks. There appear to be transitional forms between ***C. colliezi*** and ***C. flabellata.***

Material. 10 specimens.
Distribution. 1 specimen was recovered from Staffin Bay, with 4 from the ***densiplicatum*** Biozone at Balintore, 2 from the ***calloviense*** Biozone to ***athleta*** Biozone of Brora and 3 from the ***cymodoce*** Biozone at Helmsdale.

Citharina flabellata (Gümbel), 1862

(Plate 16, Figure 2)

1862 ***Maginulina flabellata*** Gümbel; p. 223, pl. 3, figs. 24a-c.
1935 ***Vaginulina*** aff. ***flabellata*** (Gümbel); Macfadyen, p. 12, pl. 1, figs. 9a-b.
1950 ***Vaginulina lancea*** Lalicker; p. 16, pl. 3, fig. 3.
1952a ***Vaginulina harpa*** Roemer; Barnard, p. 345, text-fig. D6.
1960 ***Citharina flabellata*** (Gümbel); Bielecka, p. 139, pl. 6, fig. 51.
1989 ***Citharina flabellata*** (Gümbel); Morris & Coleman, p. 222, pl. 6.3.7, fig. 1.
1989 ***Citharina*** cf. ***flabellata*** (Gümbel); Gregory, p. 185, pl. 1, fig. 1.

Description. Test medium-large, compressed and uniserial, with a gently curved growth axis which is sub-triangular in outline; large, spherical proloculus is followed and enveloped by up to 7 chambers; chambers much greater in width than height; dorsal and ventral margins are curved and sometimes faintly carinate; sutures indistinct, flush and oblique; ornament consists of several fine, long and sometimes bifurcating, meandering ribs, that are continuous over sutures; not all the ribs emanate from the prolocular region; aperture is marginal, radiate and produced on a short neck formed by the convergence of several ribs.

Remarks. The main variation is in the ornament type and density, with some representatives having very few ribs. It can be distinguished from ***C. serracostata***, which is more elongate and possesses much coarser ribbing.

Material. 30 specimens.
Distribution.
11 from Staffin Bay; ***tenuiserratum*** Sub-biozone-***mutabilis*** Biozone.
2 from Balintore; ***tenuiserratum*** Sub-biozone.
13 from Brora; ***athleta*** Biozone-***lamberti*** Biozone (***henrici*** Sub-biozone).
3 from Eathie Haven ***baylei*** Biozone-***mutabilis*** Biozone.
1 from Helmsdale; ***cymodoce*** Biozone.

Citharina heteropleura (Terquem), 1868

(Plate 16, Figure 3)

1868 ***Marginulina heteropleura*** Terquem; p. 116, pl. 7, figs. 19a-b.
1959 ***Citharina heteropleura*** (Terquem); Cifelli, p. 324, pl. 6, figs. 4-5.
1981 ***Citharina heteropleura*** (Terquem); Barnard ***et al.***, p. 423, pl. 2, fig. 7, text-fig.

27.

1981 ***Citharinella exarata*** Loeblich & Tappan; Barnard & Shipp, p. 14, pl. 2, figs. 11-12.

1989 ***Citharina heteropleura*** (Terquem); Gregory, p. 185, pl. 1, fig. 12.

Description. Test medium-large, sub-triangular and uniserial with rounded peripheries; proloculus large and is followed by a series of 4-5 curved chambers, final chamber is frondiculine or chevron-shaped; sutures distinct, depressed, oblique to curved; ornament consists of numerous, bowed, cord-like ribs which do not cross sutures; aperture is central or marginal, with several ribs converging to form a thick notched collar.

Remarks. Variation includes forms which have more continuous and finer ribbing such as illustrated by Terquem (1868, pl. 7, figs. 19a-b) for the original material.

Material. 51 specimens.
Distribution.
28 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
7 from Staffin Bay; ***cordatum*** Sub-biozone-***baylei*** Biozone.
2 from Balintore; ***mariae*** Biozone-***cordatum*** Biozone.
2 from Brora; mid ***athleta*** Biozone.
12 from Helmsdale; ***cymodoce*** Biozone.

Citharina serracostata (Gümbel), 1862

(Plate 16, Figure 4)

1862 ***Marginulina serracostata*** Gümbel; p. 333, pl. 4, fig. 23.

1960 ***Citharina lepida*** (Schwager); Lutze, p. 461, pl. 30, figs. 2-4, 7-8, text-fig. 14.

1970 ***Citharina lepida*** (Schwager); Winter, p. 17, pl. 2, figs. 64-65.

1981 ***Citharina serracostata*** (Gümbel); Barnard ***et al.***, p. 425, pl. 2, fig. 5, text-fig. 24.

1982 ***Citharina chicheryi*** (Payard); Ruget, p. 56, pl. 1, fig. 1.

1983 ***Citharina serracostata*** (Gümbel); Kalia & Chowdhury, p. 233, pl. 1, fig. 11; pl. 2, figs. 14-17.

Description. Test large, triangular, uniserial and initially curved; peripheries straight and keeled; proloculus is ovoid and sometimes aplicate, followed by up to 8 chambers; chambers broader than high, gradually increasing in width as added, proximal chambers curved; sutures flush-slightly depressed, straight-oblique; ornament consists of several coarse, blade-like and continuous, longitudinal ribs, which sometimes bifurcate distally, all the main ribs commence from the prolocular region and converge on the final chamber to the aperture; aperture is located on the dorsal margin and is radiate and produced on a short neck, with a collar.

Remarks. Variation occurs mainly in the test shape which ranges from elongate to squat, but all specimens have straight margins. *C. serracostata* is sufficiently distinct to be considered separate from *C. flabellata*, which was not the conclusion reported by Wernli (1971) and Barnard *et al.* (1981) who considered them to be synonymous.

Material. 119 specimens.
Distribution.
18 from Bearreraig Bay; top ***concavum*** Biozone-***discites*** Biozone.
79 from Staffin Bay; rare throughout the ***athleta*** Biozone-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone), but mainly concentrated in the ***tenuiserratum*** Biozone.
12 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.
10 from Brora; ***athleta*** Biozone only.

Genus *Planularia* DeFrance, 1826

This genus was recently involved in a proposed conservation to the Bulletin of Zoological Nomenclature by Hansen & Rögl (1988), who suggested suppression of its unused, senior subjective synonym ***Linthuris*** de Montfort 1808. ***Planularia*** appears to have been vindicated as the correct name (Hansen ***pers. comm.***, 1991 and Opinion 1571, 1990).

Planularia beierana (Gümbel), 1862

(Plate 16, Figure 5)

1862 ***Marginulina beierana*** Gümbel; p. 221, pl. 3, figs. 20a-b.
1952a ***Planularia protracta*** Barnard; p. 343, text-fig. C, figs, a-d.
1955 ***Lenticulina (Planularia) beierana*** (Gümbel); Seibold & Seibold, p. 106, pl. 13, fig. 7.
1959 ***Planularia beierana*** (Gümbel); Cifelli, p. 559, text-fig. 3.
1978 ***Lenticulina (Planularia) beierana*** (Gümbel); Munk, p. 47, pl. 5, fig. 4.
1989 ***Planularia beierana*** (Gümbel); Morris & Coleman, p. 228, pl. 6.3.9, fig. 10.

Description. Test variable in size, generally medium-large, being compressed and lenticular, with the initial 3-4 chambers enrolled in a loose, planispiral coil, the remaining chambers form a gentle, curvilinear series; proloculus small and sub-oval; sutures indistinct, flush to depressed, being gently curved and oblique; test wall smooth; aperture is radiate and produced on a small neck.

Remarks. Variation occurs in the degree of uncoiling and arrangement of the initial chambers, some forms also possess a thin keel on the dorsal margin.

Material. 676 specimens.

Distribution.
127 from Bearreraig Bay; top ***discites*** Biozone-***concavum*** Biozone.
129 from Staffin Bay; common from the ***athleta*** Biozone-***tenuiserratum*** Biozone.
76 from Balintore; ranges from the ***athleta*** Biozone-***lamberti*** Biozone.
252 from Brora; ***athleta*** Biozone-***lamberti*** Biozone, with an abundance in the mid-upper ***athleta*** Biozone.
92 from Helmsdale; ***cymodoce*** Biozone to ***eudoxus*** Biozone.

Planularia eugenii (Terquem), 1864

(Plate 16, Figure 6)

1864 ***Cristellaria eugenii*** Terquem; p. 414, pl. 9, figs. 16a-b.
1957 ***Planularia eugenii*** (Terquem); Nørvang, p. 381, fig. 150.
1989 ***Planularia eugenii*** (Terquem); Morris & Coleman, p. 288, pl. 6.3.9, figs. 8-9.

Description. Test loosely coiled and compressed, with an initial planispire of 4-6 chambers followed by an uncoiled, curvilinear series of 4-5 chambers; chambers broader than high and gradually increase in size as added; sutures depressed and oblique; ornamentation consists of dorsal and ventral marginal keels and longitudinal, discontinuous ribbing, some distal ribs converge on the apertural neck; aperture is marginal, radiate and produced on an elongate neck.

Remarks. Ribbing provides the greatest degree of variation both in the number and extent, occasionally covering the whole test. In test morphology, ***P. eugenii*** is similar to ***P. beierana***, but this form has no surface ornamentation.

Material. 42 specimens.
Distribution. This form is commonest in the Middle Jurassic at Bearreraig Bay, with 27 specimens from the ***concavum*** Biozone-***discites*** Biozone. 9 specimens were retrieved from the ***athleta*** Biozone-***cordatum*** Biozone at Staffin Bay and 6 came from the same zones at Balintore.

Planularia kintradwellensis Gregory, 1992

(Plate 16, Figure 7)

1958 ***Planularia curticostata*** Lloyd: p. 128, pl. 15, figs. 2a-b.
1986 ***Planularia*** sp. A. Gregory: p. 126, pl. 4, figs. 1-4.
1987 ***Saracenaria*** sp. 2 Young: p. 217, pl. 17, fig. 6.
1989 ***Planularia*** sp. A Gregory: Gregory, p. 184, pl. 2.2.1, fig. 1.
1992 ***Planularia kintradwellensis*** Gregory; p. 136, pl. 2, figs. A-D.
Derivation of name. After Kintradwell Farm, (GR. 07309330) North Sutherlandshire, north east Scotland, which also gives its name to the type formation, the Kintradwell Boulder Bed Member.

Description. Test free, medium to large with a compressed, loose planispiral coil; rounded proximal periphery, distal periphery usually keeled; 6-12 rounded chambers, greater in width than height, gradually increasing in size as added, final chamber inflated and almost always partially envelops the proloculus; proloculus small, oval, unornamented; sutures distinct, deeply depressed, arcuate; test wall calcareous, ornament distinct, forming short, coarse irregular ribbing on the base of the chambers, which does not cross sutures; final chamber marked by a series of coarse, cord-like ribs: 2 peripheral, 1 distal rib/keel and 2 ribs occurring centrally, these 5 ribs/keels converge on the apertural neck; aperture is distinct, peripheral and raised on a short neck, with a thick, notched collar formed by the ribs, that converge to form thick apertural bars. Microspheric and megalospheric generations can be identified, the latter possess a more rounded proximal region, whilst the former tend to be more pointed.

Remarks. This form resembles ***Planularia beierana*** (Gümbel) 1862 and ***Planularia eugenii*** (Terquem) 1864. It differs from the former in having ornamentation and from the latter by its more irregular, but distinct ribbing. This species was previously recorded as ***Planularia curticostata*** by Lloyd (1958) in an unpublished Ph.D. thesis. Lloyd (1959, 1962) published accounts on the distribution of agglutinated, miliolid and polymorphinid foraminifera from the type Kimmeridgian in Dorset but did not include the diverse nodosariid faunas he had recovered. Under Rule 8a of the International Code of Zoological Nomenclature (Ride, 1975), a species name is invalid if it is nominated in a publication which is not widely disseminated or in a readily available format.

Young (1987) in an unpublished Ph.D. thesis recorded a few forms that were assigned to ***Saracenaria*** sp. 2 from selected sites in the British Isles. Examination of his material suggests that this form is synonymous with ***Planularia kintradwellensis*** and represents forms that have a looser coiling mode. It is hypothesised here that coiling mode is perhaps an environmentally controlled feature and that the triangular section, normally a saracenarid feature is also enhanced by the presence of the rather coarse keel.

Material. 127 specimens.
Distribution.
109 Helmsdale; ***cymodoce-mutabilis*** Biozones (Gregory 1986, 1989).
12 from Eathie Haven; ***baylei-cymodoce*** Biozones (present work).
6 from Staffin Bay; ***baylei*** Biozone (Young, 1987 and present work).

This form is a useful biostratigraphical marker for the Lower Kimmeridgian (Gregory, 1992) and has also been recovered from the base of the ***mutabilis*** Biozone at Blackhead, Dorset (Young, 1987; Lloyd, 1958).

Planularia pseudocrepidula Adams, 1957

(Plate 16, Figure 8)

1957 ***Planularia pseudocrepidula*** Adams; p. 208, figs. 1-5.

1968 ***Planularia pseudocrepidula*** Adams; Welzel, p. 47, pl. 2, figs. 40-41.

1978 ***Lenticulina (Planularia) pseudocrepidula*** (Adams); Munk, p. 48, pl. 15, fig. 5.

1979 ***Astacolus pseudocrepidulatus*** (Adams); Exton, p. 19, pl. 6, fig. 5.

1985 ***Palmula nucleata*** (Terquem); Riegraf, p. 129, pl. 10, figs. 16-17.

Description. Test compressed with up to 10 chambers, initial 3-4 chambers arranged in a very loose, evolute, planispiral coil which is followed, but not enveloped by a curvilinear series of chambers; proloculus small, oval; chambers much broader than high and are subtriangular, gradually increasing in size as added, final chamber inflated, enveloping the preceding chambers; sutures flush, oblique and curved; aperture is radiate and located on the dorsal margin.

Material. 17 specimens.

Distribution.

7 from Bearreraig Bay; top ***discites*** Biozone-***concavum*** Biozone.

4 from Staffin Bay; ***mariae*** Biozone-***tenuiserratum*** Biozone.

6 from Balintore; ***mariae*** Biozone-***tenuiserratum*** Biozone.

Genus *Vaginulina* d'Orbigny, 1826

Vaginulina barnardi Gordon, 1965

(Plate 16, Figure 9)

1917 ***Vaginulina legumen*** (Linné); Paalzow, p. 237, pl. 45, figs. 10-11.

1937 ***Vaginulina legumen*** (Linné); Bartenstein & Brand, p. 162, pl. 15a, fig. 22; pl. 15c, figs. 10a-c.

1965 ***Vaginulina barnardi*** Gordon; p. 252, pl. 7, figs. 24-25, text-fig. 9.

1989 ***Vaginulina barnardi*** Gordon; Shipp, p. 260, pl. 6.4.3, fig. 7.

Description. Test large, compressed and uniserial with 10-14 chambers arranged in an initial, loose coil, which is followed by an uncoiled and gently curved, linear series; proloculus large, ovoid, followed and enveloped by a small coil of 2-4 chambers; chambers greatest in width and increase slowly in size as added; sutures distinct-indistinct, flush to depressed, oblique and curved; ornamentation consists of a distinct series of regularly spaced, fine striations that are more prominent distally and are continuous over the sutures; aperture is peripheral and radiate, produced on a short neck.

Remarks. Striated forms were included as ***V. legumen*** by Paalzow (1917) and Bartenstein & Brand (1937), but were considered sufficiently characteristic by Gordon

(1965) to warrant designation as a new species. There is some variation in the degree of coiling and in the size of the proloculus in microspheric and megalospheric generations.

Material. 20 specimens.
Distribution. Only recovered from the ***mariae*** Biozone (***scarburgense*** Sub-biozone) to the top ***densiplicatum*** Biozone, with an acme in the ***cordatum*** Biozone of Staffin Bay.

This form appears to be biostratigraphically restricted and limited to the ***mariae*** Biozone to ***regulare*** Biozone in the UK, with an acme in the ***cordatum*** Biozone (Gordon, 1965; Shipp, 1989).

Vaginulina contracta (Terquem), 1868

(Plate 16, Figure 10)

1868 ***Marginulina contracta*** Terquem; p. 125, pl. 8, figs. 1-24.
1956 ***Vaginulina contracta*** (Terquem); Seibold & Seibold, p. 367, text-figs. 6y, z.
1983 ***Vaginulina contracta*** (Terquem); Nagy ***et al.***, p. 120, pl. 2, figs. 7-8.
1984 ***Vaginulina contracta*** (Terquem); Riegraf ***et al.***, p. 687, pl. 1, fig. 38.

Description. Large, curvilinear, compressed and uniserial test with up to 8 chambers and rounded peripheries; ventral margin is lobulate, whilst the dorsal margin is curved; initial 2-3 chambers are involved in a small, loose, evolute coil and the remaining chambers are uncoiled; chambers sub-rectangular and much broader than high, increasing in breadth as added; sutures depressed, straight and oblique; test surface smooth; aperture radiate and placed on the dorsal margin on a short neck.

Remarks. This form is distinguished from ***V. legumen***, which possesses less oblique sutures and has a smaller initial coil.

Material. 69 specimens.
Distribution.
44 from Staffin Bay; ***cordatum*** Biozone-***cymodoce*** Biozone.
8 from Balintore; ***lamberti*** Biozone (***lamberti*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
17 from Brora; ***athleta*** Biozone only.

Vaginulina legumen (Linné), 1758

(Plate 16, Figure 11)

1758 ***Nautilis legumen*** Linné; p. 711.
1884 ***Vaginulina legumen*** (Linné) var. ***laevigata*** (Roemer); Jones, p. 769, pl. 34, text-fig. 5.
1937 ***Vaginulina legumen*** (Linné); Bartenstein & Brand, p. 162, pl. 15a, fig. 22; pl. 15c, figs. 10a-c.

1958 ***Vaginulina legumen*** (Linné); Said & Barakat, p. 260, pl. 2, fig. 22.
1989 ***Vaginulina legumen*** (Linné); Morris & Coleman, p. 229, pl. 6.3.9, fig. 20.

Description. Large, almost rectilinear test of up to 10 chambers, with a very small, evolute coil of 2-3 chambers, both dorsal and ventral margins are almost straight; chambers sub-rectangular, slightly greater in width and gradually increase in size as added; sutures depressed and sub-horizontal; test smooth; aperture radiate and located on the dorsal margin.

Material. 50 specimens.
Distribution. This form was commonest from the Aalenian/ Bajocian of Bearreraig Bay, with 46 specimens from the top ***concavum*** Biozone and ***discites*** Biozone, 2 specimens were recovered from the ***cordatum*** Sub-biozone at Balintore and 2 from the upper ***athleta*** Biozone at Brora.

Family Lagenidea Reuss, 1862

Genus ***Lagena*** Walker & Jacobs, 1798

Lagena aphela Tappan, 1955

(Plate 17, Figure 1)

1955 ***Lagena aphela*** Tappan; p. 82, pl. 28, figs. 13-14.
1968 ***Lagena aphela*** Tappan; Welzel, p. 50, pl. 3, fig. 10.
1976 ***Oolina aphela*** (Tappan); Souaya, p. 281, pl. 8, fig. 19.

Description. Very small, globular to ovoid, unilocular test; surface smooth; aperture small, radiate and produced on a short neck.

Remarks. This form corresponds well with Tappan's (1955) original description. It is most easily recognised by its small size, short neck and radiate aperture. ***L. liasica*** possesses an aplicate base and ***L. globosa***, although being roughly the same shape, is much larger and has a hispid surface texture.

Material. 62 specimens.
Distribution.
The majority of 42 specimens came from Staffin Bay, where it is present, but rare throughout, 13 specimens were recovered from the ***lamberti*** Biozone-***tenuiserratum*** Sub-biozone of Balintore, with 5 from the ***athleta*** Biozone at Brora and only 2 specimens from the ***cymodoce*** Biozone at Eathie Haven.

Lagena globosa (Walker & Boys), 1784

(Plate 17, Figure 2)

1784 ***Serpulina (Lagena) laevis globosa*** Walker & Boys, p. 3, pl. 1, fig. 8.
1803 ***Vermiculum globosum*** (Walker & Boys); Montagu, p. 253.
1863 ***Lagena globosa*** (Walker); Reuss, p. 318, pl. 1, figs. 1-3.
1967 ***Lagena globosa*** (Montagu); Gordon, p. 456, pl. 3, fig. 19.
1990 ***Oolina globosa*** (Montagu); Quilty, p. 357, pl. 3, fig. 24.

Description. Test large, globular to ovoid in outline and is unilocular; single chamber sometimes aplicate, extended distally to form a robust and large neck; chamber wall finely-coarsely hispid in texture; aperture is a simple opening produced on the pronounced neck.

Remarks. Specimens from the Jurassic can not be distinguished from Recent examples of ***L. globosa***. It can be separated from most forms of ***Lagena*** by its greater size and more hispid surface ornamentation.

Material. 69 specimens.
Distribution.
2 from Staffin Bay; ***rosenkrantzi*** Biozone.
15 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone) to ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
52 from Helmsdale; ***cymodoce*** Biozone to ***mutabilis*** Biozone.

L. globosa was reported by Gordon (1967) from the Brora Brick Pits section, but no examples were found in this study from the foreshore section at Brora.

Lagena lancelota (Terquem), 1858

(Plate 17, Figure 3)

1858 ***Oolina lancelota*** Terquem; p. 586, pl. 1, figs. 1a-b.
1937 ***Lagena elongata*** Bartenstein & Brand; p. 166, pl. 2a, fig. 15; pl. 2b, fig. 19; pl. 5, fig. 50.
1985 ***Oolina lancelota*** Terquem; Riegraf, p. 155, pl. 11, fig. 40.

Description. Small-medium, elongate, narrow and unilocular test which is more rounded proximally and extended distally; surface smooth; aperture small and appears to be radiate forming a tip to the test.

Remarks. This seems to be the first reported occurrence from the Callovian to Oxfordian interval. Bartenstein & Brand (1937) incorrectly nominated examples to a new species, when the name was already preoccupied as ***L. elongata*** (Ehrenberg).

Material. 6 specimens.

Distribution. A rare form with 2 specimens from the ***cordatum*** Biozone at Staffin Bay, 3 from the ***athleta*** Biozone-***lamberti*** Biozone at Balintore and 1 from the ***athleta*** Biozone at Brora.

Lagena liasica (Kübler & Zwingli), 1866

(Plate 17, Figure 4)

1866 ***Oolina liasica*** Kübler & Zwingli; p. 7, pl. 1, fig. 15.
1955 ***Lagena liasica*** (Kübler & Zwingli); Tappan, p. 82, pl. 28, fig. 12.
1968 ***Lagena liasica*** (Kübler & Zwingli); Welzel, p. 50, pl. 3, fig. 11.
1981 ***Lagena liasica*** (Kübler & Zwingli); Brooke & Braun, p. 26, pl. 7, fig. 7.

Description. Small-medium, globular to ovate and unilocular test, with the chamber widest at the base; base is also marked by a spine; surface smooth, aperture is a simple circular opening at the end of a narrow neck.

Remarks. ***L. liasica*** can be distinguished from most forms, such as ***L. aphela***, by its more globular outline and aplicate base.

Material. 63 specimens.
Distribution. ***L. liasica*** was most abundant in the Aalenian-Bajocian of Bearreraig Bay with only 1 specimen being retrieved elsewhere, from the ***cordatum*** Biozone at Staffin Bay.

Lagena minutissima (Kübler & Zwingli), 1870

(Plate 17, Figure 5)

1870 ***Oolina minutissima*** Kübler & Zwingli; p. 19, pl. 2, fig. 1.
1978 ***Lagena minutissima*** (Kübler & Zwingli); Copestake, p. 370, pl. 12, figs. 21-22.

Description. Very small, unilocular, conical and smooth test which is rounded at the base and slightly extended distally to a simple, flush opening that serves as an aperture.

Remarks. It compares well with the original illustrations and descriptions given by Kübler & Zwingli (1870) and Copestake (1978), with the exception that the aperture in most forms here is simple, with very few showing a simple radiate aperture. The Scottish material may therefore be attributable to the genus ***Oolina*** as defined by Wynn-Jones (1984).

Material. 23 specimens.
Distribution. This rare form was recovered sporadically from the Staffin Bay section between the ***calloviense*** Biozone and ***tenuiserratum*** Biozone, with only 3 specimens from the ***athleta*** Biozone-***densiplicatum*** Biozone at Balintore.

Lagena sulcata (Walker & Jacob), 1798

(Plate 17, Figure 6)

1798 ***Serpula (Lagena) sulcata*** Walker & Jacob; p. 634.
1859 ***Lagena sulcata*** (Walker & Jacob); Parker & Jones, p. 351, pl. 23, fig. 44.
1887b ***Lagena sulcata*** Parker & Jones; Haeusler, p. 183, pl. 5, figs. 1-4.

Description. Test small-medium, elongate, bead-like and unilocular; chamber extended distally to a robust conical neck and appears to be aplicate basally; ornament distinct, with 8-10 cord like, continuous, longitudinal ribs radiating from the basal spine and converging distally to form an apertural collar; aperture is radiate and situated at the end of the extended neck.

Remarks. This form was originally described, but not illustrated, by Walker & Jacob (1798) and so was subsequently designated by Parker & Jones (1859) to fix the type species.

L. sulcata appears to be similar to *L*. sp. 1 figured by Young (1987), but possesses less fine costae.

Material. 4 specimens, only found between the ***athleta*** Biozone and ***cordatum*** Biozone at Staffin Bay.

Family Polymorphiniidae d'Orbigny, 1839

Subfamily Polymorphininae d'Orbigny, 1839

Genus *Eoguttulina* Cushman & Ozawa, 1930
emend. Lloyd, 1962

Eoguttulina bilocularis (Terquem), 1864

(Plate 17, Figure 7)

1864 ***Polymorphina bilocularis*** Terquem; p. 293, pl. 11, fig. 9.
1960 ***Guttulina bilocularis*** (Terquem); Seibold & Seibold, p. 370, figs. 7d-f.
1960 ***Eoguttulina bilocularis*** (Terquem); Bielecka, p. 143, pl. 7, fig. 60.
1970 ***Eoguttulina bilocularis*** (Terquem); Winter, p. 39, pl. 4, fig. 134.
1984 ***Eoguttulina bilocularis*** (Terquem); Riegraf ***et al.***, p. 688, pl. 2, fig. 88.

Description. Medium to small, inflated and rounded test, usually with 2 chambers arranged in a uniserial to offset, 'biserial' arrangement; proloculus globular and aplicate, usually followed by one chamber which is also globular, this final chamber is produced to form a distal neck; suture depressed and oblique; test surface smooth; aperture radiate and produced on a short neck.

Material. 32 specimens.

Distribution.
1 from Bearreraig Bay; only from the ***concavum*** Biozone.
11 from Staffin Bay; ***lamberti*** Biozone-***baylei*** Biozone.
4 from Balintore; ***mariae*** Biozone-***cordatum*** Biozone (***bukowskii*** Sub-biozone).
16 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

Eoguttulina liassica (Strickland), 1846
(Plate 17, Figure 8)

1846 ***Polymorphina liassica*** Strickland, p. 31, text-fig. b.

1937 ***Eoguttulina liassica*** (Strickland); Bartenstein & Brand, p. 178, pl. 1a, figs. 2c, 4a-b; pl. 2b, fig. 35, pl. 3, figs. 4-9; pl. 4, figs 7; pl. 5, figs. 6-9a-b.

1964 ***Eoguttulina liassica*** (Strickland) subspecies ***liassica***; Kristan-Tollman, p. 157, pl. 35, figs. 1-4.

1990 ***Eoguttulina liassica*** (Strickland); Quilty, p. 993, pl. 2, fig. 20.

Description. Test elongate to globular, smooth and tear-drop shaped in outline; proloculus, small, angular to oblate, followed by 3-4 inflated chambers, that are spirally arranged, each less than 90° apart, final chamber inflated; sutures depressed to flush; aperture terminal and radiate.

Remarks. This is the commonest form of ***Eoguttulina*** and is commonly present as floods, particularly within Lower Jurassic sediments (e.g. Copestake, 1978; Gregory, unpublished material from Morvern).

Material. 872 specimens.
Distribution.
76 from Bearreraig Bay; ***concavum*** Biozone-***discites*** Biozone.
233 from Staffin Bay; common throughout.
130 from Balintore; ***athleta*** Biozone-***tenuiserratum*** Biozone.
335 from Brora; ***calloviense*** Biozone-***jason*** Biozone and a concentration between the ***athleta*** Biozone and ***lamberti*** Biozone.
31 from Eathie Haven; ***baylei*** Biozone-***mutabilis*** Biozone.
67 from Helmsdale; ***cymodoce*** Biozone to ***mutabilis*** Biozone.

Eoguttulina metensis (Terquem), 1864
(Plate 17, Figure 9)

1864 ***Polymorphina metensis*** Terquem; p. 301, pl. 13, figs. 38a-b.

1955 ***Eoguttulina metensis*** (Terquem); Tappan, p. 83, pl. 28, figs. 15-16.

1962 ***Eoguttulina metensis*** (Terquem); Lloyd, p. 373, pl. 1, figs. 6a-c, text-figs. 6a-b.

1984 ***Eoguttulina metensis*** (Terquem); Riegraf ***et al.***, p. 688, pl. 1, fig. 53; pl. 2, fig. 90.

Description. Medium-large, slender, elongate and fusiform test with up to 5 chambers, with a lobulate periphery; proloculus globular-ovoid, followed and enveloped by the initial globular chambers, final chambers inflated, but still elongate; sutures depressed and curved; surface smooth; aperture is radiate, terminal and usually flush with the test wall.

Remarks. Overlap of the initial chambers is not as prominent as in ***E. liassica*** or ***E. oolithica***, and it can be distinguished from ***E. polygonata*** (Terquem) which has a more lobulate appearance with less chamber overlap.

Material. 92 specimens.
Distribution.
61 from Staffin Bay; ***athleta*** Biozone-***tenuiserratum*** Sub-biozone.
8 from Balintore; ***lamberti*** Biozone-***tenuiserratum*** Sub-biozone.
23 from Brora; ***athleta*** Biozone-***lamberti*** Biozone.

Eoguttulina oolithica (Terquem), 1874
(Plate 17, Figure 10)

1874 ***Polymorphina oolithica*** Terquem; p. 299, pl. 32, figs. 1-5, 8, 10.
1937 ***Eoguttulina oolithica*** (Terquem); Bartenstein & Brand, p. 179, pl. 10, figs. 43a-b; pl. 11a, figs. 18a-c; pl. 11b, figs. 24a-b; pl. 12b, fig. 18; pl. 15a, figs. 37a-b.
1954 ***Guttulina pera*** Lalicker; Bielecka & Pozaryski, p. 192, pl. 10, figs. 48a-b.
1983 ***Eoguttulina oolithica*** (Terquem); Nagy ***et al.***, p. 120, pl. 2, figs. 13-15.

Description. Small-medium sized, ellipsoidal test which distally tapers rapidly and is non-lobulate in most lateral views; 5-7 elongate chambers are initially coiled triserially then biserially with the first few chambers being enveloped by later chambers, final chamber inflated; sutures depressed-flush, curved; surface smooth; aperture is terminal, radiate and flush.

Remarks. ***E. oolithica*** can be distinguished from ***E. liassica***, which is more squat in outline and from ***E. metensis*** which has a more pronounced, lobulate profile.

Material. 47 specimens.
Distribution.
39 from Staffin Bay; rare throughout, with a small concentration between the ***athleta*** Biozone and ***tenuiserratum*** Sub-biozone.
7 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***cordatum*** Biozone (***bukowskii*** Sub-biozone).
1 from Brora; single specimen from the ***athleta*** Biozone.

Genus ***Palaeopolymorphina*** Cushman & Ozawa, 1930

Palaeopolymorphina sp.

(Plate 18, Figure 1)

Description. Large, slender test, with up to 7 chambers; initial 2 chambers are offset in a biserial arrangement, followed by a meanderinform uniserial section; proloculus small and is followed by chambers which are initially equiant, but rapidly increase in length as added; sutures are depressed, initially oblique, becoming sub-horizontal distally; aperture is radiate, terminal and produced on a short neck.

Remarks. There were too few specimens recovered to give a definite identification of this form, but ***Palaeopolymorphina pleurostomelloides*** (Franke) as illustrated by Cifelli (1959, p. 333, pl. 7, fig. 13) is very similar, but is more compressed, whilst the biserial nature of the test is more emphasised.

Material. 4 specimens.
Distribution. 3 specimens were recovered from the ***concavum*** Biozone to ***discites*** Biozone at Bearreraig Bay, with the other specimen from the ***praecordatum*** Sub-biozone of Staffin Bay.

Subfamily Webbinellinae Rhumbler, 1904

Genus ***Bullopora*** Quenstedt, 1856

Bullopora rostrata Quenstedt, 1858
emend. Adams, 1962

(Plate 18, Figure 2)

1858 ***Bullopora rostrata*** Quenstedt; p. 580, pl. 73, fig. 28.
1866a ***Placopsilina gracilis*** Terquem; p. 419, pl. 15, figs. 21a-d.
1962 ***Bullopora rostrata*** Quenstedt; Adams, p. 157, pl. 21, fig. 4.
1985 ***Bullopora rostrata*** Quenstedt; Riegraf, p. 154, pl. 11, figs. 36-37.

Description. Test variable, medium-large and usually found attached, and is uniserial, being linear or curvilinear, with 3-6 chambers; chambers pyriform-globular connected by internal stolons; proloculus large and enveloped by subsequent chambers; sutures distinct constrictions between chambers; test wall calcareous, smooth and perforate; aperture is either located at the end of a small neck, or flush on the distal region of the chamber.

Remarks. Barnard's (1952a) diagnosis indicated that ***B. rostrata*** possessed an initial coil. Adams' (1962) description excludes such forms which probably belong within ***Nubeculinella bigoti***. Variation includes irregular growth and thin, fibrous attachments/outgrowths radiating from the marginal attached sections of the chambers.

Material. 6 specimens.

Distribution. A rare form with 2 specimens from the ***tenuiserratum*** Biozone of Staffin Bay and 4 from the ***lamberti*** Biozone-***tenuiserratum*** Sub-biozone at Balintore.

Subfamily Ramulininae Brady, 1884

Genus ***Ramulina*** Jones, 1875

Ramulina spandeli Paalzow, 1917

(Plate 18, Figure 3)

1917 ***Ramulina spandeli*** Paalzow; p. 246, pl. 47, fig. 15.
1943 ***Ramulina spandeli*** Paalzow; Weir, p. 207, pl. 10, fig. 8.
1968 ***Ramulina aculeata*** Wright; Oesterle, p. 768.
1970 ***Ramulina fusiformis*** Khan; Winter, p. 41, pl. 4, fig. 140.
1984 ***Ramulina spandeli*** Paalzow; Riegraf ***et al.***, p. 668, pl. 9, fig. 215.

Description. Small-medium sized, with globular to fusiform chambers; only single chambers were encountered, these chambers appear to be connected by stolon-like necks; surface markedly hispid; aperture is a simple, circular opening at the end of a long, thin and tubular neck.

Material. 19 specimens.

Distribution.

10 from Staffin Bay; ***athleta*** Biozone-***tenuiserratum*** Biozone.
2 from Balintore ***lamberti*** Biozone.
7 from Brora; upper ***athleta*** Biozone to ***lamberti*** Biozone.

Suborder Robertinina Loeblich & Tappan, 1984

Superfamily Duostominidae Brotzen, 1863

Family Epistominidae Wedekind, 1937

Subfamily Epistomininae Wedekind, 1937

Genus ***Epistomina*** Terquem, 1882

Epistomina sp. A

(Plate 18, Figure 4)

Description. Test small to medium, biconvex, low trochospiral coil of up to 2 whorls, with 9-11 chambers in the final whorl, the angular periphery forms a single keel; chambers gradually increase in size as added and are sub-triangular in shape; surface ornamentation obscures much of the test features and consists of a coarse, irregular reticulation which is more pronounced in the central dorsal and ventral regions; dorsal, intercameral sutures are raised and covered by the surface reticulation; aperture is obscured by the surface texture.

Remarks. Variation occurs in the degree of convexity, with that of the ventral side being less prominent than that of the dorsal side. The extent and coarseness of the reticulation is divided between the central and peripheral areas, with the former being the coarsest and more distinct, producing discrete, irregular cells.

The only similar forms previously reported in the literature are ***E. minutereticulata*** and ***E. omnirecticulata***, both recorded by Espitalié & Sigal (1963) from the Upper Jurassic of Madagaskar. However, ***E.*** sp. A is more coarsely reticulate and in both the above forms the ornamentation appears to be a pitting rather than a covering of reticulation. This is evident as both possess distinct spiral sutures. Some forms of ***E. parastelligera*** show a similar pitted effect, especially on the dorsal surface, but this appears to be a dissolution feature.

Material. 75 specimens.
Distribution. This new form was only found from 2 localities, with 63 specimens from the top of the ***athleta*** Biozone to the top of the ***tenuiserratum*** Biozone at Staffin Bay and 12 specimens from the ***mariae*** Biozone (***scarburgense*** Sub-biozone) to the ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) at Balintore.

Epistomina sp. B

(Plate 18, Figure 5)

Description. Large, plano-convex, low trochospiral test with a lobulate angular and keeled margin; test coiled into $2^1/_2$ to 3 whorls with 9-12 chambers in the final whorl; chambers crescentic in shape and wedge-out towards the periphery; ventral and dorsal intercameral sutures depressed and radial, spiral suture not visible on the dorsal surface; ornament is distinct and consists of an irregularly hispid covering of the surface which is generally concentrated in the central regions; aperture is an interiomarginal slit present on the final chamber, secondary apertures were not observed.

Remarks. There were no comparable forms in the literature surveyed.

Material. 23 specimens.
Distribution.
Again this form was only recovered from 2 localities, with 21 specimens from Staffin Bay, with a total range from the ***mariae*** Biozone (***scarburgense*** Sub-biozone) to the ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone) and an acme within the ***cordatum*** Biozone (***costicardia*** Sub-biozone-***cordatum*** Sub-biozone). 2 specimens were found from Balintore within the ***tenuiserratum*** Sub-biozone.

Epistomina mosquensis Uhlig, 1883

(Plate 18, Figure 6)

1883 ***Epistomina mosquensis*** Uhlig; p. 766, pl. 7, figs. 1-3.
1954 ***Brotzenina mosquensis*** (Uhlig); Hofker, p. 178, figs. 1-3.

1959 *Epistomina mosquensis* Uhlig; Ziegler, p. 113, pl. 5, figs. 17-18.
1987 *Epistomina mosquensis* Uhlig; Williamson, p. 54, pl. 3, figs. 21-22.
1989 *Epistomina mosquensis* Uhlig; Shipp, p. 260, pl. 6.4.3, fig. 12.

Description. Large, low trochospiral, biconvex test with a keeled, angular peripheral margin; 1-2 whorls are developed, with 6-7 chambers in the final whorl; chambers overlap and gradually increase in size as added, being crescentic in shape and wedging out to the periphery; dorsal side marked by an irregularly coiled, sharp, elevated spiral suture; intercameral sutures curved, raised; ventral sutures limbate and converge to the umbilical region to form an umbilical collar; a pustulate surface ornament is present in the cell regions defined by convergence of spiral and intercameral sutures; aperture is an oblique slit, present on the ventral side and no secondary aperture is visible.

Remarks. Morphological variation is limited to the degree of convexity of the dorsal and ventral sides, with the dorsal side always convex and the ventral side varying from planar to convex. ***E. mosquensis*** can be distinguished from ***E. ornata***, which has more irregularly developed sutures and a less well defined double keel.

Material. 644 specimens.
Distribution.
413 from Staffin Bay; very common and occurs with ***E. parastelligera*** from the ***athleta*** Biozone to ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
231 from Balintore; total range from the ***athleta*** Biozone to ***cordatum*** Biozone (***costicardia*** Sub-biozone), with an acme in the ***cordatum*** Biozone between the ***bukowskii*** Sub-biozone and ***costicardia*** Sub-biozone.

This is a widely reported form in the Upper Jurassic and Lower Cretaceous, with some workers using it as a biozonal form for the Kimmeridgian (e.g. Williamson, 1987; Williamson & Stam, 1988). Partington *et al.* (1993a, b) record a final appearance within the Early Oxfordian for the offshore Inner Moray Firth area.

Epistomina ornata (Roemer), 1841

(Plate 18, Figure 7)

1841 *Planulina ornata* Roemer; p. 98, pl. 15, fig. 25.
1954 *Brotzenia ornata* (Roemer); Hofker, p. 181, figs. 7-8.
1976 *Epistomina ornata* (Roemer); Ascoli, p. 746, pl. 3, figs. 8a-b.
1988 *Epistomina ornata* (Roemer); Williamson & Stam, p. 142, pl. 2, figs. 5-7.

Description. Large, compressed, plano-convex, low trochospiral test of 2-$2^1/_2$ whorls with 9-10 chambers in the final whorl; rounded periphery possesses a very marked irregular double keel; chambers greatest in height and gradually increase in size as added; dorsal, spiral suture is irregularly developed, being broad and raised, intercameral sutures raised and irregular to depressed, becoming curved towards the peripheral margins; ventral sutures also broad, raised and converge to form an umbilical collar; surface ornamented by coarse tubercles; aperture is not always visible, but appears to be a slit-oval shaped opening on the final chamber face.

Remarks. ***E. ornata*** is similar to ***E. mosquensis*** in possessing surface ornamentation of coarse tubercles, but differs by having a planar to gently convex dorsal surface, a poorly developed spiral suture and a double keel. These features also prove to be the most variable morphological aspects, as the spiral suture is not always well defined and the secondary keel is inevitably more weakly developed than the more peripheral primary keel.

Material. 52 specimens.
Distribution. 36 specimens were recovered from the Staffin Bay section, being restricted to the top ***athleta*** Biozone to top ***cordatum*** Sub-biozone and 16 were recovered from the ***mariae*** Biozone at Balintore.

E. ornata appears to be more common from the Lower Cretaceous being recorded from Canada (Ascoli, 1976; Williamson, 1987; Williamson & Stam, 1988) and Europe (Hofker, 1954). However, it has been reported from the Kimmeridgian of England by Shipp (1989).

Epistomina parastelligera (Hofker), 1954

(Plate 19, Figure 1)

1954 ***Brotzenia parastelligera*** Hofker; p. 180, text-figs. 4-6.
1960 ***Epistomina parastelligera*** (Hofker); Bielecka, p. 149, pl. 10, fig. 76.
1962 ***Brotzenia parastelligera*** Hofker; Lloyd, p. 377, pl. 2, figs. 8a-c, text-fig. 7b.
1965 ***Brotzenia porcellanea*** (Brückmann); Gordon, p. 859, text-fig. 11, figs. 7-8.
1965 ***Brotzenia porcellanea*** (Brückmann); Hanzlikova, p. 96, pl. 10, figs. 9a-c.
1965 ***Brotzenia tenuicostata*** (Bartenstein & Brand); Gordon, p. 859, text-fig. 11, figs. 10-14.
1981 ***Epistomina parastelligera*** (Hofker); Barnard & Shipp, p. 432, pl. 4, figs. 14-17.
1989 ***Epistomina parastelligera*** (Hofker); Shipp, p. 262, pl. 6.4.3, fig. 15.

Description. Medium to large, low trochospiral, inflated and biconvex test of $2\text{-}2^1/_2$ whorls, with up to 10 chambers in the final whorl; dorsal side is always the more convex, periphery rounded to angular; chambers crescentic in shape and gradually increase in size as added; dorsal surface is either smooth, or marked by low, broad, intercameral sutures and a spiral suture, there are also peripheral ridges and cells which indicate the presence of closed secondary apertures; ventral surface generally smooth; aperture is an interiomarginal slit and there is evidence of the development of secondary apertures.

Remarks. There is variation in the degree of biconvexity from inflated to plano-convex and in the development of the ribbing from totally smooth forms to those where the rib development is similar in extent to ***E. stellicostata.***

Material. 8727 specimens.
Distribution.
5139 from Staffin Bay; this form is exceedingly common between the ***athleta*** Biozone and ***tenuiserratum*** Biozone (***blakei*** Sub-biozone), with another small acme developed in the Lower Kimmeridgian between the ***baylei*** Biozone and ***cymodoce*** Biozone.
3297 from Balintore; also very common in this section between the ***athleta*** Biozone and ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).
280 from Brora; ranges from the ***athleta*** Biozone to ***lamberti*** Biozone.
11 from Eathie Haven; ***baylei*** Biozone-***cymodoce*** Biozone.

E. parastelligera is a widely reported and often common component of Jurassic microfaunas. Of relevance, is the distribution pattern reported by Partington ***et al.*** (1993a, b) for offshore North Sea Jurassic deposits. This taxon has a reported final appearance within the Late Oxfordian as well as an acme occurrence recorded throughout the Early and Middle Oxfordian for the Outer Moray Firth and Central Graben areas.

Epistomina stellicostata Bielecka & Pozaryski, 1954
(Plate 19, Figure 2)

1954 ***Epistomina stellicostata*** Bielecka & Pozaryski; p. 71, pl. 12, figs. 60a-b.
1988 ***Epistomina stellicostata*** Bielecka & Pozaryski; Williamson & Stam, p. 146, pl. 4, figs. 1-2.
1989 ***Epistomina stellicostata*** Bielecka & Pozaryski; Morris & Coleman. p. 224, pl. 6.3.7, fig. 13.

Description. Large, biconvex and trochospiral test with 1-2 whorls visible on the dorsal surface, ventral side generally more convex than the dorsal; periphery angular and sometimes has a single sharp keel; 6-7 chambers present in the last whorl, being sub-triangular in shape and gradually increase in size as added; dorsal side marked by a broad, low, regular and raised spiral suture; intercameral sutures, limbate and curved, both sets of sutures converge to form an incomplete central boss; ventral sutures also broad, curved and converge on the umbilical area; aperture is a slit like opening at the base of the final chamber on the ventral side.

Remarks. Some forms show partial dissolution that produces a porous, spongy meshwork on the raised area of the test. ***E. stellicostata*** is similar to ***E. tenuicostata***

Bartenstein & Brand, but the latter has a more regular spiral suture. It can be distinguished from *E. parastelligera* which is generally more smooth in view, although, in the forms that do possess raised sutures these features tend not to be as pervasive across the whole test surface.

Material. 224 specimens.
Distribution.
157 from Staffin Bay; common throughout from the ***athleta*** Biozone to ***tenuiserratum*** Biozone.
55 from Balintore; total range from the ***lamberti*** Biozone (***lamberti*** Sub-biozone) to ***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone), with an acme in the ***tenuiserratum*** Sub-biozone.
12 from Brora; only in the ***athleta*** Biozone.

Partington ***et al.*** (1993a, b) record a final appearance within the ***densiplicatum*** Biozone for this taxon from Central North Sea offshore, Jurassic deposits.

Superfamily Conorboidacea Thalmann, 1952

Family Conorboididae Thalmann, 1952

Genus ***Conorboides*** Hofker, 1952

Conorboides marginata Lloyd, 1962

(Plate 19, Figures 3-4)

1962 ***Conorboides marginata*** Lloyd; p. 380, pl. 2, figs. 10a-c.
1981 ***Conorboides marginata*** Lloyd; Shipp & Murray, p. 134, pl. 6.3.2, figs. 5, 9-10.
1988 ***Conorboides marginata*** Lloyd; Bielecka, p. 237, pl. 88, fig. 1.

Description. Small-medium, low trochospiral test which is inflated and wound in 2-2$^1/_2$ whorls, with up to 6 chambers in the final whorl, the test is concave-convex to plano-convex in lateral view and in outline the periphery is lobulate; chambers inflated and crescentic in shape and rapidly increase in size as added; sutures flush-depressed, radial and curved; test surface is smooth; aperture is an interiomarginal loop, which sometimes remains open in the preceding chambers and opens into the central, umbilical depression.

Remarks. ***C. marginata*** can be distinguished from ***C. pygmaea*** which is smaller, more compressed, has incised sutures and is elliptical in outline.

Material. 246 specimens.
Distribution. This form was only recovered from the ***baylei*** Biozone at Staffin Bay and from the ***baylei*** Biozone to ***cymodoce*** Biozone at Eathie Haven.

This species has only been previously reported from the Lower Kimmeridgian, initially from the ***mutabilis*** Biozone at the type Kimmeridgian of Dorset by Lloyd

(1962), with this record being re-confirmed by Shipp (in Shipp & Murray, 1981). Bielecka (1988) also reported *C. marginata* from the Lower Kimmeridgian of Poland.

Conorboides pygmaea Cordey, 1962

(Plate 19, Figure 5)

1962 ***Conorboides pygmaea*** Cordey; p. 396, pl. 48, figs. 45-46.
1967 ***Conorboides nudus*** (Terquem); Gordon, p. 458, pl. 4, fig. 30.

Description. Test very small, elliptical in outline, with rounded and lobulate peripheries; test is arranged in a low, flattened trochospire of 1-$1^1/_2$ whorls, with 5-6 chambers in the final whorl; chambers crescentic and gradually increase in size as added, final chamber is inflated; dorsal and ventral sutures deeply incised, straight and radial; ventral side has a small, central umbilical depression; test aragonitic and smooth; aperture is generally not visible, but is a small, interiomarginal slit which opens into the umbilical region.

Remarks. *C. **pygmaea*** can be distinguished from *C. **marginata*** which is larger, more circular in outline and is plano-convex in lateral view and not flattened.

Material. 77 specimens from the ***athleta*** Biozone to ***densiplicatum*** Biozone at Staffin Bay.

Distribution. This forms appears to endemic to the Scottish Basins, with Cordey (1962) describing the original material from Staffin Bay and Gordon (1967) recorded a form as *C. **nudus*** from the now closed Brora Brick Pits.

Suborder Globigerinina Delage & Hérouard, 1896
Superfamily Rotaliporacea Sigal, 1958
Family Globuligerinidae Loeblich & Tappan, 1984
Genus ***Globuligerina*** Bignot & Guyader, 1971
emend. Stam, 1986

Globuligerina oxfordiana (Grigelis), 1958

(Plate 19, Figure 6)

1881b ***Globigerina helvetojurassica*** (Haeusler); p. 36, pl. 2, figs. 44-44a.
1958 ***Globigerinia oxfordiana*** Grigelis; p. 110, text-fig. 1.
1971 ***Globuligerina oxfordiana*** (Grigelis); Bignot & Guyader, pl. 1, figs. 1-4.
1973 ***Polskanella oxfordiana*** (Grigelis); Fuchs, p. 459, pl. 1, fig. 7; pl. 5, fig. 1.
1980 ***Globuligerina oxfordiana*** (Grigelis); Grigelis & Gorbatchik, pl. 1, fig. 4.
1980 ***Globuligerina stellapolaris*** Grigelis; Grigelis & Gorbatchik. pl. 1, fig. 5.
1986 ***Globuligerina oxfordiana*** (Grigelis); Stam, p. 110, pl. 7, figs. 1-12; pl. 8, figs. 1-12; pl. 9, figs. 1-5; pl. 14, figs. 3-4, 8-15.
1988 ***Globuligerina oxfordiana*** (Grigelis); Bielecka, p. 235, pl. 87, fig. 8.

Description. Small, low trochospiral test which appears conical in lateral view and consists of 2-3 whorls, with 3-4 spheroidal chambers in the final whorl; periphery rounded; umbilicus small; sutures radially depressed; test wall calcareous, hyaline and tuberculate, the tubercles being irregularly spaced and large; pores small and placed between the tubercles; aperture where visible is an umbilical-extraumbilical slit-like opening with a lip.

Remarks. Planktonic foraminifera have not been previously reported from the British Jurassic. This may have been because of misidentification, or more likely, because the preservation of these forms is somewhat precarious. This would account for the generally poor appearance of the Scottish material. Riegraf (1987b, c) reported planktonic foraminifera from similar southern German Callovian-Oxfordian deposits, but only from phosphatic nodules, and not the surrounding shales.

The description of this form as ***Globigerina helvetojurassica*** (Haeusler) was considered ***nomen oblitum*** by Stam (1986) as this name had not been used for nearly 70 years. ***G. oxfordiana*** can be distinguished from ***G. bathonica*** (Pazdrow) which has a much higher trochospire and 4-5 chambers in the final whorl.

Material. 13 specimens.

Distribution. A rare form with 11 specimens recovered from the ***cordatum*** Biozone (***cordatum*** Sub-biozone) to ***glosense*** Biozone at Staffin Bay and 2 specimens from the ***lamberti*** Biozone at Balintore.

G. oxfordiana has been reported from a wide range of Jurassic localities including the Bajocian-Bathonian of Turkmerid and Caucaus, the Oxfordian of the Baltic region, the Paris Basin, Sweden, Canada and western Germany.

Suborder Rotaliina Delage & Hérouard, 1896

Superfamily Discorbacea Ehrenberg, 1838

Family Placentulinidae Kasimova, Poroshina & Geodakchan, 1980

Subfamily Ashbrookiinae Loeblich & Tappan, 1984

Genus ***Paalzowella*** Cushman, 1933

Remarks. ***Paalzowella*** was previously placed within the Involutinidae by Loeblich & Tappan (1964), however as the test is assumed to be subdivided into chambers rather than an unseptated tube, it is now placed within the subfamily Ashbrookiinae.

Paalzowella feifeli (Paalzow), 1932

(Plate 19, Figures 7-8)

1932 ***Trocholina feifeli*** Paalzow; p. 140, pl. 9, figs. 6-7.

1960 ***Paalzowella feifeli feifeli*** (Paalzow); Seibold & Seibold, p. 378, text-figs. 8h, p, q; pl. 7, fig. 2.

1960 ***Paalzowella feifeli*** (Paalzow); Lutze, p. 485, text-fig. 19.
1970 ***Patellina feifeli feifeli*** (Paalzow); Winter, p. 42, pl. 4, fig. 146v.
1989 ***Paalzowella feifeli*** (Paalzow); Shipp, p. 254, pl. 6.4.1, figs. 19-20.

Description. Small-medium, conical test consisting of a flattened, rectangular tube enrolled to give 5-6 whorls and a step like external dorsal surface, periphery angular and carinate on the final whorl; ventral side involute to evolute, with an open, depressed, axial/umbilical area which can be marked by a central pustule, ventral surface smooth and marked by radial undulations that may delineate the presence of internal septa; dorsal surface marked by a distinct, spiral sutural ridge that has a series of numerous and regularly spaced, conical pustules which are sometimes open; tube gradually increases in diameter as added; aperture is a slit-like opening at the end of the final whorl.

Remarks. This is a distinctive conical form which sometimes possesses an apical horn. The ventral surface of the tube may point to the presence of many chambers per whorl. Broken specimens show internal septa, but the extent of these is difficult to gauge.

Material. 31 specimens.
Distribution.
25 from Staffin Bay; ***lamberti*** Biozone (***lamberti*** Sub-biozone)-***cordatum*** Biozone (***bukowskii*** Sub-biozone).
6 from Balintore; ***mariae*** Biozone (***scarburgense*** Sub-biozone)-***tenuiserratum*** Biozone (***tenuiserratum*** Sub-biozone).

This is a widely reported form from shallow water Oxfordian to Kimmeridgian deposits of Germany (Paalzow, 1932; Seibold & Seibold, 1960; Lutze, 1960; Winter, 1970), of England (Barnard ***et al.***, 1981; Morris & Coleman, 1989; Shipp, 1989), Poland (Hanzlikova, 1965), Canada (Ascoli, 1976; Gradstein, 1978) and Portugal (Stam, 1986). It has a general first appearance in the ***mariae*** and ***cordatum*** Biozones of the Lower Oxfordian.

6.2. Radiolarian Taxonomy

6.2 1. Introduction

Radiolaria are planktonic protozoans that construct their test from biogenic silica and Recent taxa have a particularly long history of research. Many previous radiolarian workers have been constrained by the classification of Haeckel (1881, 1887), who in a series of monographs, erected an artificial system based upon minute differences in test geometry. Morphological variation and even dimorphism were rejected by Haeckel (1887) and so a more radical modern system has evolved, principally by Riedel (1967, 1971, 1977) and Pessagno (1973, 1977a). This system, whilst still utilising many of the names erected in elements of Haeckel's classification, is based upon the mode of construction of the radiolarian test and so is a phylogenetic system. However, as is to be expected, there are still problems in the terms of definition, especially at the generic level. These will be pointed out in the main text where relevant.

There are several orders of radiolaria, but only two were recovered from the Jurassic of Scotland. The first group consists of the spumellarians, which are basically spherical, disc-shaped, or star shaped forms that possess several inner medullary shells and one outer, cortical shell. These various shells are connected by lateral bars. The second group, or nassellarians, include all multi-segmented forms, which are generally conical in form. They possess at the least an apical system of a cephalis, a thorax and an abdomen. Many have postabdominal chambers in addition.

The suprageneric classification used here is, due to necessity, an amalgamation of many schemes, as there is still no full natural system for both the nassellarians and spumellarians. In essence, the system used herein follows the work of Pessagno (1977a, 1977b) for nassellarians, which, in turn is based on the work of Riedel (1967, 1971), and follows Baumgartner (1980, 1984) for the majority of the spumellarians, with some essential elements derived from Campbell & Moore (1954). Polycystida is raised to class level, and Nassellariina and Spumellariina are both raised to order level following the recommendations of Levine ***et al.*** (1980).

Other problems which exist, involve the actual preservation of the test features used in classification. All the Scottish radiolarian faunas have been diagentically altered in some way, as is often the case with Mesozoic taxa. The least extreme process involves conversion from the original opaline silica test to one composed of secondary quartz or calcite, with the preservation of the original features remaining remarkably faithful. More destructive is the alteration to pyrite or glauconite, which can sometimes reproduce the external features, but in the latter case results in only internal casts remaining. This diagenetic alteration destroys or obscures the inner medullary shells that many radiolaria possess and makes the use of transmitted light microscopy difficult. Therefore, scanning electron microscopy has become an important tool for Mesozoic radiolarian identification. The internal and external features of Cenozoic taxa, on the other hand, are easily discernible with ordinary light optics. This has led to a polarisation of microscope use which has created differences in attitudes to classification. The affect of the use of transmitted light microscopes, with their varying degrees of optical resolution, by Cenozoic taxonomists is that they are generally perceived as taxonomic 'lumpers' (Pessagno ***et al.***, 1984). It must also be said that Mesozoic workers would probably be considered to be 'splitters', by having a larger number of test characters available, due to the resolution possible with SEM photography, to classify forms with.

6.2.2. Radiolarian Morphological Terminology

A brief glossary of radiolarian terminology is presented below (N=Nassellarian feature, S=Spumellarian feature):

Apical System (N). Consists of 3 segments or chambers; namely a proximal cephalis, a thorax and a distal abdomen.

Aperture (N). A distal opening of the final chamber in multi-segmented tests.

Bracchiopyle (S). A cylindrical, porous tube that extends distally from the centre of the tip of the primary ray of hagiastrid radiolarians.

Central Cavity (S). A variable, central depression present in disc shaped orbiculiformids.

Circumferential Ridges (N). Ridges, that are nodose or non-nodose and separate chambers in a multicytrid test.

Cortical Shell (S). Outer spherical, latticed shell present in all spumellarians.

Costae (N). External, longitudinal ornamentation.

Lacuna (S). Central, polygonal to circular and raised cavity present in ***Crucella.***

Mammae (S). Raised, surface protuberances, present only in ***Praeconocaryomma.***

Medullary Shell (S). Inner, spherical shell of which there can be several.

Multicytrid (N). Multi-segemented test.

Patagium (S). Raised central area, that also bears a central depression.

Poreframe (N, S). Porous meshwork that is characteristic of radiolarians and is constructed of a polygonal lattice.

Pore (N, S). Central opening present within the poreframe.

Postabdominal Chamber (N). A chamber that is inserted distally after the abdomen.

Primary Ray (S). The ray that carries the bracchiopyle.

Triradiate Spines (S). Central, internal spine that projects from the rays of ***Pseudocrucella.***

6.2.3. Radiolarian Taxonomy

Class Polycystida Ehrenberg, 1838
Order Nassellaria Ehrenberg, 1875
Superfamily Crytoidea Haeckel, 1862
Family Hsuuidae Pessagno & Whalen, 1982
Genus ***Hsuum*** Pessagno, 1977

Type species ***Hsuum cuestaense*** Pessagno, 1977a

Generic description. The test is conical, being multicytrid and can possess an apical horn. Strictures are present at joints. The test is constructed of an inner lattice of poreframes and an outer of longitudinal costae.

Remarks. Concerning test construction, it is apparent from Pessagno & Whalen (1982) that the inner lattice of pore frames is secreted first and then costae are inserted between the pores as an outer lattice.

Takemura (1986) divided ***Hsuum*** into two groups based on external morphology, with ***Hsuum s.s.*** possessing distinct, continuous costae and ***Transhsuum*** being characterised by discontinuous costae. As there are many examples in the literature of species possessing both these features as an intraspecific variation, this division is considered to be an artificial one, and therefore should be actively discouraged.

Hsuum sp. 1 Dyer & Copestake, 1989

(Plate 20, Figure 1)

1986 ***Wrangellium*** cf. ***thurstonense*** Pessagno & Whalen; Gregory, p. 127, pl. 2, figs. 7, 13.

1989 ***Hsuum*** sp. 1 Dyer & Copestake; p. 227, pl. 2, figs. 1-2.

Description. Test is multicytrid, conical and apically tapering; cephalis small, conical and possesses a short, rudimentary horn; apical region is covered by a thin layer of non-perforate, microgranular material and is followed by 10 trapezoidal, postabdominal chambers that gradually increase in width as added; inner lattice of the postabdominal chambers is constructed of a massive, square pore frame with linearly arranged, square to rounded pores of 2 rows per chamber; the outer lattice is constructed of numerous, coarse, irregular, but regularly spaced, discontinuous longitudinal costae; these costae are connected both distally and proximally by coarse lateral ridges; costae are inserted between the linear pore frames and are separated by a single vertical row of pores.

Remarks. There are several taxa that appear superficially similar to ***Hsuum*** sp. A and these include; ***H. rosebudense*** Pessagno & Whalen, which has more continuous, longitudinal costae; ***H. mulleri*** Pessagno & Whalen, which has fewer, but more irregular costae and no apical microgranular sheath; ***H. belliatalum*** Pessagno & Whalen is more squat and has very few costae that are coarser; and finally ***H. mirabundum*** Pessagno & Whalen, which has a more tapering test and coarse, continuous costae. The most similar form is ***H. lipheri*** Pessagno & Whalen, which differs in having costae that commence more distally and also in possessing 2-3 rows of pores between the costae.

Material. 232 specimens were recovered only from the Lower Kimmeridgian, and were confined to the ***cymodoce*** Biozone and ***mutabilis*** Biozone of the Inner Moray Firth

Basin, with 182 from Eathie Haven and 50 from the Kintradwell Boulder Beds of the Helmsdale Outlier.

Distribution. This is a common form that has also been reported from the North Sea, Kimmeridge Clay Formation by Dyer & Copestake (1989), although they do not give a stratigraphical range. Partington ***et al.*** (1993a, b) indicate a final appearance within the ***mutabilis*** Biozone, but note that the North Sea faunas are commonly pyritised at this level, which is a feature not seen at Eathie Haven or Helmsdale.

Family Parvicingulidae Pessagno, 1977,
emend. Pessagno & Whalen, 1982

Genus ***Parvicingula*** Pessagno, 1977

Type species ***Parvicingula santabarbarenis*** Pessagno, 1977a
Generic description. Conical, multicytrid test with strictures present at joints. Abdominal and postabdominal chambers have hexagonal poreframes, with pores arranged in 3 rows per chamber to give a stepped or staggered arrangement of pores. Postabdominal chambers are characterised and separated by distinct, nodose or non-nodose, circumferential ridges.

Parvicingula blowi Pessagno, 1977
(Plate 20, Figure 2)

1977c ***Parvicingula blowi*** Pessagno; p. 85, pl. 8, figs. 11-14.
1984 ***Parvicingula blowi*** Pessagno; Pessagno ***et al.***, p. 26, pl. 2, figs. 14-15.
1986 ***Parvicingula*** cf. ***blowi*** Pessagno; Gregory, p. 28, pl. 5, fig. 12.
1989 ***Parvicingula blowi*** Pessagno; Dyer & Copestake, p. 227, pl. 2, figs. 3-4.

Description. Medium to large, proximally tapering, multicytrid test; cephalis is conical and has a short, robust, rudimentary horn; apical system and the first 3 or 4 postabdominal chambers are covered with an irregular, massive, polygonal poreframe, with large, polygonal or circular central pores; there are up to 10 postabdominal chambers developed that are thin and gradually increase only in width as added; postabdominal circumferential ridges are developed only distally and are nodose or non-nodose, being thick and low; distal poreframe structure is regular and polygonal in development, with 3 rows of staggered pores between circumferential ridges; final chamber often has a tapering projection that surrounds the distal opening of the test.

Remarks. This form is slightly different to the type material of Pessagno (1977c) as the irregular poreframe development persists further distally. In particular, it can be distinguished from most other forms of ***Parvicingula*** by the late development of postabdominal circumferential ridges. It can be distinguished from ***P. blowi*** ssp. A Dyer & Copestake, which has well developed circumferential ridges. Also, the regular development of poreframe structures is achieved more proximally. The majority of forms were preserved in calcite, but specimens recovered from the Lower Kimmeridgian of Staffin Bay were replaced by pyrite, which reflected the original external structures well.

Re-examination of material from Kintradwell (Gregory, 1986) has established that many of the forms tentatively attributed as ***P.*** cf. ***blowi*** do indeed belong to ***P. blowi***, whilst the remainder could be placed within ***P. blowi*** ssp. A. Dyer & Copestake.

Material. 1449 specimens.
Distribution. This form was restricted to the Lower Kimmeridgian, by the lack of exposure in the Eathie Haven and Staffin Bay sections and the lack of material from the Helmsdale section. 1252 specimens came from the ***baylei*** Biozone to ***mutabilis*** Biozone, with an acme between the ***cymodoce*** Biozone and ***mutabilis*** Biozone at Eathie Haven, 180 specimens were recovered from the ***cymodoce*** Biozone and ***mutabilis*** Biozone at Kintradwell, with 17 from the ***baylei*** Biozone to ***cymodoce*** Biozone at Staffin Bay.

This is a widespread species, which from this work appears to have a first appearance within the ***baylei*** Biozone. Pessagno (1977c) and Pessagno ***et al.*** (1984) indicated a total range of Kimmeridgian to Middle Volgian, whilst Dyer & Copestake (1989) recorded it from the Kimmeridge Clay Formation of the Northern North Sea, but gave no more details. Supplementary findings by Partington ***et al.*** (1993a, b) record acme tops of this form within the ***mutabilis*** Biozone, a top of pyritised forms at the top of the ***autissiodorensis*** Biozone and a final occurrence within the ***hudlestoni*** Biozone.

Parvicingula blowi Pessagno ssp. A Dyer & Copestake, 1989
(Plate 20, Figure 3)

1989 ***Parvicingula blowi*** Pessagno ssp. A Dyer & Copestake; p. 227, pl. 2, figs. 5-6.

Description. Large, robust, cylindrical and multicytrid test, with a tapering apical system; cephalis is small and conical, with a short, robust, rudimentary horn; thorax and abdomen are both small and trapezoidal; apical area is covered with a massive, irregular to polygonal poreframe structure, with irregularly spaced, circular or hexagonal pores; this section is followed by up to 12 postabdominal chambers that are thin, trapezoidal and are roughly equal in size; postabdominal segments are marked by distinct, thin, non-nodose circumferential ridges; postabdominal chambers have a well developed hexagonal to polygonal poreframe, with 3 rows of large, hexagonal or circular pores arranged in a staggered pattern between circumferential ridges.

Remarks. The Scottish material compares well with the original description given by

Dyer & Copestake (1989) and averages about 250 µm in length. It can be distinguished from ***P. blowi***, which has a more pervasive irregular poreframe structure that extends to the third or fourth postabdominal chamber. All specimens recovered were replaced by calcite, as opposed to pyrite as was the case for the material of Dyer & Copestake (*op. cit.*)

Siphocampe* ? *alexandre, a form illustrated and nominated, but not described by Kozlova (1971, p. 118, pl. 1, fig. 15), is remarkably similar to ***P. blowi*** ssp. A, and was also described from the Lower Kimmeridgian. However, his drawing does not contain enough detail to positively compare the two forms.

Material. This taxon was limited to the Lower Kimmeridgian of the Inner Moray Firth Basin, with a total of 332 specimens that were only recovered from the ***cymodoce*** Biozone to ***mutabilis*** Biozone, with 180 specimens from Eathie Haven and 152 from Kintradwell.

Distribution. This form appears to have only been reported from the Northern North Sea by Dyer & Copestake (1989) from the Kimmeridge Clay Formation.

Parvicingula aff. *jonesi* Pessagno, 1977

(Plate 20, Figure 4)

see 1977a ***Parvicingula jonesi*** Pessagno; p. 48, pl. 8, fig. 14.

1984 ***Parvicingula jonesi*** Pessagno; Pessagno ***et al.***, p. 28, pl. 3, figs. 5-7, 14, 19, 24, 25.

1989 ***Parvicingula jonesi*** Pessagno; Dyer & Copestake, p. 228, pl. 2, figs. 7-8.

Description. Thin, elongate, conical and proximally tapering, multicytrid test, that averages 260 µm in length; cephalis is small, hemispherical and sometimes bears a small, indistinct apical horn; thorax and abdomen are small and trapezoidal; apical system is dome shaped and relatively large, with an irregular, polygonal poreframe structure developed; abdomen is separated from the first postabdominal chamber by a circumferential ridge and is followed by up to 10 postabdominal chambers, that gradually increase in width as added; final postabdominal chamber is marked by a terminal, distal protuberance that surrounds approximately a third of the basal aperture; poreframe structure of the postabdominal chambers is well developed, being regular and hexagonal to polygonal in pattern, with 3 rows of staggered, circular pores present between circumferential ridges; postabdominal circumferential ridges are wide, but low and are generally nodose in form.

Remarks. This form differs from ***P. jonesi*** as described by Pessagno (1977a), by being smaller and having less well defined postabdominal circumferential ridges, and a larger apical system. All specimens were replaced by calcite, or secondary silica. The terminal projection reported by Pessagno ***et al.*** (1984) was not fully preserved in the

Scottish material, but its presence is indicated in the better preserved forms. ***P.*** aff. ***jonesi*** is very similar to ***P. excelsa*** Pessagno & Blome (in Pessagno ***et al.***, 1984) which, however, possesses a much more elongate, apical system, which is also imperforate.

Material. 35 specimens.

Distribution. ***P.*** aff. ***jonesi*** was only recorded from the Lower Kimmeridgian, with 24 specimens from the ***cymodoce*** Biozone and ***mutabilis*** Biozone of Eathie Haven and 11 from the ***cymodoce*** Biozone at Kintradwell.

Pessagno ***et al.*** (1984) record the total range of this form from the Tithonian to Berriasian, whilst Dyer & Copestake (1989) do not indicate range data for their North Sea material. Partington ***et al.*** (1993a, b) indicate several acme tops, the first in the ***mutabilis*** Biozone, within the Middle Volgian and Lower Ryazanian with a possible range top in the Ryazanian ***stenomphalus*** Biozone.

Parvicingula sp. A

(Plate 20, Figure 5)

Description. Medium to large test, averaging 210μm in length, that is distinctly tapering; cephalis is small, conical and dominated by a slender, occasionally offset apical horn; cephalis is covered with a thin, imperforate, microgranular sheath, that sometimes extends over the entire apical system; where this sheath is not present an irregular, polygonal poreframe is developed; occasionally the abdomen and thorax are separated by a poorly developed circumferential ridge; abdomen is separated from the first postabdominal chamber by a circumferential ridge; there are 8-11 postabdominal chambers that constantly increase in width as added; circumferential ridges are distinct, thin and sometimes nodose; poreframe structure is hexagonal to polygonal, with circular, central pores and there are 3 rows of pores between circumferential ridges.

Remarks. This form is very similar to ***P. veri*** Pessagno & Whalen from the Middle Jurassic, except that the poreframe of the latter is much coarser and the postabdominal chambers are not as well developed. ***P.*** sp. A can be distinguished from ***P. blowi*** ssp. A Dyer & Copestake, which has an irregular poreframe lattice covering the apical area and is not as prominently tapering. ***P. blowi*** is similar in shape, but the circumferential ridges in ***P.*** sp. A are developed earlier in test construction and are more distinct.

Material. 62 specimens.

Distribution. This species was only recovered from the Lower Kimmeridgian, with 49 specimens from the ***cymodoce*** Biozone and ***mutabilis*** Biozone of Eathie Haven and 13 from the same biozones at Kintradwell.

Multicytrid Nassellarians sp. & gen. indent

(Plate 20, figs. 6-7)

Remarks. All poorly preserved multicytrid forms are collected here.

Crytoidea Incertae Sedis

Genus *Stichocapsa* Haeckel, 1881

Type species. ***Stichocapsa jaspidea*** Rüst, 1885

Generic description. ***Stichocapsa*** consists of a multicytrid test that is elongate in the proximal half and inflated distally and is divided into several segments, each with 2-4 transverse rows of pores.

Stichocapsa devorata Rüst, 1885

(Plate 20, Figure 8)

1885 ***Stichocapsa devorata*** Rüst; p. 318, pl. 41, figs. 7-8.
1898 ***Stichocapsa devorata*** Rüst; Rüst, p. 65.
1989 ***Stichocapsa devorata*** Rüst; Dyer & Copestake, p. 228, pl. 2, figs. 9-11.

Description. Small, on average 130μm in length, conical test, that is only represented as internal casts in this material; there are an average of 7-8 chambers and the test tapers distally and more distinctly proximally; cephalis is small and hemispherical, with the remaining chambers constant in height and gradually increasing in width as added, the final 2 chambers decrease gradually in width; segment joints are depressed and gently curved; no external features are preserved.

Remarks. Unfortunately, only internal casts were preserved, mainly as glauconite or pyrite, with no external features present. Dyer & Copestake (1989) hypothesized, because of the lack of published records, that ***S. devorata*** may have been restricted in geographical extent to the northern Boreal Province. This may be correct, but another view could be that, as this species is more usually preserved as internal casts, it has been ignored or overlooked.

Material. 40 specimens.

Distribution. This form is limited to the Lower Kimmeridgian in this study, with 12 specimens from the ***baylei*** Biozone to ***cymodoce*** Biozone at Staffin Bay, 21 from the ***cymodoce*** Biozone to ***mutabilis*** Biozone at Eathie Haven and 7 from the ***cymodoce*** Biozone at Kintradwell.

Dyer & Copestake (1989) record this form from the Kimmeridge Clay Formation of the North Sea, and the stratigraphical data given by Rüst (1885, 1898) is limited to a reference to the Jurassic. Partington *et al.* (1993a, b) recorded two main acmes tops for this form in the North Sea. These are within the ***primitivus*** Biozone (Lower Volgian/Lower Portlandian) and around the ***runctoni/lamplughi*** Biozonal boundary.

It appears to have a possible final appearance in the Late Ryazanian.

Stichocapsa sp. indent

(Plate 20, Figure 9)

Description. Only preserved as internal casts, which reflect the gross chamber morphology, of which there are 8-10 chambers; a small, dome like cephalis is followed by the remaining chambers that remain constant in height and gradually increase in width as added; overall the test is conical, with lobulate peripheries and no external features are preserved.

Remarks. The majority of specimens were replaced by glauconite, being preserved as internal casts that only reflected the chamber segmentation. It is possible to separate this material from ***S. devorata***, which is constantly smaller, has fewer chambers and tapers both distally and proximally.

Material. 12 specimens.

Distribution. *S.* sp. is a very rare form that is restricted to the Upper Callovian, with 2 specimens from the ***athleta*** Biozone at Staffin Bay and 10 from the middle ***athleta*** Biozone to ***lamberti*** Biozone at Brora.

Genus *Tricolocapsa* Haeckel, 1881

Type species. ***Tricolocapsa theophrasti*** Haeckel, 1881

Generic description. Test composed of 3 segments; cephalis is small, conical or spherical and is often imperforate, thoracic segment is trapezoidal and has an irregular meshwork of pores. This is followed by a large, inflated, spherical abdomen, which is truncated distally and has a distal aperture. The abdominal surface is covered by a regularly spaced, polygonal poreframe, with circular, central pores.

Tricolocapsa sp. A

(Plate 21, Figure 1)

Description. Very small, tapering, conical test consisting of only 3 segments; the cephalis is small, conical to trapezoidal and imperforate; the thorax is narrow, trapezoidal, with irregular, polygonal pore frames and irregular to circular, central pores; the abdomen is greatly inflated, sub-globular and truncated distally, with evidence of a large, centrally placed, distal aperture; poreframe structure is tetragonal, regular, being low and indistinct; the pores at the centre of the poreframes are small, circular and regularly arranged.

Remarks. This form is characterised by its depressed strictures or joints between the segments and is very small, with a finely pitted surface that is not very evident under transmitted light. ***T*** sp. A can be differentiated from ***T.*** sp. 1 Dyer & Copestake, which possesses a much more coarse framework, as does *T.* sp. 2 Dyer & Copestake, which also has a much more prominent thorax. It is, in some ways, very similar to ***Stichocapsa japonica*** Yao, as illustrated by Gorican (1987, pl. 3, figs. 11-12).

Material. 35 specimens.
Distribution. This form was recovered from the Hebrides and Inner Moray Firth Basins from the Callovian, with a single occurrence in the Oxfordian. 24 specimens were retrieved from the ***athleta*** Biozone to ***lamberti*** Biozone of Brora, with an acme between the top ***athleta*** Biozone and ***lamberti*** Biozone, only 1 specimen was recovered from the ***mariae*** Zone at Balintore and 10 specimens from the ***athleta*** Biozone to ***lamberti*** Biozone (***henrici*** Sub-biozone) of Staffin Bay.

Tricolocapsa sp. indent.

(Plate 21, Figure 2)

Description. This is a small, poorly preserved, tricolocapsid test, showing the typical 3 segmented body; cephalis is small, robust and conical, thorax is trapezoidal, and the abdomen is large, spherical and inflated; the poreframes, where preserved are large and irregular, with coarse, circular, central pores.

Remarks. All specimens recovered were poorly preserved, with the original silica having been replaced by pyrite. Many of the forms illustrated by Matsuoka (1983) appear similar, for example, ***T. tetragona***, ***T. conica*** and ***T. plicarum*** Yao, all having coarse perforation. However, they are all typified by continuous, longitudinal ribs. The most similar species is ***T. rusti*** illustrated by Tan Sin Hok (1927) and as also illustrated by Carter ***et al.*** (1988) as ***T.*** cf. ***rusti*** from the Middle Jurassic of British Columbia.

Material. 2 specimens, only recovered from the ***cymodoce*** Biozone of Eathie Haven.

Order Spumellaria Ehrenberg, 1838

Superfamily Spongodiscacea Haeckel, 1881, emend. Pessagno, 1971, 1973

Subsuperfamily Pseudoaulophacilae Riedel, 1971,
emend. Pessagno, 1971

Family Hagiastridae Riedel, 1971, emend. Baumgartner, 1980

Subfamily Patulibracchiinae Pessagno, 1971
emend. Baumgartner, 1980

Genus ***Paronaella*** Pessagno, 1971
emend. Baumgartner, 1980

Type species ***Paronaella solanoensis*** Pessagno, 1971.
Generic description. ***Paronaella*** includes all 3 rayed patulibracchids that lack a bracchiopyle. The rays are slender with club like tips and the lattice meshwork is coarse with small, circular pores.

Remarks. Following Baumgartner (1980) forms with expanded and bulbous ray tips are included in ***Paronaella.***

Paronaella pessagnoi Blome, 1984

(Plate 21, Figure 3)

1980 ***Paronaella*** aff. ***kotura*** Baumgartner; p. 304, pl. 9, fig. 14.

1984 ***Paronaella pessagnoi*** Blome; p. 354, pl. 6, figs. 1-3, 6-7, 10-13; pl. 15, figs. 10, 18, 20-21.

Description. Small to medium sized, 3 rayed patulibracchid, with short, wedge shaped rays, the tips of which form bulbous, club like extensions that bear the remnants of several, ray tip spines; the meshwork consists of irregular poreframes, with large, circular to polygonal pores and a well developed central lacuna.

Remarks. The original figured specimen of Blome (1984) shows well developed and slender ray tip spines. Since all the Scottish material has been replaced by pyrite, these fragile features were not well represented. ***P. pessagnoi*** is similar to ***P.*** sp. B Pessagno, as illustrated in Pessagno ***et al.*** (1979) from the Upper Triassic of Baja in California, except that the rays of ***P. pessagnoi*** are shorter and the club-like processes are much more robust. ***P.*** sp. A Carter ***et al.*** and ***P. variabilis*** Carter ***et al.*** from the Middle Jurassic of British Columbia (Carter ***et al.***, 1988) are both similar, except that the former lacks a raised central region and the latter has more slender rays.

Material. 8 specimens, only recovered from the middle ***athleta*** Biozone of Brora.
Distribution. The recorded distribution of this form is limited to the Lower and Middle Callovian of Alaska and Oregon (Blome, 1984).

Subfamily Hagiastrinae Riedel, 1971
emend. Pessagno, 1971
Genus ***Crucella*** Pessagno 1971
emend. Baumgartner, 1980

Type species. ***Crucella messinae*** Pessagno, 1977a
Generic description. A 4 rayed patulibracchid that lacks a bracchiopyle, the rays are elliptical to rectangular in cross-section and taper distally to a central spine, that have robust tips. The central area is raised, with triangular poreframes and sometimes with a central patagium.

Remarks. ***Crucella*** was emended by Baumgartner (1980) to include forms erected by Kozur & Möstler (1978) that lacked a bracchiopyle or possessed a patagium.

Crucella sp. indent

(Plate 21, Figure 4)

Description. Very poorly preserved, 4 rayed test, that has a large, central patagium; rays are poorly preserved, but are short and rapidly tapering, being rectangular in cross-section; no surface ornament remains.

Remarks. All the specimens were very poorly preserved, but were similar in gross morphology and, therefore, probably belong to the same species. ***C.*** sp. is similar to ***C. cachensis*** Pessagno, which has longer rays and to ***C. angulosa*** Pessagno, which has longer rays and a smaller, central area. ***C.*** sp. Riegraf is also similar, except that it has very distinctly ornamented, central, external ray beams. The most similar form is ***C. theokraftensis*** Baumgartner, except for its long triradiate, central spines which are more indicative of ***Pseudocrucella.***

Material. 21 specimens.

Distribution. The majority of specimens were recovered from the Callovian to Oxfordian, with 3 specimens from the ***athleta*** Biozone to ***lamberti*** Biozone (***henrici*** Subbiozone) of Staffin Bay, 17 from the ***athleta*** Biozone to ***lamberti*** Biozone of Brora, 1 from the ***mariae*** Biozone at Balintore, and 1 questionable specimen from the ***cymodoce*** Biozone at Eathie Haven.

Subfamily Higumastrinae Baumgartner, 1980

Genus *Pseudocrucella* Baumgartner, 1980

Type species ***Crucella sanfilippoae*** Pessagno, 1977a.

Generic description. Test composed of 4 rays inserted at right angles, that possess tapering tips and have a long triradiate, central spine. The cortical shell has 2-3 lateral, median beams, with pores that are circular, rectangular or polygonal in shape, whilst the central area has an irregular meshwork.

Remarks. ***Pseudocrucella*** differs from other 4 rayed hagiastrids in having a rectangular, ray cross-section and an irregular pore arrangement.

Pseudocrucella plana Blome, 1984

(Plate 21, Figure 5)

?1971 ***Hagiastrum squama*** Kozlova; p. 118, pl. 1, fig. 10.

1984 ***Pseudocrucella plana*** Blome; p. 351, pl. 2, figs. 4, 6-8, 11-12, 15-17, 20-21; pl. 15, figs. 5-9.

Description. Test small to medium in size, averaging 190μm in total length, and consists of 4 parallel sided to distally tapering rays, that are arranged mutually at 90°; the generally poorly preserved rays are short and rectangular in axial section; there is some evidence of a central patagium and an irregular, poreframe lattice structure.

Remarks. All the specimens were poorly preserved and replaced by pyrite. ***P. plana*** as shown by Blome (1984) has a large range of intraspecific variation, with parallel sided to distally tapering rays. The Scottish material was most similar to the tapering forms. However, the prominent triradiate spines of the original specimens did not survive replacement. ***P. plana*** is very similar to ***Hagiastrum squama***, as illustrated by Kozlova (1971) for his Lower Kimmeridgian examples from the Timan-Urals. However, the illustrations are poor and no descriptions were given.

Material. 4 specimens.
Distribution. ***P. plana*** was only recovered from the Middle Callovian of Staffin Bay, being restricted to the ***lamberti*** Biozone (***henrici*** Sub-biozone).

Blome (1984) also reported his material from the Callovian of Alaska and Oregon.

Pseudocrucella sanfilippoae (Pessagno), 1977
(Plate 21, Figure 6)

?1971 ***Hagiastrum crassum*** Kozlava; p. 118, pl. 1, figs. 8-9.
1977c ***Crucella sanfilippoae*** Pessagno; p. 72, pl. 2, figs. 15-16.
1980 ***Pseudocrucella sanfilippoae*** (Pessagno); Baumgartner, p. 8, figs. 1, 23-24.
1981 ***Pseudocrucella sanfilippoae*** (Pessagno); Kocher, p. 88, pl. 16, fig. 1.
1982 ***Crucella sanfilippoae*** Pessagno; Aita, pl. 3, fig. 9.
1988 ***Pseudocrucella sanfilippoae*** (Pessagno); Carter ***et al.***, p. 29, pl. 7, figs. 1, 4.

Description. Test consists of 4 slender, tapering rays that are mutually arranged at 90°, with long, robust, triradiate central spines; the rays are rectangular to square in cross-section and are marked externally by a lateral, median beam; central body is sub-rectangular and sometimes raised and can have a central lacuna; surface meshwork is poorly preserved, but appears to be an irregular to polygonal poreframe.

Remarks. Unfortunately, all the specimens recovered were poorly preserved, often with rays missing, but they possessed enough salient features to be attributed to ***P. sanfilippoae***. It is similar to ***P.*** sp. B Baumgartner, in having tapering ray tips, but this form has no central beam and has a very pronounced circular, central lacuna. ***P. adriani*** Baumgartner is similar, but has parallel sided rays and a much smaller, central area.

Hagiastrum crassum as illustrated by Kozlova (1971) appears to be the same as ***P. sanfilippoae***, unfortunately his illustration is poor and there is no description, so the latter form must take precedence.

Material. 4 specimens.
Distribution. ***P. sanfilippoae*** was only found from the Lower Kimmeridgian (***cymodoce*** Biozone) of Eathie Haven.

Pessagno (1977c) recorded this form from the Upper Kimmeridgian (Zone 1-2) of the California Coast Ranges, but without the use of ammonite biostratigraphy this age is in doubt. Baumgartner (1980) indicated a Lower Kimmeridgian age for his Greek material, as did Kozlova (1971) for his material from Russia. Carter ***et al.*** (1988) have recorded the oldest examples from British Columbia, with a total range of Middle Toarcian to Lower Bajocian.

Family Orbiculiformidae Pessagno, 1973

Genus ***Orbiculiforma*** Pessagno, 1973

Type Species. ***Orbiculiforma quadrata*** Pessagno, 1973
Generic description. Test discoidal, being circular, elliptical or polygonal in outline, with a rounded or angular periphery that can bear spines. A central depression, flanked by a prominent rim is typical and this feature is used as a specific character.

Orbiculiforma sp. A

(Plate 22, Figures 1-2)

Description. Small, thin, circular and discoidal test that has a sharp, vertical margin; central cavity is very wide, covering $^9/_{10}$ to $^3/_4$ of the test diameter and is very shallow; central area of this cavity is sometimes marked by a small, slightly elevated, circular region; ridge created by the central cavity is thin and indistinct, with gently sloping, proximal slopes, and steep, vertical, distal sides; peripheral margin is marked by a wide, U-shaped circumferential notch; pore frames are irregular and spongy, with circular pores.

Remarks. The thickness of this form lies between 10μm and 20μm and is very similar to ***O. nevadaensis*** Pessagno from the Lower Cretaceous of California (Pessagno, 1977a). It possesses the same thin test and wide central cavity, but has a much finer meshwork and a less pronounced circumferential notch. ***O.*** sp. A is also similar to ***O*** sp. as illustrated by Riegraf (1986) from the Callovian of Southern Germany, in having a centrally raised area. However, ***O.*** sp. is much larger, more circular in outline and has an extremely shallow, central depression

Material. 75 specimens.
Distribution. Only recovered from the Lower Kimmeridgian of The Inner Moray Firth Basin, with 74 specimens from the ***cymodoce*** Biozone to the ***mutabilis*** Biozone at Eathie Haven and 1 specimen from the ***cymodoce*** Biozone at Kintradwell.

Orbiculiforma sp. B

(Plate 22, Figures 3-4)

Description. Small, thin test that is a roughly circular disc, with a rounded, peripheral margin that is sometimes incised with an indistinct notch; central cavity is shallow and very wide, covering $^3/_4$ to $^1/_2$ of the total test diameter; the original meshwork is not usually preserved.

Remarks. This form is similar in size to ***O.*** sp. A, except that it is two or three times thicker, and the circumferential notch is more poorly defined and not always present. Replacement by pyrite only rarely preserved the original, polygonal meshwork.

Material. 22 specimens.

Distribution. Only recovered from the Callovian, with 13 specimens from the middle ***athleta*** Biozone to ***lamberti*** Biozone of Brora, and 9 specimens from the ***lamberti*** Biozone (***lamberti*** Sub-biozone) of Staffin Bay.

Orbiculiforma iniqua Blome, 1984

(Plate 21, Figures 5, 7)

1984 ***Orbiculiforma iniqua*** Blome; p. 353, pl. 5, figs. 3-4, 6-7, 10-11, 14-16.

Description. Small, discoidal test that is compressed in peripheral view and has a vertical to rounded periphery that is also characterised by a wide and distinct ,V-shaped circumferential notch; central cavity is less than $^1/_2$ of the total test diameter, is deep, with nearly vertical sides and is produced to form a prominent ridge; poreframe meshwork is irregular to polygonal, with small, polygonal, central pores.

Material. 63 specimens.

Distribution. 15 specimens were recovered from the ***athleta*** Biozone to ***lamberti*** Biozone of Staffin Bay, and were concentrated in the ***lamberti*** Biozone (***henrici*** Sub-biozone), 43 specimens came from the lower ***athleta*** Biozone to ***lamberti*** Biozone (***henrici*** Sub-biozone) and were concentrated in the middle and upper ***athleta*** Biozone of Brora. 5 specimens were from Balintore, from the ***lamberti*** Biozone.

O. iniqua was a common constituent of the Scottish radiolarian faunas, but only within the Upper Callovian and Lower Oxfordian of the Hebrides and Moray Firth Basins and as such the range of distribution compares well with that indicated by Blome (1984) for his material from the Callovian of Alaska and Oregon. Partington ***et al.*** (1993a, b) recorded further collaborative evidence for the presence with an influx of this taxon within the ***calloviense*** Biozone and a final appearance at the ***lamberti/mariae*** Biozonal boundary for North Sea material.

Orbiculiforma lowreyensis Pessagno, 1977

(Plate 21, Figures 6, 8)

1977c ***Orbiculiforma lowreyensis*** Pessagno; p. 74, pl. 3, figs. 15-16; pl. 4, figs. 1-3.

1984 ***Orbiculiforma lowreyensis*** Pessagno; Pessagno ***et al.***, p. 22, pl. 1, figs. 9-11.

1986 ***Orbiculiforma*** cf. ***iniqua*** Blome; Gregory, p. 25, pl. 5, fig. 10.

1989 ***Orbiculiforma lowreyensis*** Pessagno; Dyer & Copestake, p. 224, pl. 1, figs. 1-2.

Description. Outline is polygonal, and the test is robust, with an angular, sloping periphery; central cavity is shallow and occupies $^1/_3$ to $^1/_2$ of the total test diameter, internal slopes are not steep, whilst the external ones slope rapidly from the central cavity to form an angular, peripheral keel; lattice meshwork consists of a regular pentagonal poreframe, with large centrally placed circular pores.

Remarks. ***O. lowreyensis*** is characterised by its polygonal outline and angular margins. It can be distinguished from ***O. mclaughlini*** which is circular in outline, has a much wider central cavity and has vertical, peripheral margins.

Material. 10 specimens.

Distribution. All specimens were recovered from the Upper Callovian from the Hebrides and Moray Firth Basins, with 6 specimens from the upper ***athleta*** Biozone to ***lamberti*** Biozone at Brora and 4 from the ***lamberti*** Biozone (***henrici*** Sub-biozone) at Staffin Bay.

Dyer & Copestake (1989) recorded this species from the North Sea Kimmeridge Clay Formation, but gave no indication of its range. Pessagno (1977c) and Pessagno ***et al.*** (1984) recovered examples from the Middle Volgian to Ryazanian of California. Partington ***et al.*** (1993a, b) record a North Sea final appearance in the ***hudlestoni*** Biozone (Lower Volgian/Late Kimmeridgian).

Orbiculiforma mclaughlini Pessagno, 1977

(Plate 23, Figure 1)

1977c ***Orbiculiforma mclaughlini*** Pessagno; p. 74, pl. 4, figs. 4-7.

1986 ***Orbiculiforma*** cf. ***mclaughlini*** Pessagno; Gregory, p. 26, pl. 5, fig. 11.

1989 ***Orbiculiforma mclaughlini*** Pessagno; Dyer & Copestake, p. 224, pl. 1, figs. 3-4.

Description. Test discoidal, being circular in outline and thick in profile, with a rounded, but quite steep peripheral margin; central cavity is distinct, deep and wide, being a $^1/_2$ to $^3/_4$ of the total test diameter; internal and external sides slope gently, giving rise to a rounded, peripheral ridge; meshwork where preserved is polygonal, with large, central, circular pores that are densest in the central area.

Remarks. ***O. mclaughlini*** can be distinguished from ***O. lowreyensis***, which is angular, and from ***O. iniqua***, which has steep, central cavity slopes. Some specimens of ***O. mclaughlini*** possess a distinct, circumferential notch and all the specimens were replaced by pyrite.

Material. 180 specimens.
Distribution. This species is an important component of the Lower Kimmeridgian deposits of both studied basins, with 128 from the ***cymodoce*** Biozone to ***mutabilis*** Biozone and an acme between the upper ***cymodoce*** Biozone and the ***mutabilis*** Biozone of Eathie Haven. 34 specimens were recovered from the ***cymodoce*** Biozone at Staffin Bay and 18 from the ***cymodoce-mutabilis*** Biozones at Helmsdale. From this distributional data, ***O. mclaughlini*** has a consistent first appearance in the ***cymodoce*** Biozone.

O. mclaughlini was reported from the Kimmeridge Clay Formation by Dyer & Copestake (1989) who indicated a total range from the Kimmeridgian to the Ryazanian. The original type material was from the Late Kimmeridgian to Early Volgian of the Californian Coast Ranges (Pessagno, 1977c). Partington ***et al.*** (1993a, b) have a North Sea final appearance at the Ryazanian/Volgian boundary and an acme top within the ***hudlestoni*** Biozone.

Subsuperfamily Spongodruppilae Haeckel, 1887

Family Cavaspongia Pessagno, 1973

Genus ***Cavaspongia*** Pessagno, 1973

Type species. ***Cavaspongia antelopensis*** Pessagno, 1973
Generic description. The test is biconvex, sub-triangular and consists of a prominent, 3 rayed cortical shell that has latticed gates present between the ray areas. The rays are generally equal in size and taper distally to rounded points. Ray tips were not observed and the cortical shell consisted of a spongy meshwork.

Remarks. There was a problem finding comparative material from the Jurassic literature for the Scottish specimens. ***Cavaspongia*** from the Cretaceous appears to be the most comparable. Other genera that were similar included ***Emiluvia*** Foreman and ***Alievium*** Pessagno. However, the former has a rectangular central body with 4 rays and the latter is roughly circular to triangular and has 3 short, primary rays.

Cavaspongia sp. A

(Plate 23, Figure 2)

Description. Very small, biconvex and 3 rayed test; rays are large, do not taper very much and are generally equal in length, being blunt and rounded distally; central area is roughly circular and sometimes has a small, central depression; poreframe meshwork is not preserved, although there is evidence of compression in the inter-ray area that suggests the original presence of latticed gates that have now collapsed.

Remarks. The Scottish material is most similar to the type species for the genus, ***C. antelopensis*** which Pessagno (1973, 1976) described from the Cenomanian to Turonian of the Californian Coast Ranges and, but it is distinguished by having more robust rays. *C.* sp. A can be differentiated from *C. californioensis* Pessagno which has rays that are pinched proximally. This is the first record of ***Cavaspongia*** from the UK and the Jurassic.

Material. 4 specimens.
Distribution. *C.* sp. was very rare, and only recovered from the Callovian, with 2 specimens from the ***athleta*** Biozone to ***lamberti*** Biozone of Staffin Bay, and 1 specimen each at Brora and Balintore, from the ***lamberti*** Biozone.

Subsuperfamily Spongodiscilae Haeckel, 1881

Family Spongodiscidae Haeckel, 1862

Genus *Spongodiscus* Ehrenberg, 1854

Type species. ***Spongodiscus resurgens*** Ehrenberg, 1845
Generic description. Biconvex to discoidal test, with a simple, central chamber surrounded by a spongy framework, with no radial spines.

Spongodiscus sp. 4 Dyer & Copestake, 1989

(Plate 23, Figure 3)

1989 *Spongodiscus* sp. 4 Dyer & Copestake; p. 225, pl. 1, fig. 16.

Description. Small to medium sized, circular, thick discoidal test with a rounded periphery that has a circumferential notch; test is arranged in several concentric rings, marked on the external surface by a series of thin, shallow, concentric grooves; surface ornament is best developed on the final, most distal ring and is a fine, evenly spaced, low, hexagonal to polygonal poreframe, with shallow, circular to polygonal, central pores; poreframe junctions sometimes bear small nodes; inner rings of the test have an irregular meshwork that is obscured by a microgranular covering.

Remarks. Dyer & Copestake (1989) gave no stratigraphical ranges for this form, which can be distinguished from their descriptions of *S.* sp. 1, *S.* sp. 2 and *S.* sp. 3, all of which are apparently larger, more flattened and are also generally smooth. Further information has been released by Partington *et al.* (1993a, b) for the North Sea area, with a final appearance at the Upper Volgian/Ryazanian stage boundary and a questionable acme top in the ***hudlestoni*** Biozone.

Material. 45 specimens.
Distribution. This form was only recovered from the Lower Kimmeridgian, with 4 specimens from the ***baylei*** Biozone to ***cymodoce*** Biozone at Staffin Bay, 28 from the ***cymodoce*** Biozone to ***mutabilis*** Biozone, with an acme in the ***mutabilis*** Biozone of Eathie Haven and 13 specimens from the ***cymodoce*** Biozone at Kintradwell.

Superfamily Liosphaeracea Haeckel, 1881 emend. Pessagno ***et al.***, 1984
Family Praeconocaryommidae Pessagno, 1976
Genus ***Praeconocaryomma*** Pessagno, 1976

Type species. ***Praeconocaryomma universa*** Pessagno, 1976
Generic description. The test consists of a latticed, spherical, cortical shell and 3 latticed, spherical medullary shells. The cortical shell is typified by numerous and evenly spaced, cone like mammae. The distal surfaces of the mammae are imperforate, have flattened tops, but can possess spines.

Remarks. ***Praeconocaryomma*** is distinguished from ***Conocaryomma*** on the basis of the number of inner, medullary shells, with the latter having 5 and the former has 3. This feature cannot be used for the Scottish Jurassic material, as even in well preserved forms from the Eathie Haven sequence only 1 or 2 medullary shells can be differentiated. However, from the literature, it is possible to indicate that ***Conocaryomma*** is only known from the Middle and Upper Eocene and ***Praeconocaryomma*** became extinct in the Middle Campanian. Therefore, the forms from Scottish Jurassic deposits are considered to belong to ***Praeconocaryomma***, whilst the true evolutionary sequence between these two genera still has to be resolved.

Praeconocaryomma sp. 1 Dyer & Copestake, 1989
(Plate 23, Figure 4)

1989 ***Praeconocaryomma*** sp. 1 Dyer & Copestake; p. 225, pl. 1, fig. 7.

Description. Small, spherical test, with only the outer cortical shell preserved; ornament is distinct and consists of numerous, regularly spaced, small, but prominent, imperforate mammae that are almost parallel sided and have flattened distal ends; there is evidence in well preserved examples of a series of 5-6 circular, intermammary pores that surround each mammae; the mammae are also connected by short, thin, lateral bars.

Remarks. The average size of this form is 120μm, which is smaller than the 150μm figure quoted by Dyer & Copestake (1989) for their material. This may be related to the spatial distribution of the final faunas, and the palaeoenvironmental conditions that prevailed, producing size sorting. ***P.*** sp. 1 can be distinguished from ***P. hexagona*** by its smaller, more numerous and better defined mammae.

Material. 40 specimens.

Distribution. ***P.*** sp. 1 was only recovered from the Lower Kimmeridgian of the Inner Moray Firth, with 39 specimens from the ***cymodoce*** Biozone and ***mutabilis*** Biozone at Eathie Haven, and 1 from the ***mutabilis*** Biozone at Kintradwell. Dyer & Copestake (1989) do not give an age range for this form, except that it occurs in deposits ranging from the Kimmeridgian to Volgian. Partington ***et al.*** (1993a, b) give some more information with an acme and final appearance recorded in the Upper Volgian ***primitivus*** Biozone.

Praeconocaryomma hexagona (Rüst), 1889

(Plate 23, Figure 5)

1889 *Acanthosphaera hexagona* Rüst; p. 12, pl. 3, fig. 10.

1977c *Praeconocaryomma hexagona* (Rüst); Pessagno, p. 77, pl. 5, fig. 13.

1989 *Praeconocaryomma hexagona* (Rüst); Dyer & Copestake, p. 225, pl. 1, figs. 5-6.

Description. Test small to medium sized and spherical; only the outer cortical shell was observed and its ornament consists of numerous, regularly spaced, dome to conical shaped mammae; all mammae have flattened distal ends and are connected by short, heavy, lateral bars.

Remarks. It was difficult to distinguish pores between the mammae as these features have been lost as a result of diagenetic replacement by calcite. ***P. hexagona*** can be distinguished from ***P.*** sp. 1 Dyer & Copestake, which has smaller and more numerous mammae. Dyer & Copestake (1989) indicated an average diameter of 150µm, but in this material the diameter was nearer 100µm. It can also be differentiated from ***P. universa*** Pessagno, which has mammae connected by a series of 3-5 ridges and has tapering mammae.

Material. 5 specimens.

Distribution. ***P. hexagona*** was only recovered from the ***cymodoce*** Biozone of Eathie Haven. Pessagno (1977c) gives a range of Middle Volgian to Ryazanian for material from the California Coast Ranges, Rüst's type material is from the Upper Jurassic and Dyer & Copestake (1989) give no indication of age data, except that it occurs in the Kimmeridge Clay Formation of the North Sea. Partington ***et al.*** (1993a, b) record several acme tops for this taxon in North Sea deposits including; within the ***mutabilis*** Biozone, at the ***autissiodorensis/elegans*** Biozone boundary (only recorded in the Inner Moray Firth), within the ***scitulus*** Biozone and a final appearance in the Upper

Ryazanian.

Family Liosphariidae Haeckel, 1882

Subfamily Ethmosphaerinae Haeckel, 1882

Genus *Cenosphaera* Haeckel, 1887

Type species. ***Cenodiscus plutonis*** Ehrenberg, 1854

Generic Description. A spherical test with a reticulate, latticed and porous poreframe meshwork. The poreframes are generally pentagonal to hexagonal, with the framework indices sometimes bearing nodes or spines.

Remarks. Dyer & Copestake (1989), in their work on the Jurassic and Lower Cretaceous radiolaria of the North Sea, concur with the view expounded by Pessagno (1977a). Their opinion is that radiolaria showing cenosphaerid features from the Mesozoic do not show sufficient phylogenetic connection with Cenozoic forms to be considered the same genus. This is probably true, however, it may also be an artefact produced by the apparent non-description of cenosphaerids, which are often poorly preserved or considered to be of secondary importance in relation to the more biostratigraphically useful nassellarians. Workers from the nineteenth century described many forms from the Jurassic, especially from Tethyan regions (e.g., Rüst, 1885, 1889; Parona, 1890). Recent work by Riegraf (1986, 1988; ***pers comm.***, 1989), and Dyer & Copestake (1989) associated with the Scottish examples, show the presence of these forms in the Boreal Realm. Cenosphaerids are an important feature of these radiolarian faunas and there appears no reason why they should not be more widespread in Boreal and Tethyan deposits. Unfortunately, descriptions of Cretaceous cenosphaerids are equally poor and this may also be a result of the processes outlined above. So, until the exact link can be established, Jurassic and Lower Cretaceous cenosphaerids should possibly be contained within a new genus. Similar reasoning was used to distinguish the Cenozoic ***Conocaryomma*** from the Mesozoic ***Praeconocaryomma.***

Cenosphaera sp. 1 Dyer & Copestake, 1989

(Plate 24, Figure 3)

1989 ***Cenosphaera*** sp. 1 Dyer & Copestake; p. 232, pl. 1, fig. 11.

Description. Very small, spherical form, with a surface marked by pitting that is produced by a fine, regular, latticed meshwork; poreframes are pentagonal, with deep, circular to polygonal, central pores; many of the poreframe intersections possess small, sharp spines or nodes.

Remarks. This is an exceedingly small form, averaging 60-70μm in diameter, and it appears faintly pitted in transmitted light. The Scottish material matches the description given by Dyer & Copestake (1989), but their illustrations do not sufficiently emphasise the extremely fine reticulation of the surface. This form is very similar to *C.* ***miniscula*** Parona (1890, pl. 1, fig. 6) and *C.* ***disporata*** Rüst (1885, pl. 1, fig. 9), but the illustrations are very poor and preclude firmer comparison. *C.* ***micropora*** Rüst, as illustrated by Riegraf (1986, pl. 3, figs. 17-18) is also similar, but is larger and has more massive poreframes that are hexagonal in construction (Riegraf, ***pers. comm.,*** 1989).

Material. 513 specimens.
Distribution. This is an important form from the Inner Moray Firth deposits, with 489 specimens from the ***cymodoce*** Biozone and ***mutabilis*** Biozone at Eathie Haven, with an acme within the ***mutabilis*** Biozone. 24 specimens were also recovered from the ***cymodoce*** Biozone and ***mutabilis*** Biozone at Kintradwell.

Dyer & Copestake (1989) give no distributional data for this species. However, Partington ***et al.*** (1993a, b) indicated that this form is biostratigraphically useful in North Sea deposits with an acme top in the ***scitulus*** Biozone, one in the ***hudlestoni*** Biozone, one at the ***fittoni/albani*** Biozonal boundary and a final appearance at the Volgian/Ryazanian stage boundary.

Cenosphaera sp. 2 Dyer & Copestake, 1989

(Plate 24, Figure 4)

1989 ***Cenosphaera*** sp. 2 Dyer & Copestake; p. 226, pl. 1, figs. 9-10.

Description. Small, coarsely reticulate, spherical test; poreframe is regularly spaced, being pentagonal to hexagonal in form, with large, circular to sub-circular, centrally placed pores; poreframe intersections are marked by a small, conical node.

Remarks. This form is larger than *C.* sp. 1, averaging 150µm, and is distinguished from it by the coarse reticulation. *C.* sp. 2 is somewhat similar in transmitted light to ***Praeconocaryomma*** sp. 1, from which it can be distinguished by the presence of a latticed meshwork, as opposed to mammae. *C.* sp. 2 was originally described from the North Sea Jurassic and Lower Cretaceous by Dyer & Copestake (1989), who indicated that much of their material had been replaced by pyrite. The material from Eathie Haven was mainly preserved in secondary silica or calcite, which replicated the original surface texture faithfully. *C.* sp. 2 is similar in size and general morphology to *C.* ***clathrata***, as described by Parona (1890, p. 148), but the figures are very poor and do not show the poreframe structure in sufficient detail. *C.* ***polygona*** Rüst is also similar, but the pore frames are more trapezoidal in construction.

Material. 49 specimens.
Distribution. This form was only recovered from the ***mutabilis*** Biozone at Eathie Haven. Neither Dyer & Copestake (1989) or Partington ***et al.*** (1993a, b) give ranges for their material from the Kimmeridge Clay Formation of the North Sea.

Cenosphaera sp. A

(Plate 24, Figure 5)

Description. Very small, spherical, smooth test, that is slightly pitted by irregular and small pores; some specimens have a small, circular depression present on the test surface.

Remarks. This form appears to be almost smooth when viewed in transmitted light and as many specimens have been replaced by calcite or secondary silica, this has possibly destroyed the original surface textures.

Material. 34 specimens.

Distribution. ***C.*** sp. A was only recovered from the ***cymodoce*** Biozone and ***mutabilis*** Biozone at Eathie Haven.

Cenosphaera sp. indent

(Plate 24, Figures 6-7)

Description. All poorly preserved, spherical radiolarian tests were included under ***Cenosphaera*** sp. indent. The majority of specimens were replaced by pyrite and showed very little in the way of original surface textures.

Material. 256 specimens.

Distribution. The largest numbers of poorly preserved cenosphaerids were recovered from the Callovian and lower-most Oxfordian, with 194 specimens from the lower ***athleta*** Biozone to ***lamberti*** Biozone and an acme in the mid ***athleta*** Biozone of Brora. 17 specimens were recovered from the ***lamberti*** Biozone to ***mariae*** Biozone of Balintore and 45 from the ***athleta*** Biozone to ***cymodoce*** Biozone of Staffin Bay, being concentrated between the ***baylei*** Biozone and ***cymodoce*** Biozone.

Superfamily Cenosdiscicae Haeckel, 1887

Family Cenodiscidae Haeckel, 1887

Subfamily Cenodiscinae Haeckel, 1887

Genus ***Cenodiscus*** Ehrenberg, 1854

Type species. ***Cenodiscus phacoides*** Haeckel, 1887

Generic description. Test form is always biconvex and discoidal with the periphery lacking spines and there is no medullary shell present. Surface is latticed and spongy with regular to irregular poreframes developed.

Remarks. The same phylogenetic problem outlined for ***Cenosphaera*** exists with cenodiscids, with the exception that these forms are even more poorly represented or described from the Jurassic and Cretaceous. The forming of an evolutionary linkage between these forms is therefore unlikely without much more extensive research. So, Mesozoic cenodiscids do appear to warrant designation as a 'new' genus.

Cenodiscus sp. A

(Plate 23, Figures 6-7)

Description. Test medium to large in size, averaging 160µm in diameter, that is discoidal and biconvex, with gently sloping sides, converging to give a sharp, angular margin; test surface is coarsely reticulate with large hexagonal to polygonal poreframes; pores are central, large and circular to polygonal in shape; the degree of depression of the pores has the effect of producing a raised lattice, the junctions of which are produced to short, blunt nodes or spine bases.

Remarks. Dyer & Copestake (1989) illustrated 3 new forms of ***Cenodiscus***, all of which were smooth and finely pitted. Cenodiscids are very poorly documented from the Jurassic, but are an important feature of the Lower Kimmeridgian deposits of Eathie Haven and Kintradwell. This form is distinctly reticulate and most specimens were preserved in silica or calcite.

Material. 649 specimens.
Distribution. 643 specimens were recovered from the ***cymodoce*** Biozone and ***mutabilis*** Biozone of Eathie Haven, with an acme developed in the ***mutabilis*** Biozone. Only 6 specimens came from the ***cymodoce*** Biozone at Kintradwell.

Cenodiscus sp. indent.

(Plate 24, Figures 1-2)

Description. Very small, discoidal, biconvex test, with rapidly sloping sides and an angular to rounded margin; there are no other discernible features, except for the development of occasional patches of a polygonal framework.

Remarks. All poorly preserved cenodiscids are included here and these forms are generally from the Callovian and Oxfordian. The original silica has been replaced by pyrite, and in some cases glauconite, which only reflects the gross external morphology.

Material. 153 specimens.
Distribution. 121 specimens were recovered from the ***athleta*** Biozone to ***lamberti*** Biozone of Brora, with 26 from the ***lamberti*** Biozone (***lamberti*** Sub-biozone) of Balintore and 6 from the ***athleta*** Biozone to ***baylei*** Biozone of Staffin Bay.

CHAPTER 7
BIOSTRATIGRAPHICAL AND PALAEOENVIRONMENTAL SYNTHESIS

7.1. Introduction

The sections at Staffin Bay, Bearreraig Bay, Brora, Balintore, Helmsdale and Eathie Haven have been covered individually in terms of foraminiferal and radiolarian distribution with local palaeoenvironmental interpretations derived wherever possible from their distributional patterns and facies types.

These sections are now considered within a regional context to correlate, if possible, biostratigraphical and palaeoenvironmental events. In doing so, conclusions concerning microfaunal distribution and its relevance to biostratigraphy and palaeoenvironmental interpretation are assessed.

7.2. Biostratigraphical Correlation

7.2.1. Introduction

A novel biozonation has been erected for the Lower Callovian to Lower Kimmeridgian, based on the most complete section available at Staffin Bay (Fig. 4.23). Figure 7.1 illustrates the ranges of selected indices and their distribution from Staffin Bay and all other sections within the Inner Moray Firth Basin. Comments within the taxonomy section (Chapter 6) also outline the broad world-wide Jurassic ranges of these indices, as well as the associated forms, where definition was possible from the large literature dataset. Intra and interbasinal correlations based on material from the Inner Moray Firth Basin and the biozonal template at Staffin Bay, within the Hebrides Basin, have been plotted onto Figure 7.2.

Radiolarian distribution patterns at the generic level are additionally illustrated on Figure 7.3 from the sites of interest.

Each locality is discussed below in detail and in terms of the biozonation outlined in Section 4.3.7 and illustrated in Figure 4.23.

7.2.2. Brora

The first marine sediments at Brora were deposited within the ***calloviense*** Biozone of the Lower Callovian. The occurrence of abundant agglutinated foraminiferids including an acme of ***Recurvoides sublustris*** within the ***calloviense*** Biozone, associated with specimens of ***Ammobaculites deceptoria*** in the ***jason*** Biozone, suggests the presence of the JM1 agglutinated dominated microfaunal biozone.

It was unfortunate that foraminiferal recovery was non-existent from the ***coronatum*** Biozone of the Glauconitic Sandstone Member, as this would have helped to

Figure 7.1. Comparison of ranges of the selected foraminiferal and radiolarian biozonal indices from the study areas plotted against the Boreal ammonite scheme

complete the representation of this biozone within the sediments of Staffin Bay. The assemblages developed within the Lower and Middle Callovian part of the section at Brora were very similar to those seen at Staffin Bay, being dominated by agglutinated taxa, with minor lagenids and spirillinids.

No foraminifera were recovered from the basal part of the ***athleta*** Biozone within the Brora Brick Clay Member. The top of the ***phaeinum*** Sub-biozone is well developed within the Fascally Siltstone Member, which overall yielded a moderately diverse microfauna. The final occurrence of rare specimens of ***R. sublustris*** may suggest the presence of Sub-biozone JM2a. However, the first appearances of a consistent radiolarian fauna associated with ***Marginulina batrakiensis*** and ***Nodosaria minuta*** show good correlation with the base of JM2b as defined at Staffin Bay. The first appearance of consistent specimens of the radiolarian taxa ***Orbiculiforma iniqua*** is associated with the first appearance of a consistent and diverse radiolarian fauna within the ***proniae*** Sub-biozone which corroborates this correlation. ***Lenticulina ectypa*** has a slightly lower first appearance at Brora, within the top of the ***phaeinum*** Sub-biozone as opposed to the base of the ***proniae*** Sub-biozone at Staffin Bay. This disparity is probably a consequence of definition of the ***athleta*** Biozone at Staffin Bay, which is represented by a comparatively thin sequence there, compared to the much thicker sequence at Brora. However, its occurrence is still sufficiently close to confirm the presence of Sub-biozone JM2b.

The decrease in radiolarian faunas associated with the final occurrence of ***Orbiculiforma iniqua*** may indicate the base of JM2c within the ***henrici*** Sub-biozone. This attribution could not be definitely placed due to the nature of the exposure at Brora, with the transition to the less favourable facies of the Fascally Sandstone Member.

7.2.3. Balintore

The Lower to Upper Callovian sediments at Balintore are notable for their highly condensed nature within the Cadh'-an-Righ Shale Member. However, the majority of microfaunal biozones can be defined over his interval. The ***coronatum*** Biozone, however, is barren of microfossils, so the Balintore section does not add any information for this particular biozone either.

In detail, Biozone JM1 is suggested by the occurrence of an agglutinated dominated fauna within the ***jason*** Biozone which has similarities with the assemblages developed at Staffin Bay and at Brora. However, the biozonal indices are lacking. Sub-biozone JM2a is suggested by the first appearance of relatively common ***Gaudryina*** aff. ***sherlocki*** around the condensed ***phaeinum/proniae*** boundary. Subsequent first occurrences of ***Nodosaria minuta*** and consistent ***Lenticulina ectypa*** mark the base of Subzone JM2b within the ***proniae/spinosum*** condensed level.

Although the radiolarian marker taxa do not allow subdivision of Sub-biozone JM2c they do at least confirm the presence of Biozone JM2 over the ***athleta/lamberti*** Biozones. Additionally, the first appearance of ***Lenticulina ectypa*** spp. ***costata***

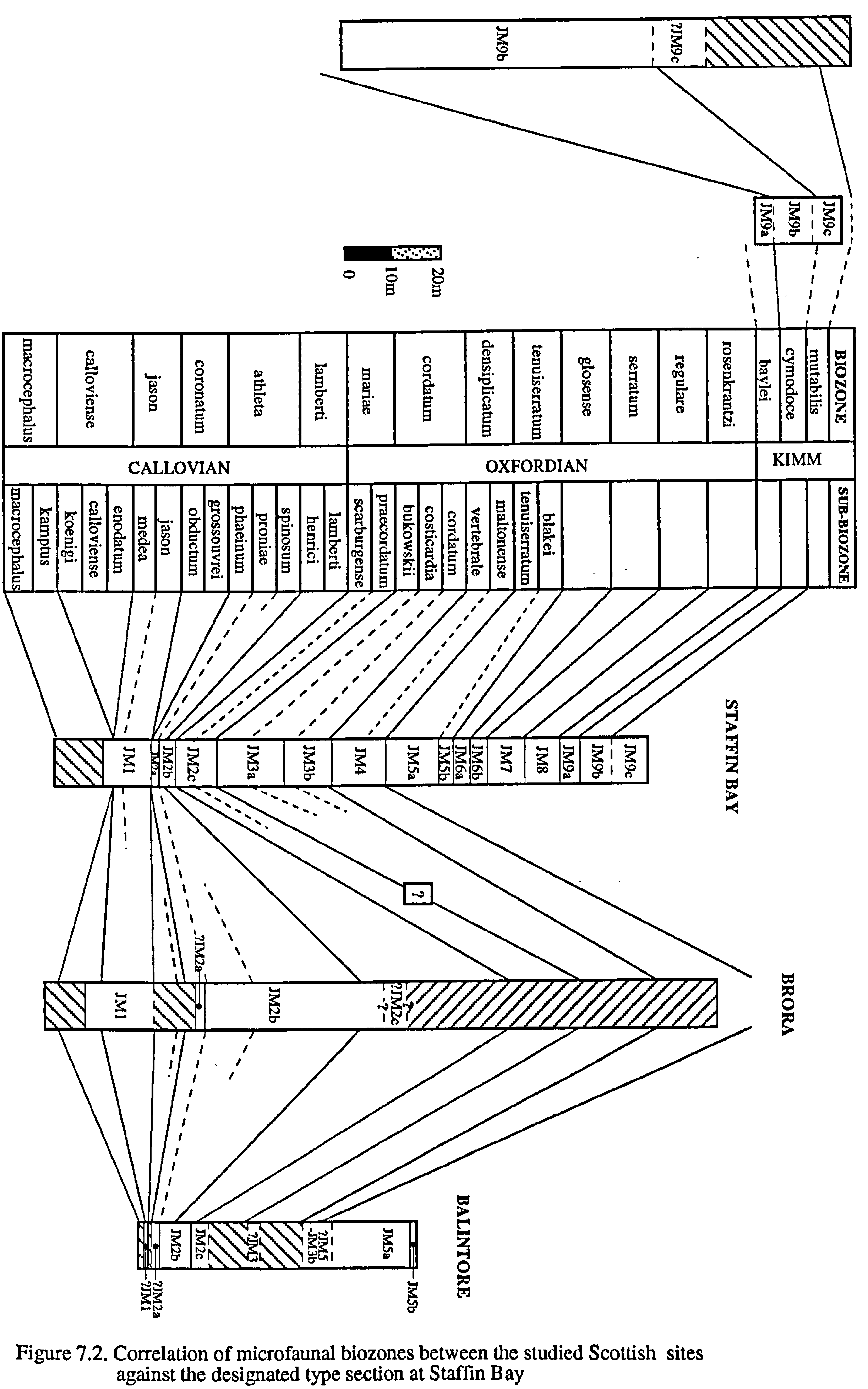


Figure 7.2. Correlation of microfaunal biozones between the studied Scottish sites against the designated type section at Staffin Bay

within the ***lamberti*** Biozone is consistent with a similar event within the Staffin Bay section and indicates Sub-biozone JM2c.

The base of Biozone JM3 could not be ascertained with any certainty, except that the presence of the non-index taxa ***Ophthalmidium purtonensis***, around the ***cordatum/mariae*** Biozonal boundary, may be consistent with that seen at Staffin Bay and, therefore, may tentatively suggest this sub-biozone.

The interval encompassing JM3b-JM5 is suggested by the presence and final appearance of the non-index ***Marginulina costata*** within the ***tenuiserratum*** Biozone. Additionally, ***Marginulina batrakiensis*** indicates the presence of Biozone JM4, however, its final appearance at the top of the ***cordatum*** Biozone does not correlate with that selected at Staffin Bay at the base of the ***tenuiserratum*** Biozone. This may be due to the highly condensed nature of the ***densiplicatum*** Biozone or explained by palaeoenvironmental evidence showing that this interval, represented by deposition of the Port-an-Righ Ironstone Member, was not conducive to foraminiferal colonisation.

The top of Sub-biozone JM5a, towards the top of the succession, is marked by the final appearance of ***Recurvoides sublustris***. The subsequent continued occurrence of ***L. ectypa*** spp. ***costata*** and acme of ***Epistomina parastelligera*** in the final samples indicates the presence of Sub-biozone JM5b. Lack of further exposure precluded the definition of further biozones.

7.2.4. Helmsdale

Helmsdale represents an unusual environment, which is dominated by a long ranging and facies dependent spirillinid and, to a lesser extent, lagenid benthic fauna transported into deeper water environments. Transportation may cause problems with biozonation, although this should be negligible given the fact that radiolarian faunas occur (these should be relatively unaffected by this process due to their planktonic lifestyle) and also that the actual transportation of benthic faunas appears to be constant and rapid. Evidence supports this view since the sediments that are exposed show good microfaunal biozonal correlation.

Biozone JM9 is indicated overall by the presence of ***Planularia kintradwellensis***, an abundant radiolarian fauna including ***Parvicingula blowi*** and common ***Haplophragmoides canui*** within the ***cymodoce*** Biozone. The appearance of ***Orbiculiforma mclaughlini*** at the base of the ***cymodoce*** Biozone allows the attribution of Sub-biozone JM9b to this interval. The base of Sub-biozone JM9c is indicated by the decrease in lagenid taxa around the ***cymodoce/mutabilis*** boundary, which shows an approximate correlation of this uncertain boundary at Staffin Bay.

Microfaunal recovery from younger sediments at Helmsdale was unfortunately poor to non-existent and did not permit further microfaunal biozonation.

7.2.5. Eathie Haven

Lack of exposure limits this section to an interval encompassing the ***baylei*** to ***mutabilis***

Biozones, however, a relatively close correlation is possible with the sections at Staffin Bay and Helmsdale.

The presence of large numbers of agglutinated foraminiferids associated with minor lagenid and abundant radiolarian faunas places this entire interval within the Lower Kimmeridgian JM9 Biozone. In more detail, the combined first appearances of common ***Haplophragmoides canui*** and ***Planularia kintradwellensis*** indicate the presence of Sub-biozone JM9a within the ***baylei*** Biozone.

The range of ***Conorboides marginata*** is slightly longer at Eathie Haven than at Staffin Bay, but still confirms a Sub-biozone JM9a attribution for this level.

Radiolaria also occur relatively higher in the succession, but their presence similarly indicates JM9. However, the first appearance of ***Orbiculiforma mclaughlini*** low in the ***cymodoce*** Biozone still points to the presence of Subzone JM9b.

The base of Sub-biozone JM9c is indicated by the final appearance of lagenids, which in this section lie in proximity to the ***cymodoce/mutabilis*** Biozonal boundary.

7.2.6. Radiolarian Distribution

This section is included to compare the distribution of radiolarian faunas, with Figure 7.3 showing the generic correlation between the various sites. It is apparent that there is relatively good correlation of the total ranges, particularly within the Upper Callovian/Lower Oxfordian and within the Lower Kimmeridgian between the Hebrides Basin and the sites of the Inner Moray Firth Basin. Differences in the actual first and final appearances may be attributed to the extent of the changes in relative sea-levels and the actual palaeogeographical position of the sites in relation to the 'palaeoshoreline'.

There is a distinct Upper Callovian to Lower Oxfordian radiolarian distribution at Brora, Balintore and Staffin Bay and they are of similar faunal composition and species numbers. The greatest difference is that there are fewer cenodiscids and cenosphaerids at Staffin Bay and Balintore. In terms of total abundances Brora outranks Staffin Bay which in turn outranks Balintore. Distribution of radiolaria at the latter also extends into younger Lower Oxfordian sediments. Forms in common between all sites are ***Cenodiscus/Cenosphaera*** spp., ***O. iniqua, Cavaspongia, Spongodiscus*** and ***Tricolocapsa***. There are a few more species in common between Staffin Bay and Brora which also include ***O. lowreyensis, Tricolocapsa*** sp. A and ***Stichocapsa*** sp. A.

The most abundant and pervasive radiolarian fauna occurred within the Lower Kimmeridgian with a total range encompassing the ***baylei*** and ***mutabilis*** Biozones of Staffin Bay, Helmsdale and Eathie Haven. The ranges of the taxa are broadly comparable, but their total extent may be limited by the lack of exposure before the ***baylei*** Biozone at Helmsdale and partially at Eathie Haven and after the ***mutabilis*** Biozone at Eathie Haven and Staffin Bay. However, radiolaria were not recovered from the ***baylei*** Biozone at Eathie Haven, nor from sediments younger than the ***mutabilis*** Biozone at Helmsdale.

Eathie Haven has the most abundant and diverse faunas, followed by Helmsdale

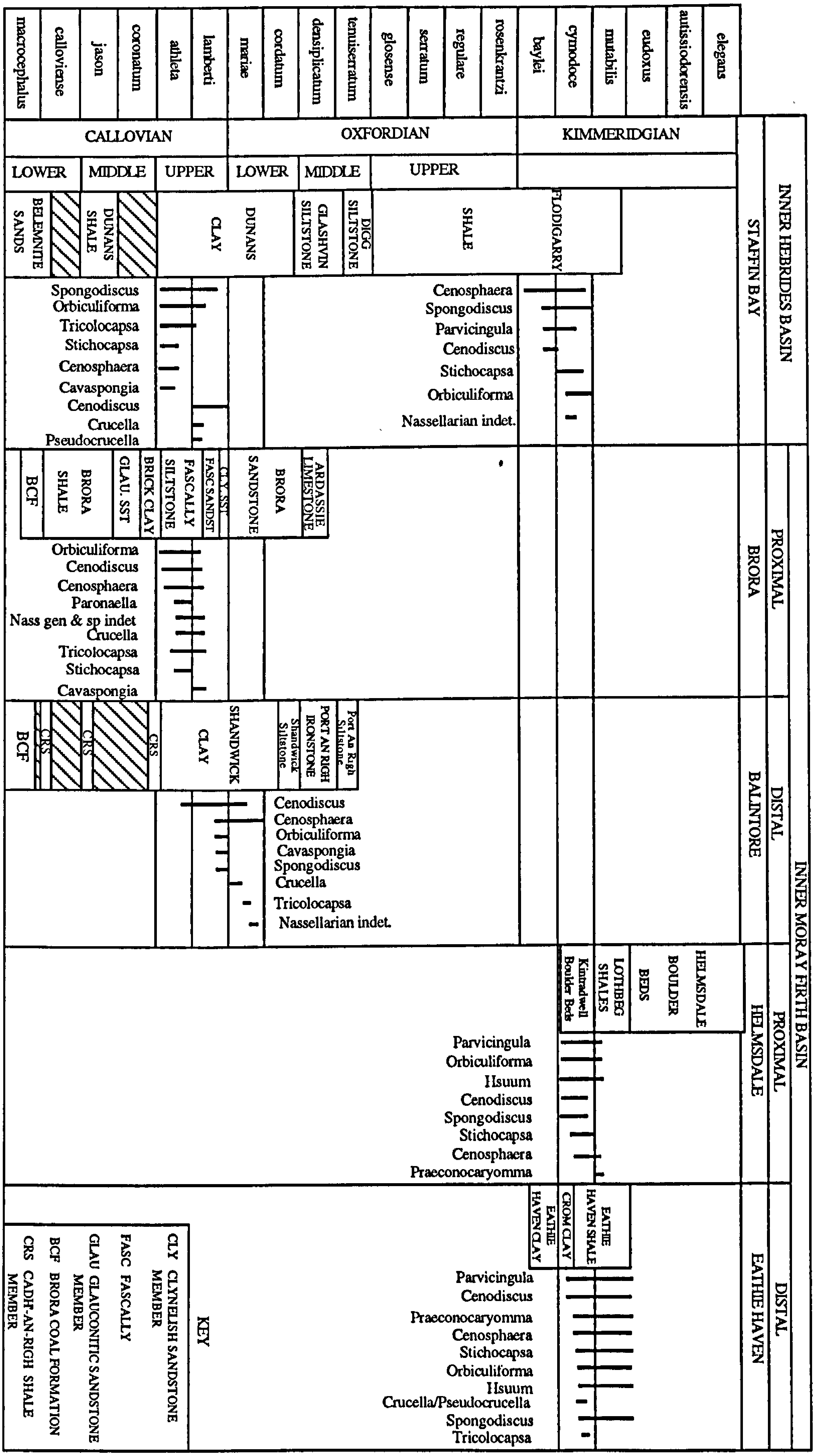


Figure 7.3. Radiolarian distribution in the Hebrides and Inner Moray Firth Basins plotted against facies (members) and ammonite biostratigraphy

whilst Staffin Bay has moderate to low diversities and low abundances. The total generic compositions appear to be generally similar, but there is however, better correlation between Eathie Haven and Helmsdale. Particular common taxa include ***Parvicingula blowi*, *P. blowi*** ssp. A, ***Cenodiscus*** spp., ***Cenosphaera*** spp., ***Orbiculiforma mclaughlini*, *Stichocapsa devorata*, *Praeconocaryomma hexagona*** and ***Hsuum*** sp. 1. All sites are marked by 'pulse' occurrences. Overall, Helmsdale was dominated by nassellarians, Eathie Haven was initially dominated by parvicingulids and then spumellarians, this latter distribution pattern is similar to that at Staffin Bay.

7.2.7. Comparison with Published Biozonations

Historically, few biozonal schemes have been erected throughout the world for the Middle and Upper Jurassic, especially in comparison with the number that have been constructed for the Lower Jurassic (see Copestake & Johnson, 1989). This absence may be in part due to the difficulties inherent in the facies dependent nature of benthic foraminiferal distribution, possibly related to the evolutionary maturity of the lagenids in the Middle and Upper Jurassic, a group which appeared to be more adaptive in the Lower Jurassic. Schemes have been erected predominantly for the Northern Hemisphere, particularly for the northern Boreal Province, which place heavy use on agglutinated dominated faunas. These would appear to be more facies restrictive in their requirements. Whether this agglutinated dominance is an original feature of the faunal character, or is due to dissolution of an originally calcareous fauna is open to debate. However, given that these faunas are often the only element actually recovered from northern Boreal deposits, attempts have been made to develop biozonations, at least on a localised scale.

Figures 7.4 and 7.5 illustrate the majority of the more important and complete published biozonations and datum levels for the Middle and Upper Jurassic. These sites are predominantly located in the Boreal Province and include the Russian Platform, onshore western and offshore eastern Canada, Svalbard and Alaska. All show similarities in terms of the gross faunal development and a dominance of agglutinated taxa, particularly throughout the Upper Oxfordian and Kimmeridgian. This is a feature which characterises similarly aged deposits from the Scottish basins, with the exception of Helmsdale which was influenced by a unique set of palaeoenvironmental factors. Previously published biozonations for the onshore UK successions, which should provide type sections, are almost non-existent. Those that have been produced have been generally based on small isolated parts of successions, using markers which are distinctive, but somewhat limited due to their facies dependent distribution (e.g. Medd, 1983).

The more relevant biozonations are discussed in a little more detail below. However, comparison with previously erected schemes can be difficult as the actual methodology used to define the biozonal definition is often missing, or ambiguous.

One of the first attempts at a foraminiferal biozonation was by Bartenstein & Brand (1937) for the Lias to Callovian succession of Germany. They attached

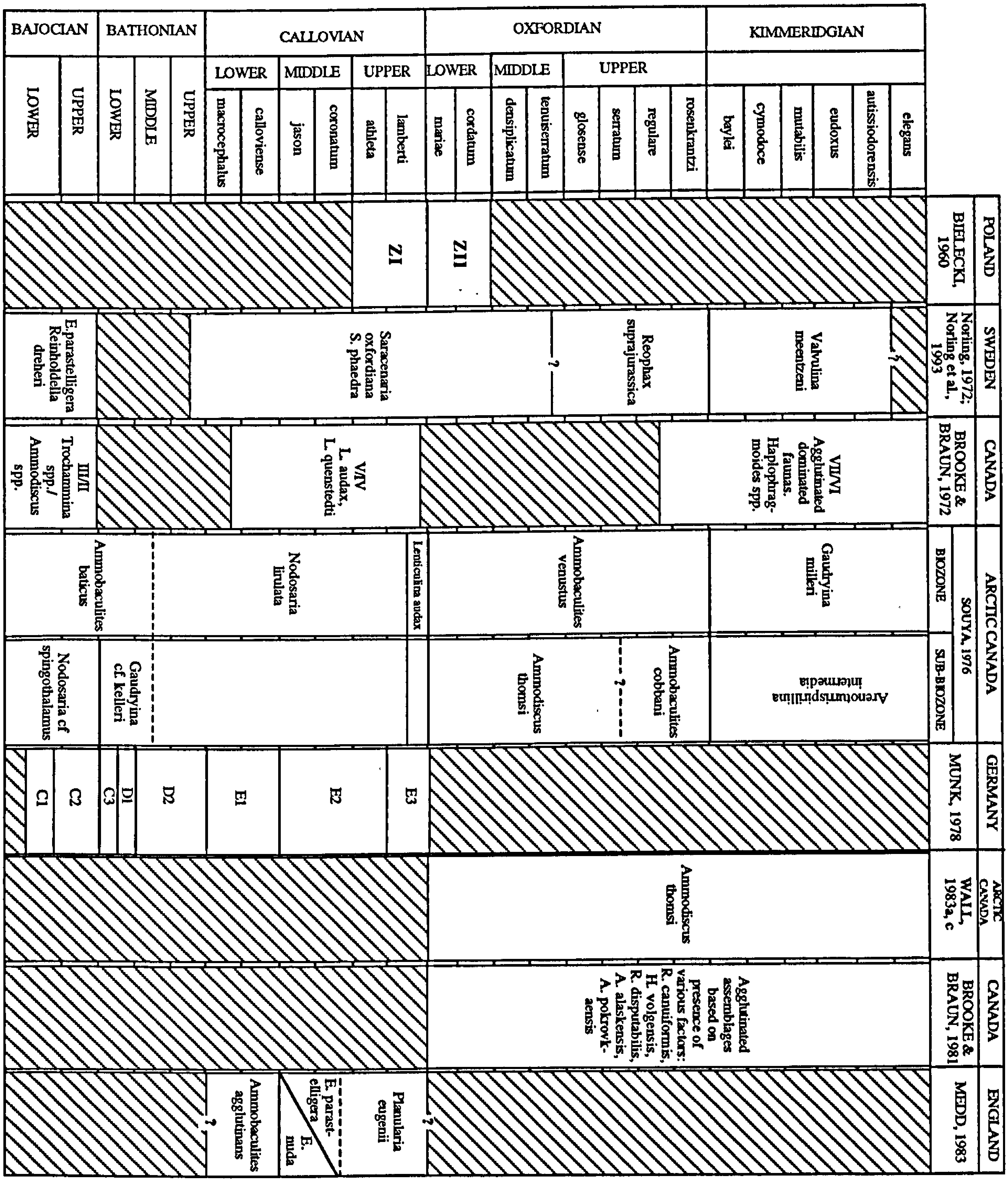


Figure 7.4. Previous Middle and Upper Jurassic foraminiferal biozonation schemes. Part A

biostratigraphical importance to the generic status of the faunas, as well as noting restricted specific taxa, such as the first appearance of ***Lenticulina quenstedti*** within the Lower Bajocian.

Bielecka (1960) divided the Polish Upper Callovian and Lower Oxfordian into several biozones. Only two can be confidently placed, however, as their stratigraphical range could not be ascertained from the text. ZI, within the Upper Callovian, was characterised by an abundant lagenid and robertinid fauna. This is similar to faunas developed in the Scottish Basins. Interestingly, she also indicated that radiolaria occurred in this biozone, which allows good correlation with the Scottish material. ZII was similar in faunal composition, but with no radiolaria, which is also relatively close to the Scottish material.

Norling (1972) established a broad biostratigraphical biozonation for the entire Jurassic of Sweden, which was initially developed on borehole material and was later expanded to cover outcrop (Norling ***et al.,*** 1993). Unfortunately, the ammonite biostratigraphy was not well defined due to the absence of biozonal forms. Middle Jurassic strata were predominately non-marine, leading to poor recovery except from thin marine incursions. The Upper Jurassic biozonation was based almost wholly on core material and 4 biozones were developed. These show a very rough correlation with the Scottish material in that the Callovian to Middle Oxfordian was dominated by calcareous taxa, whilst the Upper Oxfordian and Kimmeridgian were dominated by agglutinated forms. However, none of the biozonal forms nominated were recovered from the Scottish area.

Brooke & Braun (1972, 1981) produced broad biozonations for deposits in Northern Canada and Oregon. The Bajocian was characterised by ***Trochammina*** spp. and ***Ammodiscus*** spp., the Callovian by ***Lenticulina quenstedti*** and ***L. audax*** and the Oxfordian to Kimmeridgian demarcated by a wide range of agglutinated foraminifera.

Dain (1972) devised a highly detailed biozonation for many Russian areas based on the predominately agglutinated faunas. However, there appear to be discrepancies in the ammonites used for subdivision and between the semi-regional correlations. Additionally, the microfaunal biozones that were nominated appeared to be highly localised and were correlated laterally with many different biozones. This work is in need of revision, a task which Efimova & Mesezhnikov (1991) did not appear to have attempted. Dain's (1972) taxonomic work is, however, very detailed and appears not to be in question.

Souaya (1976) produced a broad biozonation for the Canadian Arctic area, which was also partially divided by Wall (1983a, c). The Callovian was separated using lagenids, with the Oxfordian to Kimmeridgian broadly divided using agglutinated taxa. None of these taxa were recovered from the Scottish region.

A comprehensive biozonation was devised for the Bajocian to Callovian of Germany by Munk (1978). Her biozones are expanded in a little detail below. Biozones C1 and C2 which characterised the Bajocian were assemblage based and dominated by

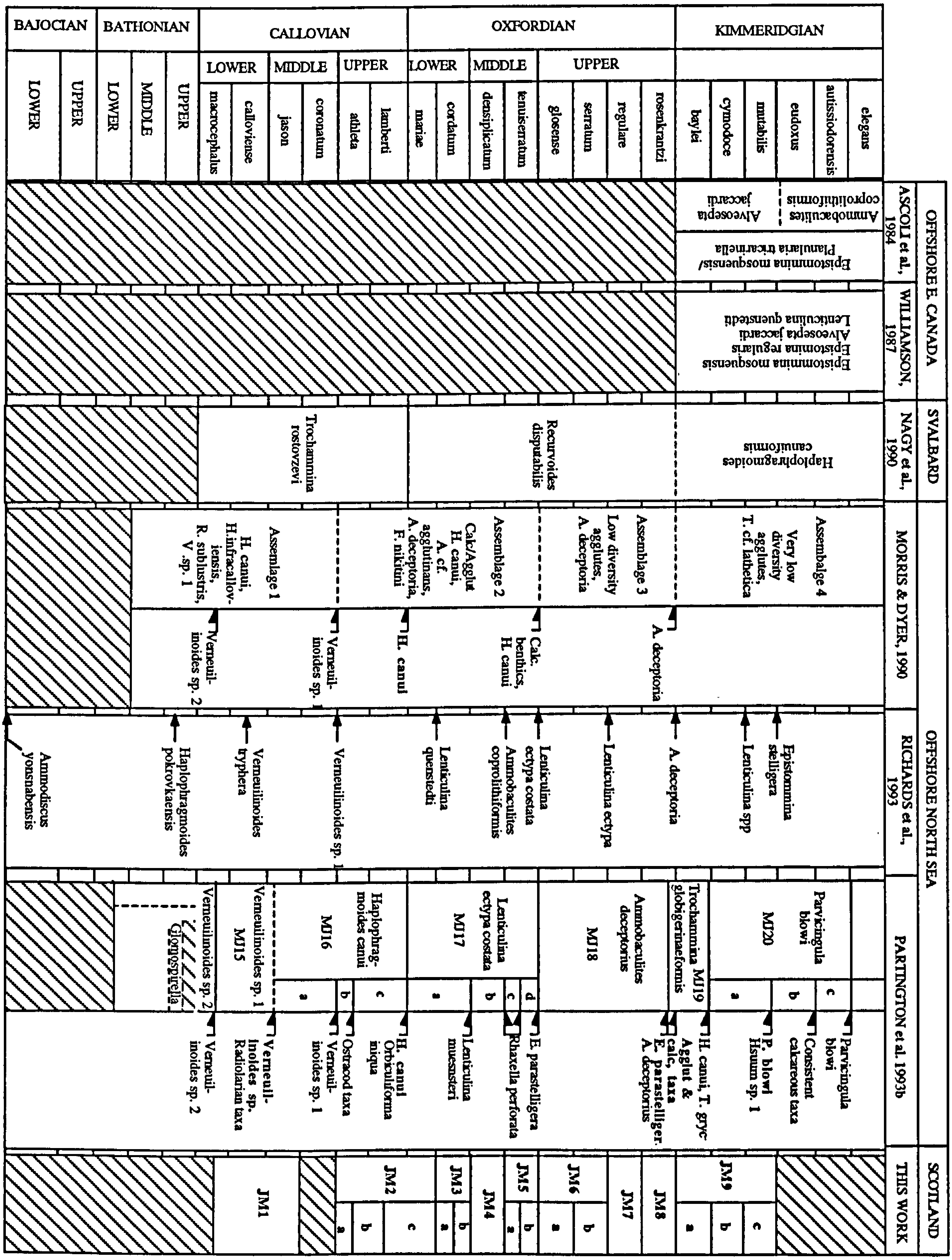


Figure 7.5. Previous Middle and Upper Jurassic foraminiferal biozonation schemes. Part B

miliolids and lagenids with no particular restricted taxa, with the exception that C2 has agglutinated taxa. The Lower to Upper Bathonian was divided into C3, D1 and D2, based on the presence of sculpted lenticulinids. All were characterised by ***Lenticulina dictyodes*** and ***L. volubilis***; C3 was further characterised by the presence of ***Epistomina parastelligera***; D1 by ***L. argonata*** and D2 by ***L. quenstedti.*** E1, which covered the Lower Callovian, was characterised by lenticulinids, robertinids and ***Globuligerina.*** E2 characterised the Middle and majority of the Upper Callovian, with a facies dominated assemblage of lagenids and miliolids. The uppermost biozone, which covered the remaining Callovian, was characterised by ***Epistomina*** spp. and rare ***Globuligerina.*** There are some similarities with the Scottish succession in terms of the overall assemblages, particularly in the Bajocian and the Upper Callovian. The Lower and Middle Callovian were different, however, being characterised by a calcareous dominated fauna instead of an agglutinated dominated one.

Ascoli ***et al.*** (1984) and Williamson (1987) investigated offshore sediments from eastern Canada, which covered the Kimmeridgian to Cretaceous. They both broadly characterised these sequences by agglutinated and calcareous taxa, particularly ***Epistomina mosquensis, Ammobaculites coprolithiformis*** and ***Alveosepta jacardi.***

The Svalbard region has been the focus of intense investigation over the last 15 years, however, there is only one published account of a biozonation, produced by Nagy ***et al.*** (1990a). This region was characterised by an agglutinated dominated fauna from the Callovian to Lower Cretaceous and the succession was divided into stages by agglutinated foraminiferids. However, it is not made clear whether tops, bases or acmes were used in defining the biozones.

Recently, several schemes have been published for the North Sea commercial sector, which all appear to use the same database (Morris & Dyer, 1990; Partington ***et al.***, 1993b; Richards ***et al.***, 1993), listing industrially defined foraminiferal, and more rarely radiolarian, datums of the North Sea offshore sector.

A major criticism of such industrially derived schemes that datum definition is often based on well ditch cuttings samples from which only the 'tops' or extinctions can be relied upon. This methodology, however, reduces the problems associated with using the normal stratigraphical procedure of defining the first evolutionary event, which would be obscured by cavings and contamination from younger uphole sediments during the drilling process. Another restriction is the large sampling interval often used, which averages between 30' and 60'. Additionally, general faunal associations are rarely discussed and more often than not the key taxa are not illustrated or described. Often, a few specimens are deemed sufficient to mark a datum. The major drawback, however, is that there is no independent direct correlation of this foraminiferal data with the standard ammonite biozonations. The ties between the ammonite and microfaunal datums are provided by cross correlation with one of the many standard offshore/onshore palynological zonations available (e.g. Riley & Fenton, 1982; Woollam & Riding, 1983;

Riley *et al.,* 1990; Riding & Thomas, 1992). This probably results in an associated loss of resolution and information.

The microfaunal datums and biozones generated from these studies are included in Figure 7.5 for completeness. Generally, there appears to be good correlation between the scheme developed herein, based on a wide range of biozonal types, and those discussed below.

Morris & Dyer (1990) produced a broad assemblage biozonation for the North Viking Graben which, additionally utilised information from Morris & Coleman (1989). They erected 4 assemblage zones based on predominantly agglutinated foraminiferids which were tied to some major stage boundaries. Assemblage 1, which covered the Middle Bathonian to Middle Callovian, was characterised by agglutinated dominated assemblages such as those seen in the Lower to Middle Callovian of the Scottish region, with a dominance of ***Haplophragmoides*** ssp. and ***Recurvoides sublustris.*** Assemblage 2 covered the interval from the Upper Callovian to Middle Oxfordian and comprised a mixed fauna of lagenid taxa, particularly ***Lenticulina ectypa,*** and agglutinated taxa including ***Haplophragmoides canui***, ***Ammobaculites*** cf. ***agglutinans*** and ***A. deceptoria.*** Assemblage 3 delimited the Upper Oxfordian and was characterised by low diversity, agglutinated dominated faunas, the most common taxon being ***A. deceptoria.*** Assemblage 4 covers the Kimmeridgian and was typified by low diversity, agglutinated faunas dominated by ***Trochammina*** cf. ***lathetica.*** All the assemblages are similar to those developed in the onshore successions, with the exception that there are fewer calcareous forms and the faunas tend to be lower in diversity and abundances.

Richards ***et al.*** (1993) produced a lithostratigraphical nomenclature for the North Sea Jurassic and included an event driven biostratigraphy based on the extinction of taxa from the Bajocian to Kimmeridgian. This was based on details provided by Cox (1990), who in turn derived his information from Morris & Coleman (1989), Shipp (1989) and Morris & Dyer (1990). All the events are indicated on Figure 7.5.

The scheme developed by Partington ***et al.*** (1993b), which utilises some of the present author's unpublished data, is the most complete bizonation to date and shows reasonable correlation with the onshore material. The scheme of Partington ***et al.*** (1993b) is outlined in Figure 7.5 and is based primarily on acme tops and extinctions and is commercially driven, hence the limitations discussed above apply to this dataset. It is the only published account which integrates foraminiferal and radiolarian datums (again some of these radiolarian datums have been provided by the present author's research). Radiolaria have been of particular importance within the Kimmeridgian to Ryazanian of the North Sea, especially within the deeply buried and therefore high temperature/high pressure wells of the Central Graben, where the organic walled palynoflora has been destroyed, thereby limiting the primary biostratigraphic tool of the commercial sector.

Overall, the Callovian was characterised by agglutinated faunas, associated with radiolarian datums. The Lower and Middle Oxfordian was characterised by a calcareous dominated fauna, with the Middle/Upper Oxfordian boundary marked by a major influx of agglutinated taxa, which were only modified in the Lower Kimmeridgian by the occurrence of calcareous taxa and radiolaria. These events all show good correlation with the onshore Scottish material. However, as previously noted, the faunas derived from the North Sea commercial work are lower in diversities and abundances, which could be attributed to the more distal localities in the North Sea Basins, compared with the more proximal sediments of the Inner Moray Firth Basin.

7.3. Palaeoenvironmental Interpretation and Correlation

7.3.1. Introduction

The various palaeoenvironmental interpretations presented for each section in the study area have been generated through an integration and comparison of microfaunal assemblages, or groupings, and macrofaunal distribution (particularly ammonites, belemnites and bivalves) and also from facies types. The major foraminiferal and radiolarian patterns are assessed here and then correlated at inter and intra basinal levels.

7.3.2. Foraminiferal Assemblages

The exact ecological ranges of microfaunas from the Middle and Upper Jurassic do not appear to coincide with their modern day equivalents, whose requirements can be derived from direct observation of modern environments; therefore, uniformitarianism cannot be consistently applied. Evidence has to be gathered from an analysis of the facies present.

Foraminiferal assemblages have been studied here in terms of the major suborders present, taking into account the importance of a predominance of particular groups. Where substrate conditions were at an optimum and where there were sufficient niches and nutrients present a mixed assemblage, with all the suborders may have developed. However, where one or two groups begin to assume ascendance, this may have occurred as a direct consequence of ecological pressures caused by an environmental change. Such change would cause selection pressure, which would then produce a particular assemblage apparently adapted to survive or excel under such conditions. Assemblages based upon a dominance of one, or a few, of the suborders can possibly be used to indicate a particular depositional regime. When assessed throughout an evolving basin, such a study may help reconstruct the palaeoenvironmental changes that occurred.

Various parameters which may have been responsible for producing a particular group's dominance are raised below. The Scottish sections are subsequently discussed (Section 7.3.4) in terms of the assemblages present and points of correlation are suggested.

Lagenids were a very important component of Jurassic assemblages, but it is apparent that they did not totally dominate in the majority of the nominated assemblages in proportional terms. However, they were more often than not the most diverse in terms of species numbers and were often the common factor occurring in all but the most extreme habitats. This is contrary to their modern day distribution patterns, where they form a minor component of most shelf conditions and appear to be successful only in deeper environments (Sliter, 1972).

Within the Jurassic this group also appear to be adaptive to many specific niche types. In particular, robust taxa such as ***Lenticulina, Planularia, Citharina, Eoguttulina*** and costate dentalinids were probably indicative of a shallow infaunal and mobile lifestyle, being adapted to a higher energy environment. Therefore, in abundance, they can be used to pinpoint shallower or regressive conditions. Some lenticulinids were also adapted for mobility within the sediment as indicated by possessing a sharp keel. As there appears to be no evidence of an attached mode of life, they were probably absent from the highest energy environments, unless they could adapt their test shape to the surroundings. Hitchings (1980) recorded a lenticulinid which appeared to be able to secrete its test into limited 'spaces'.

The only faunas in the Scottish area where lagenids form a substantial relative proportion were within mixed assemblages. These occur; within the mixed assemblage in the ***tenuiserratum*** Biozone of the Staffin Bay section; within the miliolid dominated assemblages at Bearreraig Bay; and within the Fascally Siltstone Member at Brora where they occur with agglutinated taxa. The common factor in all of these assemblages is all were apparently shallow water and relatively higher energy environments, dominated by a silty, muddy sediment. The distinction between assemblages many have been caused by differing levels of organic debris input, an excess of which would start building up restrictive substrate conditions.

Whatever the ecological requirements of lagenid taxa, some have proved to be particularly useful from a stratigraphical point of view as they appeared to be able to colonise a wide range of Middle and Upper Jurassic habitats. This is also true for the Lower Jurassic, especially for species of ***Lingulina*** and ***Frondicularia***. The particular genera that belong to this adaptive group in the Middle and Upper Jurassic include ***Lenticulina, Marginulina, Planularia*** and ***Nodosaria***.

Spirillinid dominated assemblages only occurred at Helmsdale, which was influenced by an unusual set of parameters. The assemblages were dominated in particular by ***Spirillina tenuissima*** and, to a lesser extent, by ***S. infima*** and ***Conicospirillina trochoides***. A dominance of spirillinids is taken, from facies evidence and from a comparison with modern sediments and Jurassic palaeoecological studies of Stam (1986) and Johnson (1976), to indicate a shallow, marine environment. It was also well oxygenated, at least at the substrate/sea water interface, as indicated by the associated infaunal macrofauna. The main factor of interest is that this environment was probably affected by wave base activity, where an ability to attach to plant/algae and substrate would be advantageous. Spirillinids appear to have a consistent adaptation for this lifestyle (Myers, 1935, 1936; Murray, 1973; Brasier, 1975; Haynes, 1981). Actual sediment may also have been limited in this particular substrate, as it appears to have been regularly stripped from this environment by tectonic activity. This would probably have limited the presence of other groups, except those robust enough to withstand such buffeting, such as robust and costate lagenids.

Some authors have placed spirillinids in both shallow and deep water environments (e.g. Stam, 1986). This may also have occurred as a consequence of their epifaunal attached habit, which removed the need to exploit an infaunal environment, which could have been dysaerobic. This may explain the presence of small numbers of spirillinids in the distal and moderately deep water setting at Eathie Haven within the ***mutabilis*** Biozone. Associated infaunal elements were almost absent from this interval at Eathie Haven, indicating dysaerobic substrates.

Miliolid dominated assemblages appear to indicate a moderately shallow, well oxygenated environment. This overall conclusion is generated from a combination of the dominance of these forms in silty shales, which were apparently well oxygenated as indicated by the presence of bioturbation, and a wide range of bivalves with differing ecological requirements. Other authors have also concluded that this assemblage was indicative of shallow waters. This includes include study of Jurassic sediments from the Polish Lowlands by the authors as discussed in Chapter 2; Section 2.2.3. Barnard ***et al.*** (1981) also suggested a shallow water preference for these taxa from the Middle and Upper Jurassic of Southern England. Taken as a group, miliolids may have been able to colonise proximal environments more successfully than, say, lagenids due to an attached mode of life.

Two types of environment appear to be present within the Scottish basins that were colonised by a higher proportion of miliolids.

The first is marked by a dominance of taxa such as ***Palaeomiliolina,*** as seen at Bearreraig Bay, and common ***Ophthalmidium,*** within the Staffin Bay and Balintore successions. ***Palaeomiliolina*** occurred in a silty shale, which would have been a relatively firm substrate, and as such this may suggest a shallow infaunal or epifaunal lifestyle. The elongate test shape suggests the former in this case. Many of the Jurassic forms of ***Ophthalmidium*** had a flattened test shape which may therefore have been adapted to either a shallow infaunal or a surface, epifaunal lifestyle. In the case of a soupy substrate, a flattened test shape would aid 'buoyancy'. Additionally, input of sediment would not overwhelm such a semi-mobile assemblage.

The second, miliolid dominated, assemblage is characterised by ***Nubeculinella*** (or ***Nubecularia***) which is most often cited as developing as an attached form. This was first suggested by Berz (1931). If this form were attached to surface objects or to a hardground substrate, any rapid deposition would cause it to be buried beyond its optimum survival range. Therefore, common occurrence of such taxa probably points to sediment shut off or starvation. Alternate cycles of sedimentation and sediment starvation would give rise to the typical 'flood' or seesaw distribution patterns, whereby attached foraminiferids expire after periods of rapid deposition and flourish in periods of non deposition.

Robertinid dominated faunas can be a common feature of some Middle and Upper Jurassic assemblages and hypotheses have been put forward for this, with the majority favouring a relatively deep water environment (e.g. Stam, 1986). This conclusion may have arisen due to a uniformitarian approach, but as is the case with the lagenids in modern sediments, they appear to have had their total niche capabilities curtailed by more effective competition from successful Recent groups.

In the Scottish sections, the dominant form was the robust and smooth form ***Epistomina parastelligera***, which was recovered mainly from siltstones, also often rich in organic debris (R1 assemblage). This association therefore appears to occur in relatively shallow shelf environments. A similar shallower, shelf habitat was suggested by Barnard ***et al.*** (1981). The relevant Scottish environments were affected by high sedimentation rates and the 'streamline' test shape of ***Epistomina*** suggests that this form could have been mobile. It could have, therefore, maintained a relative optimum position in a rapidly changing substrate, which may have excluded other less mobile and infaunal groups.

Therefore, the presence of large numbers of robertinids could directly reflect an adaptation to such a high energy environment. Alternatively, their presence could be explained by a chemical factor. Aragonite is highly susceptible to dissolution, thus, a high sedimentation rate may remove foraminiferal tests from contact with circulating sea water by burial. This may then limit dissolution. In reality their actual survival in the Jurassic fossil record was probably related to a combination of these two factors.

The presence of often diverse and abundant, agglutinated dominated faunas from the Middle and Upper Jurassic is an unusually pervasive feature of the Boreal Province. Records include Arctic Canada, British Columbia, Svalbard, offshore North Sea, the Barents Sea, northern Russia and Siberia (see Chapter 2 and Figure 7.9 for distributions). This also compares well with material recorded from Staffin Bay, in which microfaunas dramatically change from a calcareous dominated to an agglutinated dominated assemblage with the transition from Middle to Upper Oxfordian.

The debate surrounding these assemblages focuses on whether they represent an original assemblage or a relict dissolution fauna. The major assumption is that agglutinated foraminiferids were more tolerant of the oxygen depleted bottom waters that led to the deposition of the often dysaerobic shales characteristic of the Oxfordian and Kimmeridgian. Further evidence has been gathered here regarding the macrofaunal content and facies type. The additional presence of radiolaria in the Kimmeridgian, and indeed palynomorphs such as dinoflagellates throughout the Jurassic, suggest that there was at least an active sea water circulation and water mass oxygenation. Stratification of such water masses could have led to sluggish bottom water circulation, which would have produced an oxygen deficient substrate.

Whatever the reason for the dominance of agglutinated foraminiferid assemblages, their usefulness is undoubted, particularly in at least delimiting local and sub-regional biostratigraphy and palaeoenvironmental relationships in the North Sea area (e.g. Morris & Coleman, 1989; Morris & Dyer, 1990; Partington ***et al.***, 1993a, b).

Nagy (1985a, b, 1992), Nagy ***et al.*** (1990b) and Nagy & Johansen (1991) related foraminiferal assemblages to facies, correlating moderately diverse agglutinated dominated faunas with 'organic-lean' shelf regions. A high dominance of ***Ammodiscus*** represented terrestrial influences, whilst organic rich silts were reflected by a high abundance of ***Haplophragmoides*** spp. Distal deltaic conditions were typified by a low diversity and dominance of ***Trochammina, Verneuilinoides*** and ***Reophax.*** Proximal deltaics differed, being dominated by either lagenids and spirillinids or with a total dominance of agglutinates, reflecting a change in environment from normal marine shelf to one dominated by low diversity agglutinates. The sediments present within the Scottish area do not represent deltaic conditions, but this does not detract from palaeoenvironmental similarities between the faunas and their development.

Within the Scottish region a wide range of habitats were exploited by agglutinated foraminiferids, which also appeared in large numbers in the mixed assemblages. However, there were three agglutinated dominated assemblages, which appear to represent specific conditions. The first (characterised as assemblage A1 at Staffin Bay) is a very low diversity and low abundance fauna represented by opportunistic taxa including ***Reophax, Haplophragmoides*** and ***Trochammina.*** All of these appear to have exploited oxygen deficient, possibly dysaerobic niches, which were high in organic debris and possibly affected by salinity fluctuations. Habitats exploited were either shallow infaunal, or epifaunal, as detritivors and deposit feeders, which would have been an advantage in such a setting. The next assemblage type (A2) was not particularly pervasive in the Scottish region and was represented by a relatively mixed assemblage, with common ***Haplophragmoides, Reophax, Lagenammina*** and ***Gaudryina.*** Lagenids such as ***Lenticulina, Dentalina*** and ***Eoguttulina*** were of localised importance, along with the robertinid ***Epistomina.*** This assemblage probably reflected a more equitable environment, which allowed an agglutinated assemblage to develop related to a particular facies type, influenced by moderately rapid sedimentation and input of silty material. Lloyd (1959) attempted to relate such agglutinated distribution patterns with availability of test building material, which may explain the prevalence of agglutinated taxa here. The third assemblage (A3) was characterised by a diverse and abundant agglutinated, dominated fauna, almost to the exclusion of calcareous fauna. A wide range of agglutinated foraminifera were recorded, especially ***Haplophragmoides, Trochammina, Recurvoides, Gaudryina, Ammobaculites, Reophax*** and ***Spiroplectammina.*** All of these taxa were probably shallow infaunal or epifaunal with some mobility and were deposit feeders/detritivors which meant that they could take advantage of the high organic debris present. This facies was probably deeper water and more distal, as also indicated by the presence of radiolaria, with an oxygen depleted substrate, as indicated by the limited macrofaunal bivalve content.

7.3.3. Radiolarian Distribution

Jurassic planktonic radiolaria were a more important component of the microfaunas in relation to modern day environments and other holoplanktonic groups such as planktonic foraminiferid. They also provided an important source/sink of silica before the apparent establishment of common marine diatoms in the Cretaceous.

Radiolarian faunas were particularly well developed in the Upper Callovian and Kimmeridgian of the Hebrides and Inner Moray Firth Basin and were useful for biozonation and palaeoenvironmental analysis.

As indicated previously, radiolaria have been most commonly recovered from radiolarites from Middle and Upper Jurassic geosynclinal areas (Chapter 2 for details; Figure 7.9). There have been several hypothesises put forward for the distinctive Middle and Upper Jurassic radiolarite distribution that developed in the Mediterranean, Californian and Japanese basins. Jenkyns & Winterer (1982), in their sedimentological, palaeoceanographical and geochemical study, recorded that the most common radiolarian deposits were ribbon radiolarites. These have a distinctive repetitive bedding pattern of cherts intercalated with argillites and were present in deeper water orogenic belts, derived as thrust sheets, ostoliths or as part of a mélange. Within the Tethyan regions, these radiolarites extended throughout the Jurassic, whilst in the Boreal and Sub-Boreal Californian Franciscan and Great Valley sequences they were generally Middle to Upper Jurassic in range.

Interestingly, authors including Ramsey (1973) and Steinberg (1981) have indicated that radiolarite deposition was common in the Middle/Upper Jurassic as a consequence of 'privileged' siliceous sedimentation related to a set of unique oceanographic factors, including upwelling. Jenkyns & Winterer (1982) also hypothesised that these radiolarites were established in numerous small basins, which became rich in siliceous organisms due to the effects of small basin hydrology. This included efficient nutrient cycling, associated with deep water inflow and shallow water outflow.

However, both the North Sea and Hebrides area were relatively shallow, epi-continental seas within the Jurassic (Brown, 1984) and, as such, connection to more open marine situations would not always have been established and may have been threatened during regressive, low relative sea-level events.

The presence of radiolaria within an epi-continental sea, in the Jurassic, was probably due to the enrichment of the water column with silica as well as the necessary establishment of other factors. Enrichment with silica, which is not usually the norm in sea water masses (Broecker, 1974), could have been as a direct response to the presence of volcanic activity and an associated hydrographic change. Deepening and improved circulation would produce a higher nutrient level in the upper water mass, due to movement of lower latitude surface water. This probably led to improved surface water mixing and upwelling. The stratified nature of the Kimmeridgian water mass, suggested by Cox & Gallois (1977) and Tyson *et al.* (1979), may also support this latter explanation. Limited Jurassic volcanic activity has been recorded from the Central North Sea and the associated deposits are widely distributed throughout the Forties area and the Outer Moray Firth Basin (Smith & Ritchie, 1993). There were four main Jurassic eruptive areas, which were particularly active during the Aalenian-Bathonian and Callovian (Smith & Ritchie, 1993). Little volcanic activity occurred in the Oxfordian and younger sediments. However, crustal extension during the period of latest Oxfordian to Volgian led to erosion and subsequent derivation of volcanic debris. Therefore, material could have been liberated which would then have provided a silica source during the Callovian through the Kimmeridgian. This was also associated with a deepening water column during transgressive events. Together these factors probably alleviated the normal undersaturation of sea water with respect to silica. This would enable positive secretion of a siliceous test and also give a reasonable chance of preservation before diagenetic reclamation and subsequent mobilisation of the siliceous skeletal lattice.

An additional factor which can be seen to have been of some consequence for the preservation of radiolaria in the Hebrides and Inner Moray Firth Basins during the Callovian and Kimmeridgian is the observation (Ramsey, 1973; De Wever, 1983; Koutsoukos *et al.*, 1990) that radiolaria appear to be preferentially preserved in environments rich in organic carbon matter. Such conditions are related to transgression and the development of a restricted environment. Restricted regimes would limit oxidation of siliceous test material and allow the test to be buried before eventual, subsequent dissolution. If dissolution did take place then at least the test had a chance to be preserved in other diagenetic materials such as pyrite, calcite, glauconite or even secondary silica. The radiolaria recovered from the Scottish areas were often preserved in such materials.

7.3.4. Regional Palaeoenvironmental Correlation

This section considers all of the evidence generated from the Middle and Upper Jurassic of the Scottish basins using a palaeoenvironmental approach (Figs. 7.3, 7.6). The microfaunal assemblages, which have been discussed in terms of either the dominance of one group or as mixed faunas, are assessed within evolving basins. The Staffin Bay succession acts as a template as it is the most complete succession in the study area. The results of relative sea-level changes on a fixed point in a basin depend on the relative locality of the site. It is possible to assign a rough proximal/distal attribution for the sites based on a combination of the facies type, the relative thickness of the sequence (i.e. whether there are any condensed or expanded successions) and from an analysis of the major microfaunal group distribution. The various sites in the Inner Moray Firth Basin have already been set into their sub-regional context with Balintore and Eathie Haven both representing distal equivalents to their respective successions at Brora and Helmsdale. This section examines the similarities and differences between sites.

Relative sea-level changes appear to produce particular microfaunal responses, particularly in relation to transgressions, regressions and periods of stabilisation. This is due directly to the facies dependent distribution of benthic taxa. Planktonic radiolaria were also indirectly affected by relative sea-level changes, which could limit or favour development of optimum conditions for survival and exploitation. The initiation, specific faunal characteristics and extent of these assemblages do, however, vary according to the

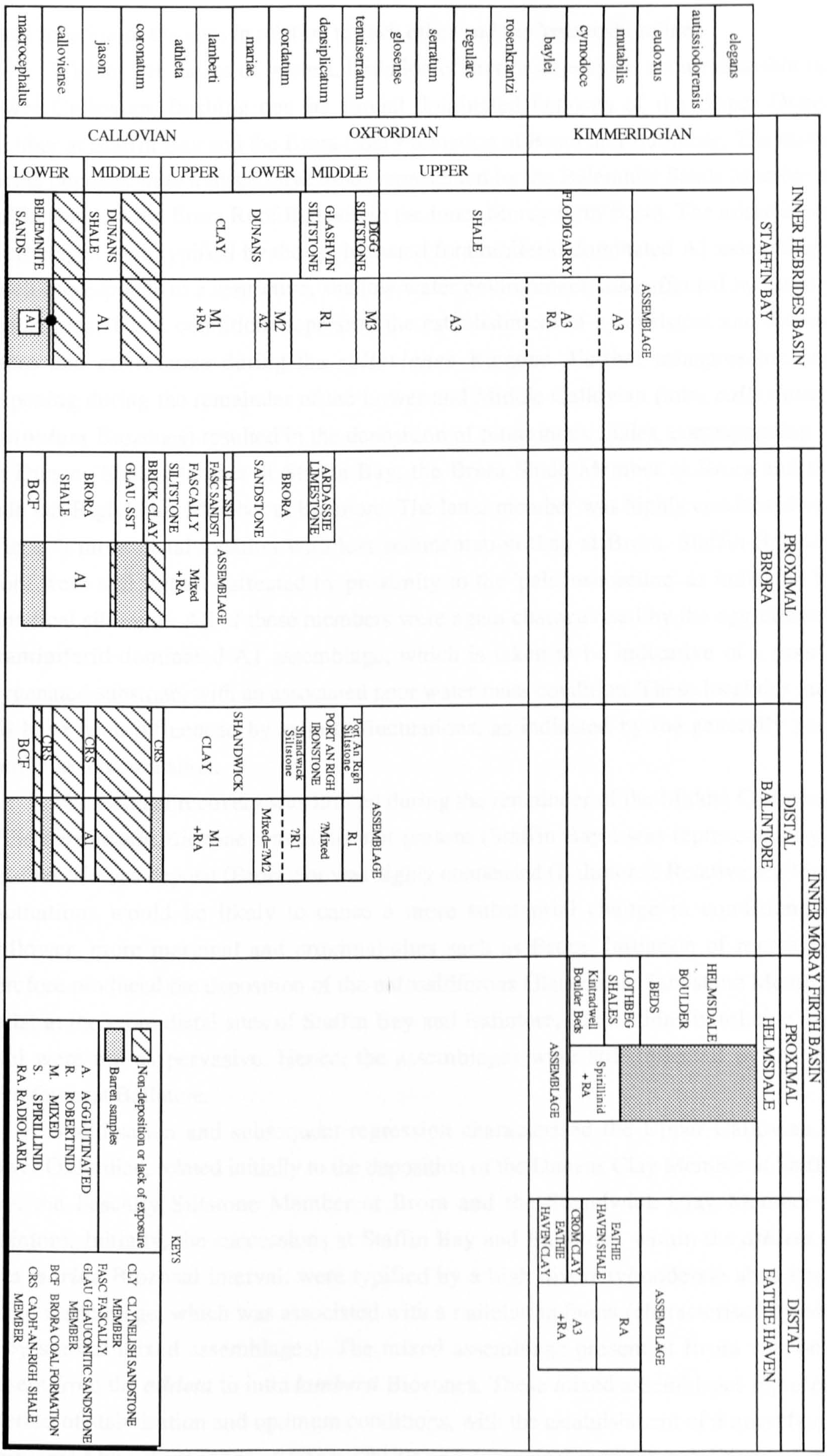


Figure 7.6. Microfaunal assemblage distribution in the Hebrides and Inner Moray Firth Basins plotted against facies (members) and ammonite biostratigraphy

actual location of the sites in relation to each other and the 'palaeoshoreline'.

Within both basins of interest, initiation of marine deposition occurred within the Lower Callovian, flushing out the fluvial dominated deposits of the Upper Ostrea Member at Staffin Bay and the Brora Coal Formation at Brora and Balintore. The initial marine deposits were transgressive sands represented by the Belemnite Sands Member at Staffin Bay and the Brora Roof Bed within the Inner Moray Firth Basin. The microfaunal assemblages were typified by the agglutinated foraminiferid dominated A1 assemblage, which corresponds to a restrictive, shallow water environment, also affected by salinity fluctuations. These conditions repressed the establishment of a consistent and diverse macro and microfauna during the ***calloviense*** Biozone. Further transgression and deepening during the remainder of the Lower and Middle Callovian (intra ***calloviense-coronatum*** Biozones) resulted in the deposition of bituminous shales, corresponding to the Dunans Shale Member at Staffin Bay, the Brora Shale Member at Brora and the Cadh'-an-Righ Shale Member at Balintore. The latter member was highly condensed and reflects a more distal location with less sedimentation than at Brora. Staffin Bay and Brora were still initially affected by proximity to the 'palaeoshoreline' as indicated by periodical silt input. All of these members were again characterised by the agglutinated foraminiferid dominated A1 assemblage, which is taken to be indicative of a poorly oxygenated substrate, with an associated poor water mass condition. These localities may still have been influenced by salinity fluctuations, as indicated by the generally poor ammonite representation.

Microfaunal recovery was limited during the remainder of the Middle Callovian, as the ***coronatum*** Biozone was either not present (Staffin Bay); was represented by a non-fossiliferous deposit (Brora); or was highly condensed (Balintore). Relative sea-level fluctuations would be likely to cause a more substantial change in conditions in shallower, more marginal and proximal sites such as Brora. Initiation of regression therefore produced the deposition of the unfossiliferous Glauconitic Sandstone Member, whilst at the more distal sites of Staffin Bay and Balintore, fluctuations in relative sea-level were not as pervasive. Hence, the assemblages were still reflected by the A1 microfauna at Balintore.

Stabilisation and subsequent regression characterised the Upper Callovian to Lower Oxfordian, related initially to the deposition of the Dunans Clay Member at Staffin Bay, the Fascally Siltstone Member at Brora and the Shandwick Clay Member at Balintore. Initially, the successions at Staffin Bay and Balintore, within the ***athleta*** to intra ***mariae*** Biozonal interval, were typified by a high diversity/moderate abundance mixed assemblage, which was associated with a radiolarian fauna (characterised by M1, or by similar mixed assemblages). The mixed assemblage present at Brora was only present from the ***athleta*** to intra ***lamberti*** Biozones. These mixed assemblages represent a period of stabilisation and optimum conditions, with the establishment of a microfauna represented by a wide range of trophic levels and ecological requirements. Water depth may not necessarily have been very great, as indicated by the moderately diverse, low abundance spumellarian dominated, radiolarian faunas. Balintore and Staffin Bay were still distal sites, whilst the more proximal site at Brora was marked by a higher clastic input and a modified mixed assemblage dominated by lagenids and agglutinated taxa. Radiolaria were still present at Brora, but as Riegraf (1986, 1987b), who retrieved radiolaria, planktonic foraminifera and sponge spicules from the Callovian of Germany, surmised, such faunas could have existed in a shallow shelf, under the influence of upwelling from the south due to the Callovian transgression.

Subsequent regression and additional filling of the accommodation space by sediment characterised all of the sites through the remainder of the Lower to Middle Oxfordian from the intra ***mariae*** to ***cordatum/densiplicatum*** Biozones, with minor deepening during the ***densiplicatum*** Biozone at Brora and Balintore.

This regression is more consistently reflected at Staffin Bay by an increase in silts from the upper part of the Dunans Clay Member to the Digg Siltstone Member, covering the ***mariae*** to ***tenuiserratum*** Biozones. This continued regression was characterised by a change in assemblages. Initially, the agglutinated dominated A2 assemblage was present, within the ***mariae*** Biozone, which may have developed as a result of increased silt input, whilst the substrate was probably still moderately well oxygenated. This was followed by the mixed M2 assemblage within the ***cordatum*** Biozone, which may indicate a period of stabilisation. Rapid sedimentation and an increased input of organic debris within the Glashvin Siltstone Member was reflected by the robertinid dominated R1 assemblage, covering the interval from within the ***cordatum*** Biozone to within the ***tenuiserratum*** Biozone. The final assemblage in this regressive cycle was the mixed M3 fauna within the ***tenuiserratum*** Biozone. It was characterised by an increase in the presence of lagenids, as well as robertinids, and probably developed due to an increase in water energy and the quantity of clastic material in the Digg Siltstone Member.

As indicated above, the pattern over this Lower to Middle Oxfordian interval appears to be more complex at Brora and Balintore. The regressive cycle was established earlier at Brora, from the intra ***lamberti*** to intra ***densiplicatum*** Biozones, due to its more proximal position. This resulted in the deposition of the Fascally Sandstone, Clynelish Sandstone and Brora Sandstone Members from the ***lamberti*** to within the intra ***densiplicatum*** Biozones. A change in the depositional regime is marked by the deposition of the Ardassie Limestone Member during the ***densiplicatum*** Biozone; this may represent a minor deepening. Unfortunately, none of these members yielded foraminifera or radiolaria. At Balintore a similar pattern was recorded, however differences in facies type and a consistent marine fossil record pinpoint this site's more distal locality in the Inner Moray Firth Basin when compared to Brora. The remainder of the Shandwick Clay Member, during the ***mariae*** and ***cordatum*** Biozones, was characterised by a mixed assemblage, which had a low diversity, high abundance pattern. This may equate to the mixed M2 assemblage and represents the initiation of a regressive cycle. Microfaunal recovery from the Shandwick Siltstone Member was poor, however there appears to be some correlation with the robertinid dominated R1 assemblage, indicative of further regression and shallowing during the remainder of the ***cordatum*** Biozone. Deposition of the condensed Port-an-Righ Ironstone Member suggests sediment shut-off and possible deepening. Unfortunately, microfaunal recovery was poor, but that retrieved appears to be mixed. Re-establishment of regression is indicated by the deposition of the thick Port-an-Righ Siltstone Member within the ***tenuiserratum*** Biozone. This member was characterised by the robertinid dominated R1 assemblage and the sediments were carbonaceous rich, silts and fine grained sandstones.

The transition from the Middle to Upper Oxfordian at the ***glosense*** Biozone is marked by the Flodigarry Shale Member of Staffin Bay, which was deposited during a period of major transgression. This led to the flushing of the underlying shallow water deposits and their associated microfaunal assemblages, which resulted in an assemblage solely characterised by the agglutinated dominated faunas of the A3 assemblage. Initially, water and substrate conditions were probably poorly oxygenated through the Upper Oxfordian. The Lower Kimmeridgian, comprising the ***baylei*** to ***mutabilis*** Biozones, was marked by stabilisation of deep waters due to transgression, with a consequent improvement of sea water conditions. This was marked by the introduction of a consistent radiolarian fauna across the basins, associated with the development of a modified A3 assemblage, which also yielded rare calcareous foraminiferid taxa. The remainder of the ***mutabilis*** Biozone at Staffin Bay was marked by the 'normal' A3 assemblage and therefore substrate and water conditions may have worsened due to further transgression.

The Lower Kimmeridgian of the Inner Moray Firth Basin sites at Helmsdale and Eathie Haven can be correlated to Staffin Bay and to each other by specific taxa, although the assemblages do show some differences. The foraminiferal assemblage at Helmsdale, throughout the ***cymodoce*** Biozone and intermittently in the ***mutabilis*** and ***eudoxus*** Biozones, reflects the site's proximity to the 'palaeoshoreline' and was characterised by spirillinid dominated assemblages associated with a diverse and abundant radiolarian fauna. Productive samples at Eathie Haven, from the ***baylei*** and ***cymodoce*** Biozones of the Eathie Haven Clay and Cromarty Clay Members, were represented by the agglutinated dominated A3 assemblage, which as at Staffin Bay was modified initially by the presence of rare calcareous foraminifera and subsequently by a radiolarian fauna from the ***cymodoce*** Biozone. Radiolaria were continuously recovered throughout the ***mutabilis*** Biozone, whereas foraminiferal faunas disappear over this interval as a consequence of further transgression related to the deepening phase of the North Sea Basin (Partington ***et al.***, 1993a, b).

Ternary diagrams based on a combined distribution of foraminifera and the two major radiolarian groups have been plotted (Figs. 7.7, 7.8) to assess whether such a technique can be used for estimating the distance from the 'palaeoshoreline', in a similar manner to the benthic:planktonic ratio. As radiolaria are planktonic, their distribution should be relatively independent of substrate types. This is reflected by their occurrence within a wide range of facies types and assemblages, for example; within the Upper

Callovian/Lower Oxfordian they are associated with a mixed foraminiferal assemblage. The Lower Kimmeridgian at Helmsdale is characterised by an association with a spirillinid assemblage, whilst at Eathie Haven and Staffin Bay radiolaria are associated with an agglutinated dominated foraminiferal fauna.

The ternary diagram for Helmsdale (Fig. 7.7), although interesting is probably best treated with caution, due to the depositional setting with a derived foraminiferal fauna. The plots do show that the radiolarian faunas were dominated by nassellarian taxa, indicative of a moderate depth, which, due to the tectonic setting, was also probably relatively nearshore.

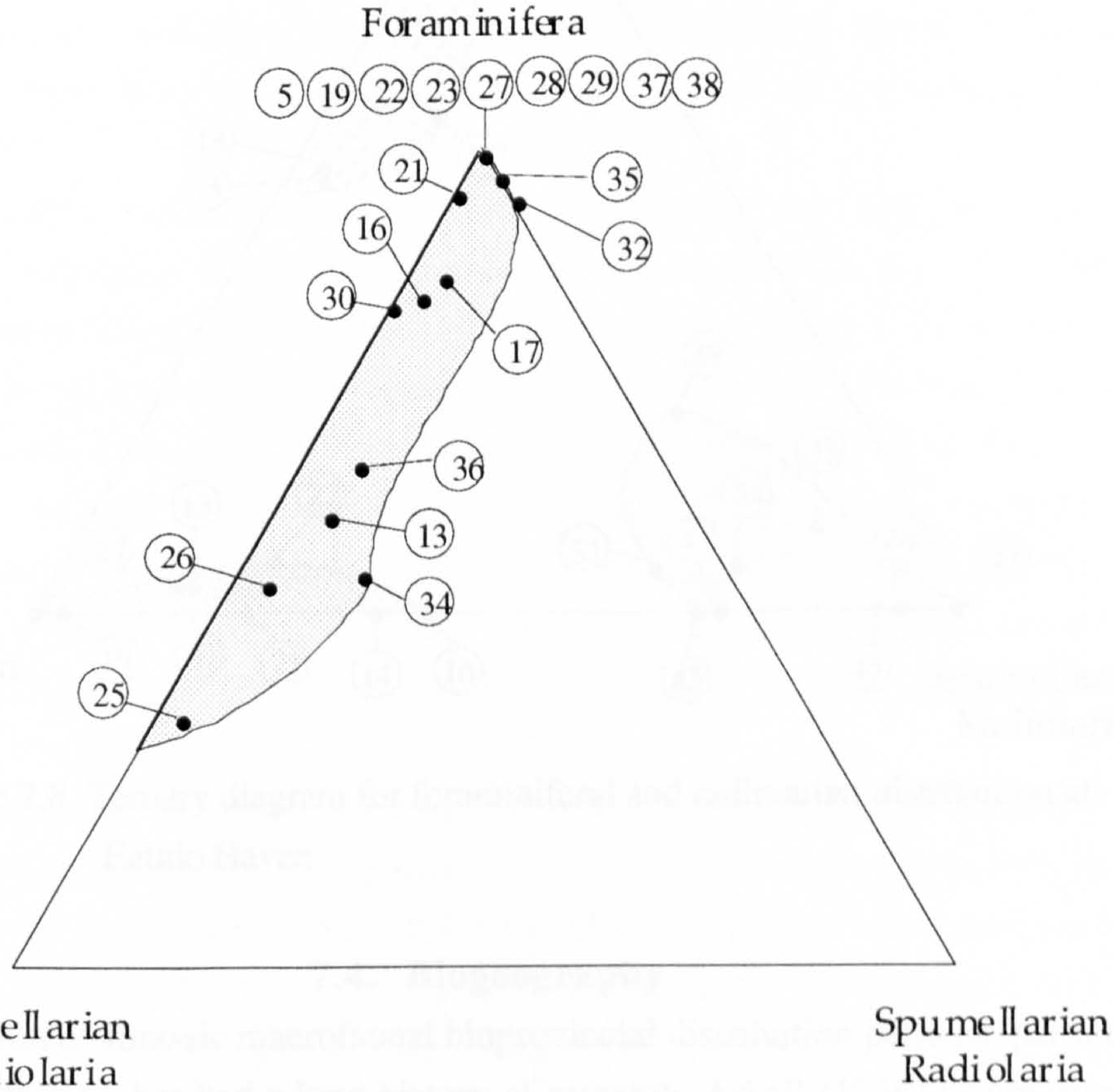


Figure 7.7. Ternary diagram for foraminiferal and radiolarian distribution at Helmsdale

The ternary plot for the assemblages at Eathie Haven (Fig. 7.8) is much more useful, as transport of fossil material is not considered to be an influencing factor. Initially, the samples were dominated by foraminifera which were agglutinated and indicated only a shallow to moderately deep situation. This factor cannot be assessed directly from the plot and is derived from an analysis of the facies. Subsequent productive samples between 12 and 22 were increasingly dominated by nassellarian radiolaria, which corresponds to a basinal deepening and an increasing distance from the 'palaeoshoreline'. Further samples between 31 and 45 were dominated by spumellarian radiolaria, which indicates further deepening with an associated decrease in foraminifera and nassellarian taxa.

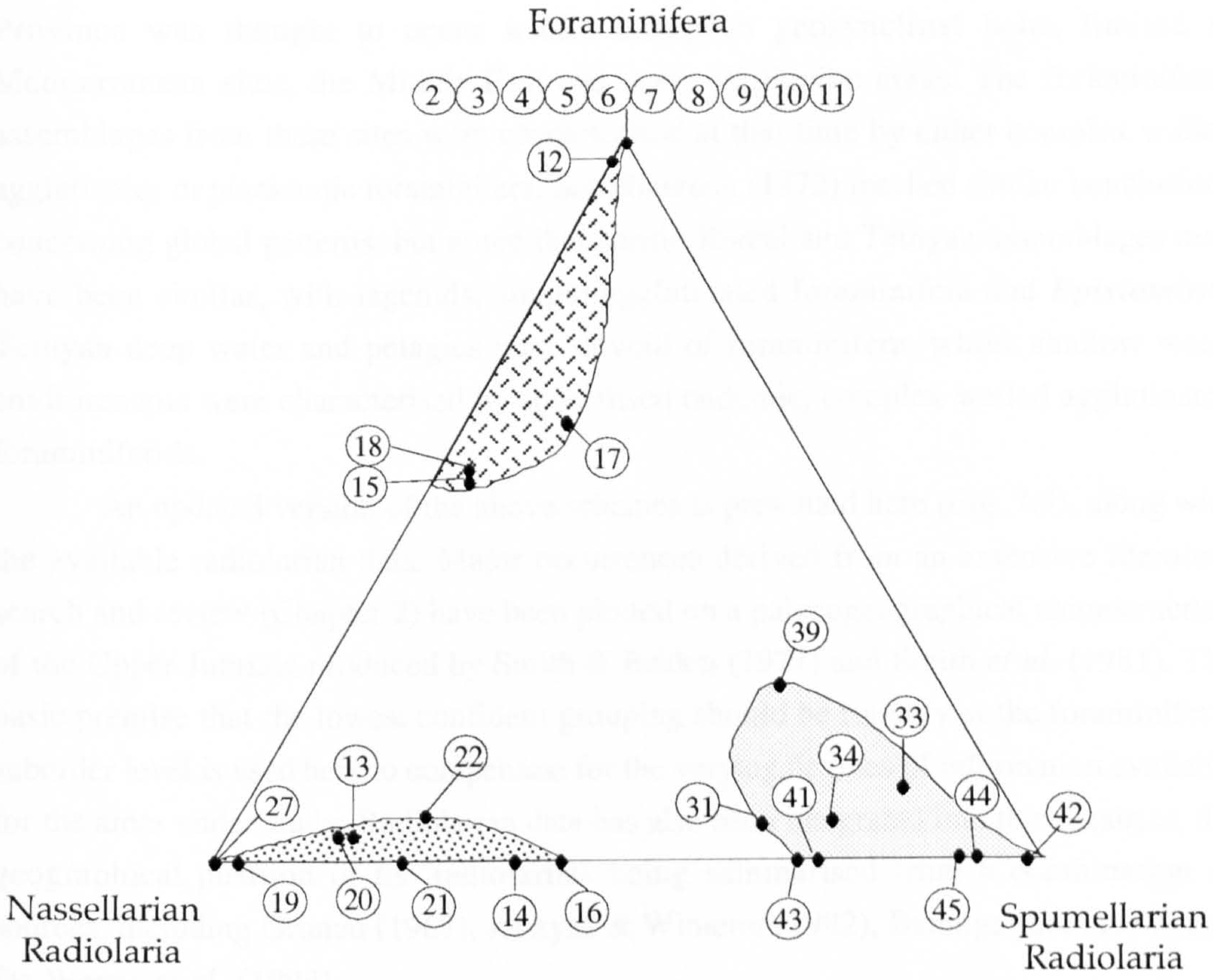


Figure 7.8. Ternary diagram for foraminiferal and radiolarian distribution at Eathie Haven

7.4. Biogeography

Characterisation of Jurassic macrofaunal bioprovincial distribution patterns, particularly of ammonite faunas, has had a long history of research. Arkell (1956) summarised the ammonite data and characterised two provinces, the Boreal Province and the Tethyan Province; this data was later updated by Hallam (1969, 1971, 1972, 1975). The Boreal Province characterised north west Europe, whilst the Tethyan Province was southern Mediterranean and equatorial in extent. These provinces were heavily biased to the northern hemisphere due to the heavy concentration of fossil data from Europe.

Hallam (1975) noted that generic level was the lowest taxonomic level which could be used for ammonite comparison, due mainly to the lack of consistency in taxonomic approach.

Gordon (1970) constructed a first pass biogeography for Middle and Upper Jurassic foraminifera based upon a literature search and the macrofossil based bioprovincial studies of Arkell (1956). Gordon (1970) divided foraminiferal assemblages into several distinct types and related these to geographical areas. His shelf types, which appear to be confined to central northern Europe and several north American sites, were characterised by lagenid dominated or lagenid mixed assemblages with simple agglutinated taxa and other conspicuous calcareous taxa such as robertinids or miliolids. Gordon (1970) equated these shelf assemblages to the Boreal Province. The Tethyan Province was thought to occur within European geosynclinal belts, limited to Mediterranean sites, the Middle East and some Philippine areas. The foraminiferal assemblages from these sites were characterised at that time by either complex walled agglutinates or planktonic foraminifera. Scheibnerova (1972) reached similar conclusions concerning global patterns, but noted that neritic Boreal and Tethyan assemblages may have been similar, with lagenids, simple agglutinated foraminifera and ***Epistomina***. Tethyan deep water and pelagics were devoid of foraminifera, whilst shallow water environments were characterised by specialised endemic, complex walled agglutinated foraminiferids.

An updated version of the above schemes is presented here (Fig. 7.9), along with the available radiolarian data. Major occurrences derived from an extensive literature search and review (Chapter 2) have been plotted on a palaeogeographical reconstruction of the Upper Jurassic produced by Smith & Briden (1977) and Smith ***et al.*** (1981). The basic premise that the lowest confident grouping should be roughly at the foraminiferal suborder level is used here to compensate for the varying degrees of information available for the areas under study. Radiolarian data has also been integrated into this database, the geographical position of the radiolarites being summarised from a combination of sources, including Grunau (1967), Jenkyns & Winterer (1982), Baumgartner (1987) and De Wever ***et al.*** (1994).

The provinces are constructed from the foraminiferal and radiolarian assemblages and four provinces have been defined which show some correspondence to those derived for ammonite and bivalve data. Boundaries are marked as uncertain as the database is still limited, with many of the reports being of uncertain quality. It is evident that these boundaries moved depending on the prevailing conditions. Additionally, some groups represented by a planktonic lifestyle such as planktonic foraminifera and radiolaria, were by virtue of their mobility, able to migrate and mix within other provinces.

The most northerly province is the Boreal Province which is characterised by pervasive agglutinated dominated foraminifera, generally characterised by a moderately diverse and abundant assemblage, with a wide range of morphotypes. As indicated elsewhere, this fauna occurs throughout the Middle and Upper Jurassic of Alaska, northern Canada, Svalbard, Siberia and the North Sea, and from several discrete age packages from initially Middle and predominantly Upper Jurassic of onshore Scottish sites. These agglutinated dominated faunas were not recovered from Helmsdale, which represents an unusual shallow water, spirillinid dominated taxa which were derived into a deeper water, possibly anaerobic substrate. If these assemblages are a true reflection of

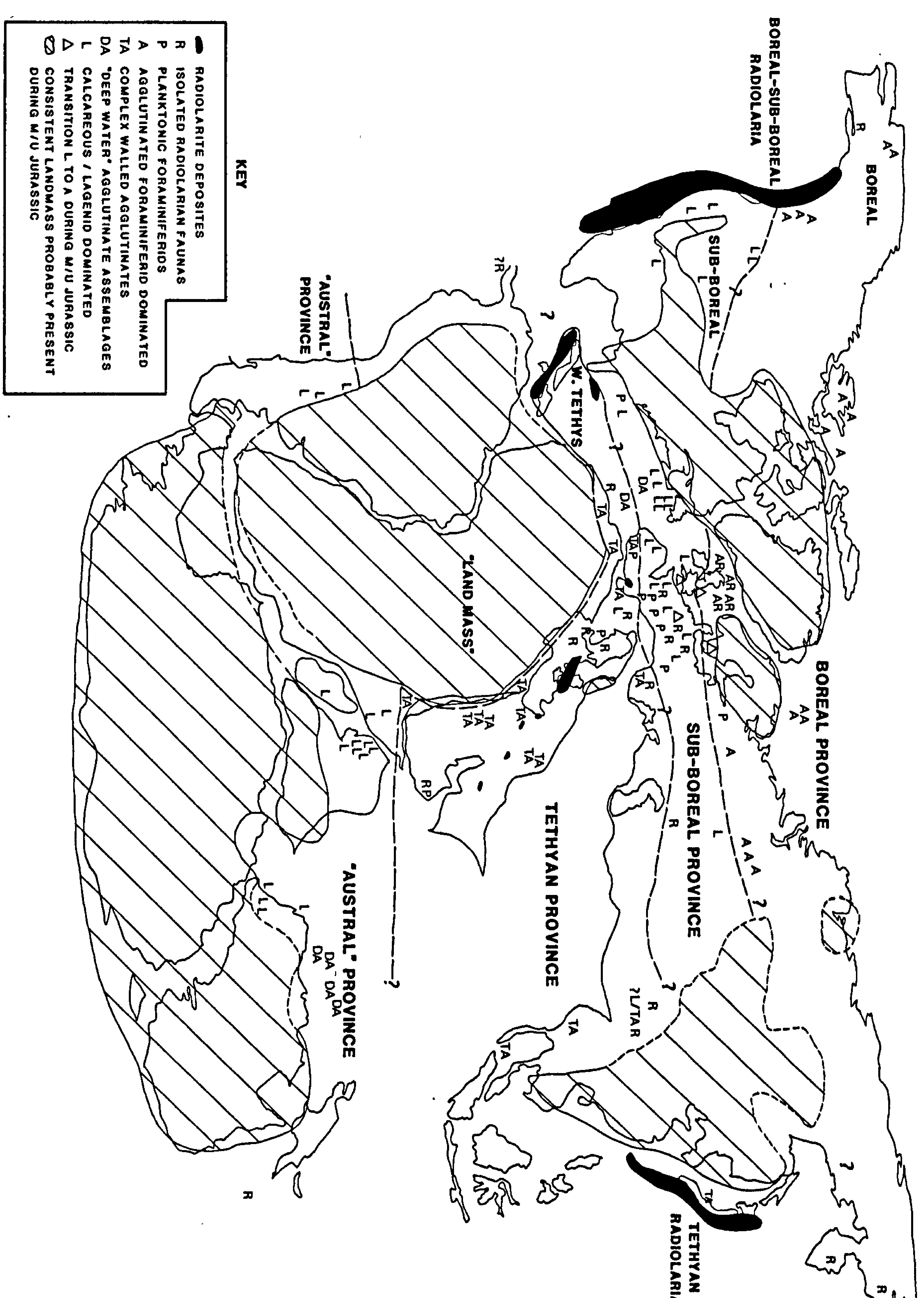


Figure 7.9. Middle and Upper Jurassic palaeocontinental reconstruction with biogeographical distribution of major foraminiferal and radiolarian faunas and tentative bioprovincial boundaries. Radiolarite distribution patterns are adapted from De Wever et al. (1994); Pessagno (in press), with the Jurassic palaeocontinental reconstruction adapted from Smith & Briden (1977); Smith et al. (1981)

the original assemblage, rather than a dissolution relict fauna, then the distribution of agglutinated dominated faunas may have been limited by some palaeoenvironmental factors, possibly including a latitudinal temperature gradient. Some of the more southerly deposits in England, such as South Ferriby and Dorset, and also from northern France, were initially dominated by a calcareous foraminiferal fauna during the Callovian and much of the Oxfordian. However, these sites also subsequently became influenced by a higher agglutinated foraminiferal presence from the latest Oxfordian and Kimmeridgian. This may relate to an extended influence of the Boreal Province, allowing similarities to develop. Indeed the assemblages from the majority of the Callovian to Middle Oxfordian sites in Scotland represent faunas identical to the Sub-Boreal Province defined below, again indicating the migration of the actual boundary. Pessagno (1991b) characterised the northern Boreal Province, which corresponds to the Boreal province as defined here, by abundant ***Parvicingula*** and an absence of pantanelliid taxa. The radiolaria recovered from the Scottish region and from the offshore North Sea were characterised by often common ***Parvicingula*** with no pantanelliids and therefore show a good correspondence. The radiolarites from the American region were arbitrarily divided by Pessagno (1991b) around the Canadian/USA border into a Northern Boreal and a Southern Boreal Province.

The Sub-Boreal Province includes the Sub-Boreal and Mediterranean Provinces as defined by Sykes & Callomon (1979). This province corresponds to Gordon's (1970) Boreal province, with a foraminiferal assemblage represented by a dominance of calcareous taxa, particularly lagenids, miliolids and robertinids with some simple agglutinated foraminifera. It appears to have covered much of north west Europe (excluding some of the Mediterranean area), the United States of America and the eastern Canadian Grand Banks during the Middle and Upper Jurassic. Pessagno (1991b) assigned the Californian radiolarite region to the Southern Boreal Province, which was characterised by an increase in pantanelliid radiolarian taxa still associated with common species of ***Parvicingula.*** There appears to be less correlation with the limited radiolarian fauna recovered from the Sub-Boreal areas of north west Europe, especially in Germany, where spumellarian taxa such as ***Crucella*** and ***Pseudocrucella*** dominate. This may represent a mixing of faunas from the Tethyan region to the south. However, the deposits from Germany which yielded radiolaria during the Callovian were estimated by Riegraf (1986, 1987b) to be relatively shallow, which may also have had an effect on the radiolarian faunal composition.

The Tethyan Province has been well established from macrofossil data, such as ammonites and bivalves, and the microfaunal equivalent agrees very closely. The main areas of deposition within this province were within the Mediterranean, including South Portugal, South France, Italy, Greece, Bulgaria and Israel; Africa including, Ethiopia and Morocco; Middle Eastern sites including Saudi Arabia, Egypt, Iran and Oman; and the Far East areas, including Japan and Thailand, with an area of uncertainty in Tibet. A western Tethyan area was delineated, by radiolarites, to occur within the Caribbean area

(Baumgartner, 1987).

Microfaunas from the Tethyan Province can be divided into two types. The first represented shallow, warm, carbonate dominated environments which were typified by larger, complex walled agglutinates such as ***Kurnubia, Pfenderina*** and ***Orbitopsella,*** or by calcareous taxa, represented by ***Trocholina*** spp. The second type occurs within the deeper water geosynclinal areas which were characterised by either radiolarite deposition and/or planktonic foraminiferids, the latter of which were becoming relatively common in such areas. This region probably straddled the Jurassic equatorial region and, as in the modern day, would have been a site of nutrient upwelling. There appear to have been areas of faunal mixing or influx, which were apparent with influxes of planktonic foraminifera and radiolaria from Tethyan areas in the south, to Sub-Boreal and Boreal regions including Germany, France, and Scotland. This migration of planktonic taxa was most prevalent during the Callovian and Kimmeridgian transgressions. The limited presence of planktonic foraminiferids recovered in this study from Scotland indicate the connection between the epi-continental Jurassic North Sea and Sub-Boreal and Tethyan areas.

Radiolarites occur within the deeper Tethyan areas in the Mediterranean region, from the Japanese area and from the western Tethyan area of the Caribbean as defined by Baumgartner (1987). The faunas were often very diverse and abundant and were typified by a high incidence of pantanelliids, hagiastrids and other spumellarian taxa, with distinct forms such as ***Mirifusus, Xiphostylus*** and ***Tripocyclia*** occurring to the exclusion of ***Parvicingula.***

Due to an increase in the publication rate since the 1970's, particularly from the southern hemisphere, it is possible to delineate a province which appears to correspond to the Sub-Boreal Province defined in the northern hemisphere. This is termed the 'Austral Province', a part of which includes the Anti-Boreal Province of Bhalla & Abbas (1976) and the Ethiopian Province of Hallam (1975). The microfaunas were dominated by lagenid taxa, with no planktonic foraminiferids or complex walled agglutinated foraminiferids and radiolaria were particularly rare. It covered the antipodean region, including sites from onshore and offshore western Australia and New Zealand; many sites from the Indian subcontinent; some eastern African areas including Somalia and Madagascar; and possibly a few sites from the interior of Argentina.

This bipolarity of the Sub-Boreal and 'Austral' Provinces must have arisen as a consequence of the development of similar palaeoceanographical conditions.

There are a few areas in the world, which have inevitably been drilled by the DSDP, predominantly from offshore north western Australia, offshore Morocco and the eastern Atlantic, which have yielded unusual agglutinated rich assemblages (marked as DA on Fig. 7.9). These comprised tubular and simple spherical morphologies belonging to Astrorhizacea, Ammodiscacea, Hormosinacae and Lituolacea, not found in any numbers from the provinces described above. Assemblages include ***Bathysiphon*** and ***Rhabdammina*** dominated faunas; similar faunas have often been described from flysch or basinal areas from the Cretaceous and Tertiary (e.g. Kuhnt & Kaminiski, 1990; Gooday, 1990; Charnock & Jones, 1990) and may correspond to deep water deposition, probably beneath the CCCD.

CHAPTER 8

MAJOR CONCLUSIONS AND FURTHER RESEARCH

8.1. Major Conclusions

This chapter outlines some of the major conclusions generated from this integrated foraminiferal and radiolarian biostratigraphy and palaeoenvironmental analysis of the Scottish Middle and Upper Jurassic. Specific conclusions have been covered in the relevant sections in Chapters 4, 5 and 7.

The sites investigated include the Bajocian of Bearreraig Bay and the Callovian to Lower Kimmeridgian of all the major marine sections from the Inner Hebrides and Inner Moray Firth Basin. Biostratigraphical and palaeoenvironmental changes have been outlined using specific foraminiferal and radiolarian taxa and assemblages respectively. A major conclusion is that an integrated approach to palaeoenvironmental reconstruction and analysis of microfaunal assemblages relies upon a biostratigraphical framework to define spatial and temporal relationships. This in turn is based upon the fundamentals of a rigid and consistent taxonomic approach and an understanding of the palaeoecological requirements and limitations of taxa from an analysis of the facies types present.

The initial phase of this study was to provide a reconnaissance survey of Middle and Upper Jurassic foraminifera and radiolaria from the areas of interest. The majority of the samples yielded microfossils, with their taxonomy being investigated in detail to enable biostratigraphical and palaeoenvironmental correlation. 183 foraminiferal taxa were described, 16 of which were considered to have been previously not recorded. 29 radiolarian taxa were described, some in more detail than the original descriptions; 7 were considered to have been previously undescribed.

Foraminiferal and radiolarian events were tied into the precise ammonite biozonal and sub-biozonal Boreal scheme. This allowed the construction of a major new microfaunal biozonation scheme based on the most complete section at Staffin Bay. 9 biozones and 12 sub-biozones were defined. These biozones were subsequently correlated with sections of comparable age in the Inner Moray Firth Basin at Brora, Balintore, Eathie Haven and Helmsdale. There appeared to be good correlation of the events chosen.

One aim of this study was to assess the usefulness of radiolaria for biostratigraphically delineating deposits. Their value is becoming apparent, particularly when related to the Kimmeridgian to Ryazanian deposits of the North Sea. The Scottish material also shows that there were distinctly correlatable events within the Callovian and Kimmeridgian, which can be traced at either inter or intra basinal level. The positive points in favour of radiolaria are that they are planktonic and can therefore be widely dispersed in a relatively short time; they are rapidly evolving, and Jurassic taxa have a wide range of distinctive morphotypes. However, there are limitations that affect the extent of their distribution. Firstly, in order for radiolaria to be established, certain other factors have to be prevalent. These include a relatively thick water column; the shallower the environment, the less taxa appear capable of colonising it. Radiolaria also need water circulation patterns to be established in order to produce nutrient upwelling. Finally, oxygen depleted sea water seems to have a detrimental effect on their distribution. All of these factors, which appear to be deleterious for biostratigraphical analysis, are, however, useful for bracketing or delineating palaeoenvironments, especially when integrated with foraminiferal information.

A major limitation of radiolaria relates to their test mineralogy. As sea water is undersaturated with respect to silica, test secretion requires certain conditions, which includes a source for the silica. Also, dissolution would appear to be particularly common, therefore in order for tests to survive at least until burial, when they can be preserved by mineral replacement, they must either be buried rapidly (as at Brora) or be deposited in an organic rich dysaerobic to anaerobic environment in which oxidation is retarded. This latter case appears to be the most common, particularly in relation to the Kimmeridge Clay Formation of the North Sea and the sites at Staffin Bay, Eathie Haven and Helmsdale.

Only general palaeoecological characteristics of Jurassic benthic foraminifera have been suggested in this thesis, because much work still has to be carried out on the ecology of Recent faunas in order for comparisons to be applied to fossil taxa. What has been attempted here is a integrated approach, where the foraminiferal populations have been characterised by gross distributional patterns of the major suborders in conjunction with lithofacies and macrofaunal elements. All of these factors indicate that facies dependence can be utilised as a tool in sequential basin development analysis. However, there were different degrees of substrate dependence, with some specific taxa appearing able to colonise several different palaeoenvironments. This ability adds to their usefulness in biostratigraphy; the lagenid group were the most successful at colonising Jurassic habitats. This dual use of degree of facies dependent distribution allows the integration of biostratigraphical and palaeoenvironmental events.

Facies controlled distribution arises because foraminiferal ability to secrete a test, or colonise a particular facies type or niche, is constrained by changes in salinity, levels of substrate and sea-water oxygenation, organic carbon present in the sediment, water temperature, availability of calcium carbonate and sedimentation rate. Many of these factors may be qualitatively related to water depth or distance from the shore and can therefore be assessed in terms of palaeoenvironments caused by relative sea-level changes. For example, transgressions, caused by eustatic sea-level changes or subsidence, initially produce marine, restricted environments, which with further deepening increase the number of niches available. This eventually allows the establishment of an increasingly diverse and abundant foraminiferal and radiolarian fauna. Regression reverses this situation. However, there generally appears to be a time lag before the effects are reflected in the geological record by microfaunal assemblages. Additionally, there appear to be periods of stabilisation representing transition between transgression and regression, which may give rise to optimum conditions and therefore maximum faunal response.

As indicated above, the microfaunas have been grouped into assemblages, based mainly upon the major foraminiferal suborders, in order to categorise sea-level changes across the Scottish basins. The distribution and particular type of microfaunal assemblage and the relevant facies information are then used to indicate major palaeoenvironmental changes, which equate to the relative sea-level and the resulting transgressive/regressive cycles. Foraminiferal and radiolarian events have been correlated between the Inner Moray Firth and Inner Hebrides Basins, with overall good comparison of the major transgressive and regressive cycles. Additionally, radiolarian distribution was assessed to indicate the maximum extent of transgression within the Upper Callovian and Lower Kimmeridgian.

Differences in the overall extent of assemblages correspond to the palaeogeographical position during relative sea-level change. For example, distal sites have more pervasive foraminiferal assemblages or longer ranging radiolarian faunas. Staffin Bay and Balintore appear to represent distal sites, whilst Brora occupied a relatively proximal, or near shore, position. Eathie Haven and Staffin Bay appear to be more distal in relation to Helmsdale during the Lower Kimmeridgian.

A biogeographical reconstruction has been presented for the Middle and Upper Jurassic foraminiferal and radiolarian assemblages, based upon a review of published literature. Four relatively distinct provinces have been defined, based on the differences in major foraminiferal and radiolarian groups.

8.2. Further Research

During the course of this study many diverse avenues were explored which, due to allocation of time, had to remain relatively undeveloped. Some of these are offered here as further research, whilst others are felt to be a natural progression of the work contained herein.

1). Comparison of other sites to test the validity of regional correlation or the development of provinciality. The obvious sites from the North Sea and Hebrides offshore basins were not made available for this study due to the commercial confidentiality of data. However, the best choice for correlation appears to be the Middle and Upper Jurassic deposits of East Greenland, which are well known and have an established ammonite biostratigraphy.

2). Further refinement of biostratigraphy and palaeoecology by bed/bed analysis. The initial aim of this project was a reconnaissance and this refinement would help delimit first and last appearances. An example of this improvement in detail was recorded for the section at Bearreraig Bay at which the definition of the basal Bajocian boundary improved with subsequent collecting. This kind of detailed sampling could be useful for analysing the cyclical bedding present in the Dunans Clay Member, for example.

3). Further studies are required concerning the ecology and habitat characteristics of Recent foraminifera in order to understand more completely the significance for Jurassic foraminiferal palaeoecology.

4). Refinement of Jurassic foraminiferal taxonomy. The most notable problem with Jurassic foraminifera is the profusion of synonymous forms arising from poor illustration and splitting of the initial workers. An example is Terquem's collections on the "Systeme Oolithique" which, like his revised Lias collections (Macfadyen, 1941; Ruget 1976), requires updating and restudy.

5). Thin sectioning of carbonates, oolitic ironstones and some calcareous sandstones. Preliminary results of non-diagenetic primary limestones from the Lower Jurassic of Morvern and Mull showed promise.

6). Analysis of marine sandstones and coarse siltstone facies. This would require extensive picking, or a development of heavy liquid separation techniques. Some Middle Jurassic sandstones and siltstones, such as those at Bearreraig Bay, have shown the validity of looking at coarser grained sediments for microfossils.

7). Preparation of phosphatic nodules using acid etching for example, from the Dunans Clay Member of the Staffin Shale Formation. These nodules have been reported elsewhere (Riegraf, 1986, 1987b; from German Callovian deposits), as preserving the more easily dissolved tests of planktonic foraminifera and siliceous radiolaria.

8). Study of the Lower Jurassic foraminifera of the Hebrides Basin. There are extensive Scottish Lower Jurassic deposits that are comparable to sequences at the Mochras borehole. Diverse foraminiferal faunas were recovered during this PhD project from Morvern, Mull, Skye, Strathaird and Raasay. The scope and extent of this thesis did not allow the inclusion of the provisional results and more work is required. However, the biostratigraphical implication of these faunas provide a method of comparing and validating the various biostratigraphical biozonations for the Lower Jurassic, such as defined by Copestake (1978), Johnson (1976) and Copestake & Johnson (1981, 1984, 1989).

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APPENDIX A
TAXONOMIC INDEX

Foraminiferal Taxa

Radiolarian Taxa

PLATES

SAMPLE NUMBERS AND LOCALITIES

HELMSDALE

KW KWN	KINTRADWELL
LB	LOTHBEG
CL	CRACKAIG LINKS
GM	GARTYMORE
HE HN	HELMSDALE
N	NAVIDALE

STAFFIN BAY, SKYE

DS DC	DUNANS
GS	GLASHVIN
D	DIGG
F PC	FLODIGARRY

BRORA, NE SCOTLAND

BR BRS	BRORA FORESHORE
BC	BRORA RIVER

BEARRERAIG BAY, SKYE

U	COLLECTED BY GREGORY
MP M	COLLECTED BY MORTON

BALINTORE, NE SCOTLAND

CR	CADH'-AN- RIGH
PR	PORT-AN-RIGH

PLATE 1

Figure 1. Bathysiphon anomalocoelia Tappan, 1955
Maximum Length 412µm. Sample No. DC5

Figure 2. Psammosphaera metensis (Terquem), 1862
Maximum Diameter 233µm. Sample No. PR21

Figure 3. Lagenammina compressa (Paalzow), 1932
Maximum Length 360µm. Sample No. E7

Figure 4. Lagenammina difflugiformis (Brady), 1879
Maximum Length 655µm. Sample No. DC5

Figure 5. Saccammina sp.
Maximum Diameter 169µm. Sample No. DC15

Figure 6. Thurammina papillata Brady, 1879
Maximum Diameter 271µm. Sample No. F16

Figure 7. Jaculella elliptica (Deeke), 1884
Maximum Length 407µm. Sample No. PR36

Figure 8. Ammodiscus asper (Terquem), 1863
Maximum Diameter 261µm. Sample No. F8

Figure 9. Ammodiscus siliceus (Terquem), 1862
Maximum Diameter 202µm. Sample No. U10

PLATE 1


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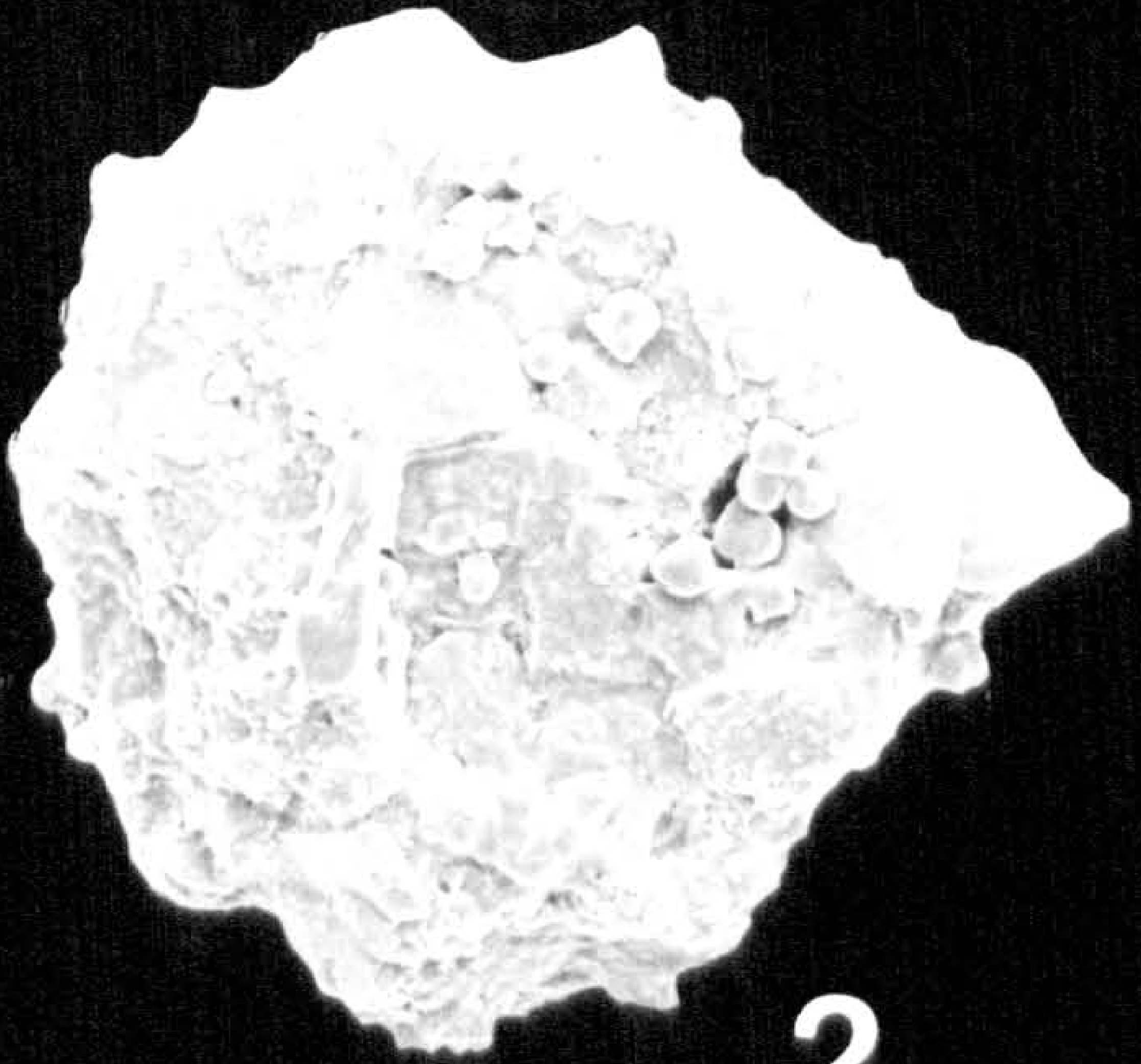
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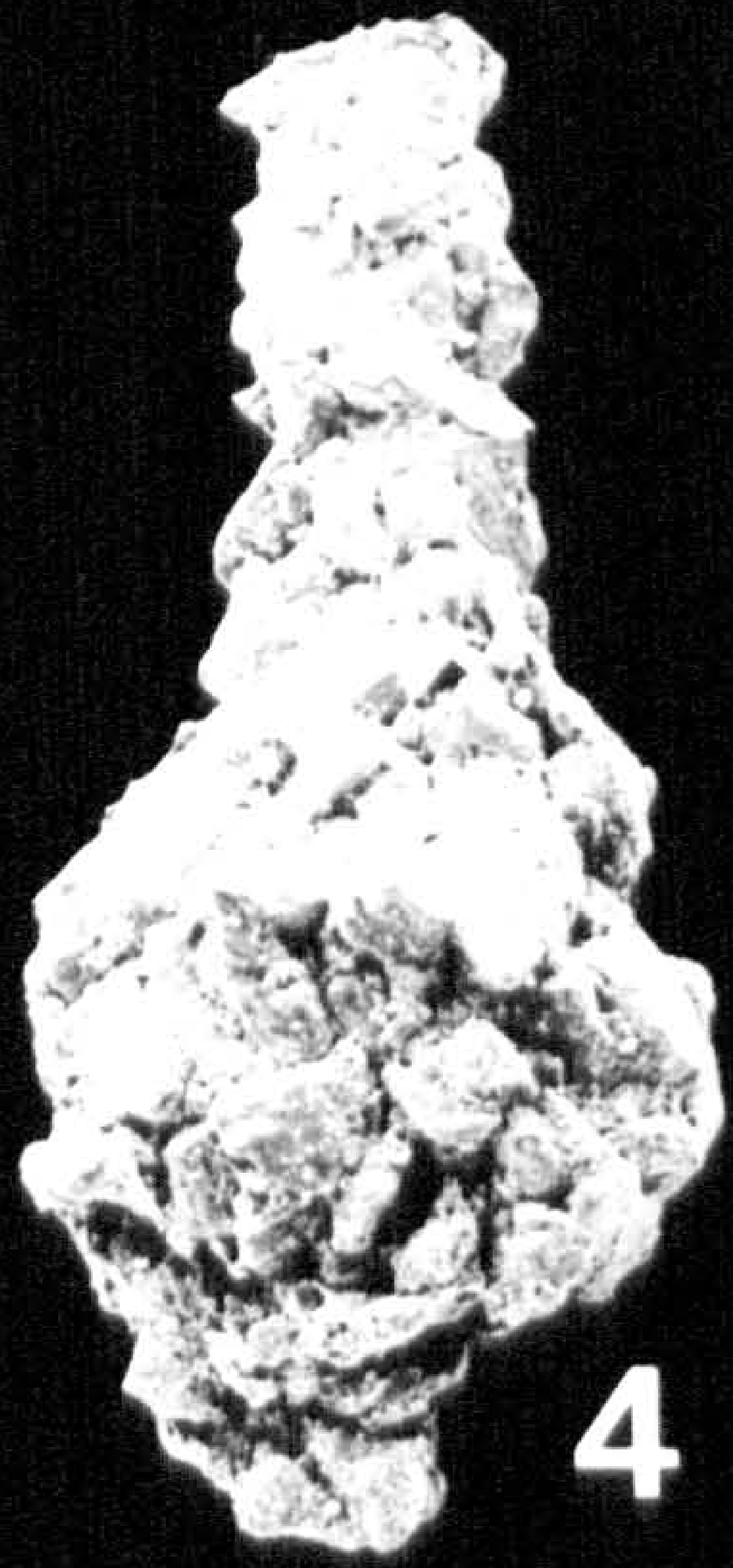
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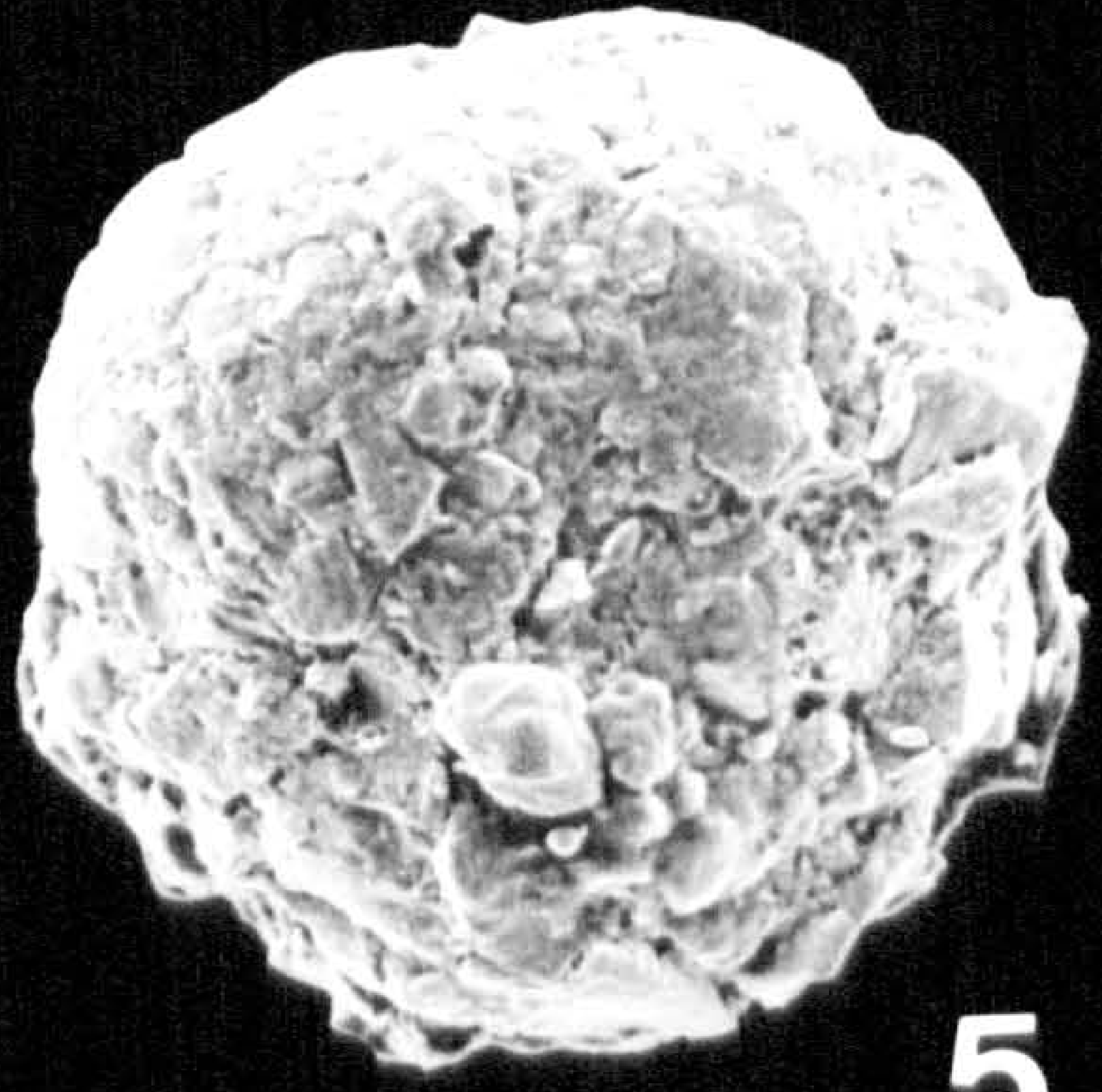
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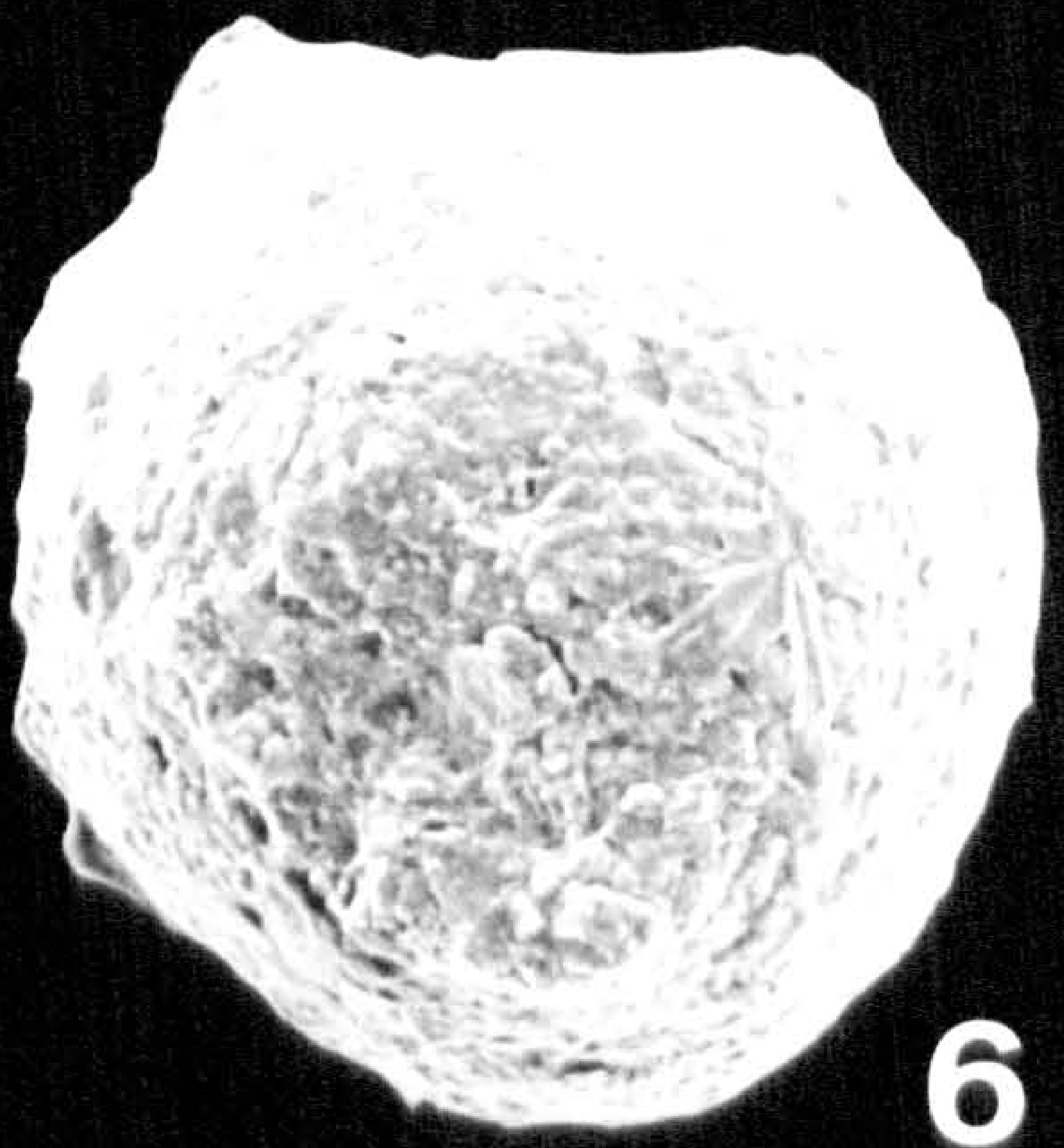
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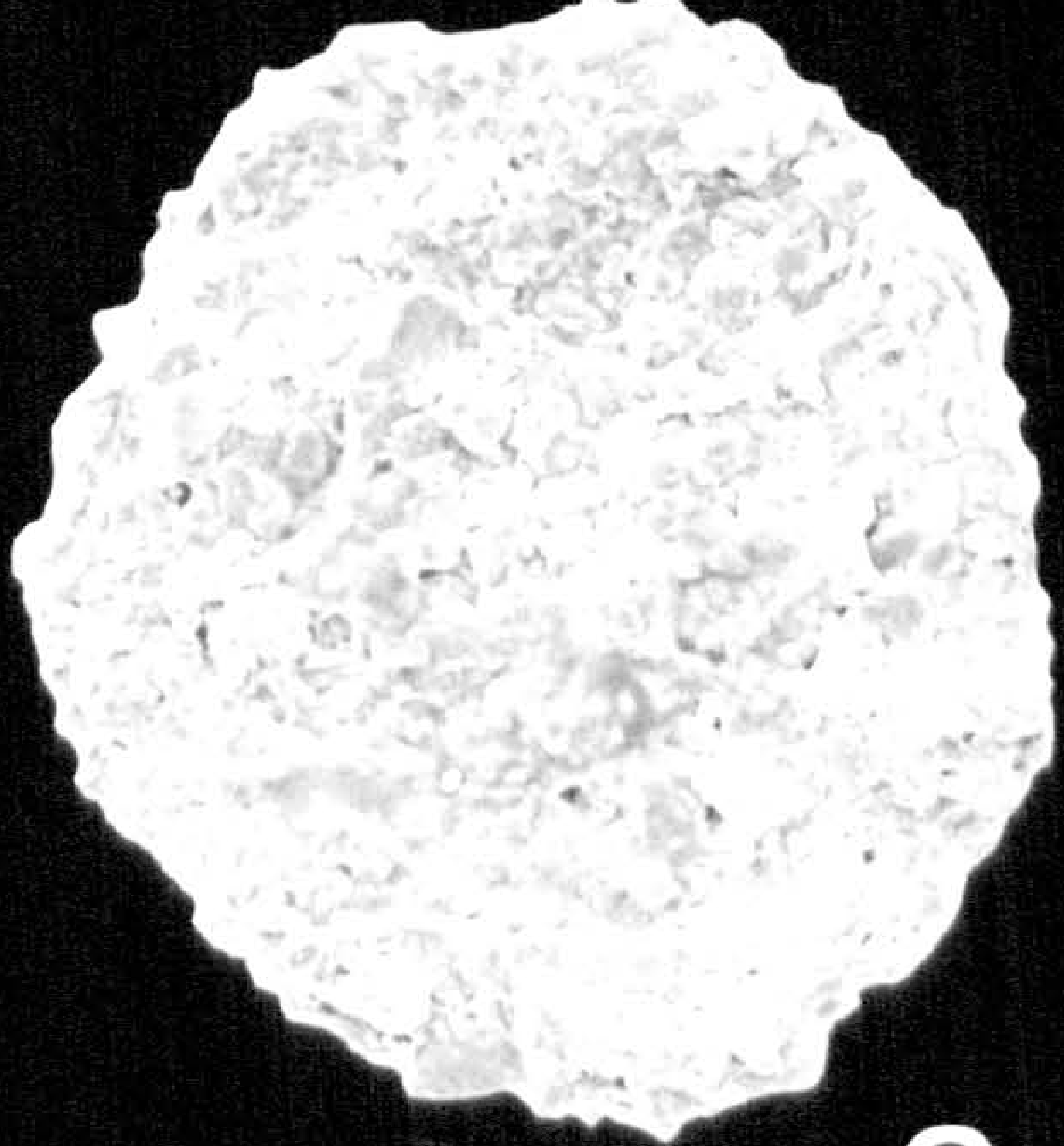
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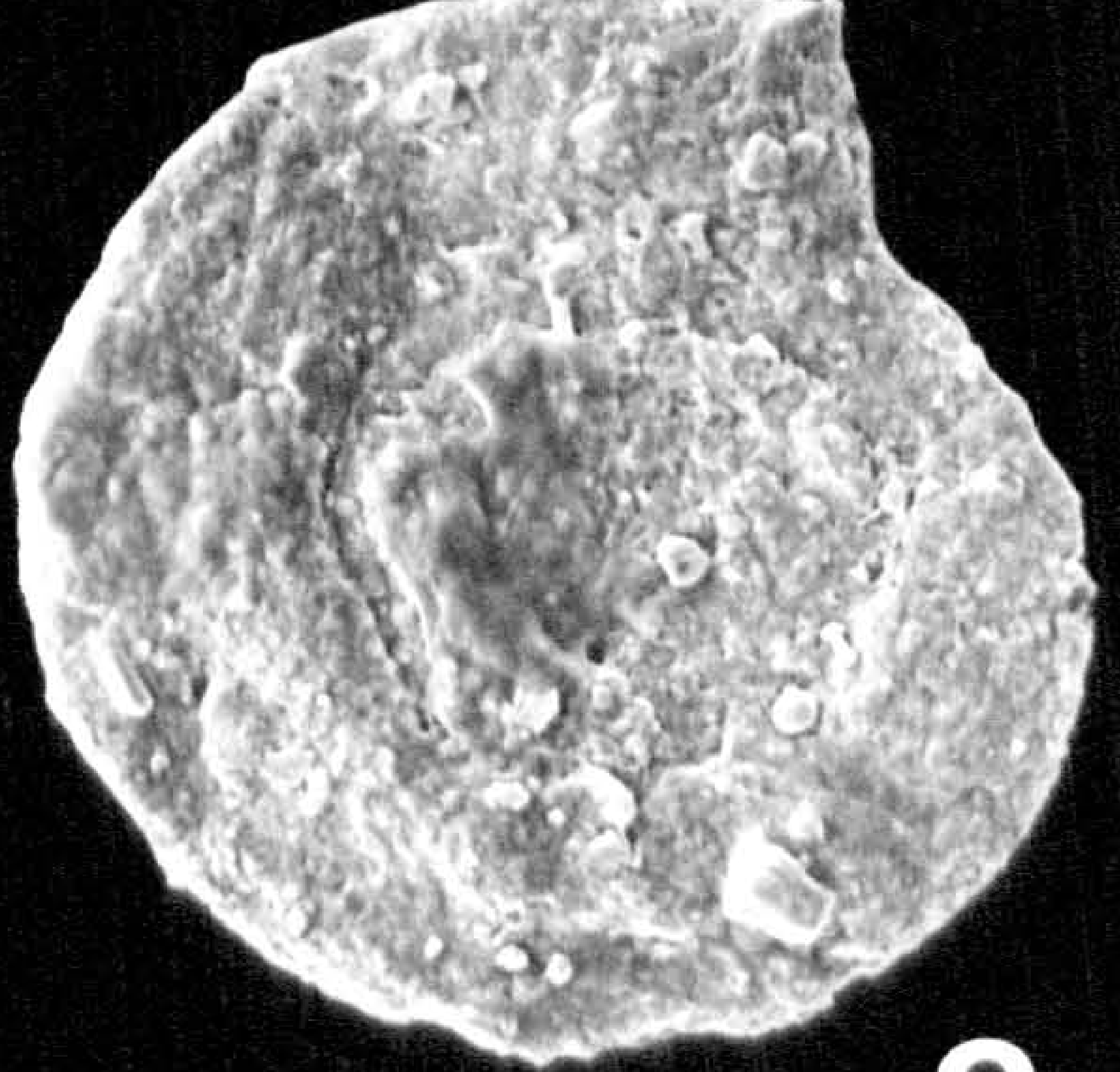
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PLATE 2

Figure 1. Glomospira gordialis (Jones & Parker), 1860
Maximum Diameter 260µm. Sample No. DC2

Figure 2. Glomospira perplexa Franke, 1936
Maximum Diameter 200µm. Sample No. BRS15

Figure 3. Reophax sp. A
Maximum Length 344µm. Sample No. DC16

Figure 4. Reophax agglutinans (Terquem), 1870
Maximum Length 588µm. Sample No. PC1

Figure 5. Reophax complanata Franke, 1936
Maximum Length 277µm. Sample No. PC1

Figure 6. Reophax densa Tappan, 1955
Maximum Length 420µm. Sample No. DC16

Figure 7. Reophax helvetica (Haeusler), 1881
Maximum Length 469µm. Sample No. PC2

Figure 8. Reophax horridus (Schwager), 1865
Maximum Length 660µm. Sample No. F19

Figure 9. Reophax hounstoutensis Lloyd, 1959
Maximum Length 388µm. Sample No. PC3

Figure 10. Reophax metensis Franke, 1936
Maximum Length 480µm. Sample No. DC24

Figure 11. Reophax multilocularis Haeusler, 1883
Maximum Length 531µm. Sample No. BRS1

Figure 12. Reophax sterkii Haeusler, 1890
Maximum Length 501µm. Sample No. BRS2

PLATE 2


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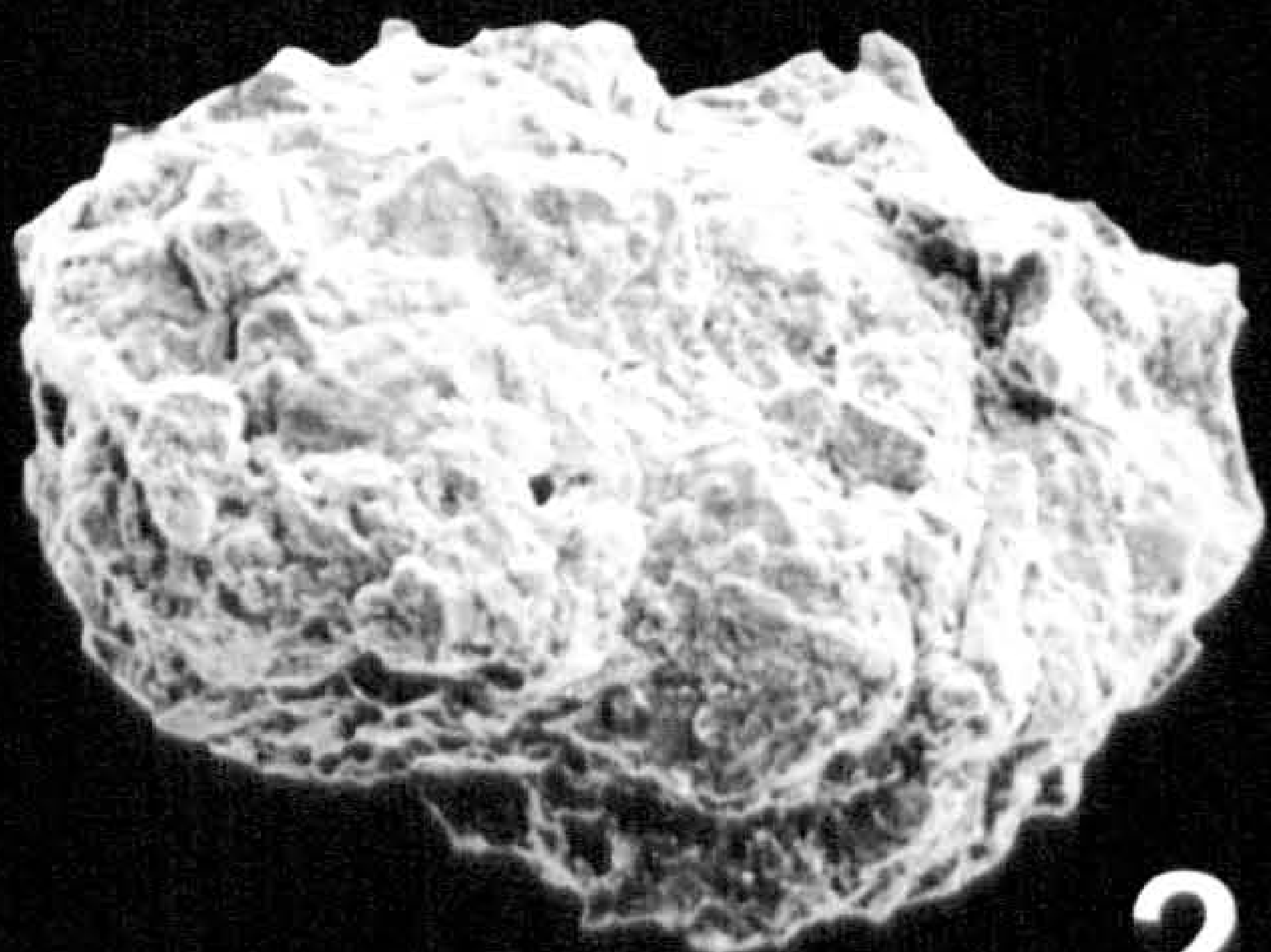
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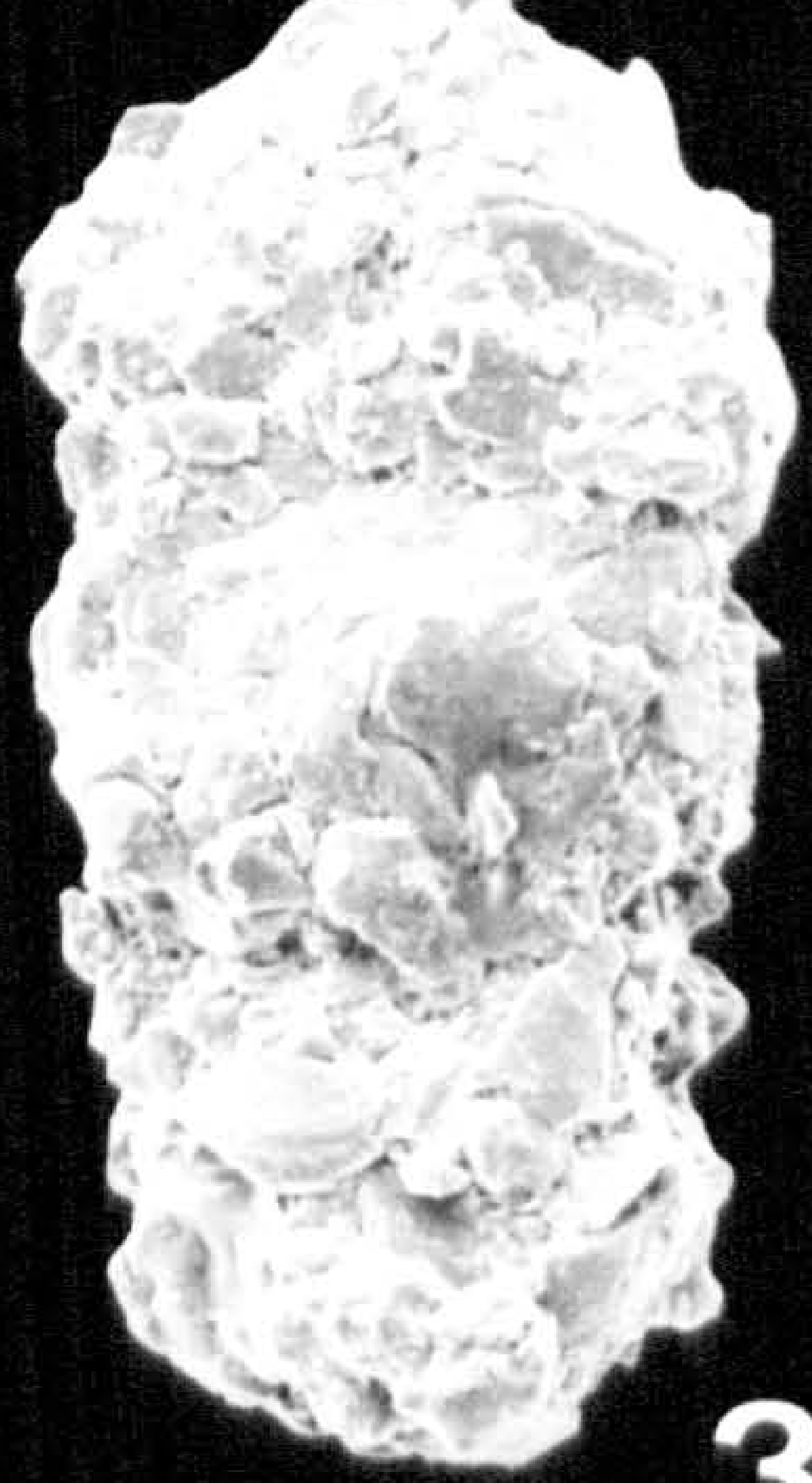
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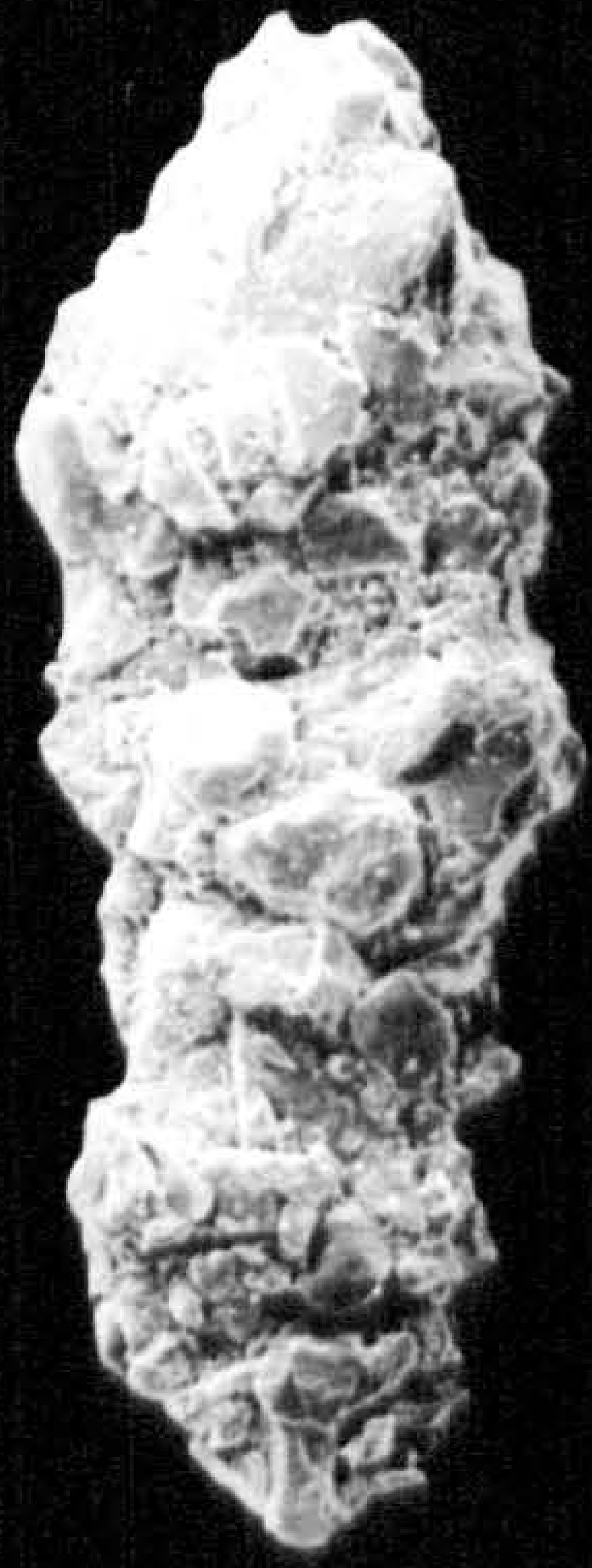
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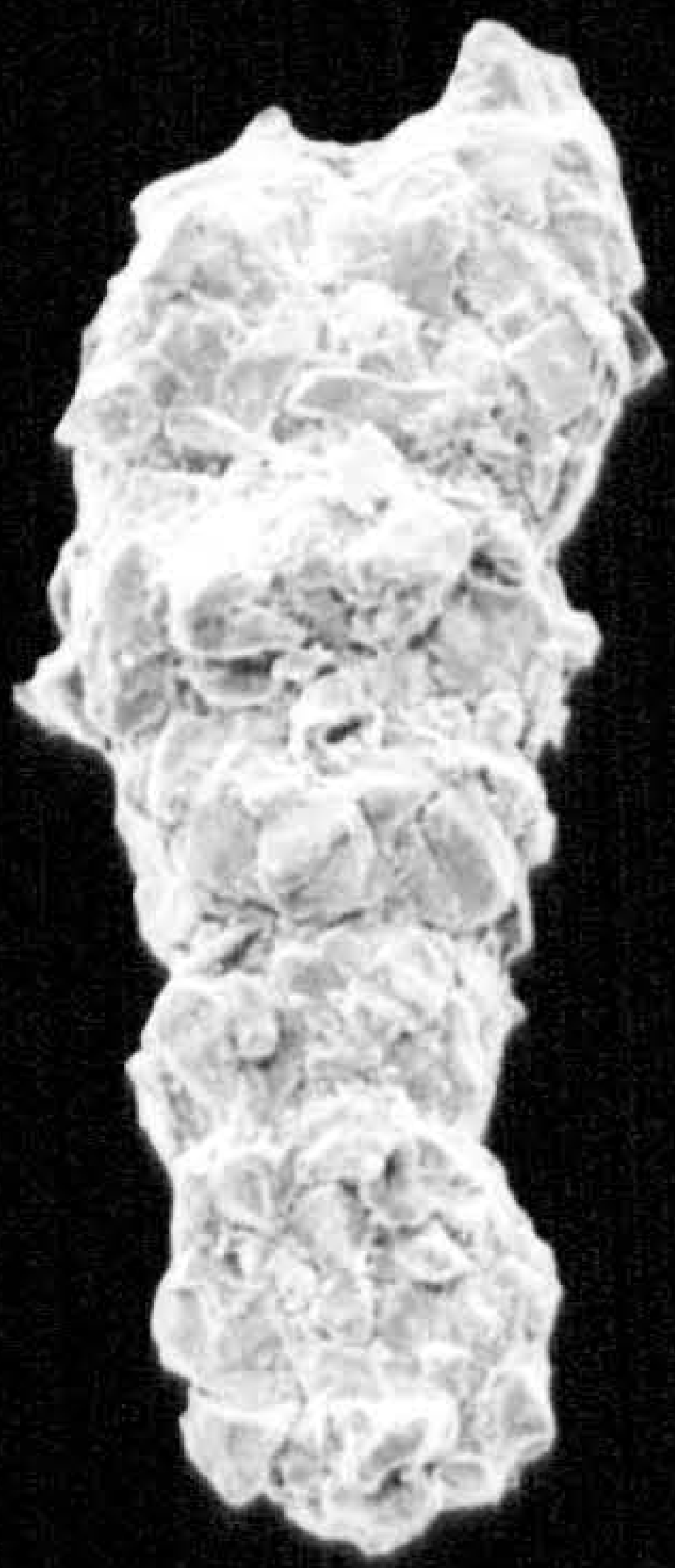
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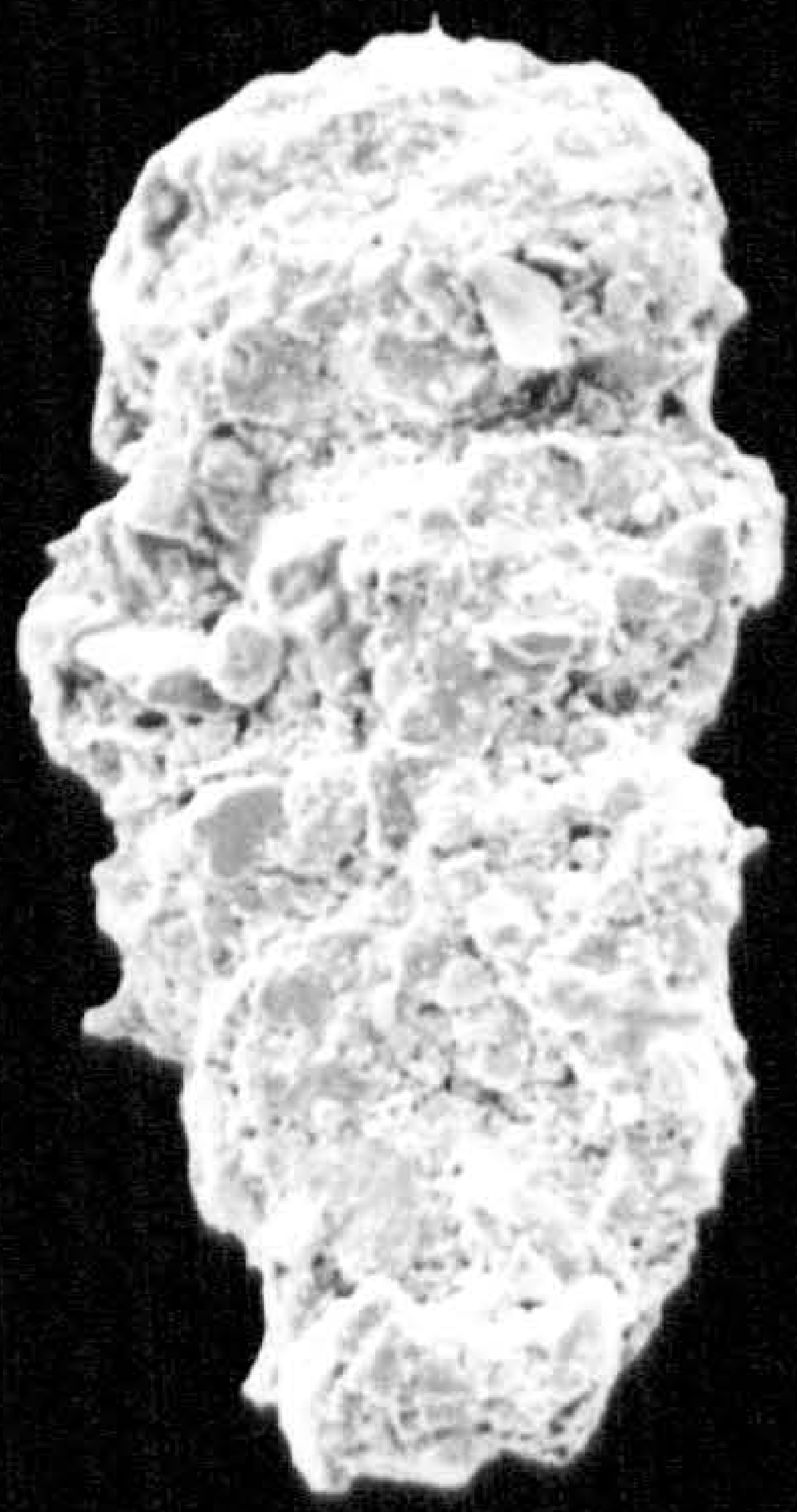
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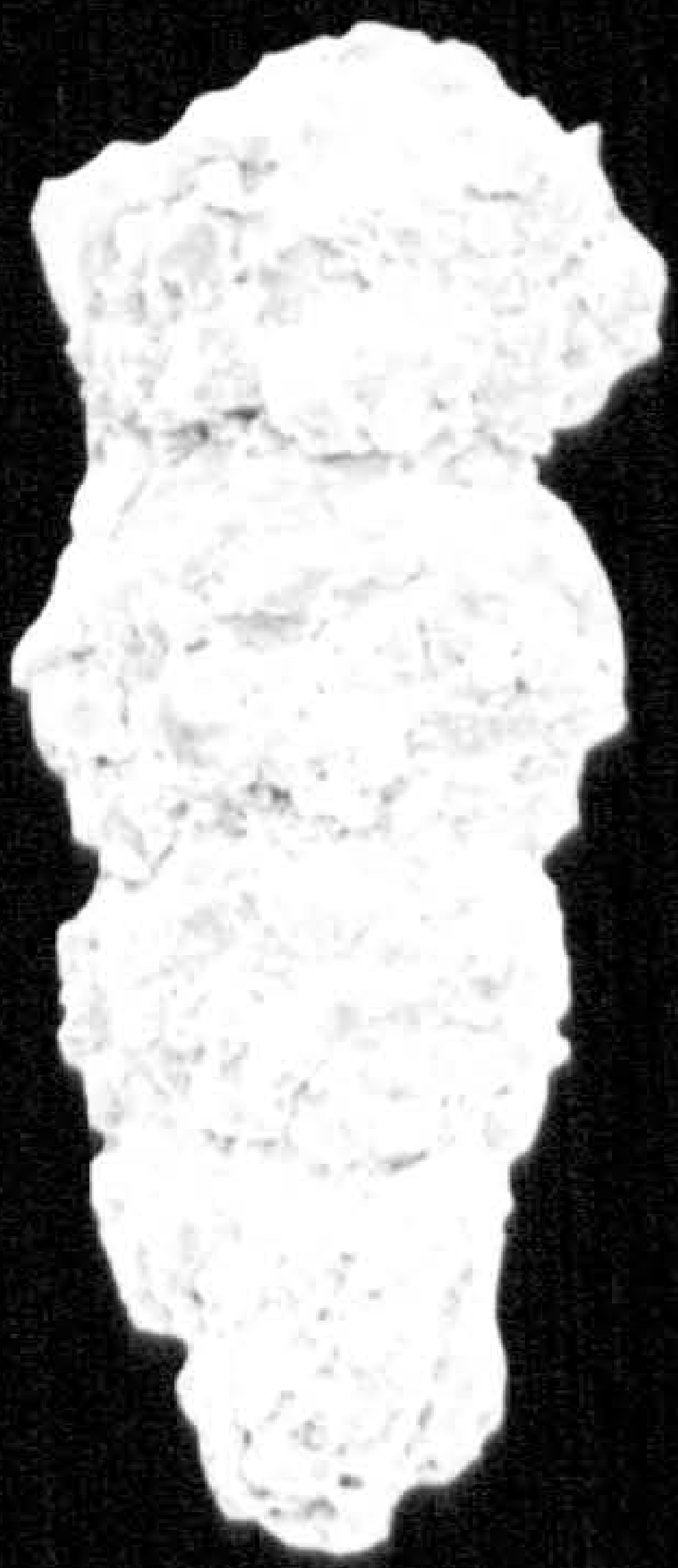
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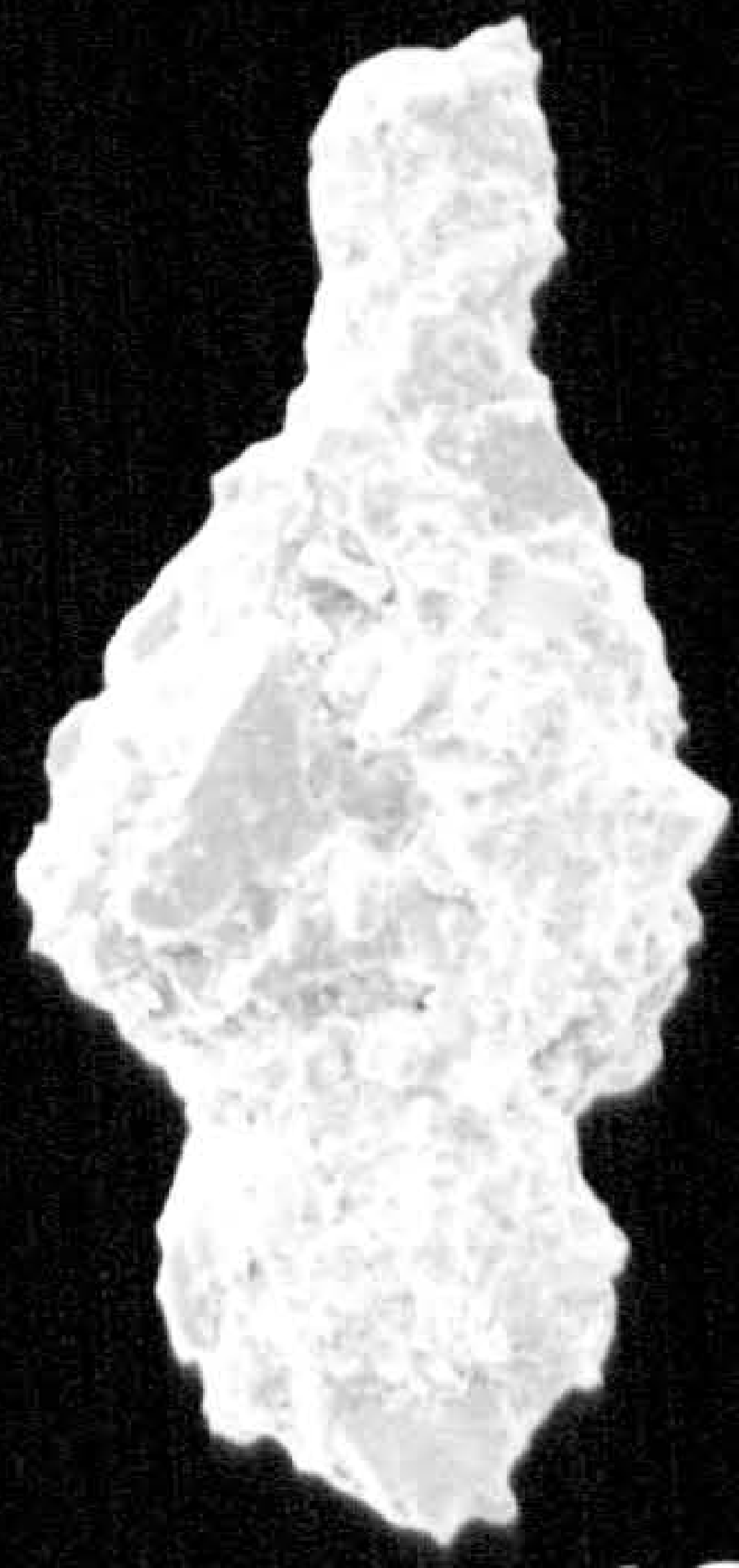
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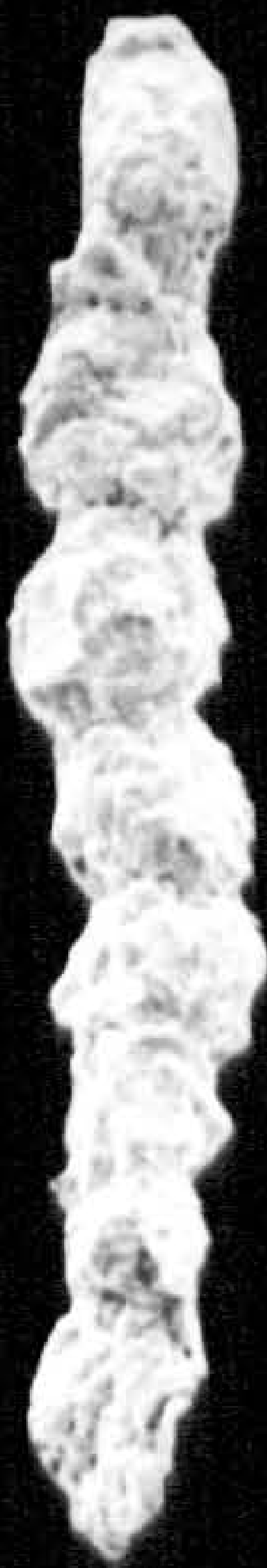
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PLATE 3

Figure 1. Haplophragmoides barrowensis Tappan, 1951
Maximum Diameter 345µm. Sample No. F2

Figure 2. Haplophragmoides canui Cushman 1930
Maximum Diameter 324µm. Sample No. DC8

Figure 3. Haplophragmoides globigeriniformis (Haeusler), 1882
Maximum Diameter 510µm. Sample No. PC2

Figure 4. Haplophragmoides hyalinus (Haeusler), 1886
Maximum Diameter 259µm. Sample No. BRS15

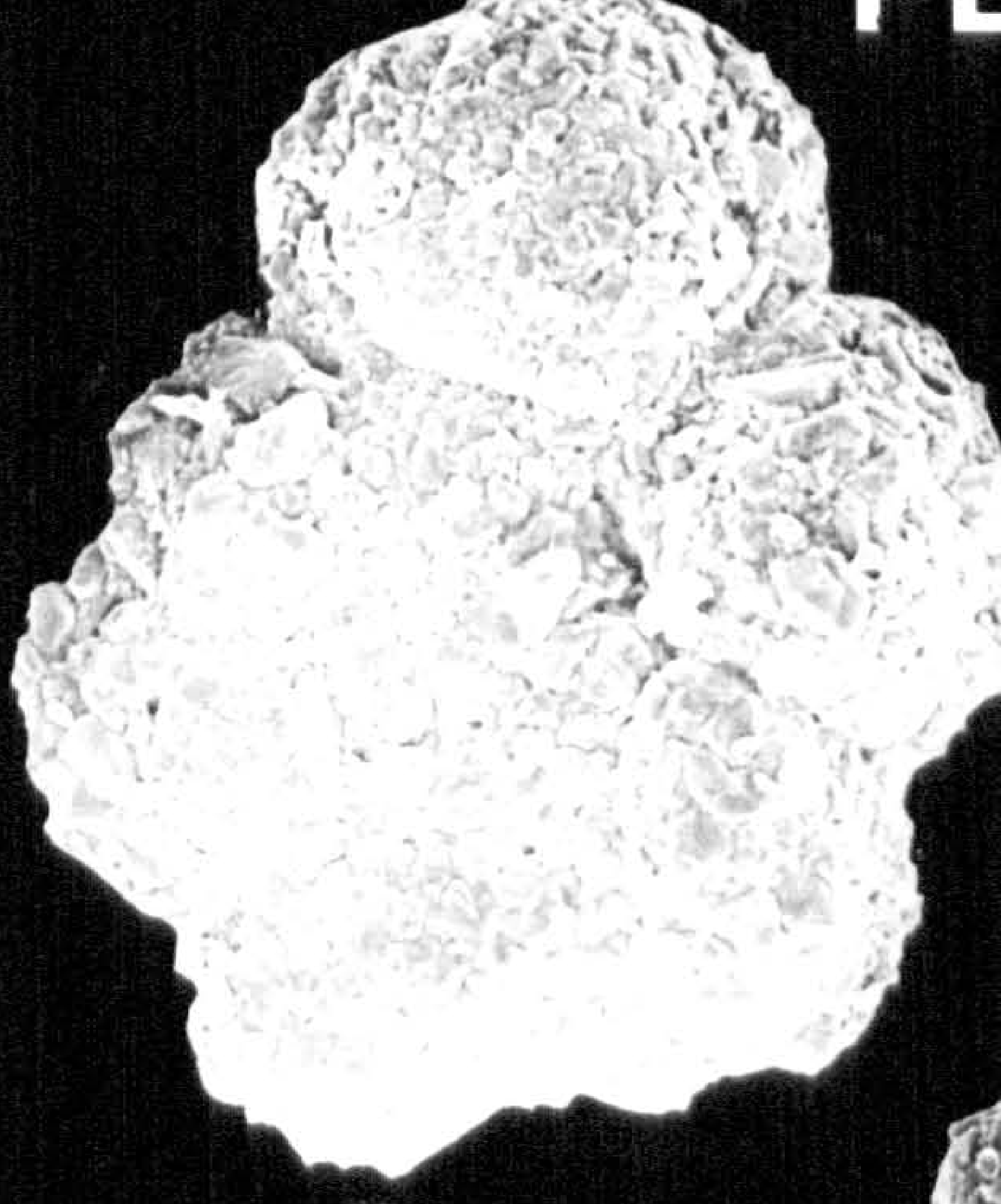
Figure 5. Haplophragmoides canuiformis Dain, 1972
Maximum Diameter 292µm. Sample No. DC10

Figure 6. Haplophragmoides infracalloviensis Dain, 1948
Maximum Diameter 514µm. Sample No. GS4

Figure 7. Haplophragmoides kingakensis Tappan, 1955
Maximum Diameter 306µm. Sample No. DC2

Figure 8. Haplophragmoides pygmaeus (Haeusler), 1881
Maximum Diameter 215µm. Sample No. BRS13

PLATE 3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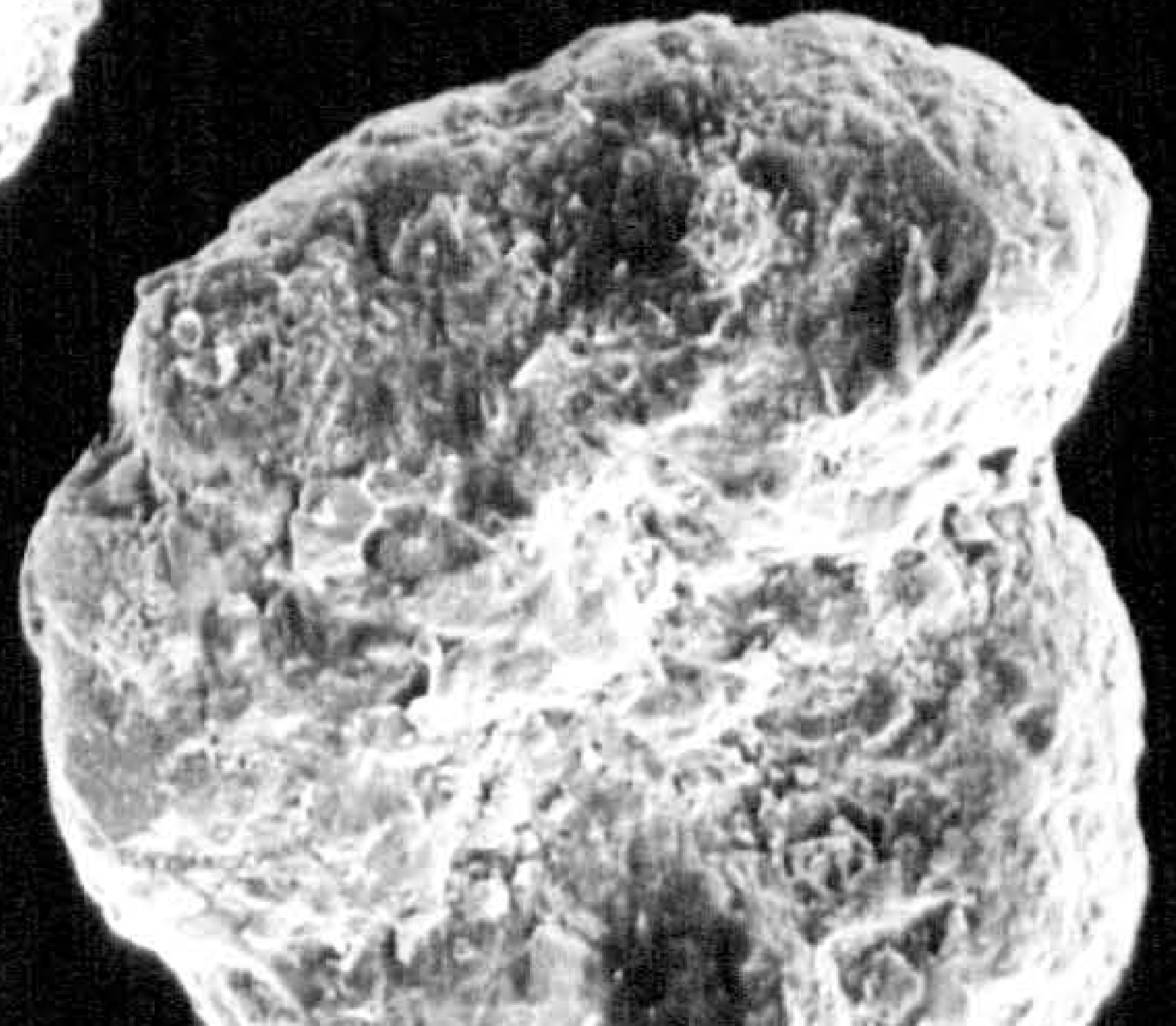
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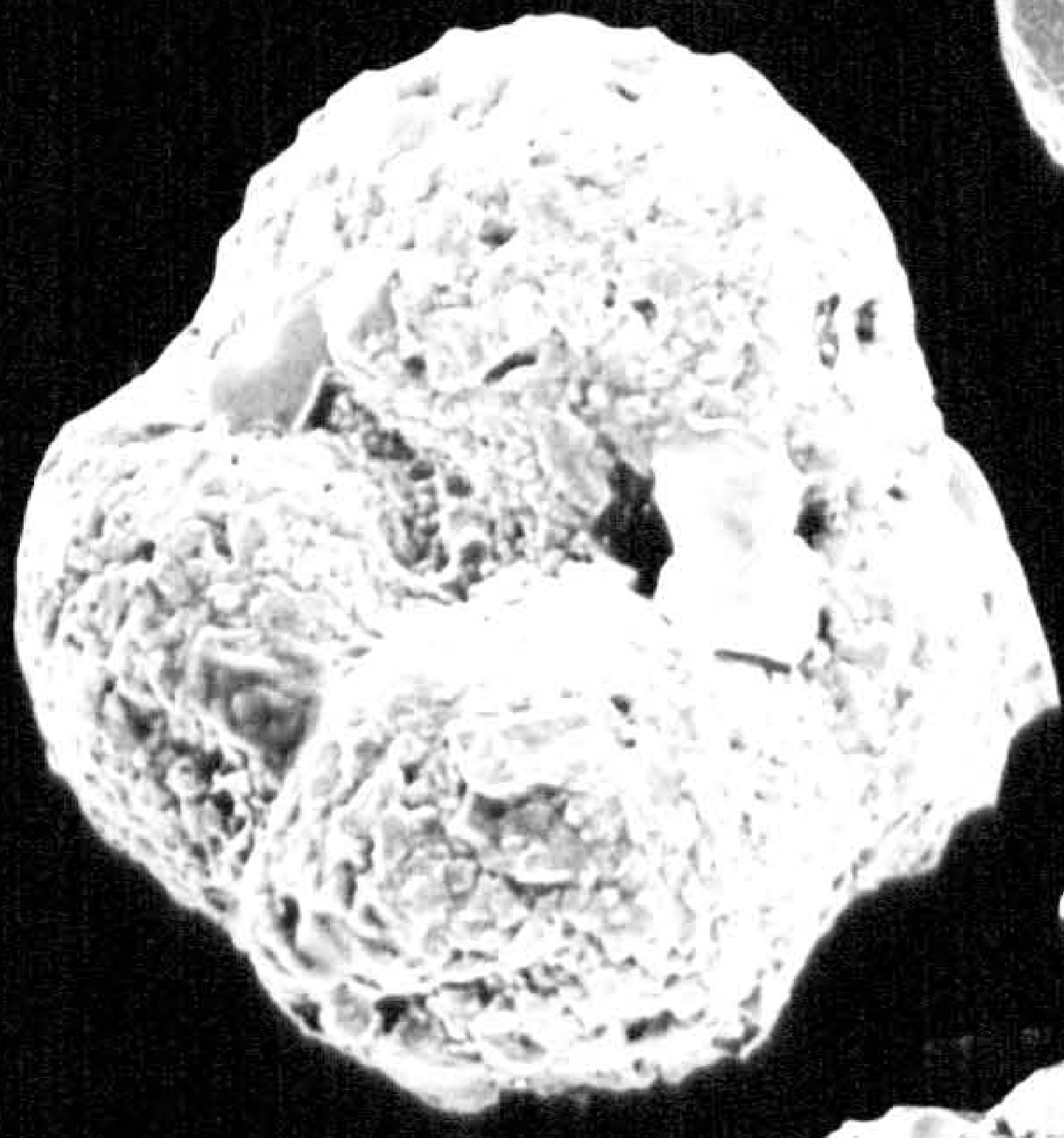
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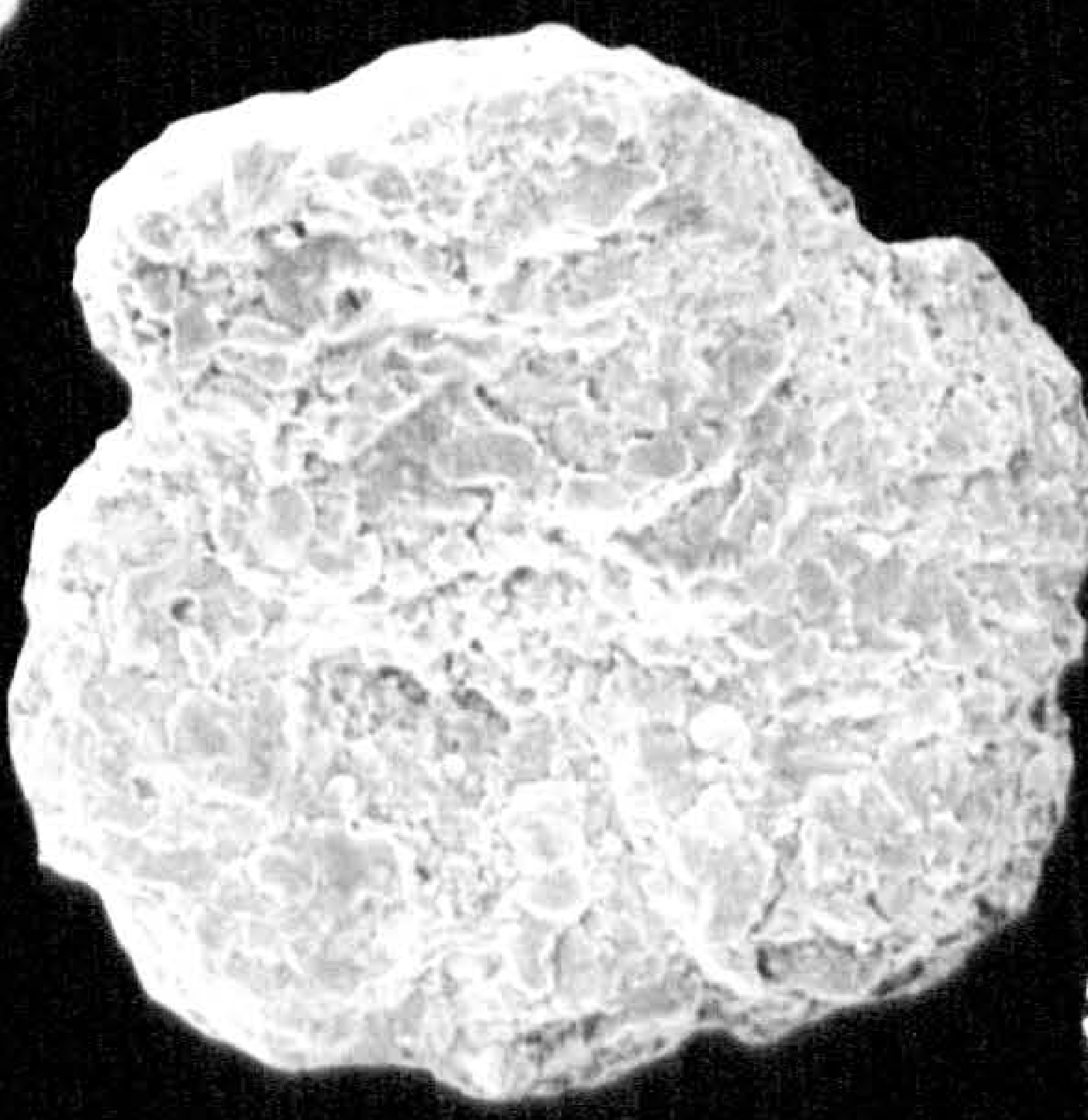
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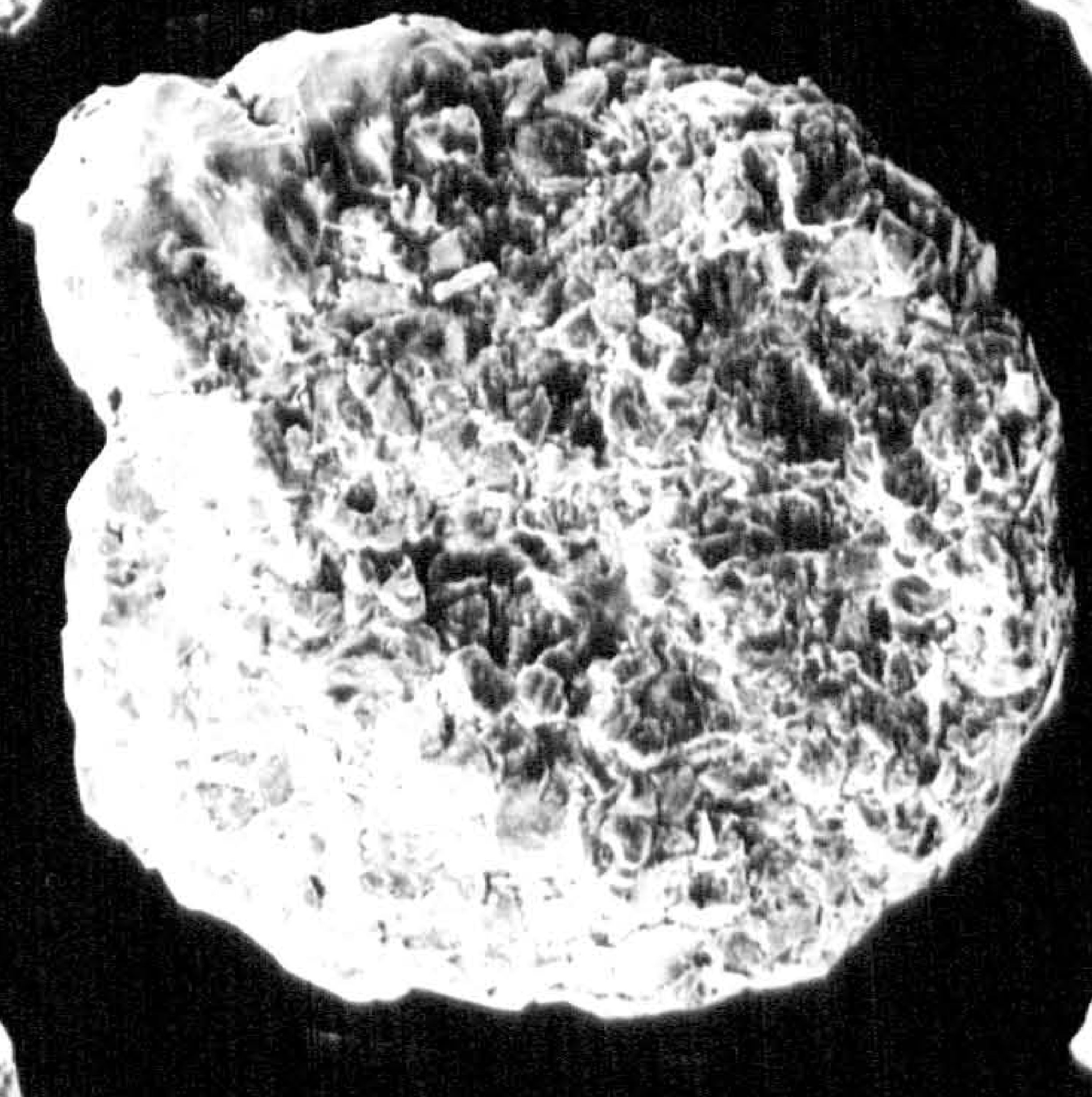
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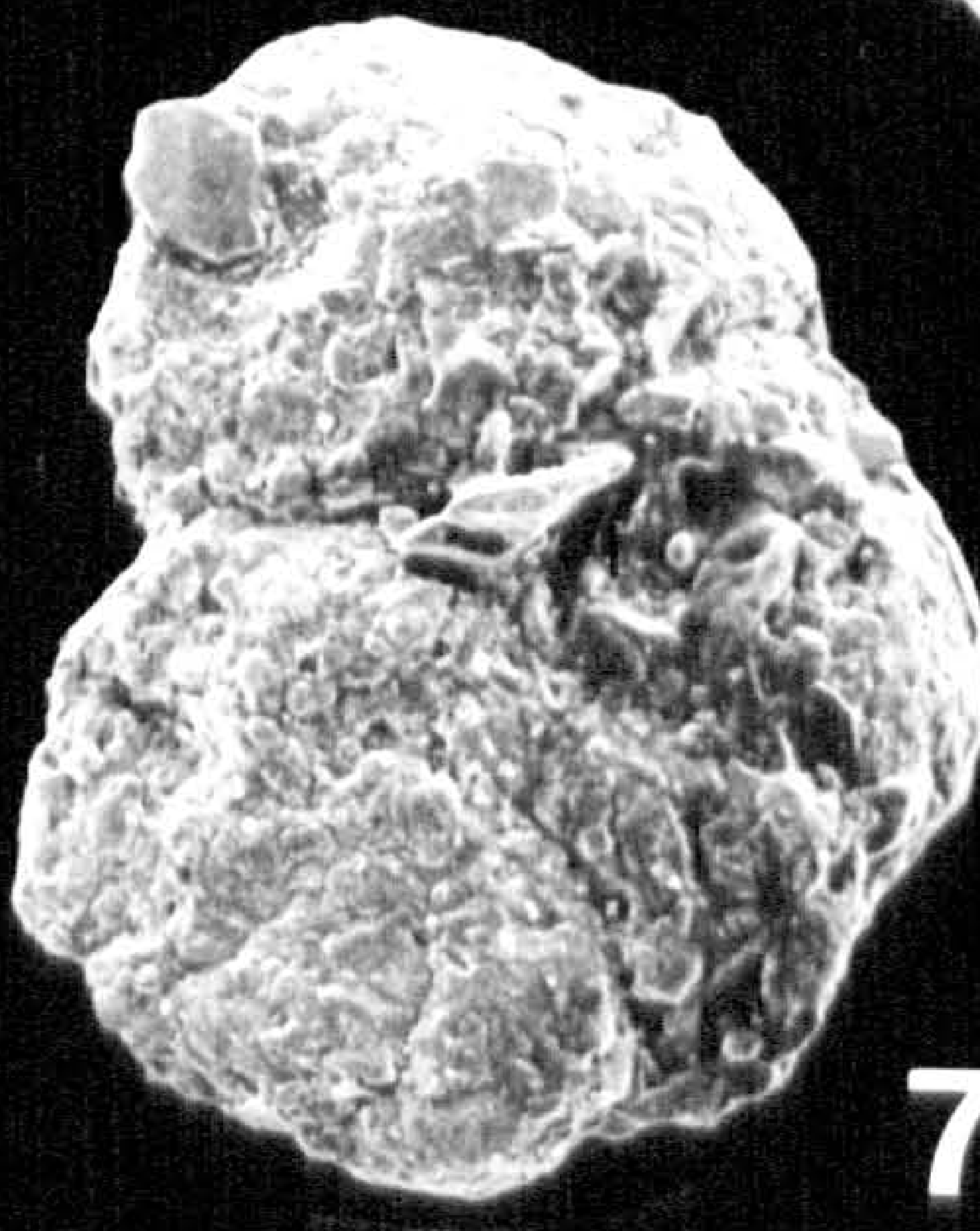
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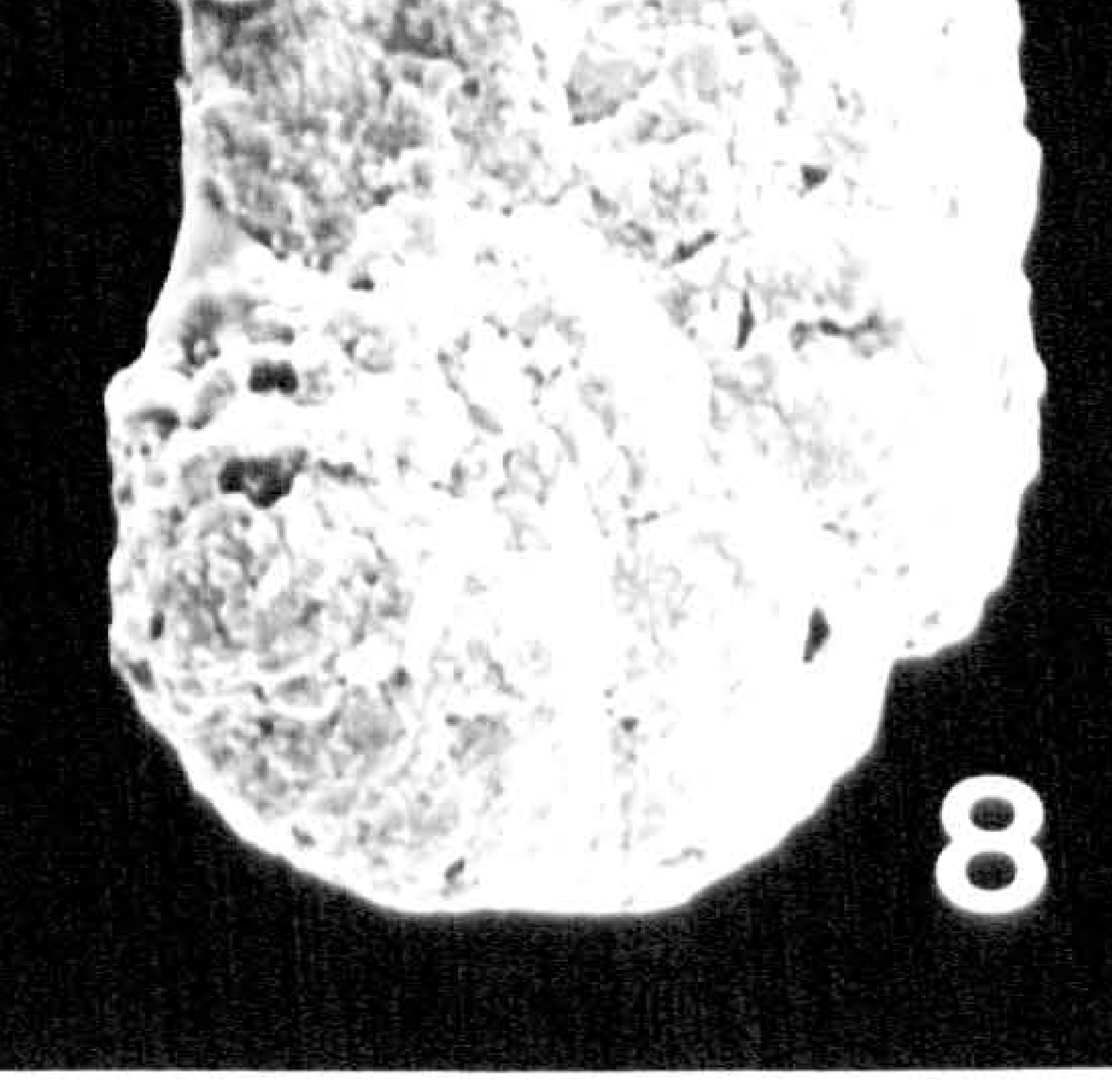
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PLATE 4

Figure 1. Lituotuba sp. A
Maximum Length 394µm. Sample No. BRS13

Figure 2. Lituotuba irregularis Tappan, 1955
Maximum Length 255µm. Sample No. BRS2

Figure 3. Ammobaculites agglutinans (d'Orbigny), 1846
Maximum Length 592µm. Sample No. DC5

Figure 4. Ammobaculites coprolithiformis (Schwager), 1867. Uncoiled
Maximum Length 1.36mm. Sample No. PR14

Figure 5. Ammobaculites coprolithiformis (Schwager), 1867. Coiled
Maximum Length 1.59 mm. Sample No. PR14

Figure 6. Ammobaculites deceptoria (Haeusler), 1890
Maximum Length 463µm. Sample No. GS11

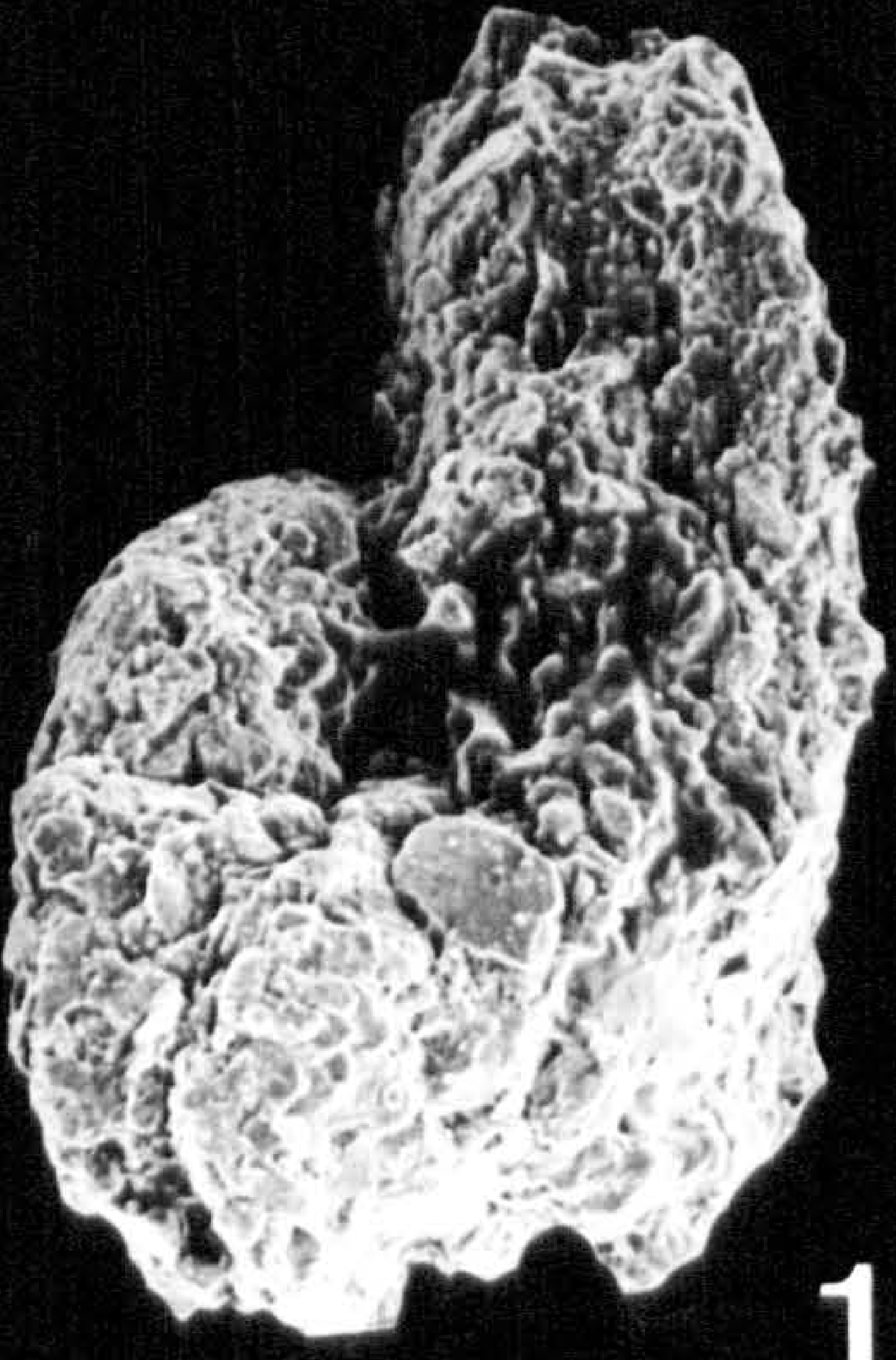
Figure 7. Ammobaculites fontinensis (Terquem), 1870
Maximum Length 515µm. Sample No. PC2

Figure 8. Ammobaculites vetusta (Terquem & Berthelin), 1875
Maximum Length 811µm. Sample No. BRS2

Figure 9. Triplasia acuta Bartenstein & Brand, 1951
Maximum Length 1.64mm. Sample No. BRS8

Figure 10. Placopsilina argoviensis Haeusler, 1881
Maximum Length 146µm. Sample No. DC5

PLATE 4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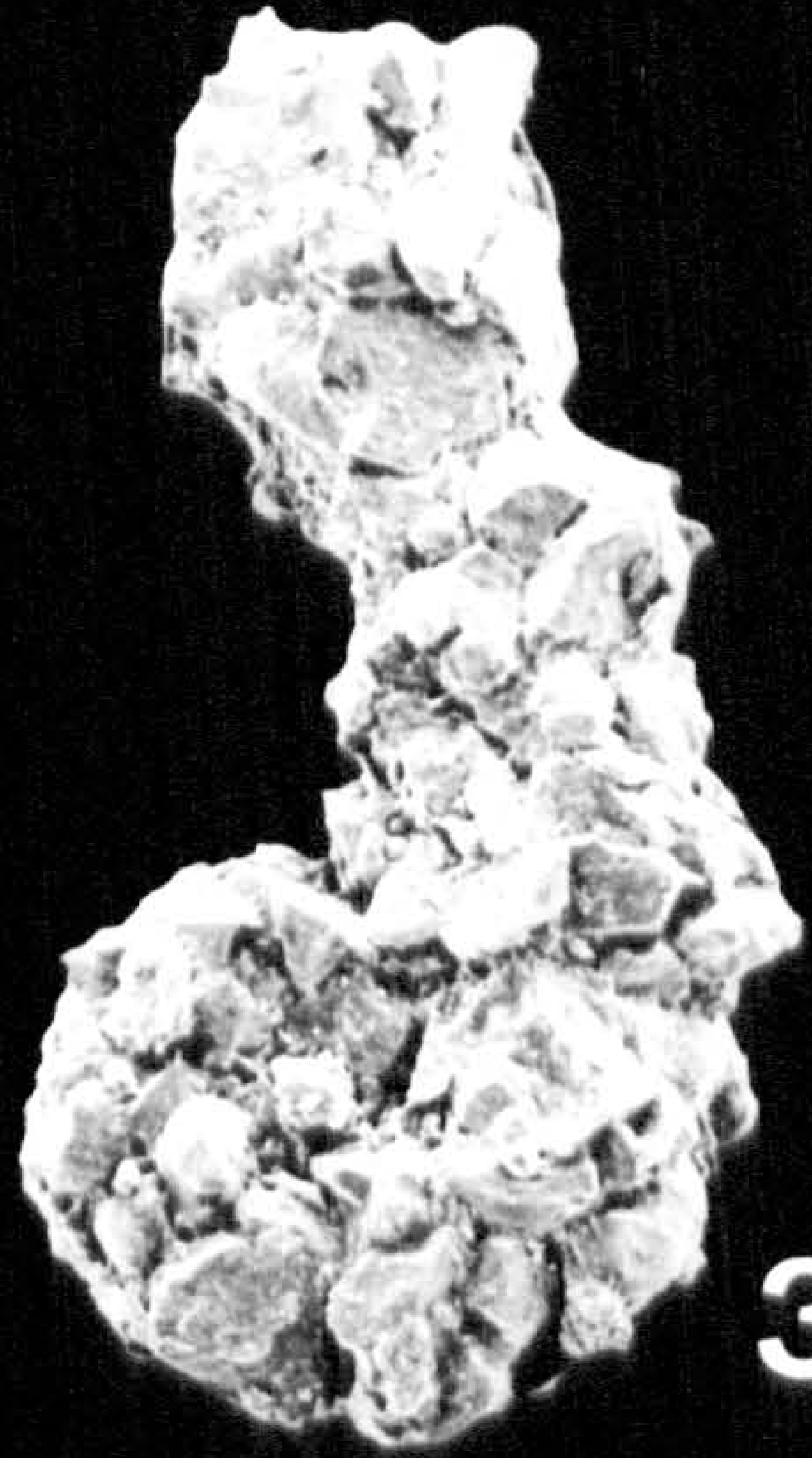
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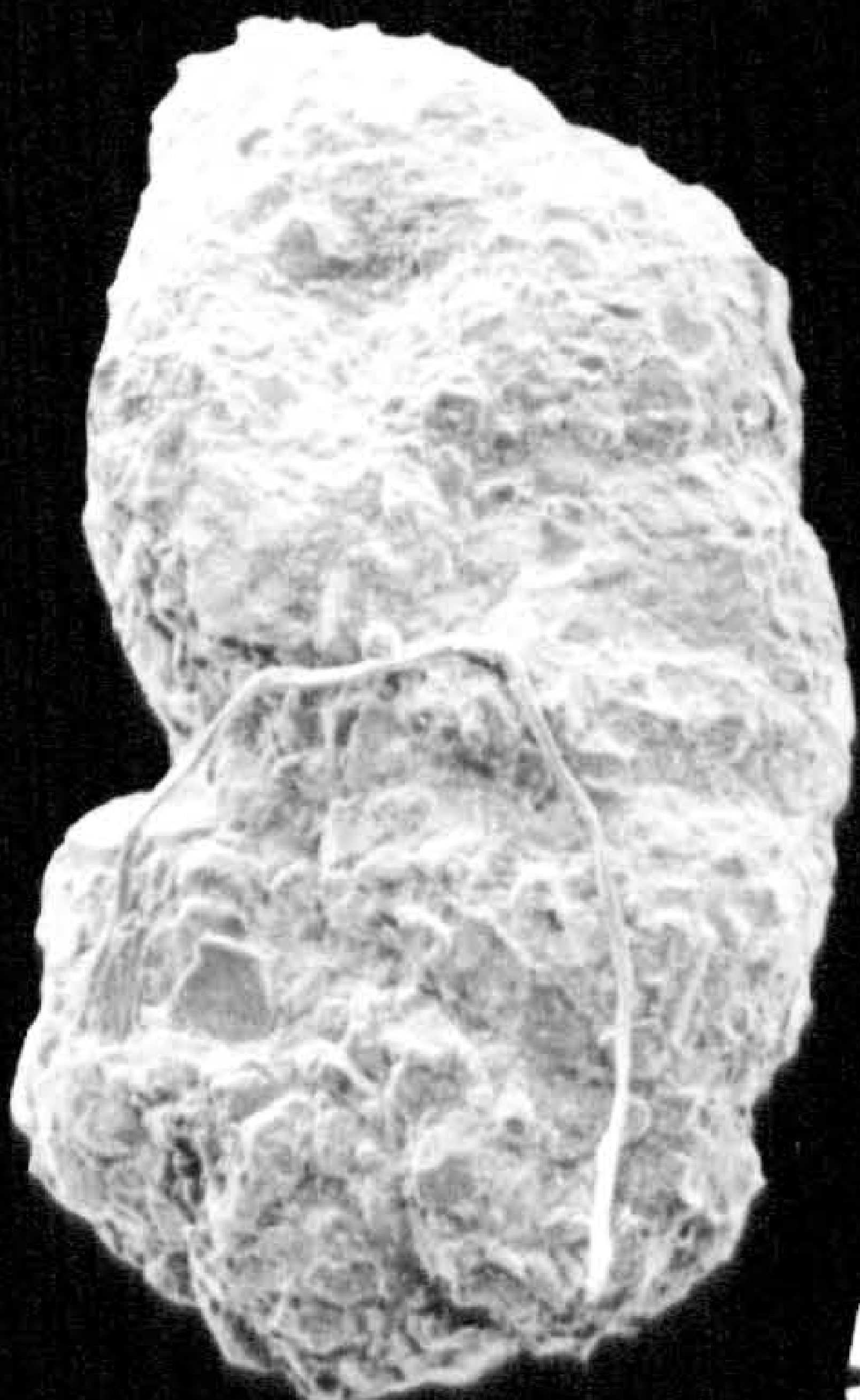
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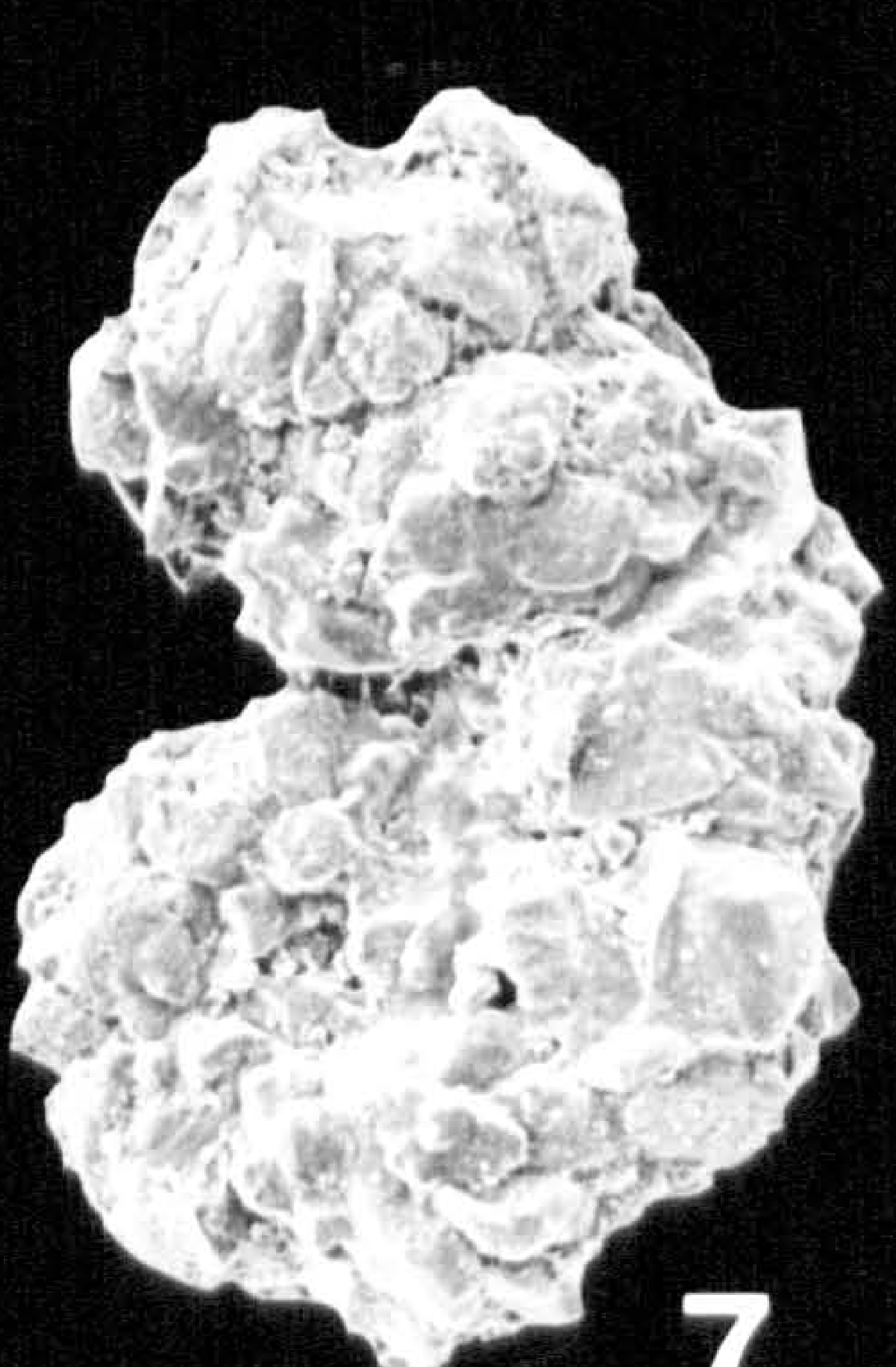
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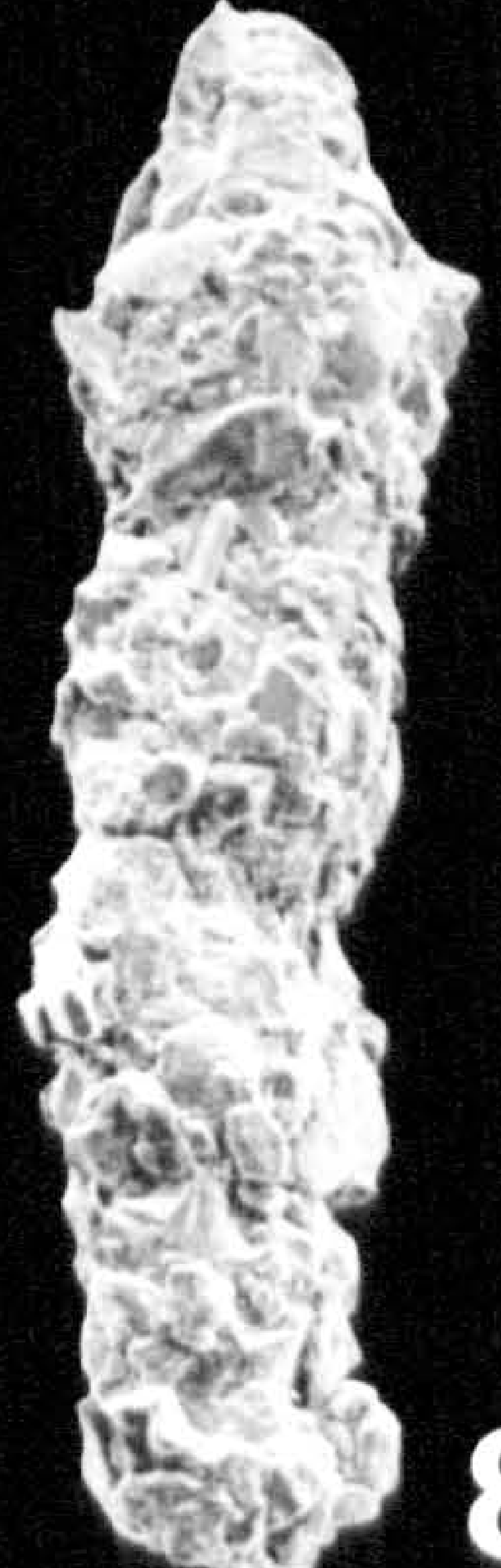
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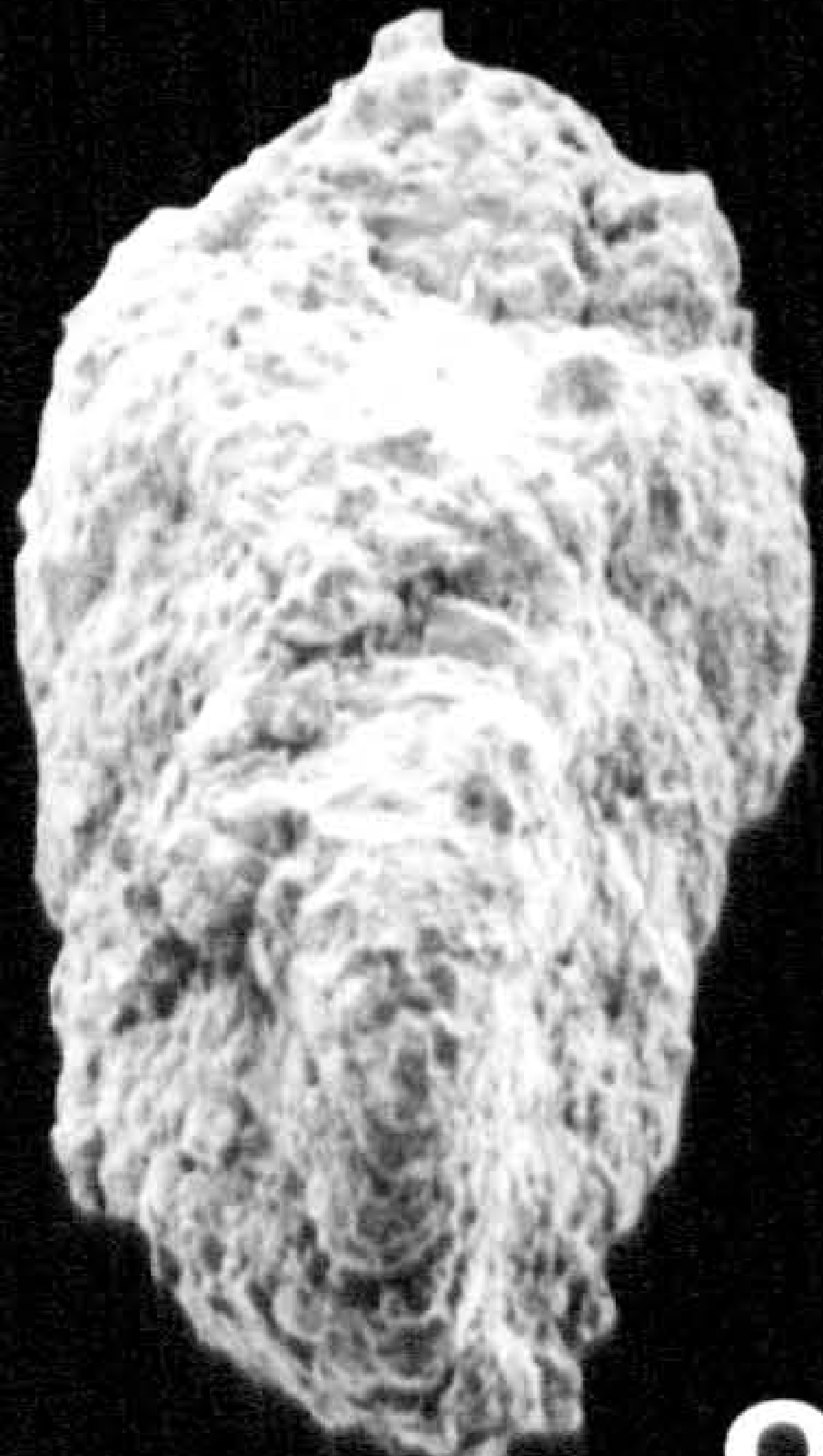
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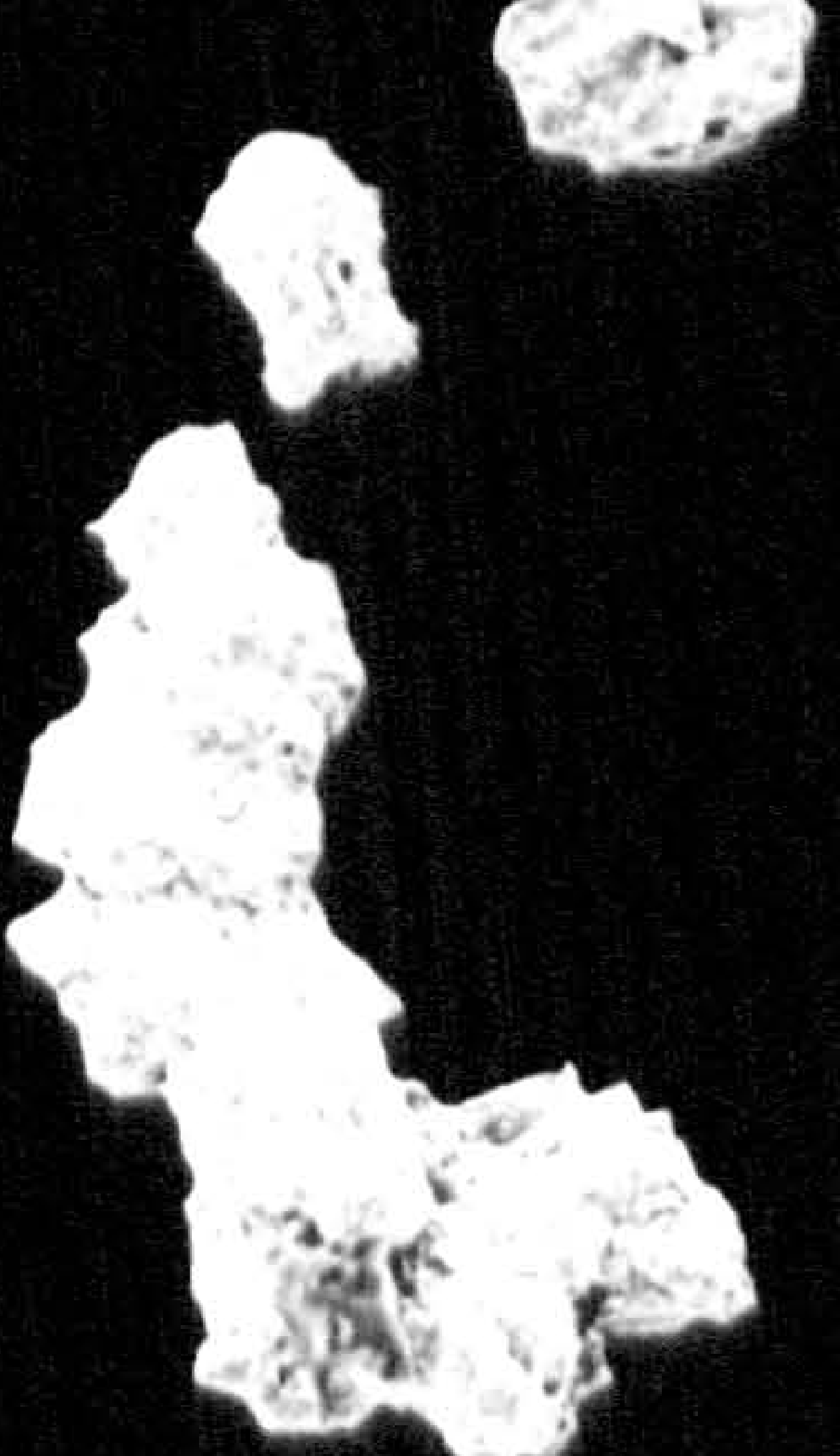
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PLATE 5

Figure 1. Recurvoides disputabilis Dain 1972
Maximum Diameter 271µm. Sample No. DS3

Figure 2. Recurvoides sublustris Dain, 1972
Maximum Diameter 381µm. Sample No. PC4

Figure 3. Spiroplectammina biformis (Parker & Jones), 1865
Maximum Length 197µm. Sample No. BRS11

Figure 4. Spiroplectammina vicinalis Dain, 1967
Maximum Length 531µm. Sample No. F28

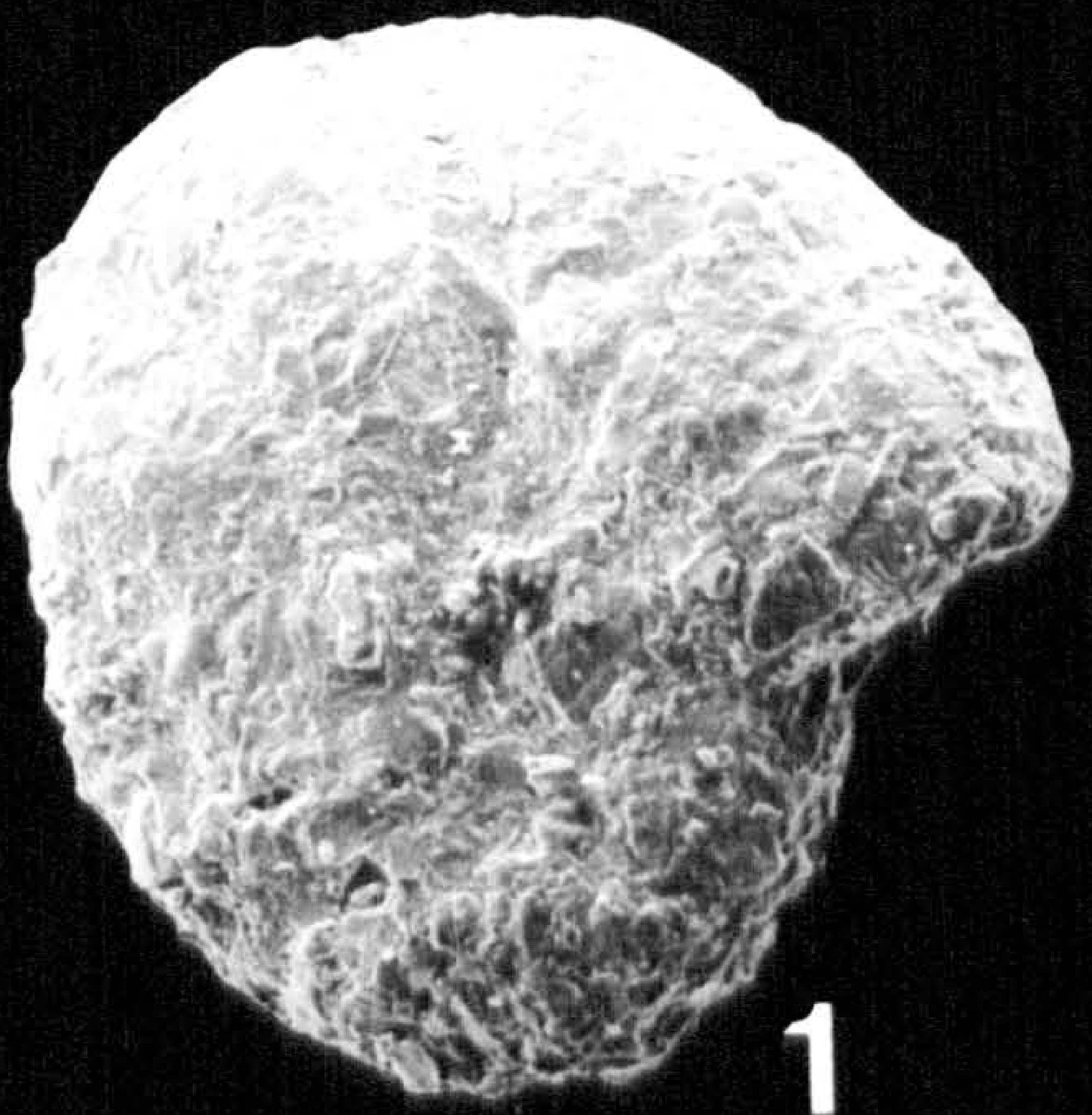
Figure 5. Trochammina canningensis Tappan, 1955
Maximum Diameter 161µm. Sample No. F4

Figure 6. Trochammina sablei Tappan, 1955
Maximum Diameter 285µm. Sample No. DC2

Figure 7. Trochammina squamata Parker & Jones, 1860. Spiral View
Maximum Diameter 305µm. Sample No. F23

Figure 8. Trochammina squamata Parker & Jones, 1860. Umbilical View
Maximum Diameter 264µm. Sample No. F23

PLATE 5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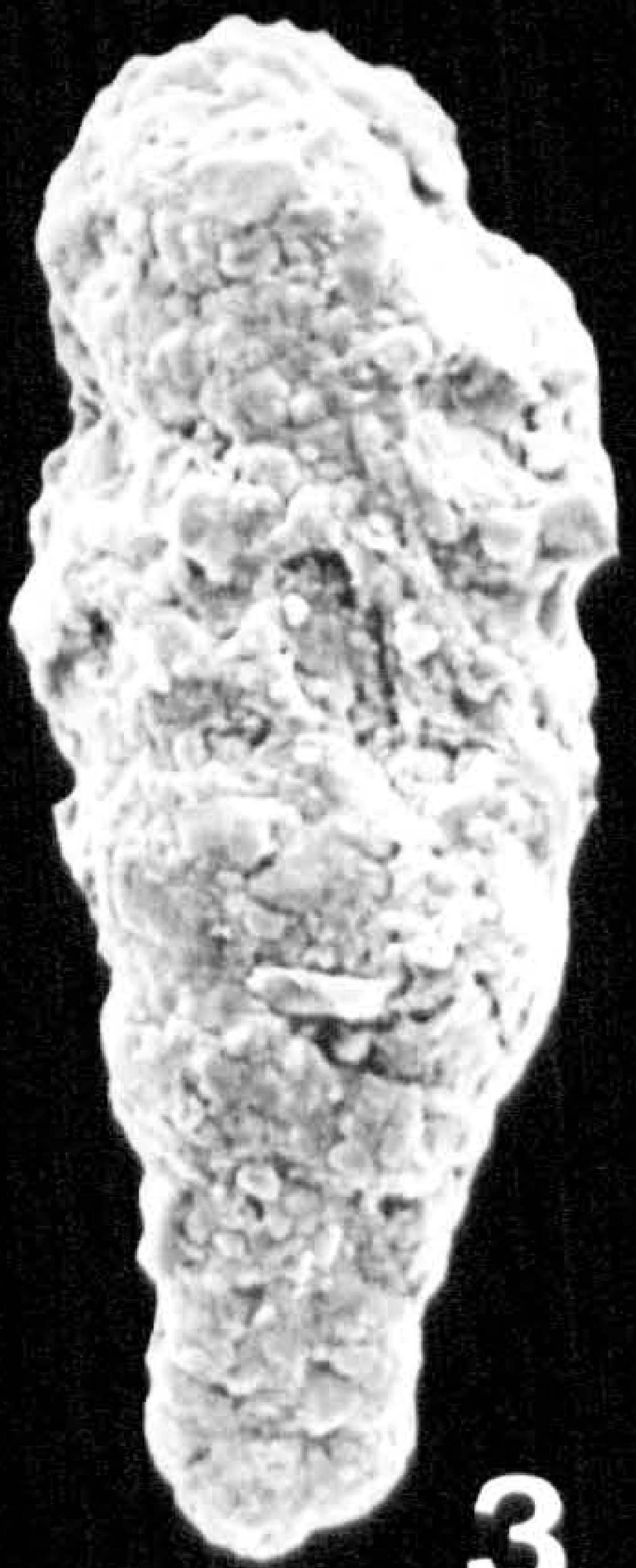
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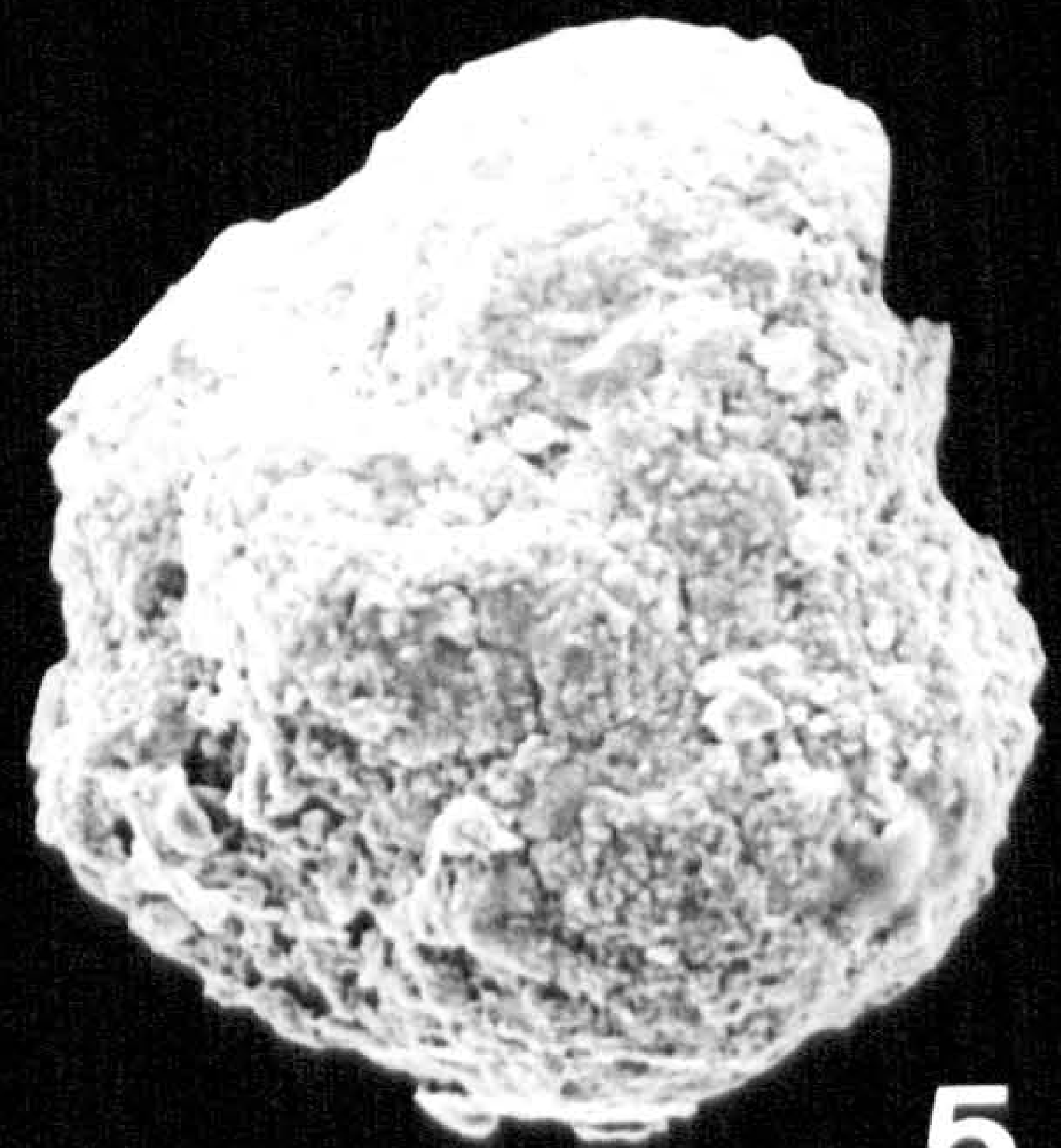
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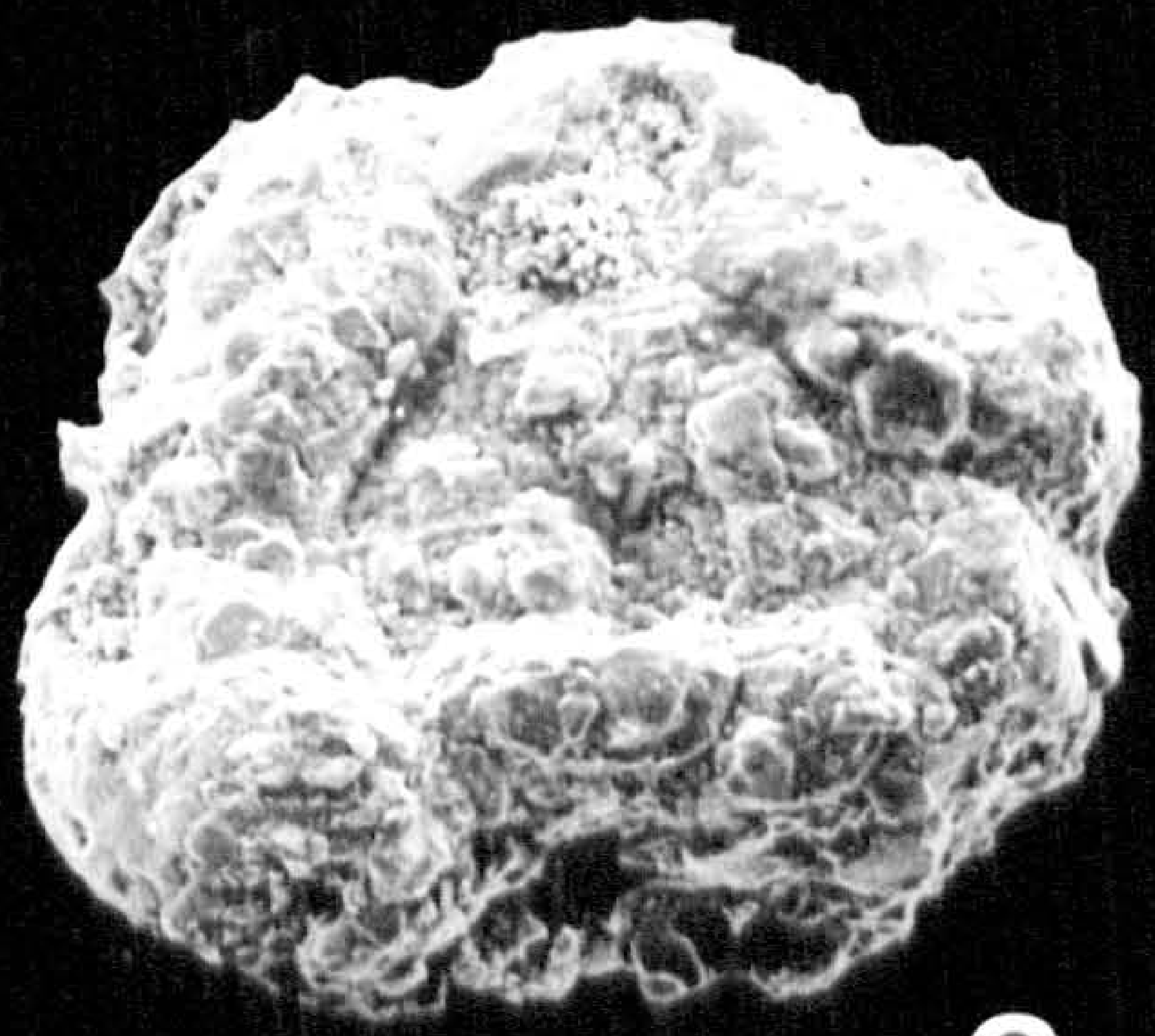
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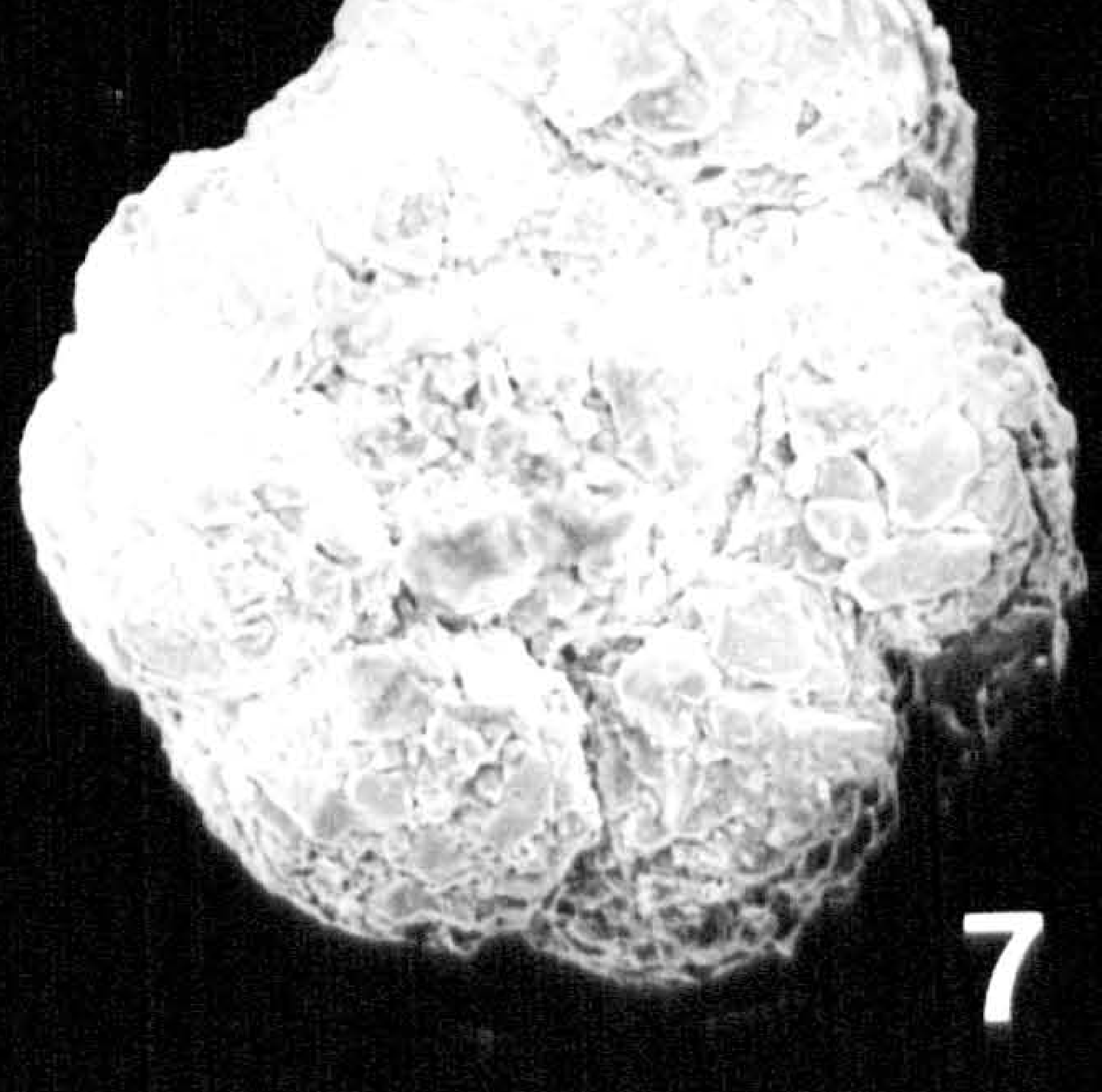
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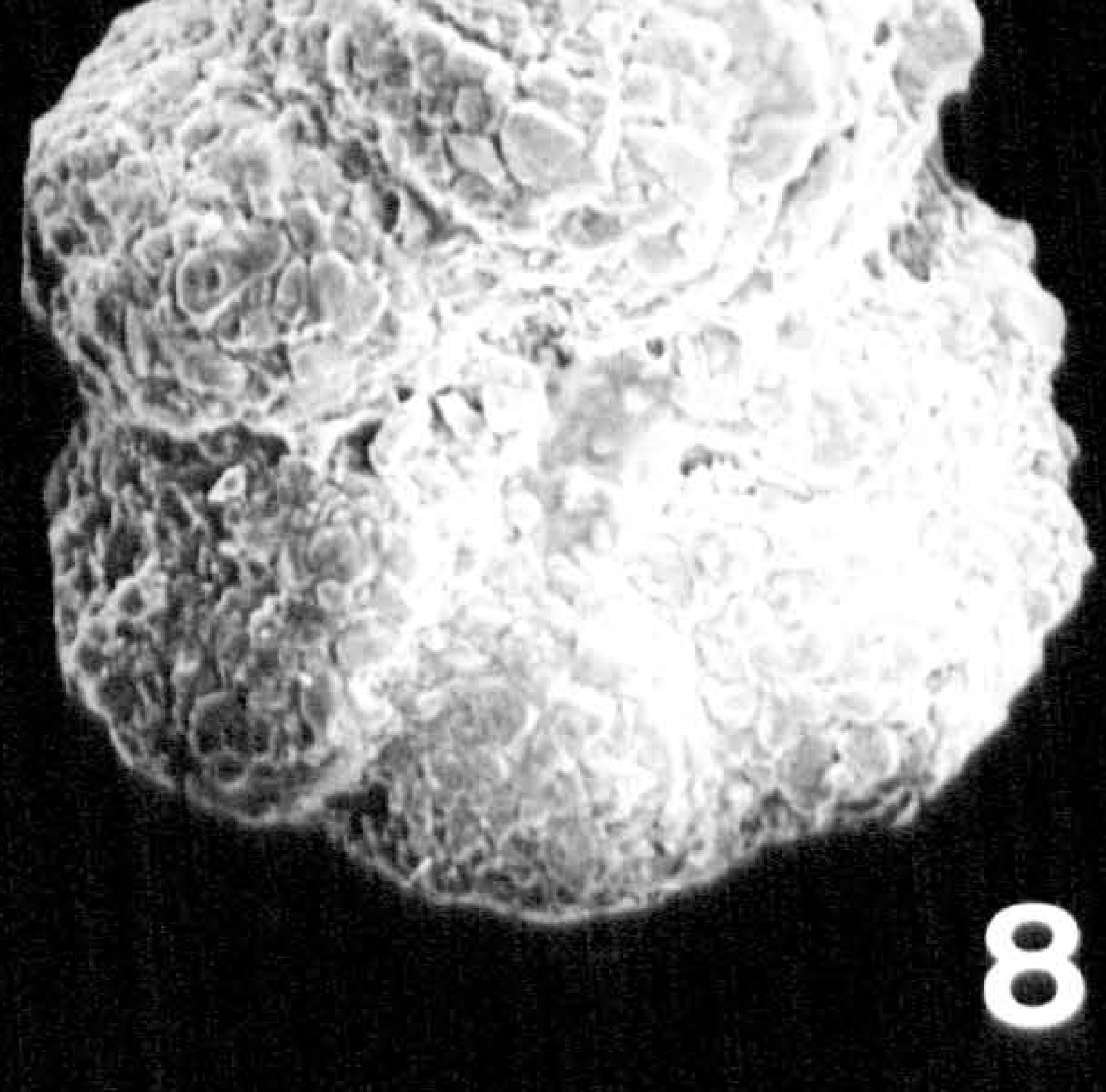
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PLATE 6

Figure 1. Trochammina topagorukensis Tappan, 1955 Spiral View
Maximum Diameter 326µm. Sample No. F22

Figure 2. Trochammina topagorukensis Tappan, 1955. Side View
Maximum Diameter 326µm. Sample No. F22

Figure 3. Verneuilinoides sp. 2 Morris & Coleman, 1989
Maximum Length 147µm. Sample No. DC2

Figure 4. Verneuilinoides mauritii (Terquem), 1866
Maximum Length 165µm. Sample No. BRS22

Figure 5. Verneuilinoides tryphera Tappan, 1955
Maximum Length 210µm. Sample No. BRS12

Figure 6. Gaudryina sp. A
Maximum Length 592µm. Sample No. D14

Figure 7. Gaudryina aff. sherlocki (Bettenstaedt), 1952
Maximum Length 536µm. Sample No. DC18

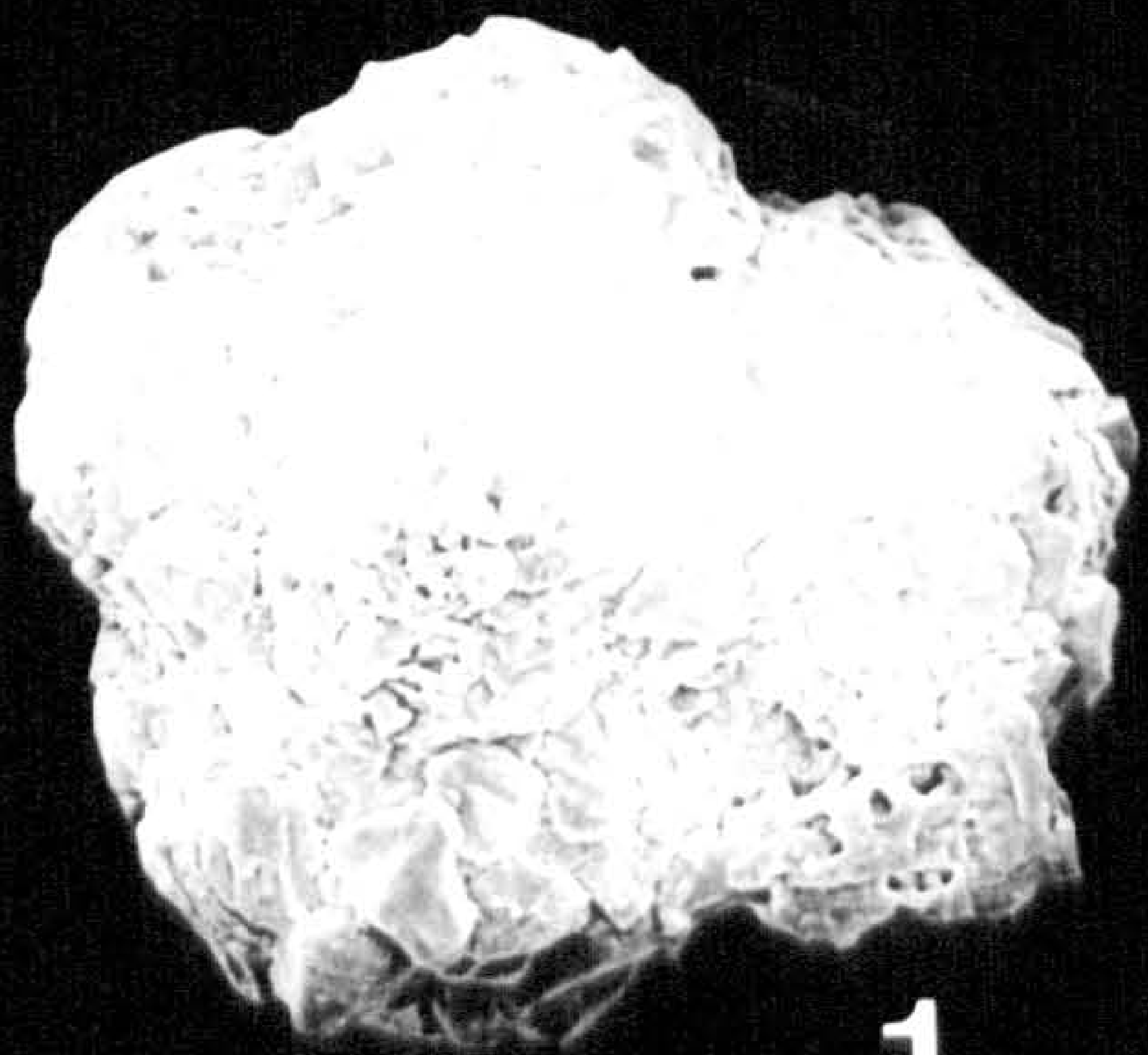
Figure 8. Textularia sp. A
Maximum Length 210µm. Sample No. PC2

Figure 9. Textularia areoplecta Tappan, 1955
Maximum Length 197µm. Sample No. PR28

Figure 10. Textularia jurassica (Gümbel), 1862
Maximum Length 292µm. Sample No. DC2

Figure 11. Bigenerina sp.
Maximum Length 171µm. Sample No. F12

PLATE 6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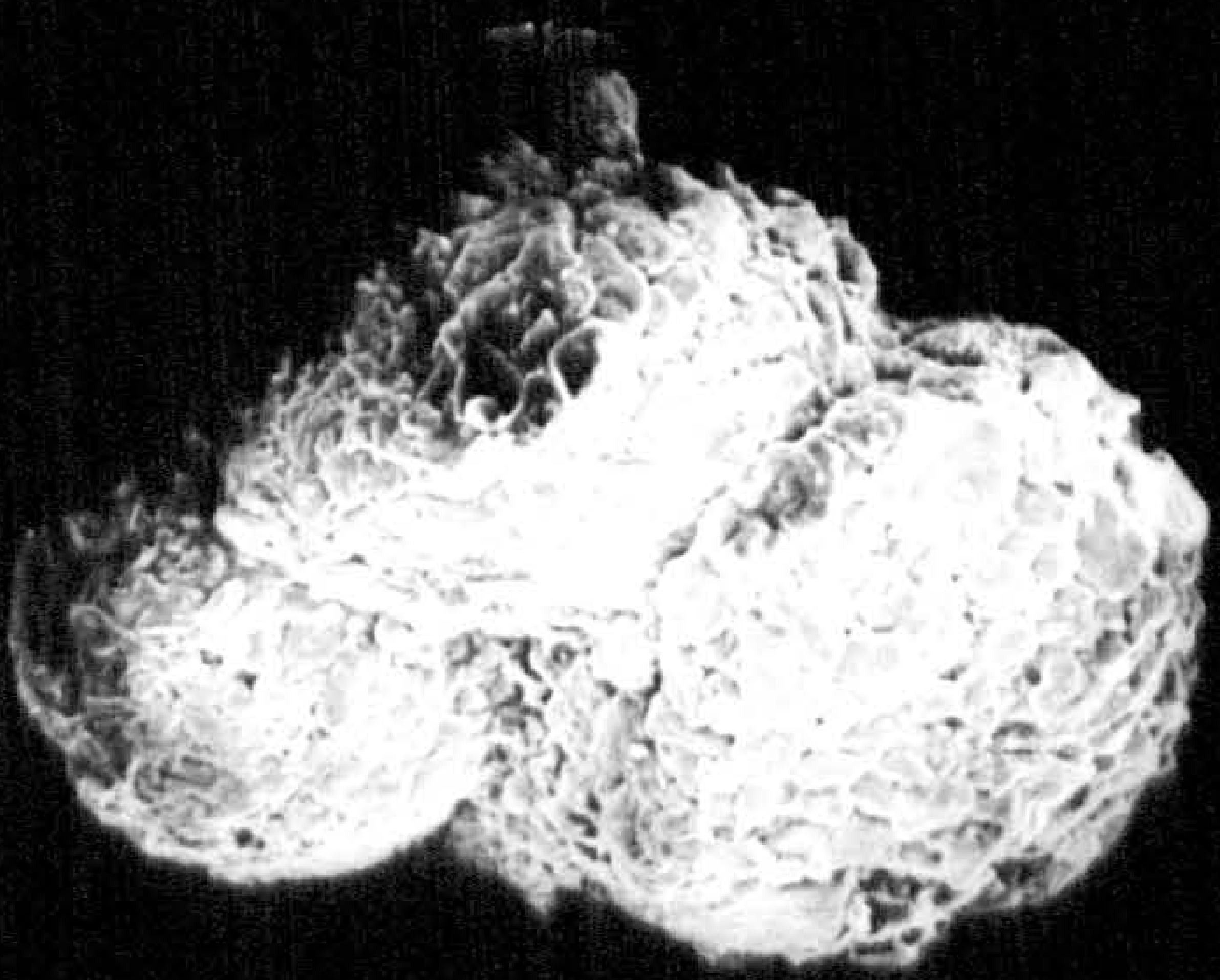
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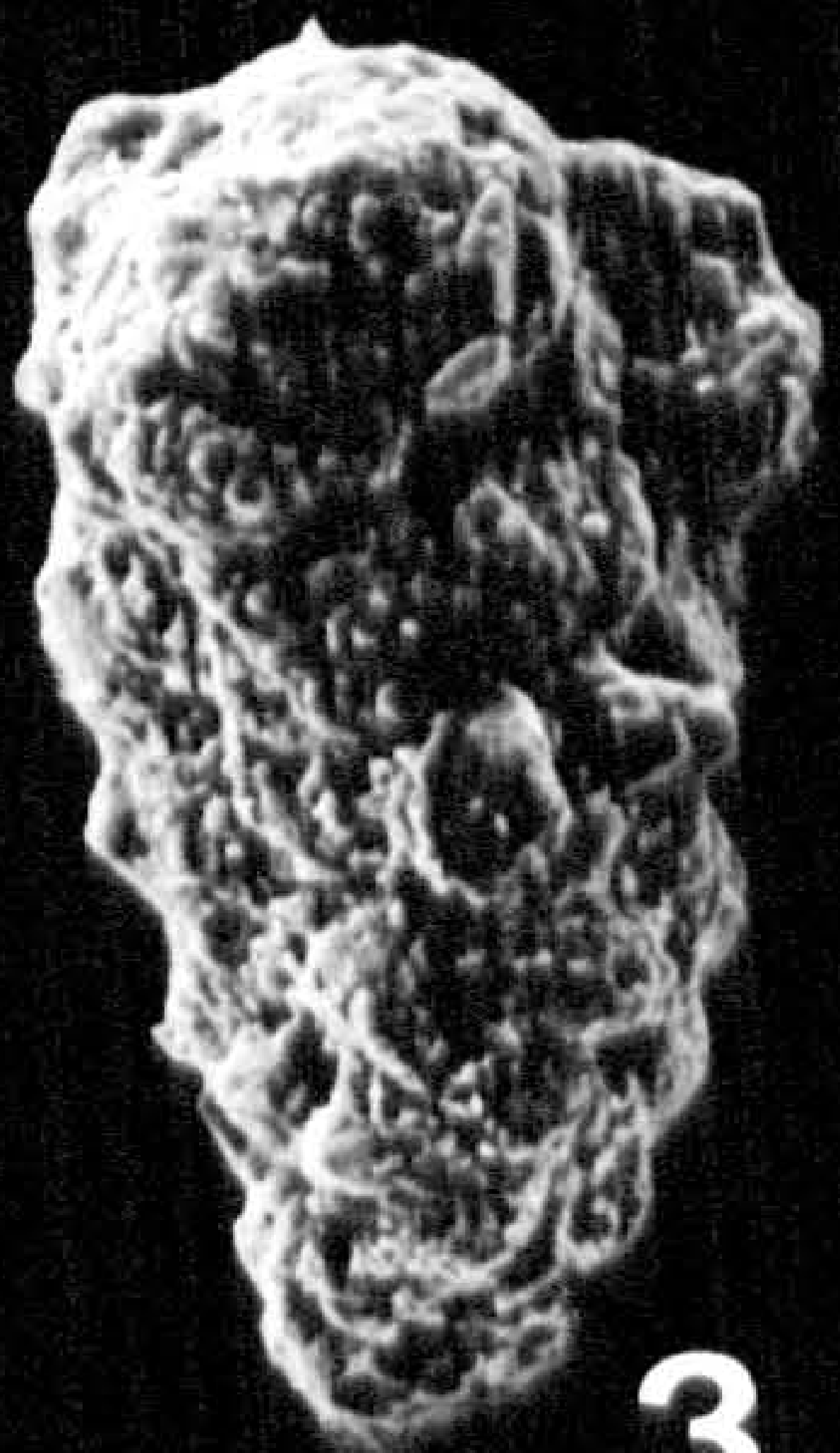
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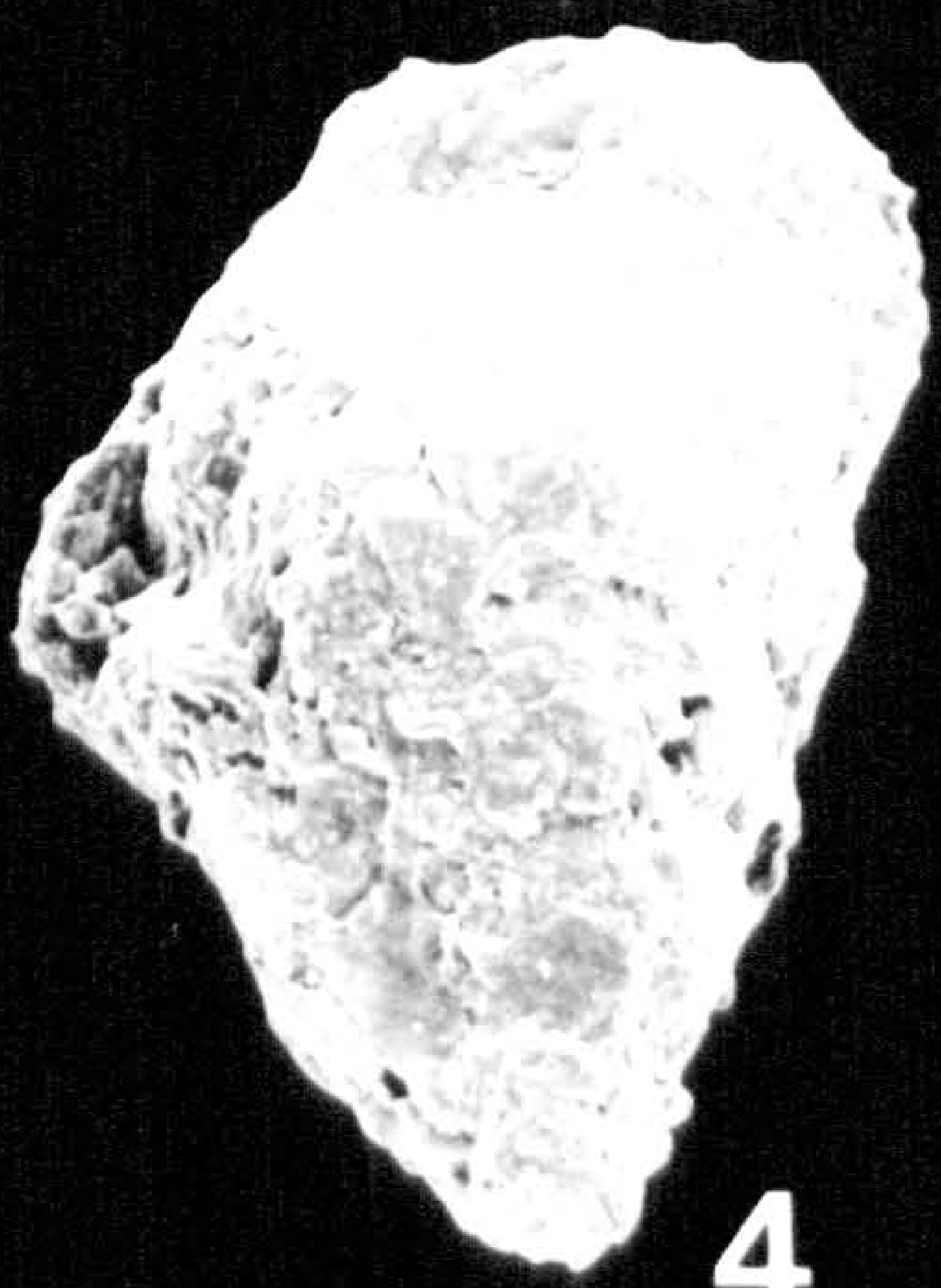
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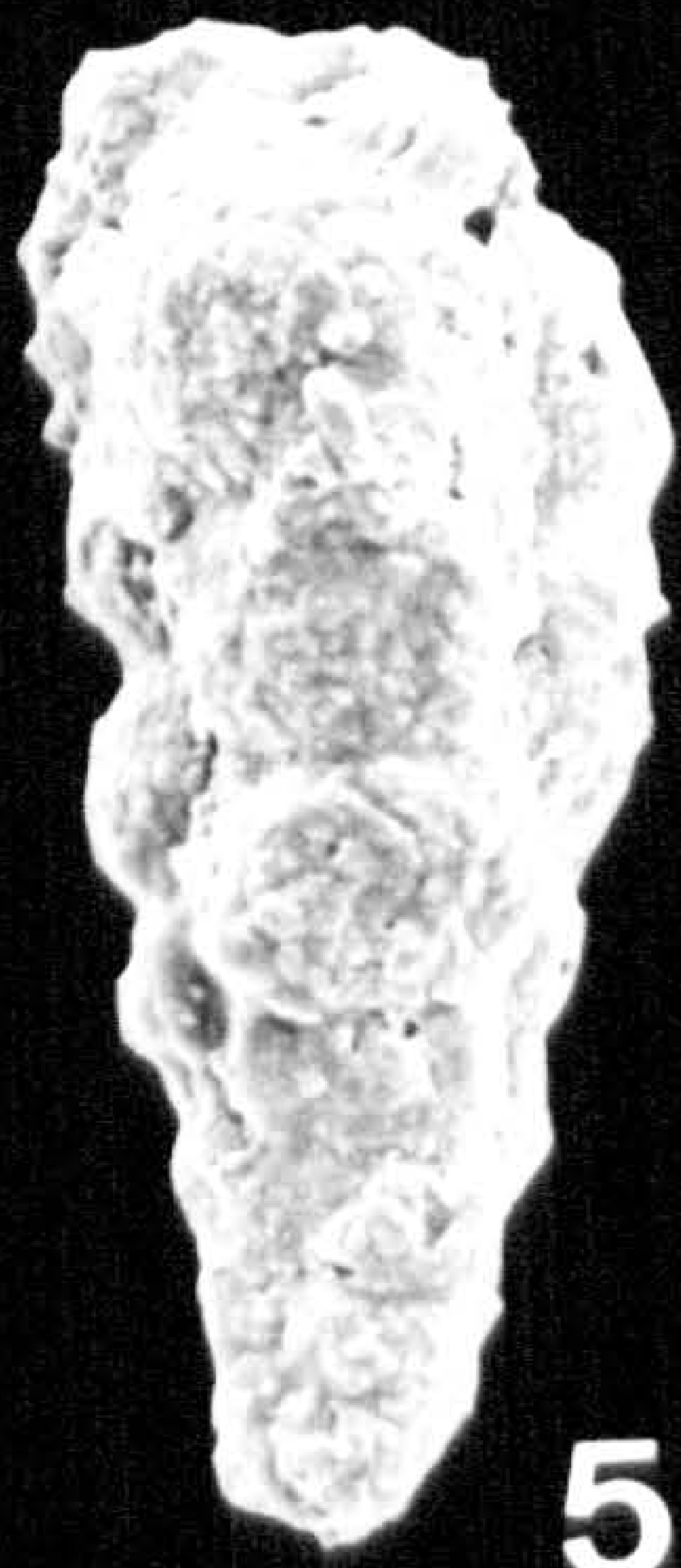
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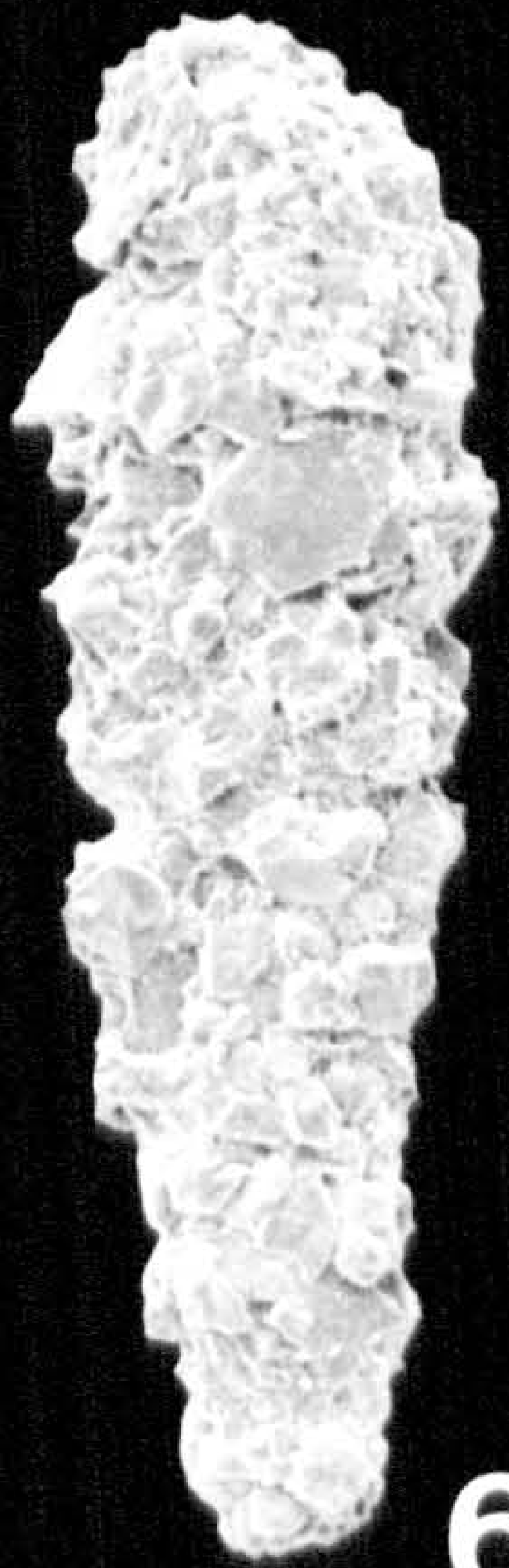
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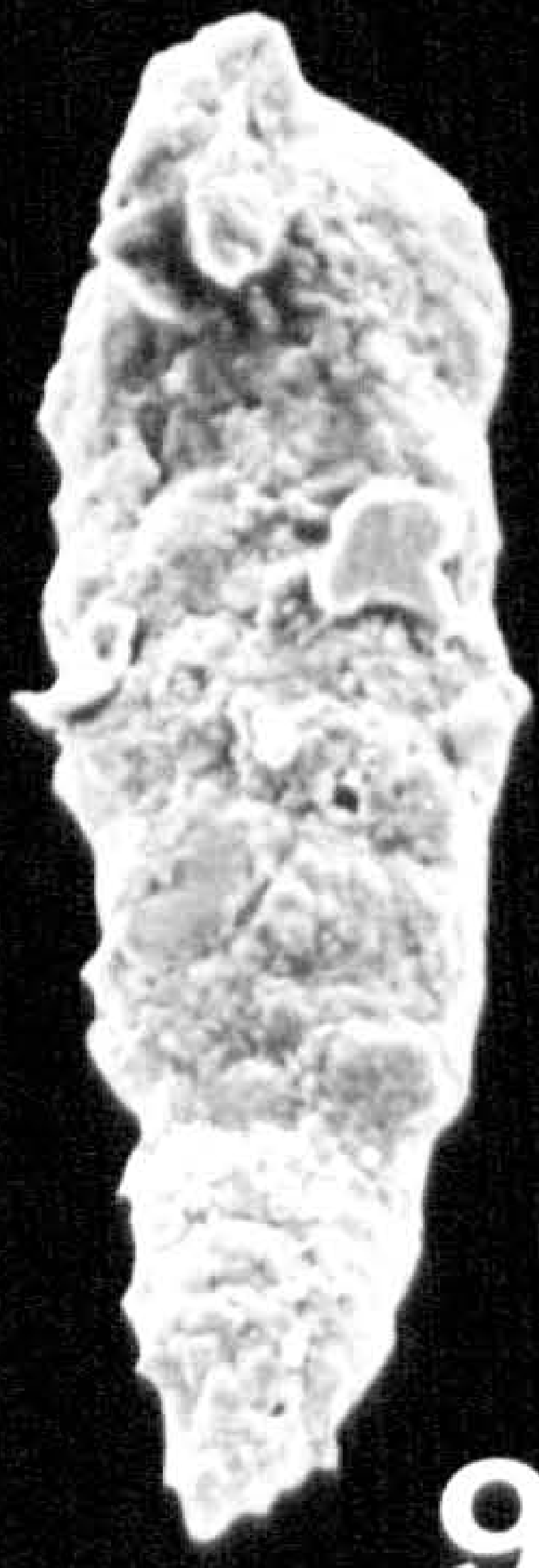
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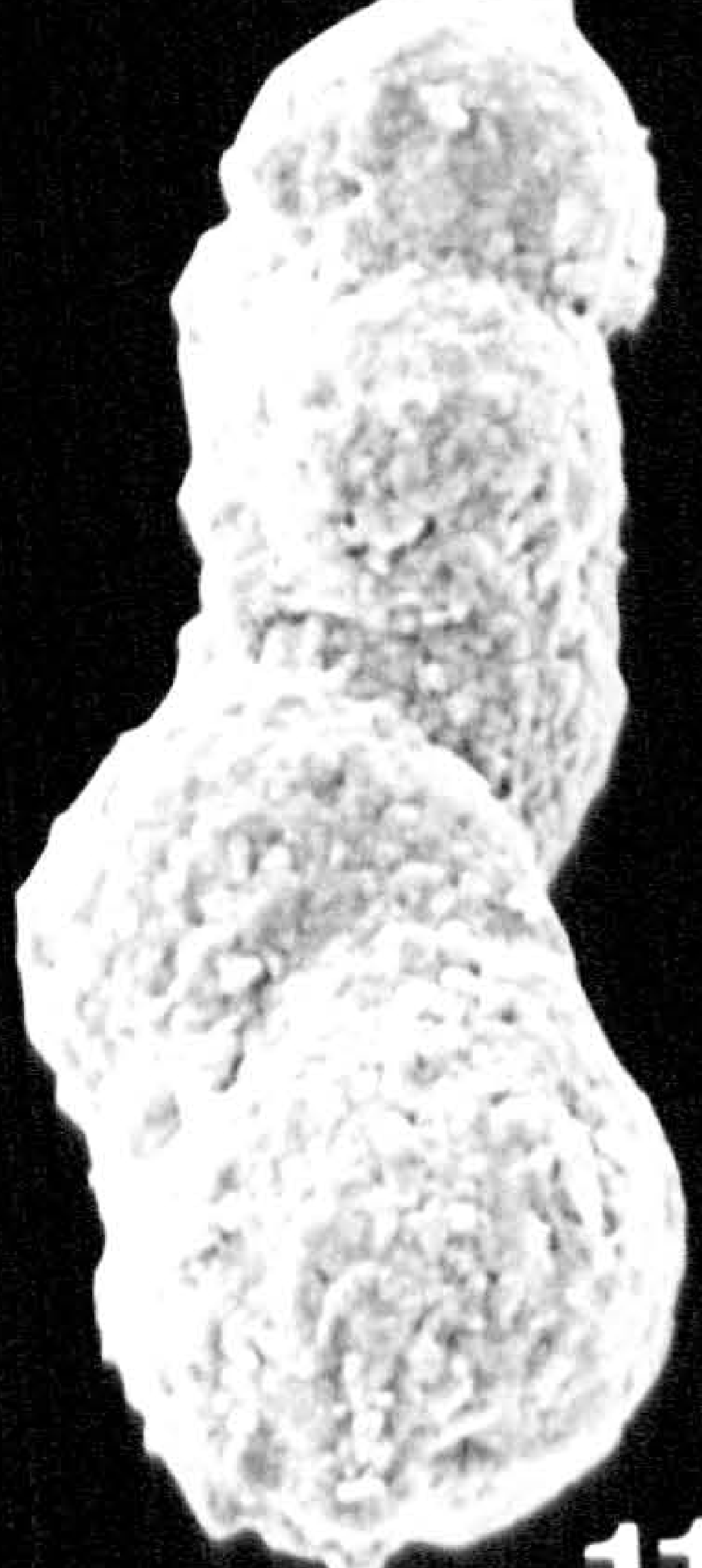
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PLATE 7

Figure 1. ?Valvulina sp.
Maximum Length 256µm. Sample No. PR33

Figure 2. ?Trocholina sp.
Maximum Diameter 223µm. Sample No. PR1

Figure 3. Spirillina elongata Bielecka & Pozaryski, 1954
Maximum Diameter 291µm. Sample No. GS13

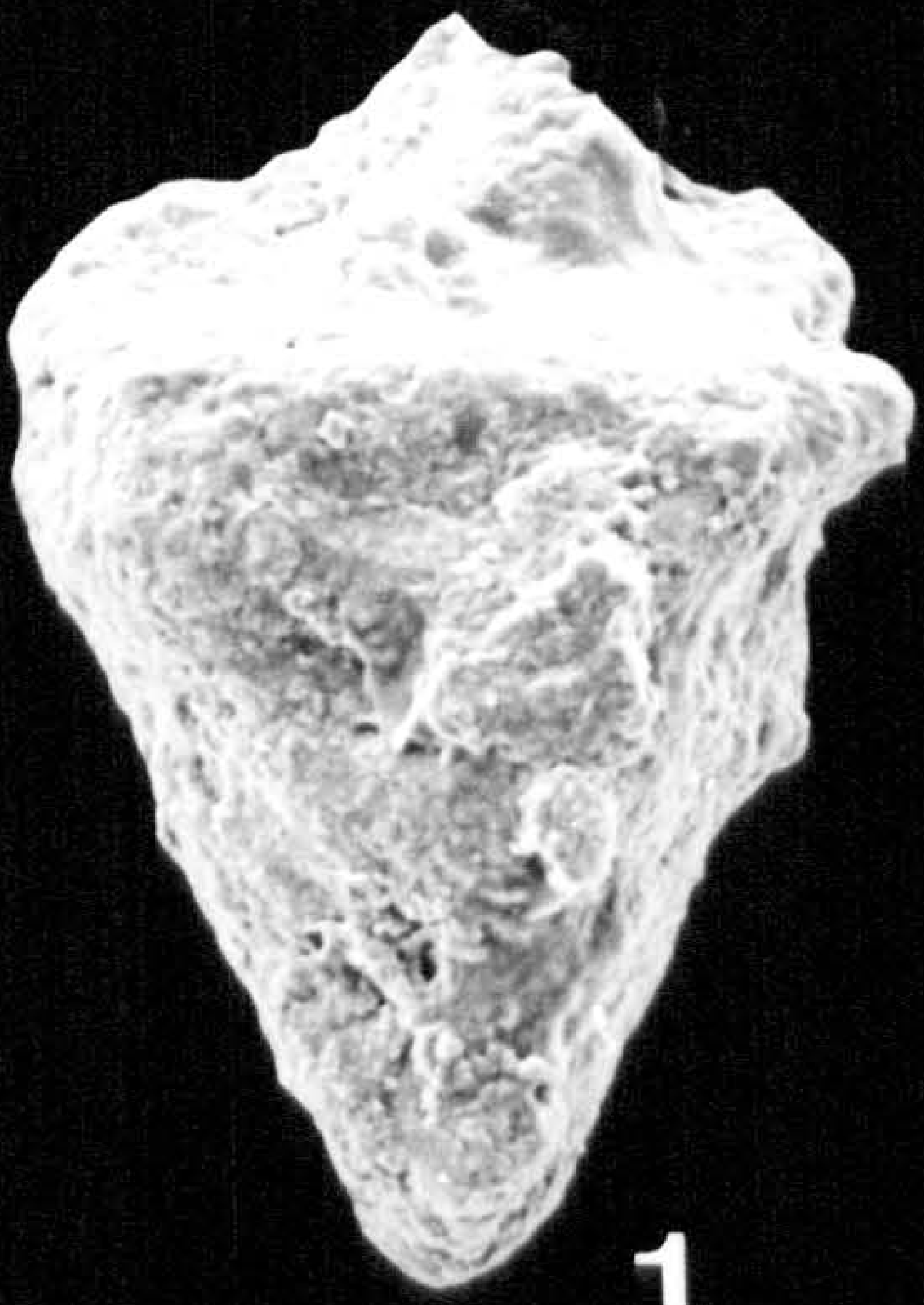
Figure 4. Conicospirillina trochoides (Berthelin), 1879
Maximum Diameter 220µm. Sample No. KWN9

Figure 5. Spirillina infima (Strickland), 1846
Maximum Diameter 230µm. Sample No. KW9

Figure 6. Spirillina tenuissima Gümbel, 1862
Maximum Diameter 405µm. Sample No. KW10

Figure 7. Cornuspira eichbergensis Kübler & Zwingli, 1870
Maximum Diameter 480µm. Sample No. KWN4

PLATE 7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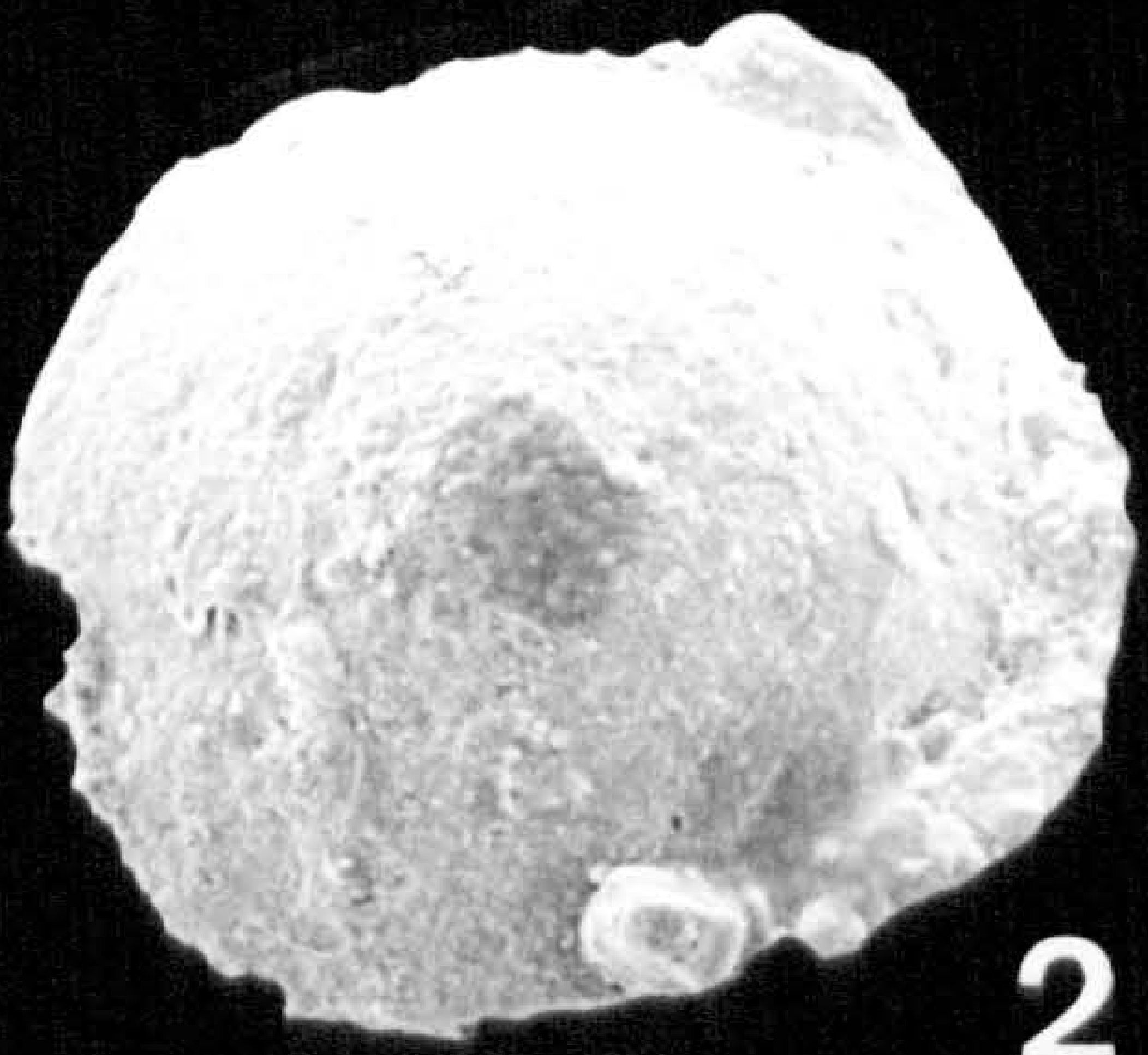
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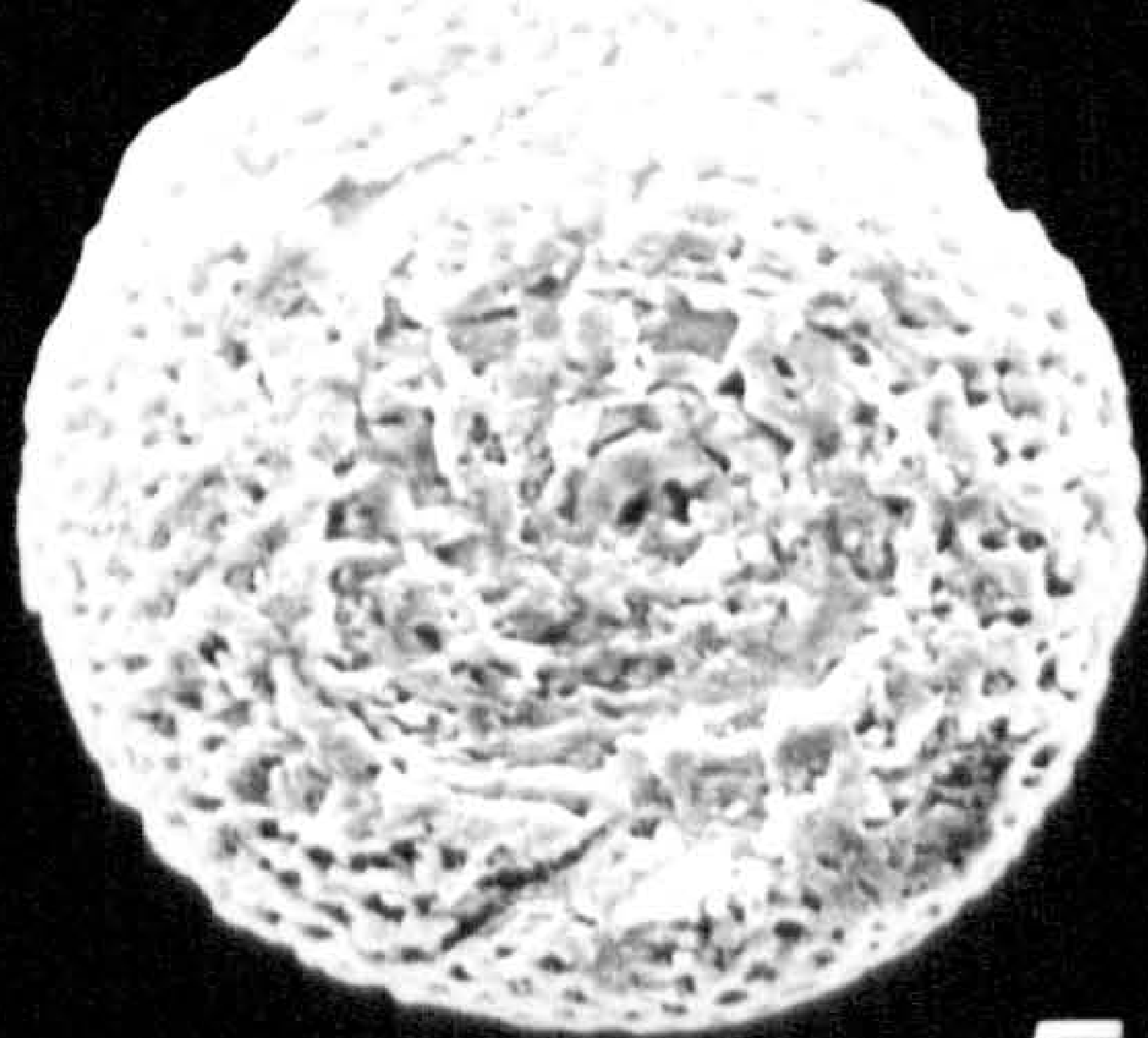
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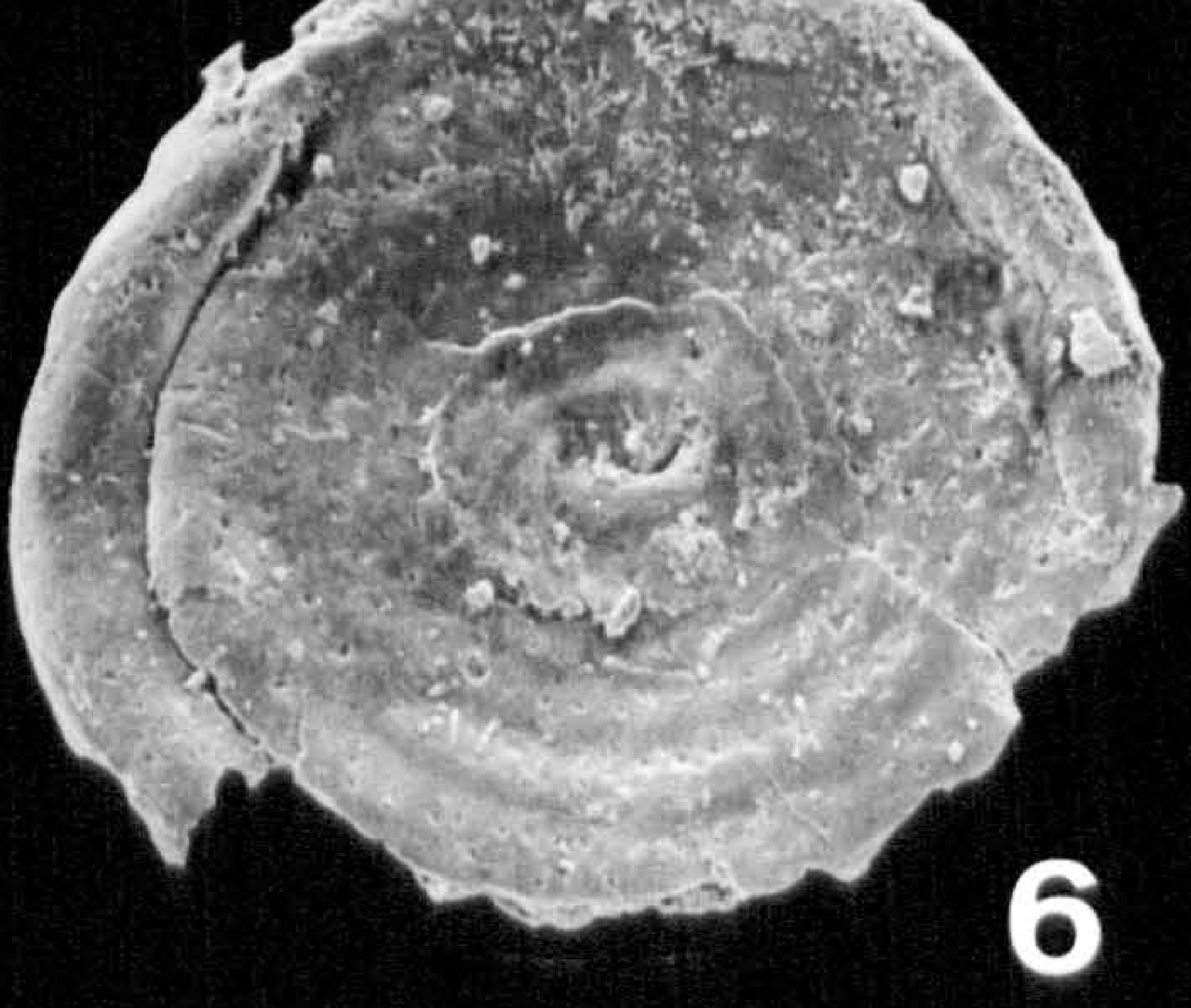
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PLATE 8

Figure 1. Cornuspira liasina Terquem, 1866
Maximum Diameter 269µm. Sample No. PR5

Figure 2. Nubeculinella tibia (Jones & Parker), 1860
Maximum Length 413µm. Sample No. GS13

Figure 3. Nubeculinella tibia (Jones & Parker), 1860
Maximum Length 197µm. Sample No. DC6

Figure 4. Nubecularia infraoolithica (Terquem), 1870
Maximum Length 421µm. Sample No. GS8

Figure 5. Nubecularia triloculina Ten Dam, 1950
Maximum Length 159µm. Sample No. DC20

Figure 6. Ophthalmidium sp. B
Maximum Length 252µm. Sample No. DC3

Figure 7. Ophthalmidium sp. A
Maximum Length 215µm. Sample No. U12

Figure 8. Ophthalmidium sp. C
Maximum Length 485µm. Sample No. DC17

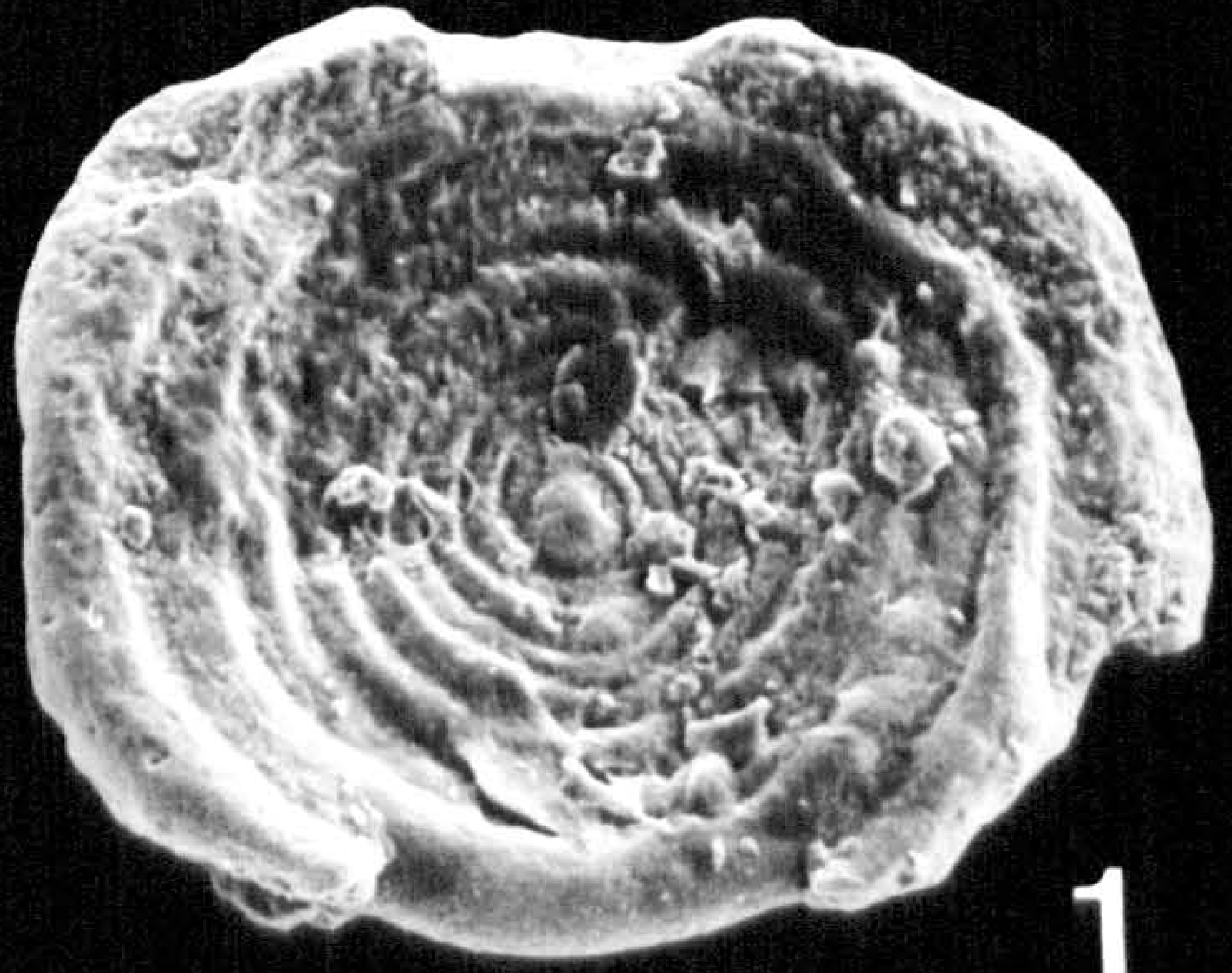
Figure 9. Ophthalmidium birmenstorfense Kübler & Zwingli, 1870
Maximum Length 423µm. Sample No. DC27

Figure 10. Ophthalmidium carinatum (Kübler & Zwingli), 1866
Maximum Length 248µm. Sample No. U14

Figure 11. Ophthalmidium liasicum (Kübler & Zwingli), 1866
Maximum Length 224µm. Sample No. U13

Figure 12. Ophthalmidium milioliniforme (Paalzow), 1932
Maximum Length 335µm. Sample No. DC7

PLATE 8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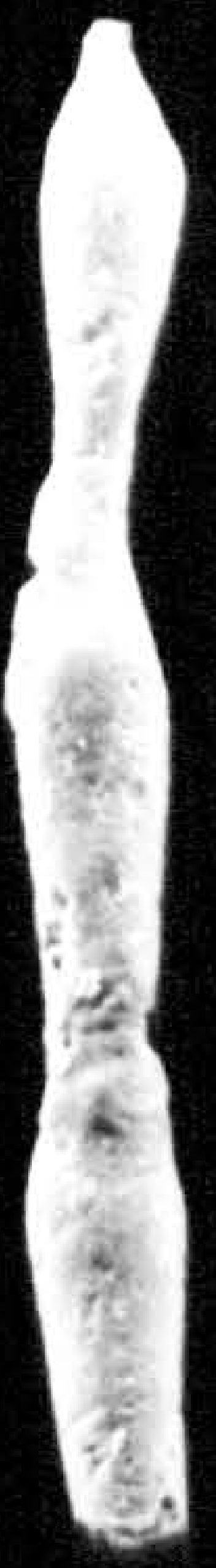
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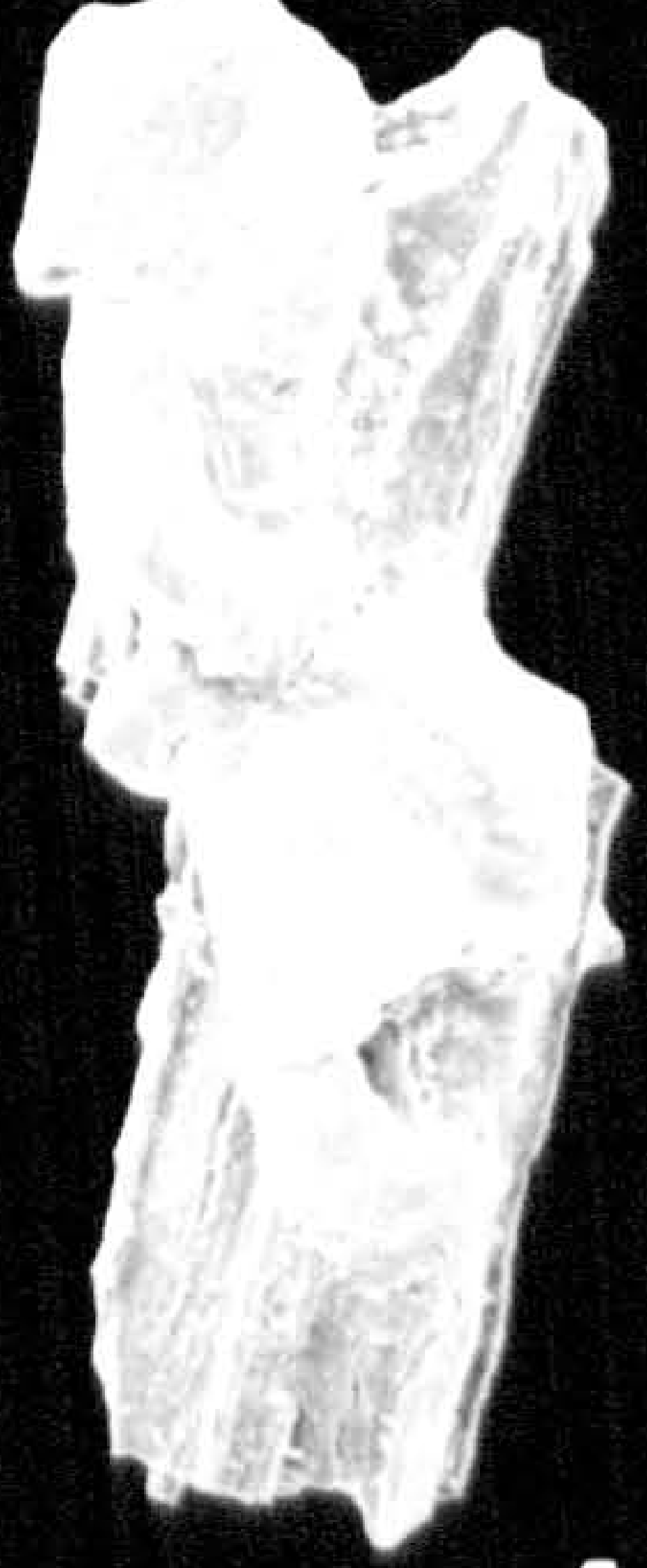
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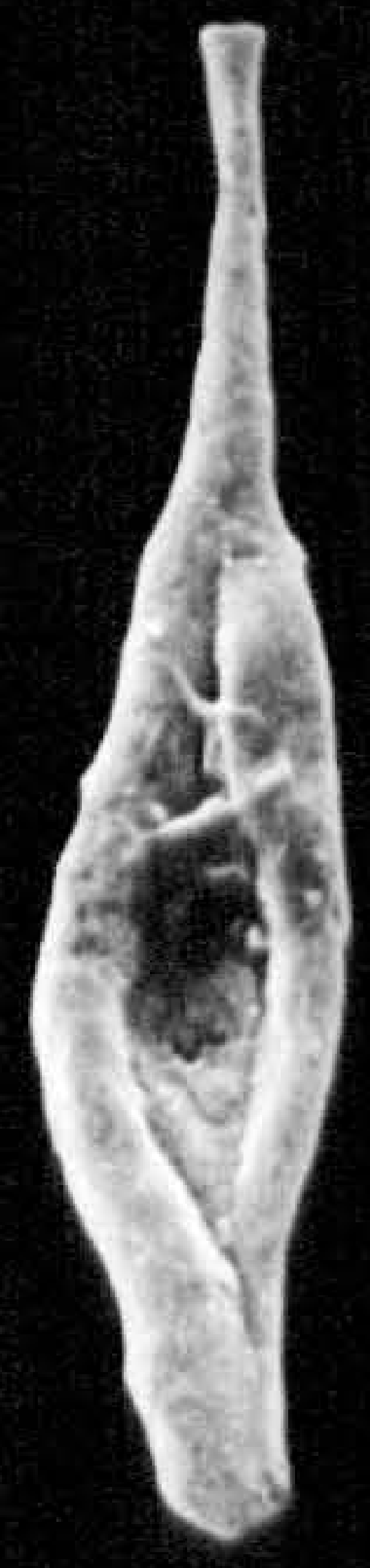
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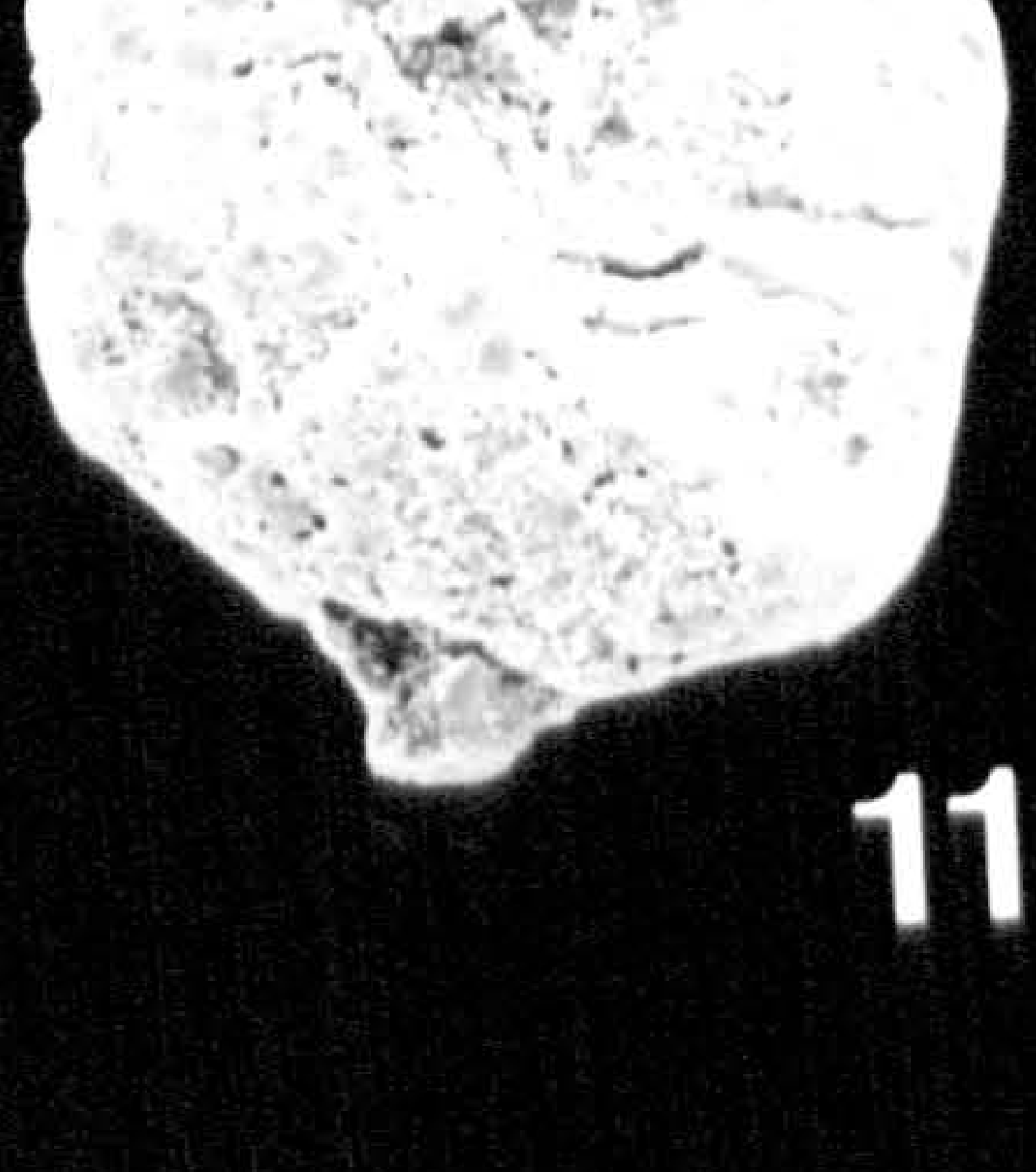
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PLATE 9

Figure 1. Ophthalmidium purtonensis Barnard et al., 1981
Maximum Length 389µm. Sample No. GS16

Figure 2. Ophthalmidium strumosum (Gümbel), 1862
Maximum Length 375µm. Sample No. BRS19

Figure 3. 'Duoplanum' sp. A
Maximum Length 248µm. Sample No. PR28

Figure 4. 'Duoplanum' sp. A
Maximum Length 260µm. Sample No. PR28

Figure 5. Palaeomiliolina czestochowiensis (Pazdrowa), 1959
Maximum Length 179µm. Sample No. U9

Figure 6. Palaeomiliolina rawiensis (Pazdrowa), 1959
Maximum Length 157µm. Sample No. U4

Figure 7. Falsopalmula deslongchampsi (Terquem), 1863
Maximum Length 226µm. Sample No. U16

Figure 8. Dentalina cuneiformis Terquem 1870
Maximum Length 257µm. Sample No. BRS13

Figure 9. Dentalina exilis Franke, 1936
Maximum Length 310µm. Sample No. BRS11

Figure 10. Dentalina guembeli Schwager, 1865
Maximum Length 292µm. Sample No. U19

Figure 11. Dentalina integra (Kübler & Zwingli), 1870
Maximum Length 213µm. Sample No. BRS22

PLATE 9


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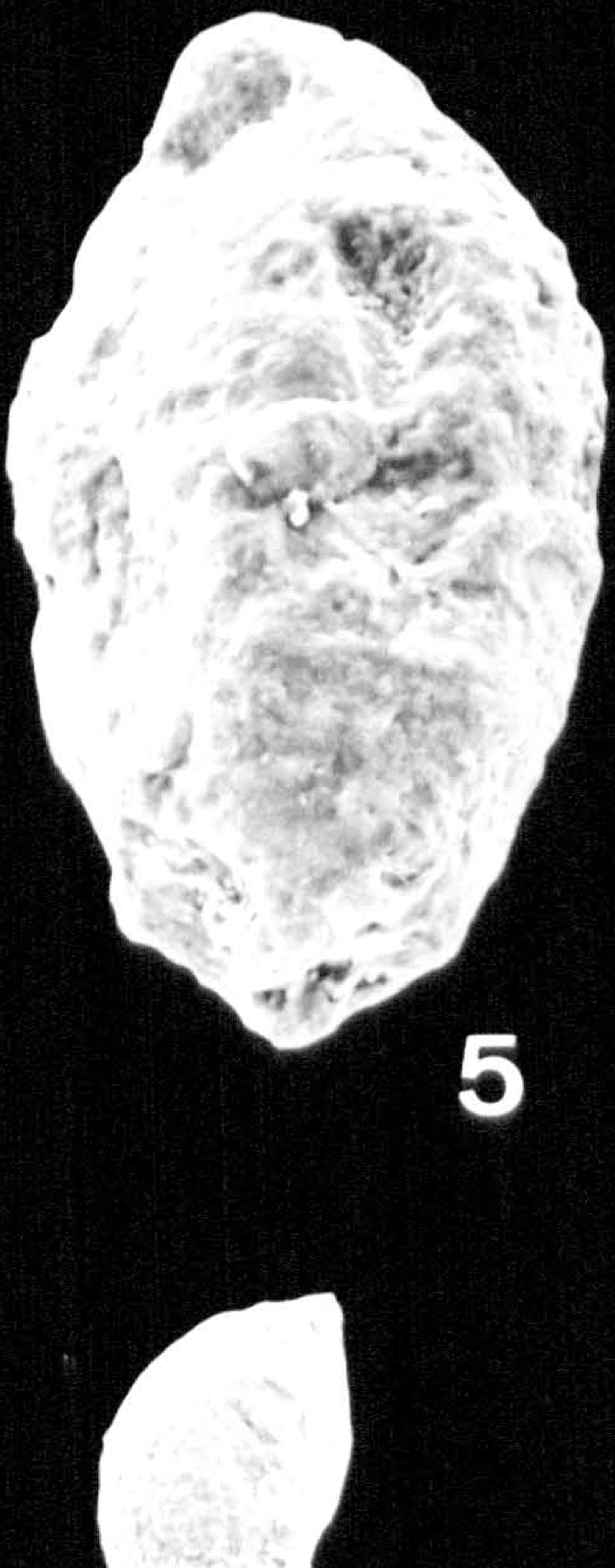
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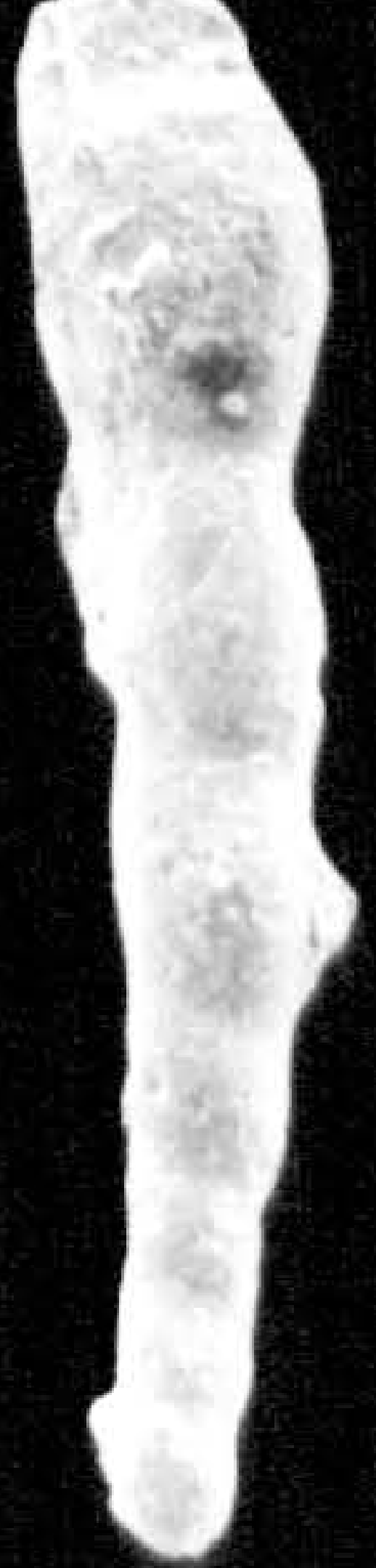
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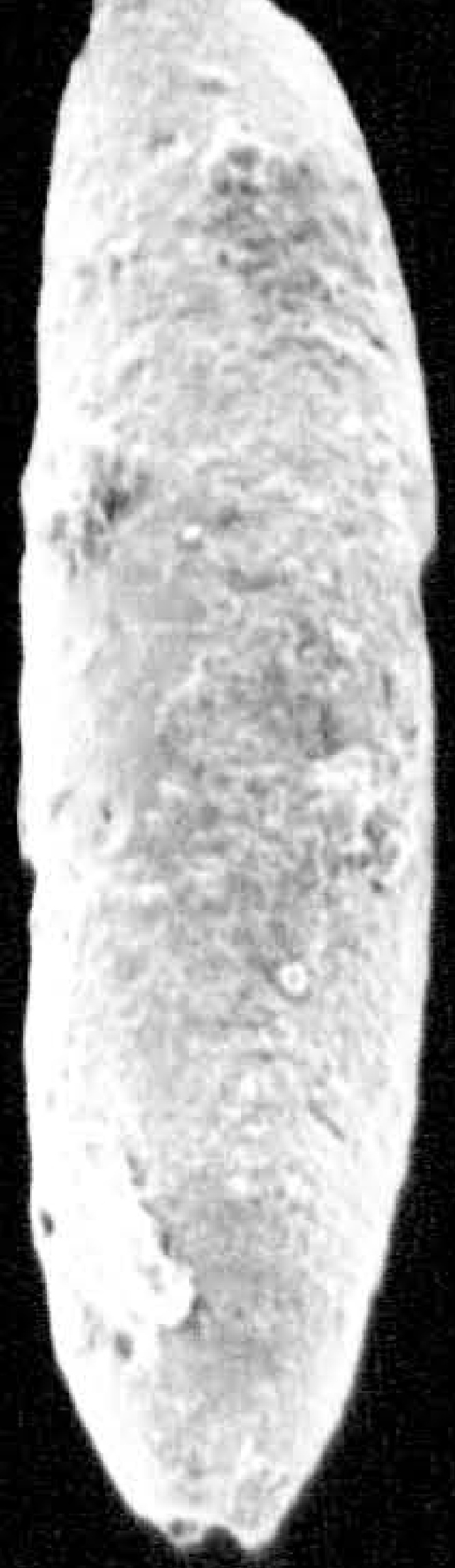
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PLATE 10

Figure 1. Dentalina intorta Terquem, 1870
Maximum Length 173µm. Sample No. U11

Figure 2. Dentalina propinqua Terquem, 1870
Maximum Length 441µm. Sample No. U19

Figure 3. Dentalina pseudocommunis Franke, 1936
Maximum Length 609µm. Sample No. GS4

Figure 4. Dentalina pseudocruata Seibold & Seibold, 1960
Maximum Length 108µm. Sample No. DC13

Figure 5. Dentalina sinemurensis Terquem 1858
Maximum Length 714µm. Sample No. BRS6

Figure 6. Dentalina tenuistriata Terquem, 1866
Maximum Length 393µm. Sample No. PR2

Figure 7. Dentalina torta Terquem, 1858
Maximum Length 493µm. Sample No. DC6

Figure 8. Dentalina tortilis Franke, 1936
Maximum Length 406µm. Sample No. GS3

Figure 9. Dentalina varians Terquem, 1866
Maximum Length 283µm. Sample No. DC15

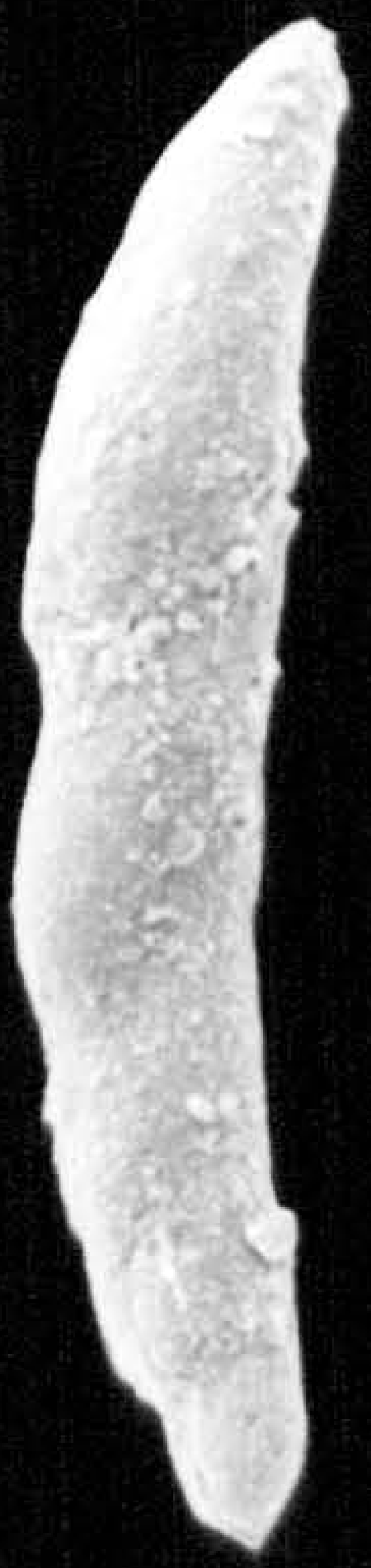
Figure 10. Dentalina ventricosa Franke, 1936
Maximum Length 280µm. Sample No. PR10

Figure 11. Nodosaria sp. A
Maximum Length 246µm. Sample No. DC6

Figure 12. Nodosaria elongata (Ehrenberg), 1844
Maximum Length 368µm. Sample No. DC25

Figure 13. Nodosaria apheilolocula Tappan, 1955
Maximum Length 359µm. Sample No. DC4

PLATE 10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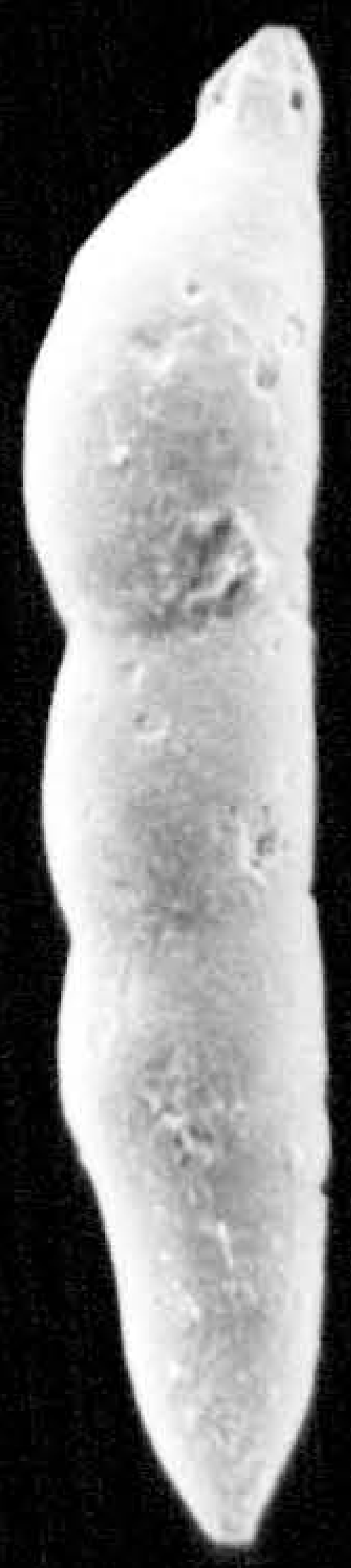
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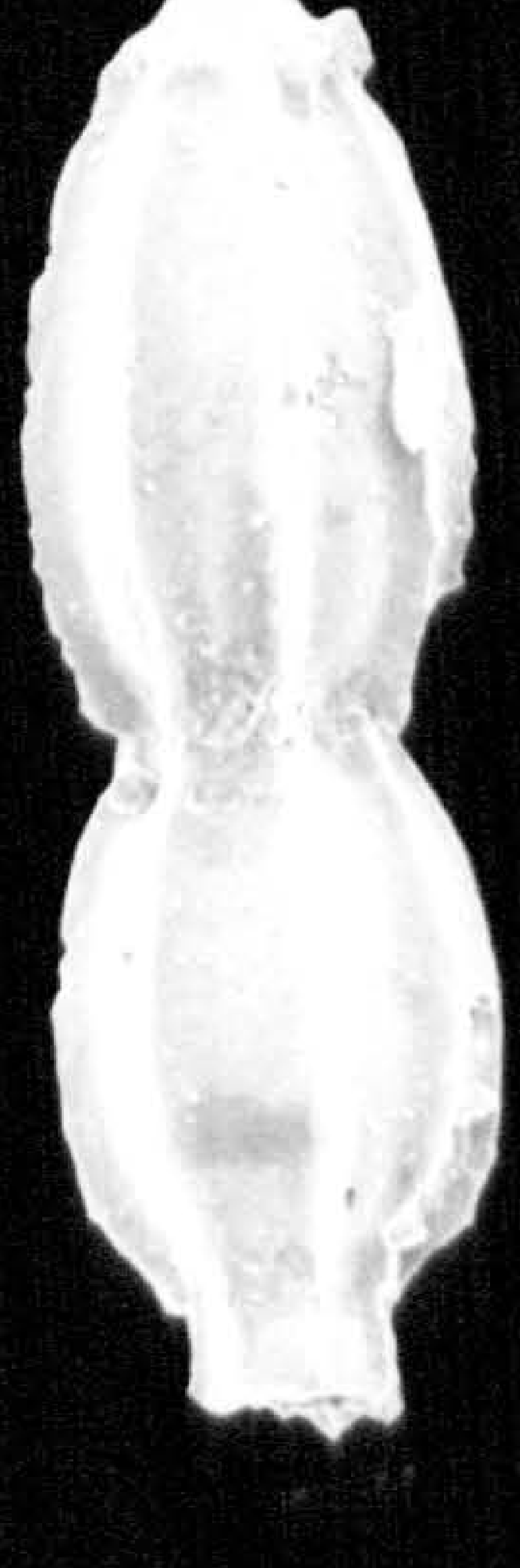
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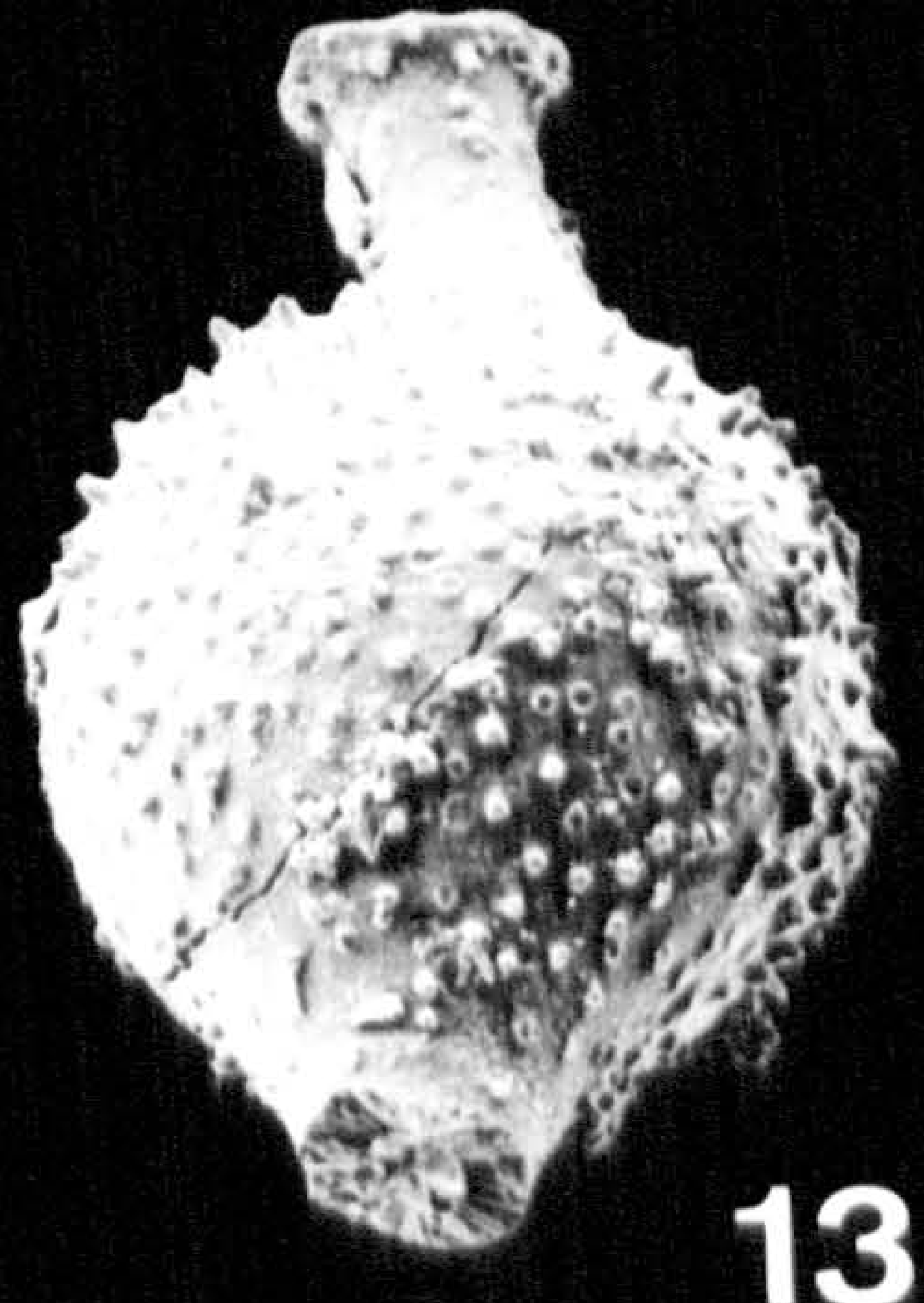
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PLATE 11

Figure 1. Nodosaria berthelini Tappan, 1955
Maximum Length 148µm. Sample No. DC3

Figure 2. Nodosaria corallina Gümbel, 1862
Maximum Length 210µm. Sample No. BRS15

Figure 3. Nodosaria dispar Franke, 1936
Maximum Length 285µm. Sample No. BRS8

Figure 4. Nodosaria fontinensis Terquem, 1870
Maximum Length 583µm. Sample No. GS8

Figure 5. Nodosaria hortensis Terquem, 1866
Maximum Length 285µm. Sample No. GS17

Figure 6. Nodosaria metensis Terquem, 1863
Maximum Length 284µm. Sample No. U12

Figure 7. Nodosaria minuta Cordey, 1962
Maximum Length 176µm. Sample No. DC3

Figure 8. Nodosaria nitidana Bartenstein & Brand, 1937
Maximum Length 477µm. Sample No. PR1

Figure 9. Nodosaria opalini Bartenstein & Brand, 1937
Maximum Length 277µm. Sample No. MP11

Figure 10. Nodosaria pectinata (Terquem), 1870
Maximum Length 290µm. Sample No. U7

Figure 11. Nodosaria procera Franke, 1936
Maximum Length 309µm. Sample No. BRS9

Figure 12. Nodosaria raphanistriformis (Gümbel), 1862
Maximum Length 290µm. Sample No. KW9

Figure 13. Nodosaria regularis Terquem, 1862
Maximum Length 556µm. Sample No. DC5

PLATE 11


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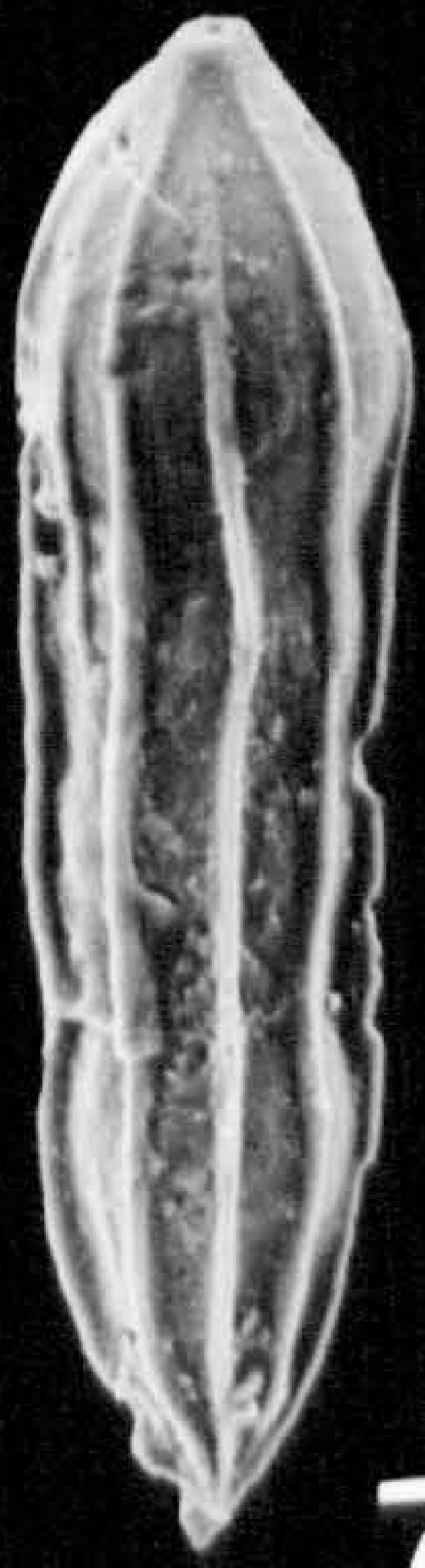
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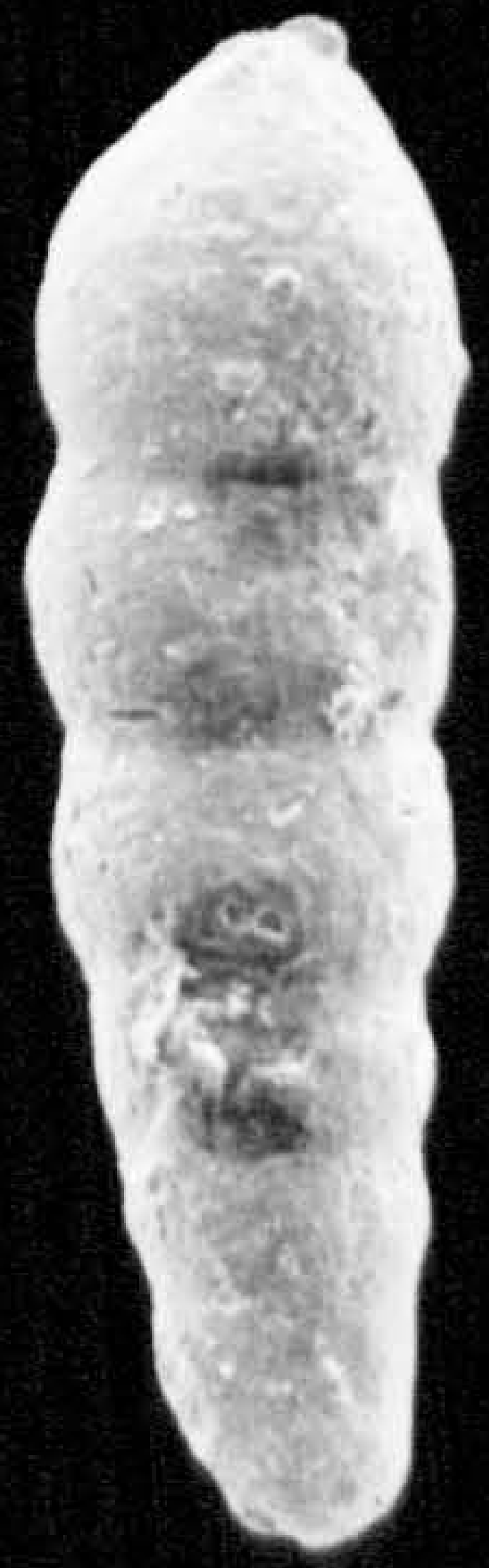
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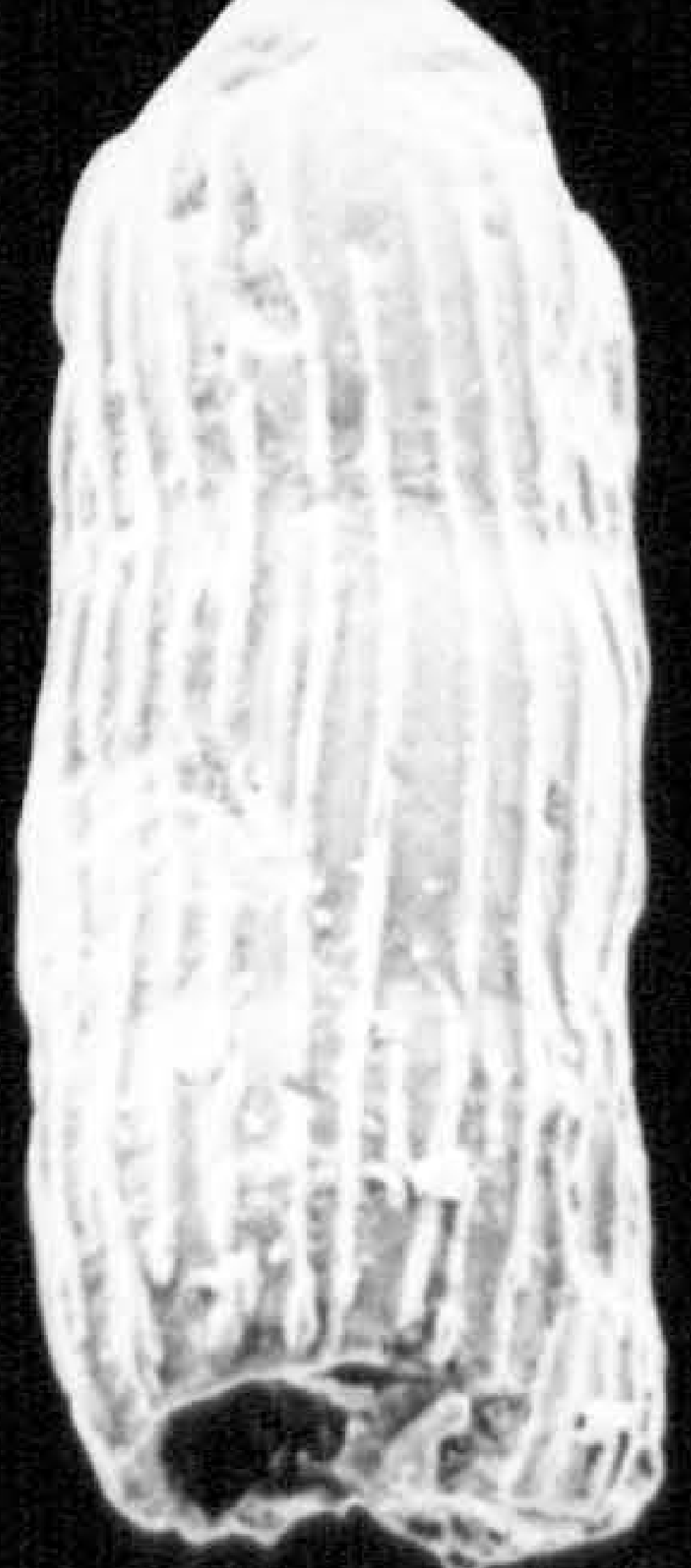
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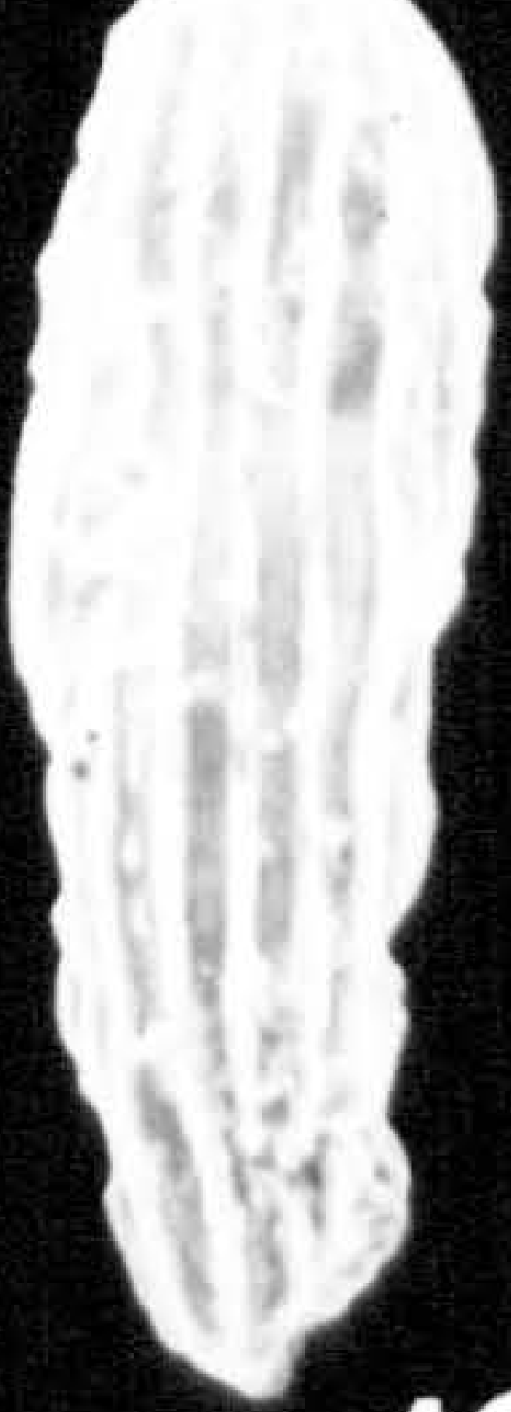
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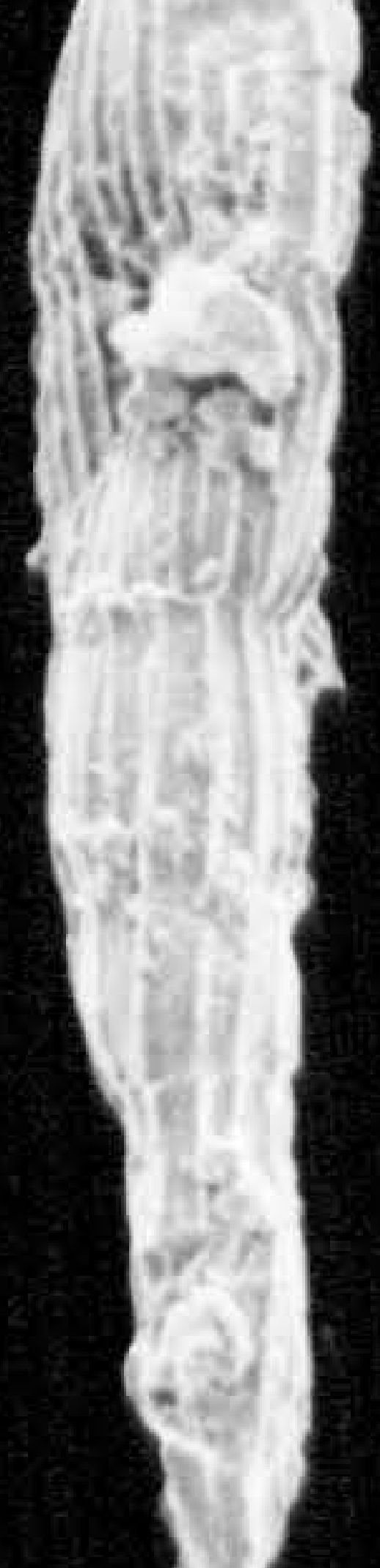
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PLATE 12

Figure 1. Nodosaria simplex Terquem, 1858
Maximum Length 356µm. Sample No. D9

Figure 2. Nodosaria sphingothalamus Loeblich & Tappan, 1950
Maximum Length 515µm. Sample No. PR14

Figure 3. Pseudonodosaria sp. A
Maximum Length 148µm. Sample No. GS3

Figure 4. Pseudonodosaria annulifera (Frentzen), 1941
Maximum Length 221µm. Sample No. MP10

Figure 5. Pseudonodosaria dubia (Terquem), 1870
Maximum Length 319µm. Sample No. BRS22

Figure 6. Pseudonodosaria douglasi (Weir), 1943
Maximum Length 650µm. Sample No. DC18

Figure 7. Pseudonodosaria vulgata (Borneman), 1854
Maximum Length 181µm. Sample No. DC25

Figure 8. Pseudonodosaria vulgata (Borneman) ssp. A
Maximum Length 338µm. Sample No. GS1

Figure 9. Lingulina longiscata (Terquem), 1870
Maximum Length 248µm. Sample No. DC4

Figure 10. Lingulina tenera Borneman, 1854
Maximum Length 241µm. Sample No. U20

Figure 11. Frondicularia franconica Gümbel, 1862
Maximum Length 423µm. Sample No. GS9

PLATE 12

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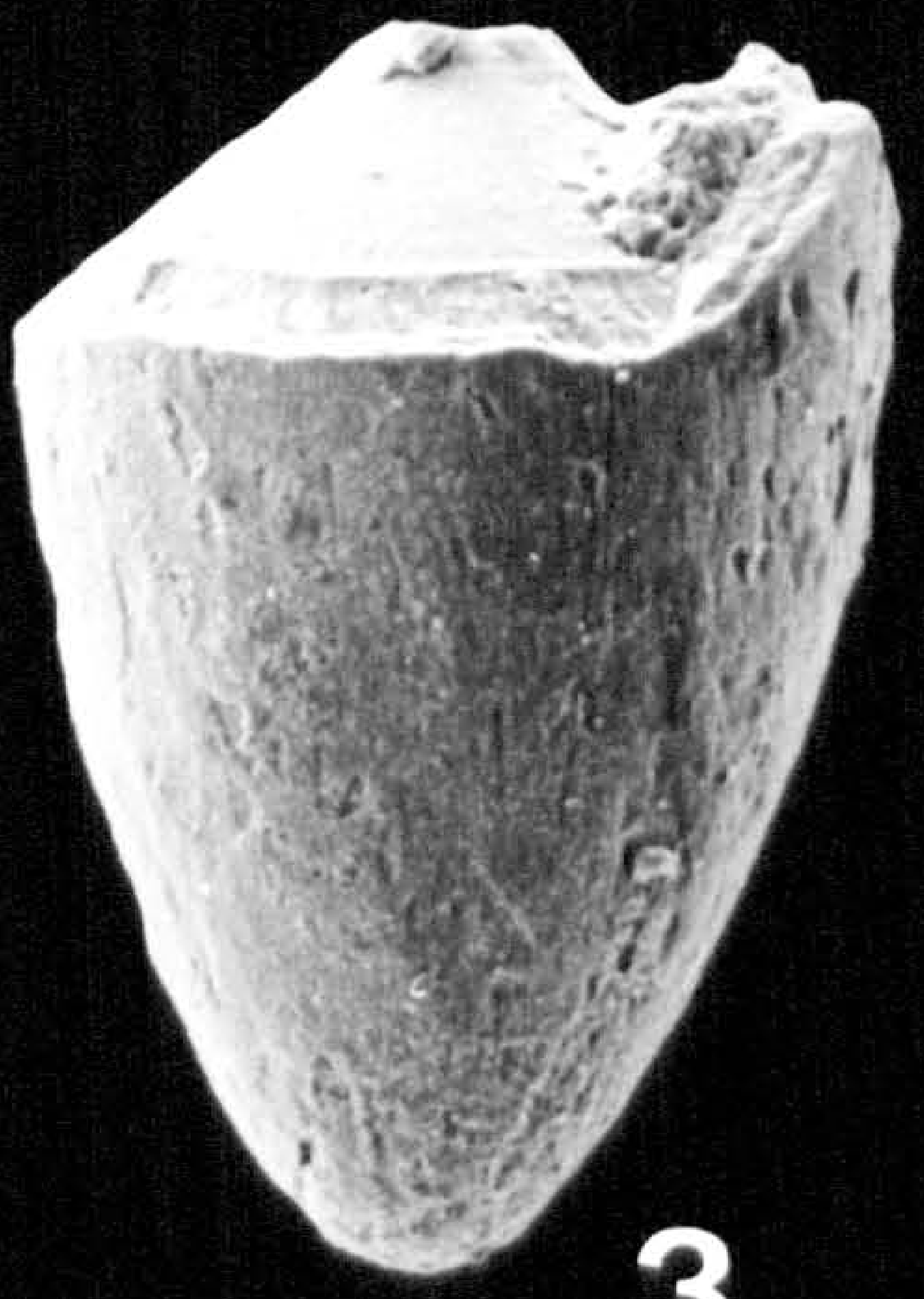

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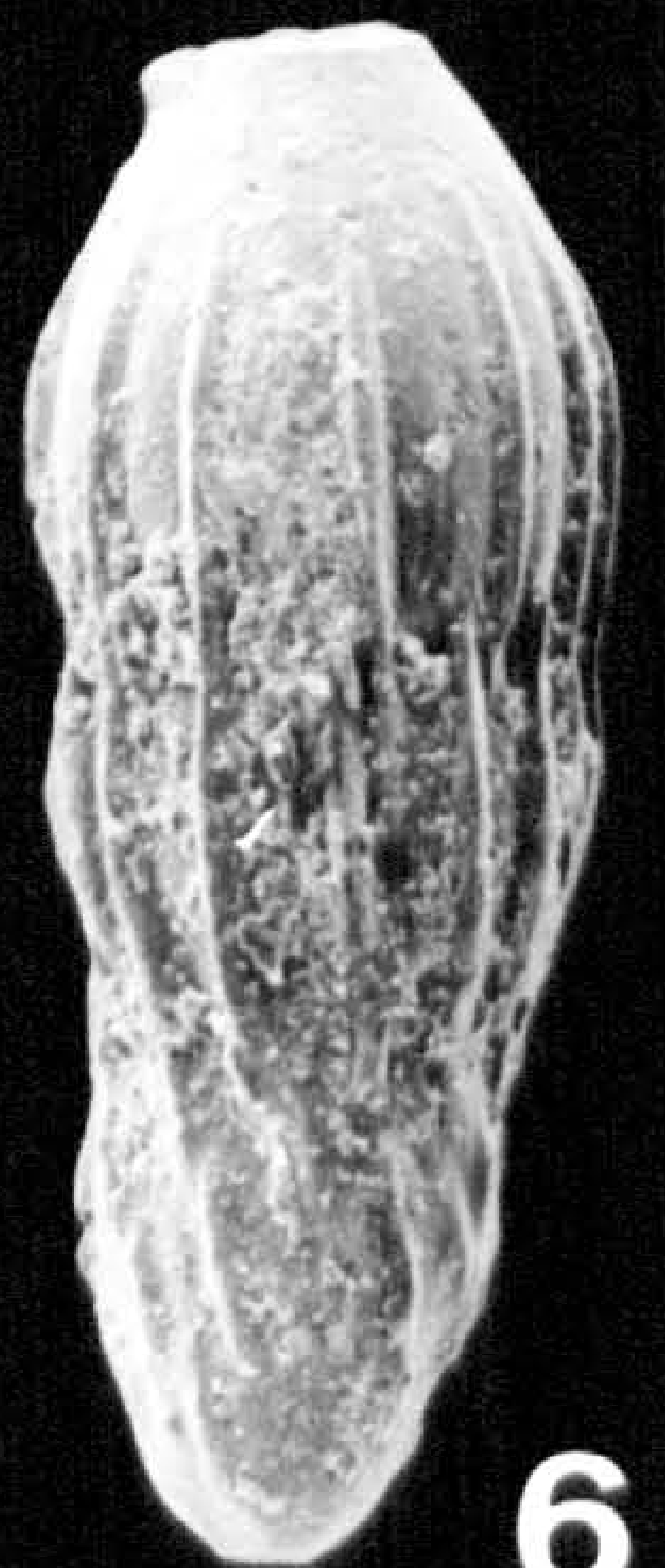

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PLATE 13

Figure 1. Frondicularia kuldharensis Kalia & Chowdhury, 1983
Maximum Length 591µm. Sample No. BRS6

Figure 2. Frondicularia laevissima Terquem, 1866
Maximum Length 276µm. Sample No. BRS19

Figure 3. Frondicularia lignaria Terquem, 1866
Maximum Length 389µm. Sample No. BRS12

Figure 4. Frondicularia oolithica Terquem, 1870
Maximum Length 600µm. Sample No. U12

Figure 5. Frondicularia moelleri Uhlig, 1883
Maximum Length 727µm. Sample No. DC5

Figure 6. Frondicularia nikitini Uhlig, 1883
Maximum Length 635µm. Sample No. GS1

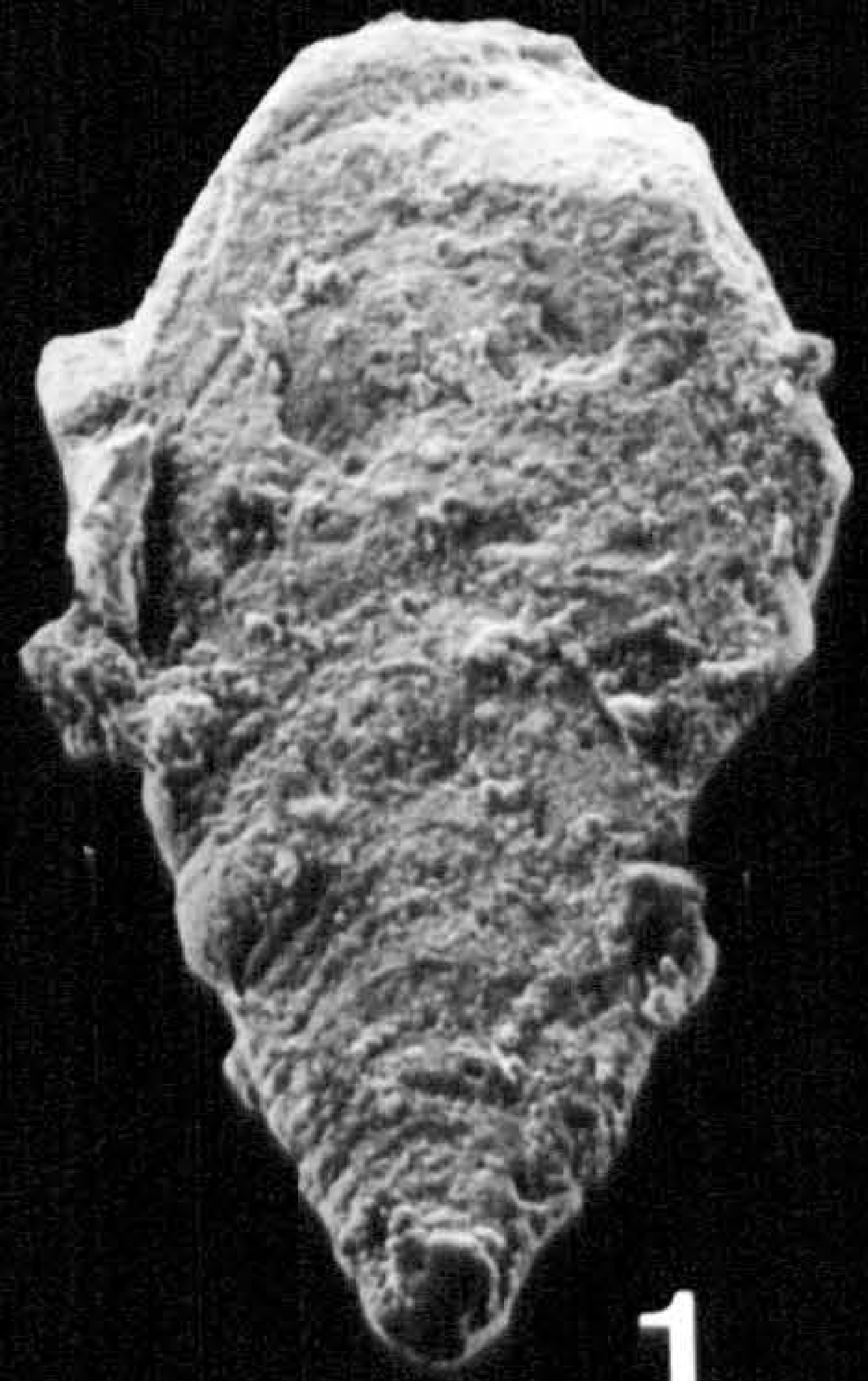
Figure 7. Tristix oolithica (Terquem), 1866
Maximum Length 342µm. Sample No. DC31

Figure 8. Tristix reesidei Loeblich & Tappan, 1950
Maximum Length 207µm. Sample No. PR8

Figure 9. Lenticulina brevispira (Wisniowski), 1890
Maximum Length 389µm. Sample No. DC15

Figure 10. Lenticulina chicheryi Payard, 1947
Maximum Diameter 460µm. Sample No. BRS5

PLATE 13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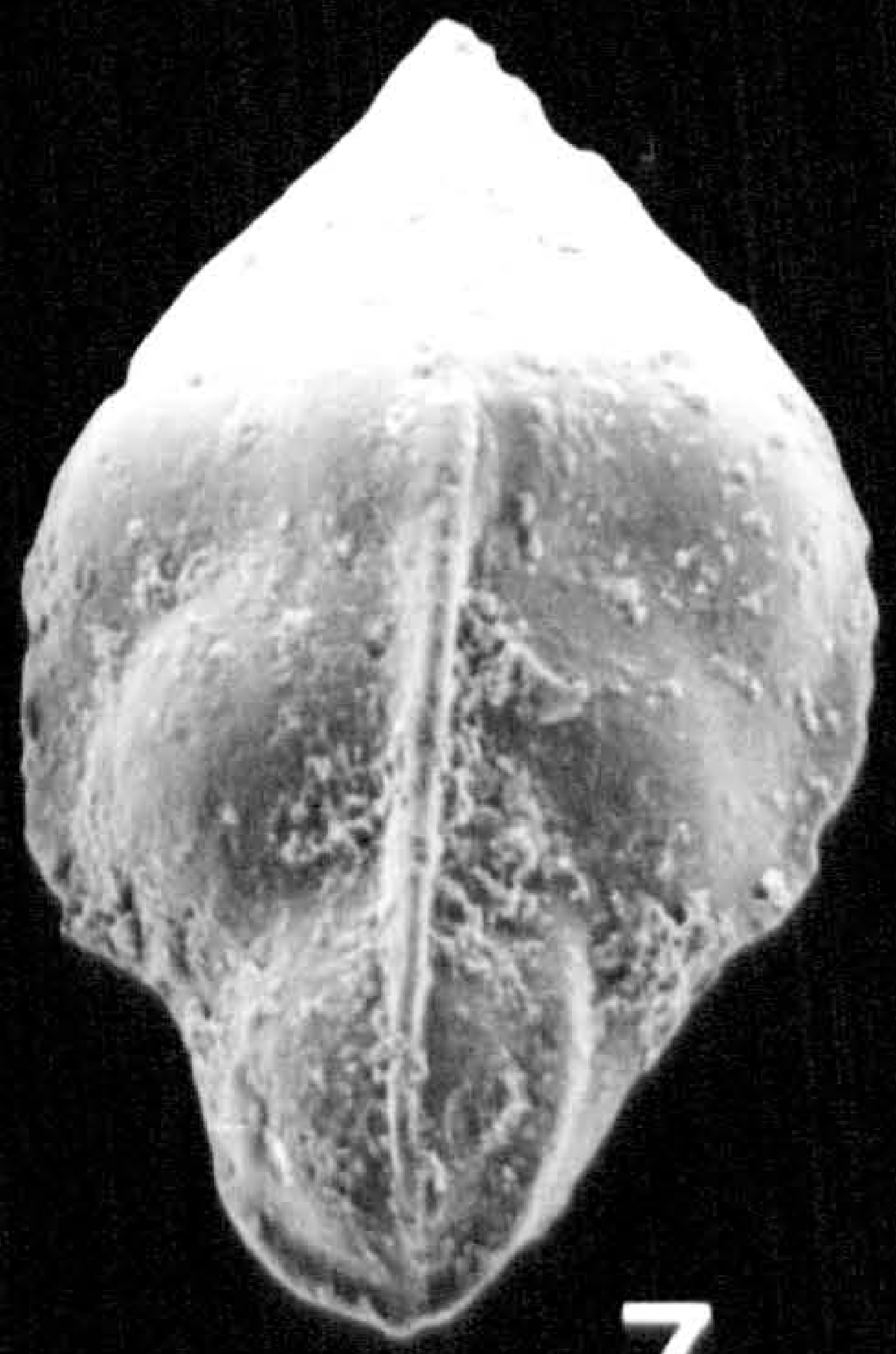
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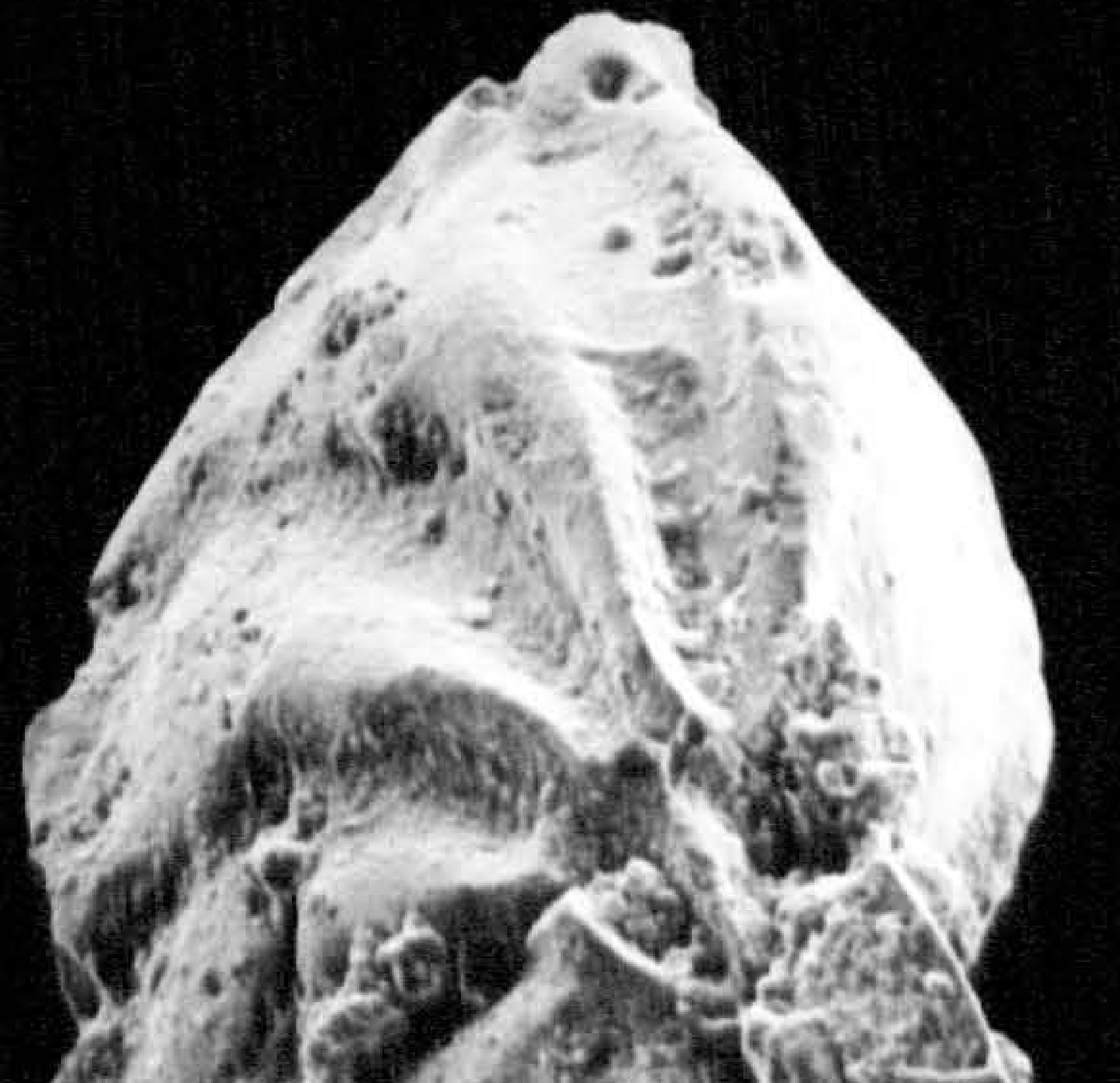
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PLATE 14

Figure 1. Lenticulina dictyodes (Deeke), 1884
Maximum Length 325µm. Sample No. MP3

Figure 2. Lenticulina d'orbigny (Roemer), 1839
Maximum Length 275µm. Sample No. MP8

Figure 3. Lenticulina exgaleata Dieni, 1985
Maximum Length 296µm. Sample No. DC3

Figure 4. Lenticulina ectypa (Loeblich & Tappan), 1950 ssp. costata Cordey, 1962
Maximum Length 378µm. Sample No. DC6

Figure 5. Lenticulina ectypa (Loeblich & Tappan), 1950
Maximum Length 286µm. Sample No. DC5

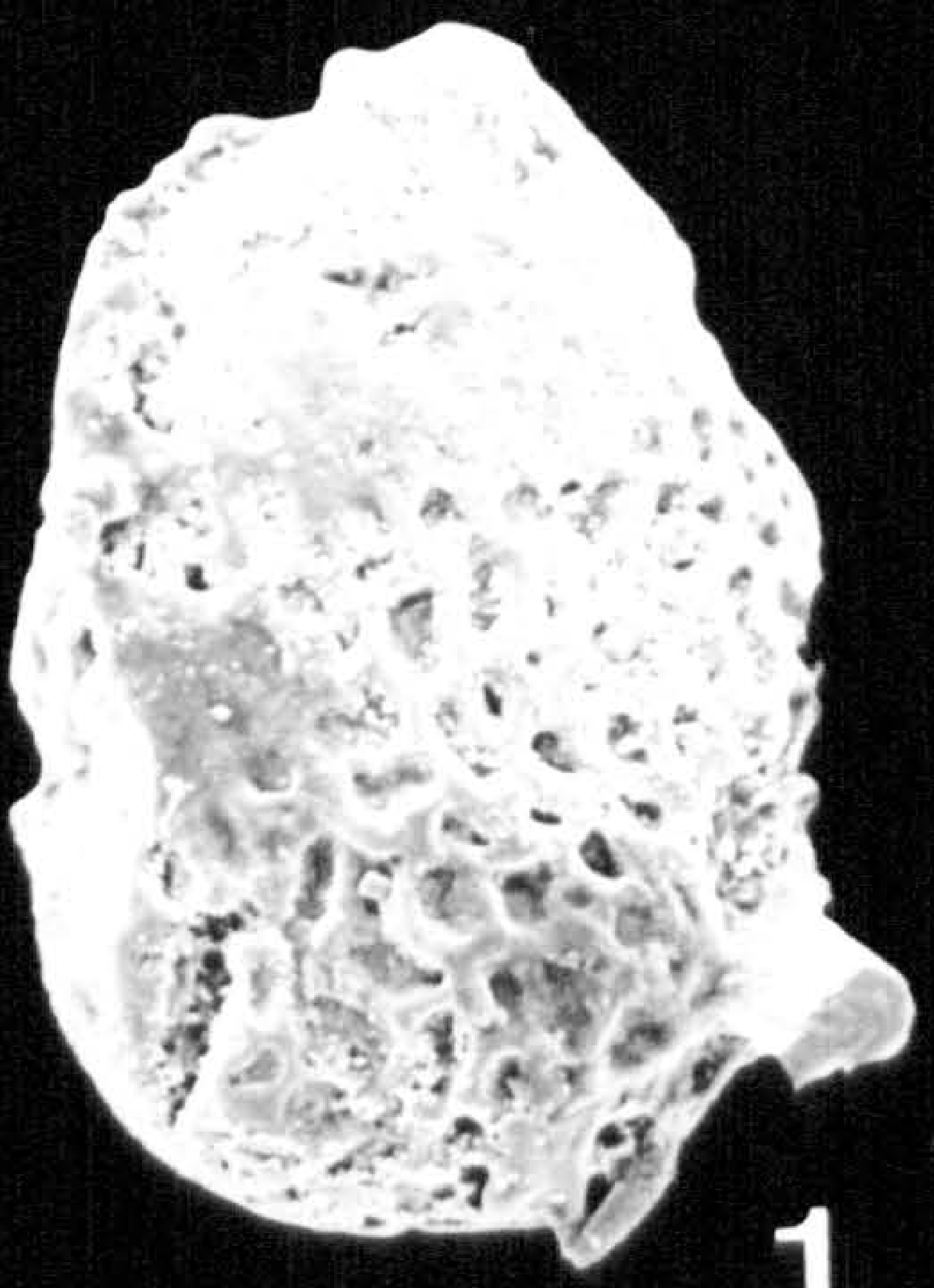
Figure 6. Lenticulina gottingensis (Borneman), 1854
Maximum Diameter 305µm. Sample No. BRS20

Figure 7. Lenticulina major (Borneman), 1854
Maximum Length 822µm. Sample No. DC36

Figure 8. Lenticulina muensteri (Roemer), 1839
Maximum Diameter 928µm. Sample No. GS2

Figure 9. Lenticulina polygonata (Franke), 1936
Maximum Diameter 236µm. Sample No. DC3

PLATE 14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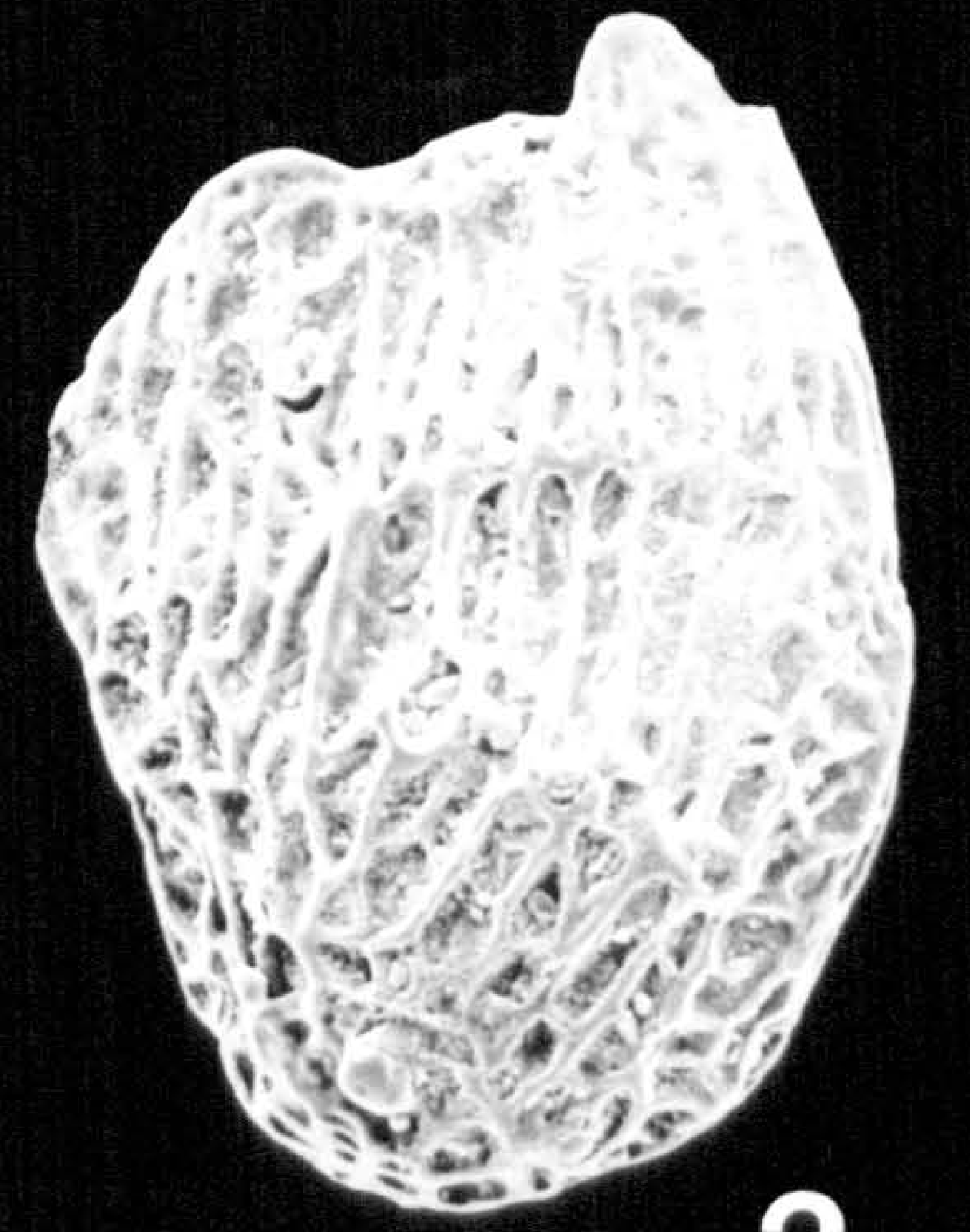
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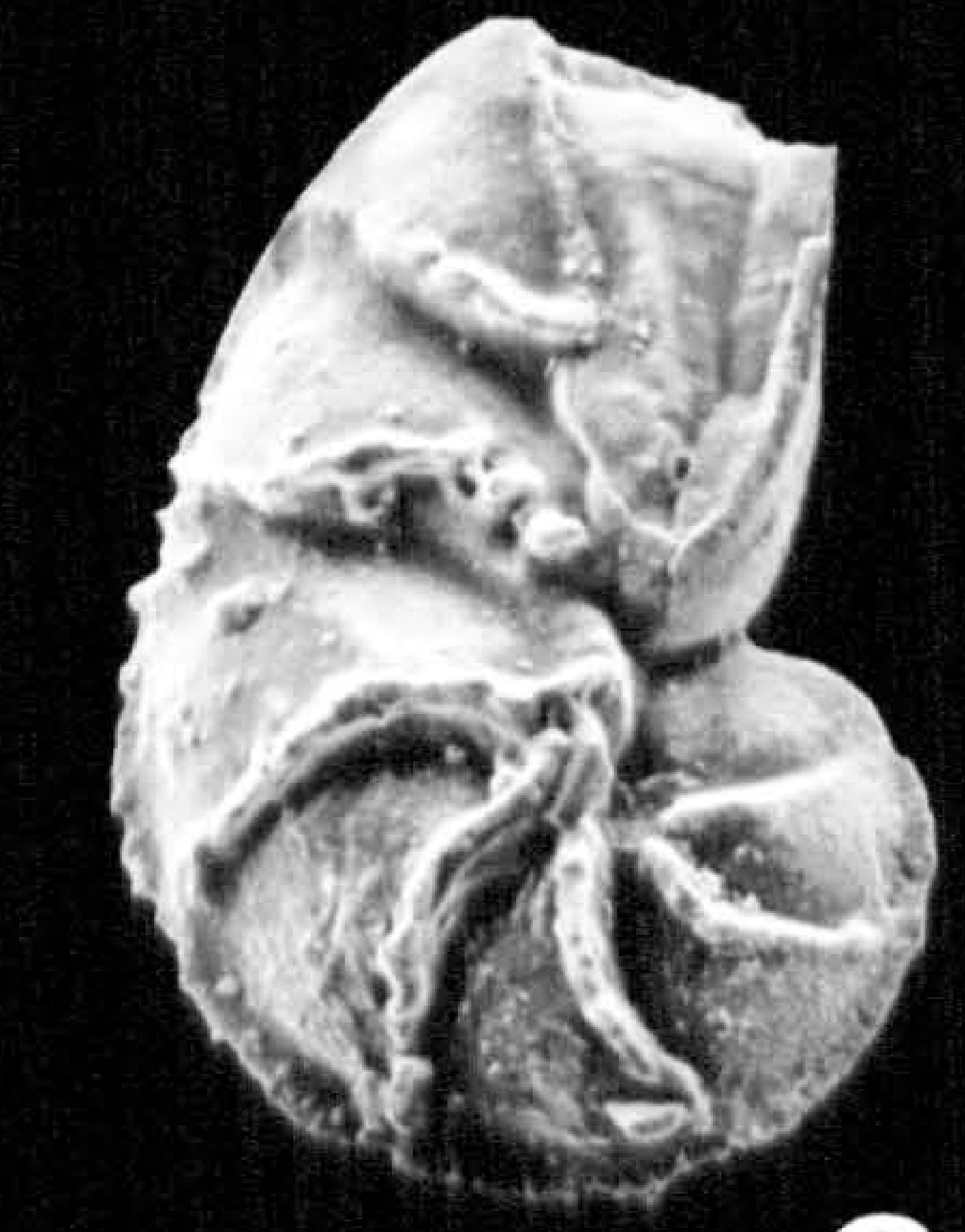
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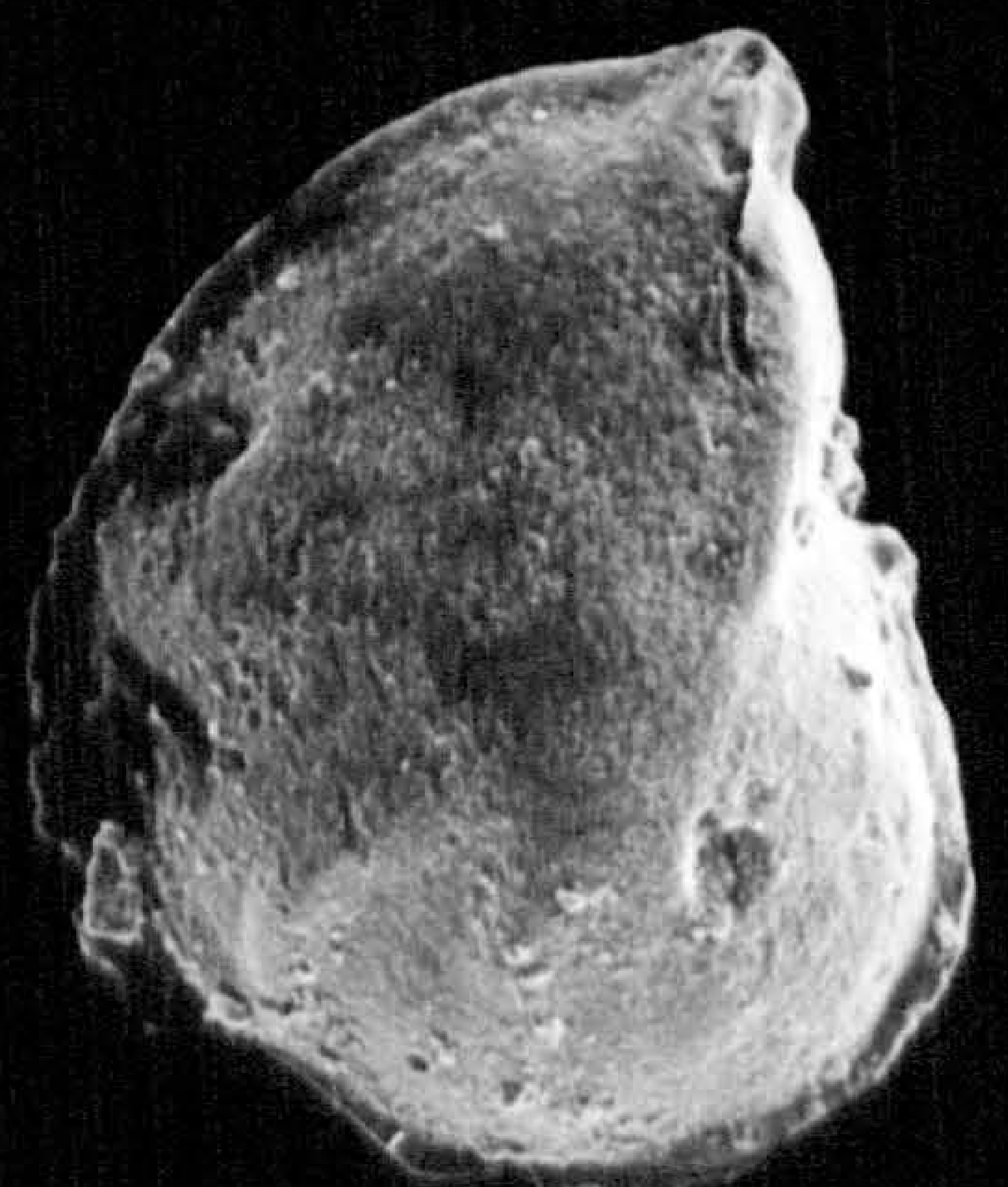
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PLATE 15

Figure 1. Lenticulina quenstedti (Gümbel), 1862
Maximum Length 282µm. Sample No. DS11

Figure 2. Lenticulina subalata (Reuss), 1854
Maximum Diameter 523µm. Sample No. DC31

Figure 3. Lenticulina varians (Borneman), 1854
Maximum Length 500µm. Sample No. GS16

Figure 4. Lenticulina volubilis Dain, 1958
Maximum Length 591µm. Sample No. M4

Figure 5. Saracenaria oxfordiana Tappan, 1955
Maximum Length 365µm. Sample No. DC7

Figure 6. Marginulina sp. A
Maximum Length 486µm. Sample No. DC31

Figure 7. Marginulina batrakiensis (Myatluik), 1939
Maximum Length 235µm. Sample No. GS6

Figure 8. Marginulina costata (Batsch), 1791
Maximum Length 433µm. Sample No. GS20

Figure 9. Marginulina epicharis (Loeblich & Tappan), 1950
Maximum Length 582µm. Sample No. BRS8

Figure 10. Marginulina irregularis Gümbel, 1862
Maximum Length 447µm. Sample No. DC5

PLATE 15


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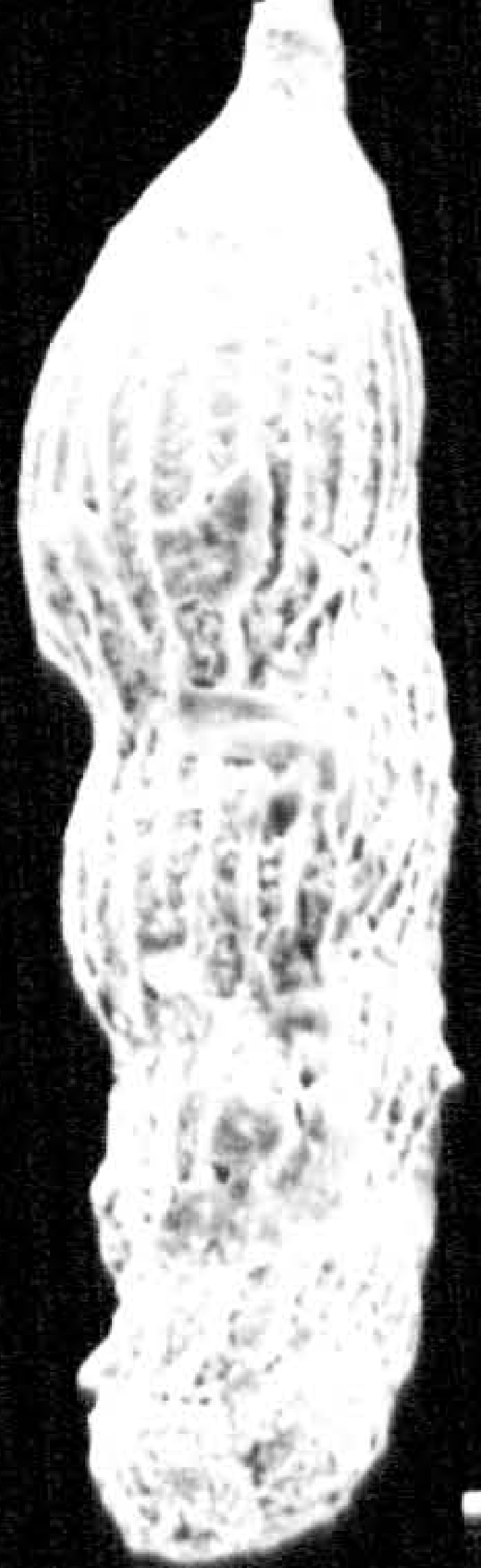
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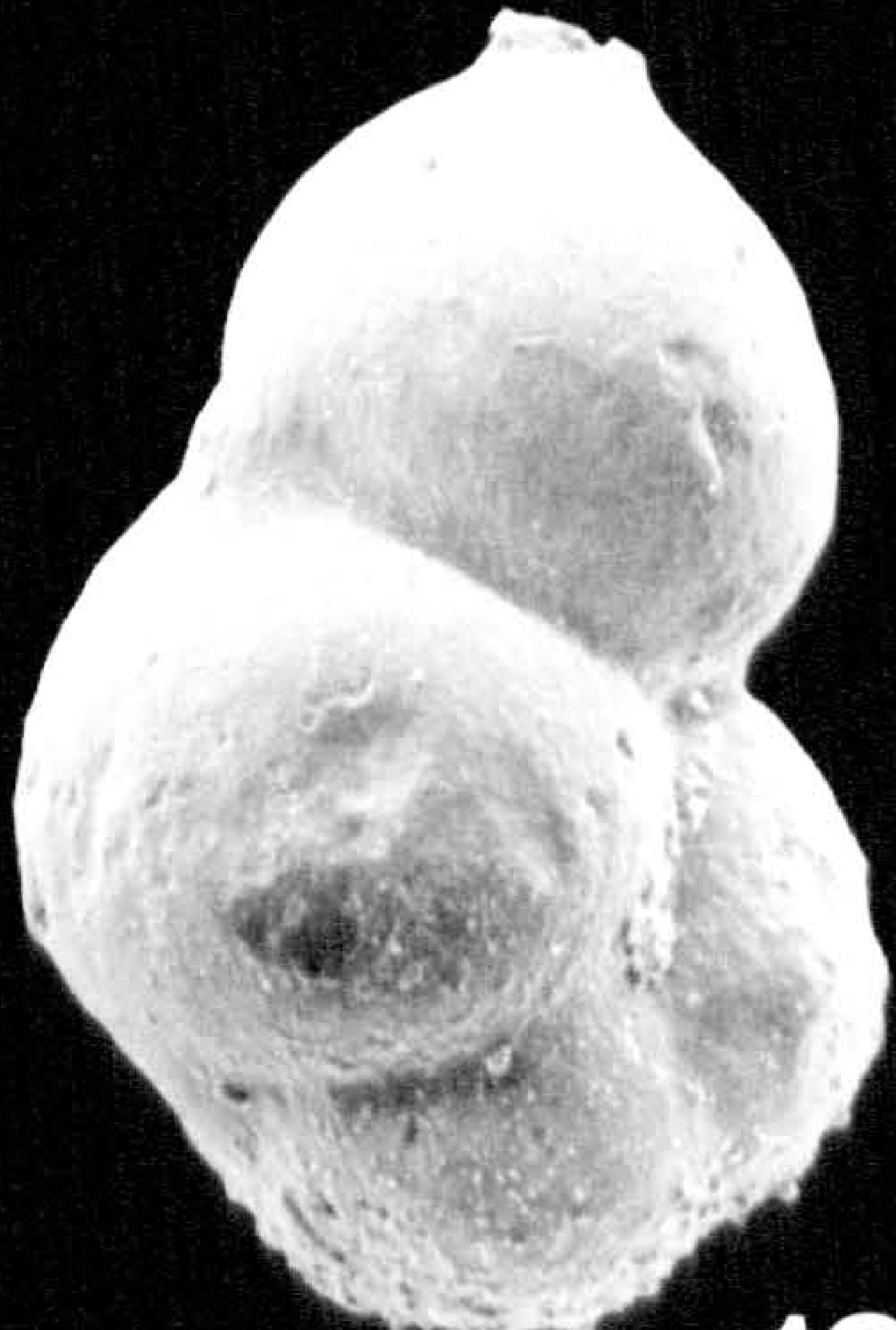
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PLATE 16

Figure 1. Citharina colliezi (Terquem), 1866
Maximum Length 600μm. Sample No. KW12

Figure 2. Citharina flabellata (Gümbel), 1862
Maximum Length 489μm. Sample No. GS15

Figure 3. Citharina heteropleura (Terquem), 1868
Maximum Length 464μm. Sample No. DC34

Figure 4. Citharina serracostata (Gümbel), 1862
Maximum Length 1.03mm. Sample No. GS13

Figure 5. Planularia beierana (Gümbel), 1862
Maximum Length 515μm. Sample No. DC5

Figure 6. Planularia eugenii (Terquem), 1864
Maximum Length 362μm. Sample No. DC5

Figure 7. Planularia kintradwellensis Gregory 1992
Maximum Length 310μm. Sample No. KW10

Figure 8. Planularia pseudocrepidula Adams, 1957
Maximum Length 554μm. Sample No. DC8

Figure 9. Vaginulina barnardi Gordon, 1965
Maximum Length 850μm. Sample No. GS2

Figure 10. Vaginulina contracta (Terquem), 1868
Maximum Length 463μm. Sample No. D9

Figure 11. Vaginulina legumen (Linné), 1758
Maximum Length 280μm. Sample No. D9

PLATE 16


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PLATE 17

Figure 1. Lagena aphela Tappan, 1955
Maximum Diameter 359µm. Sample No. DC29

Figure 2. Lagena globosa (Walker & Boys), 1784
Maximum Diameter 200µm. Sample No. LB4

Figure 3. Lagena lancelota (Terquem), 1858
Maximum Diameter 185µm. Sample No. BRS23

Figure 4. Lagena liassica (Kübler & Zwingli), 1866
Maximum Diameter 147µm. Sample No. U13

Figure 5. Lagena minutissima (Kübler & Zwingli), 1870
Maximum Diameter 86µm. Sample No. DC3

Figure 6. Lagena sulcata (Walker & Jacob), 1798
Maximum Diameter 222µm. Sample No. F7

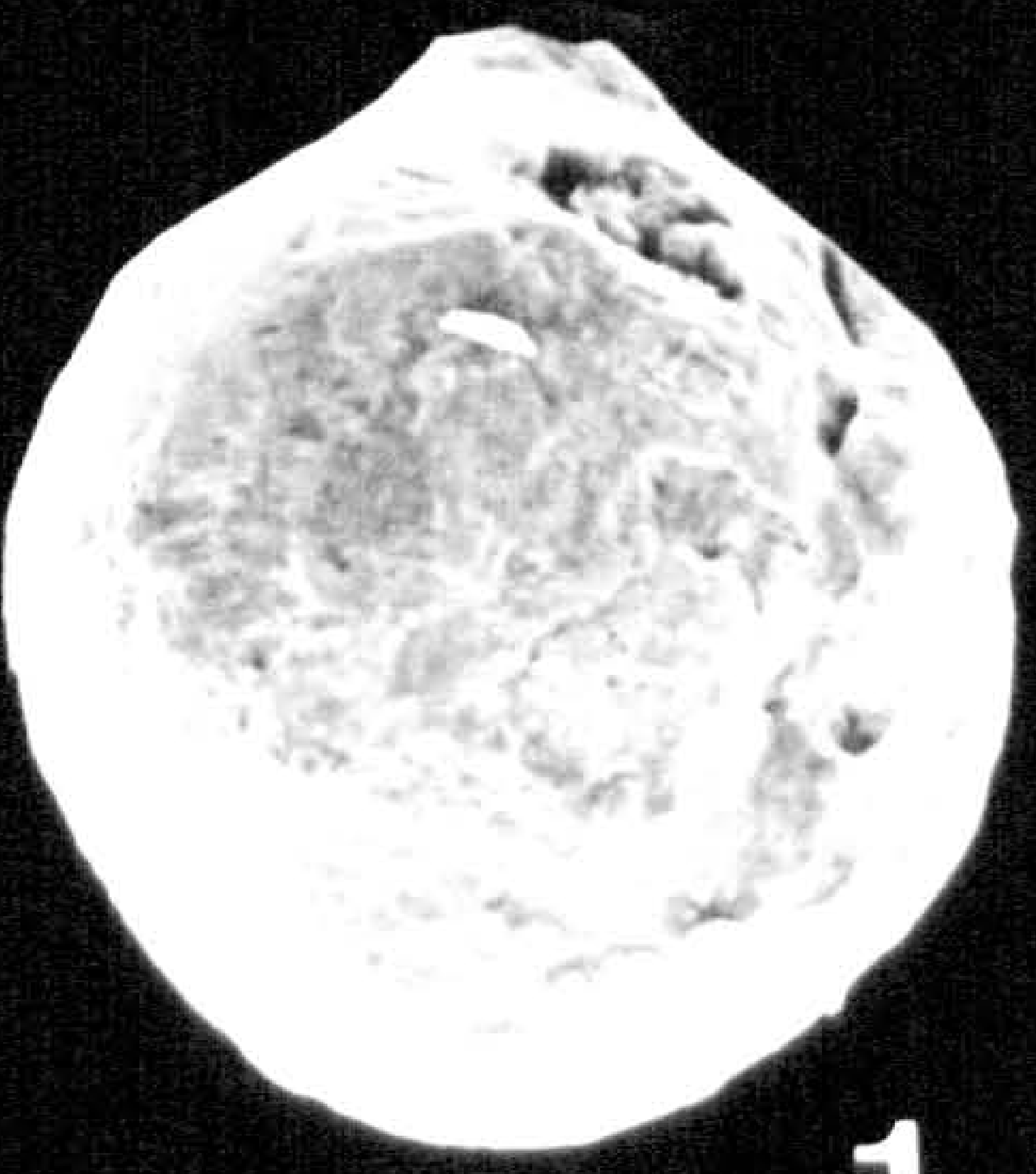
Figure 7. Eoguttulina bilocularis (Terquem), 1864
Maximum Length 341µm. Sample No. BRS10

Figure 8. Eoguttulina liassica (Strickland), 1846
Maximum Length 305µm. Sample No. U12

Figure 9. Eoguttulina metensis (Terquem), 1864
Maximum Length 445µm. Sample No. DC19

Figure 10. Eoguttulina oolithica (Terquem), 1874
Maximum Length 387µm. Sample No. DC2

PLATE 17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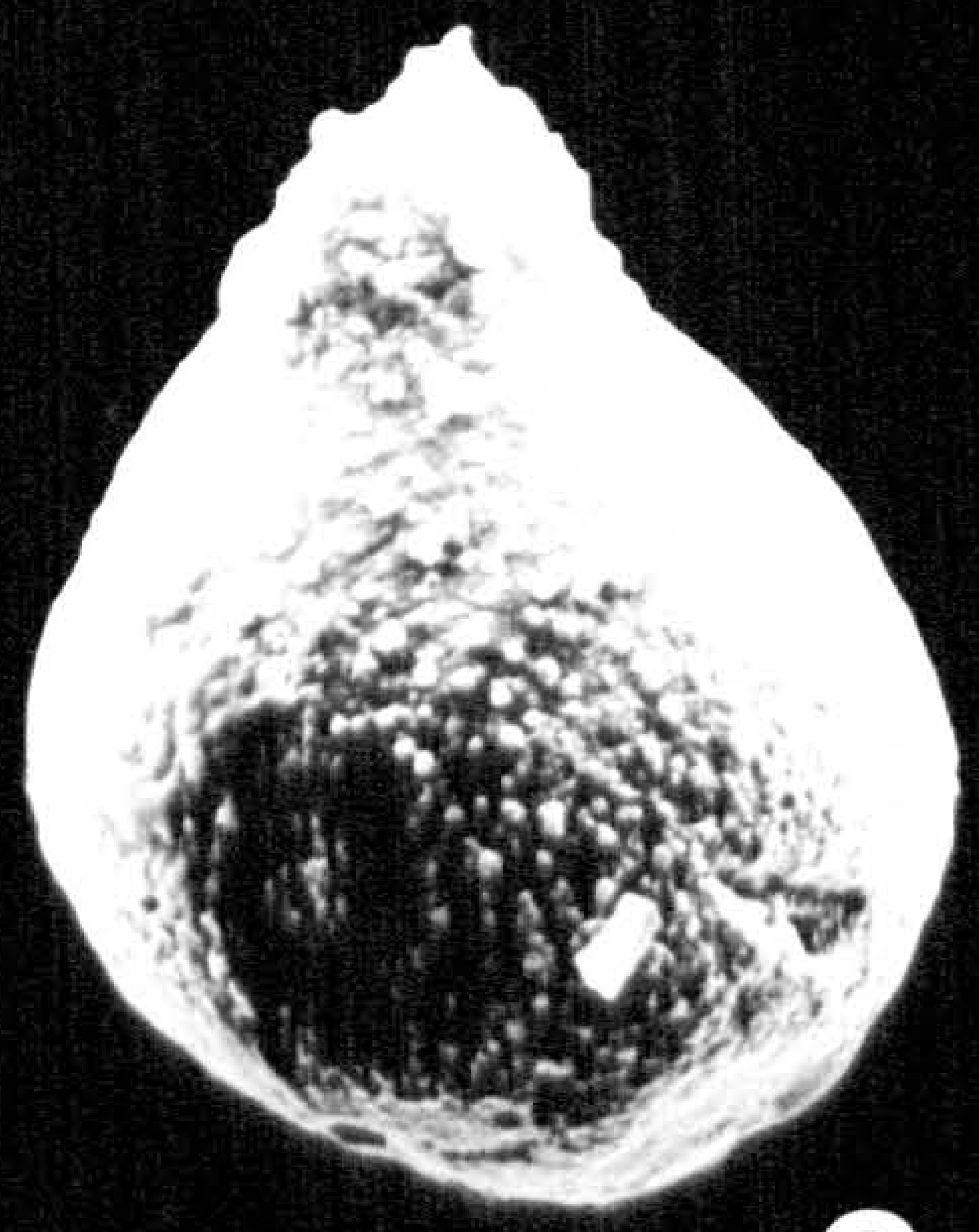
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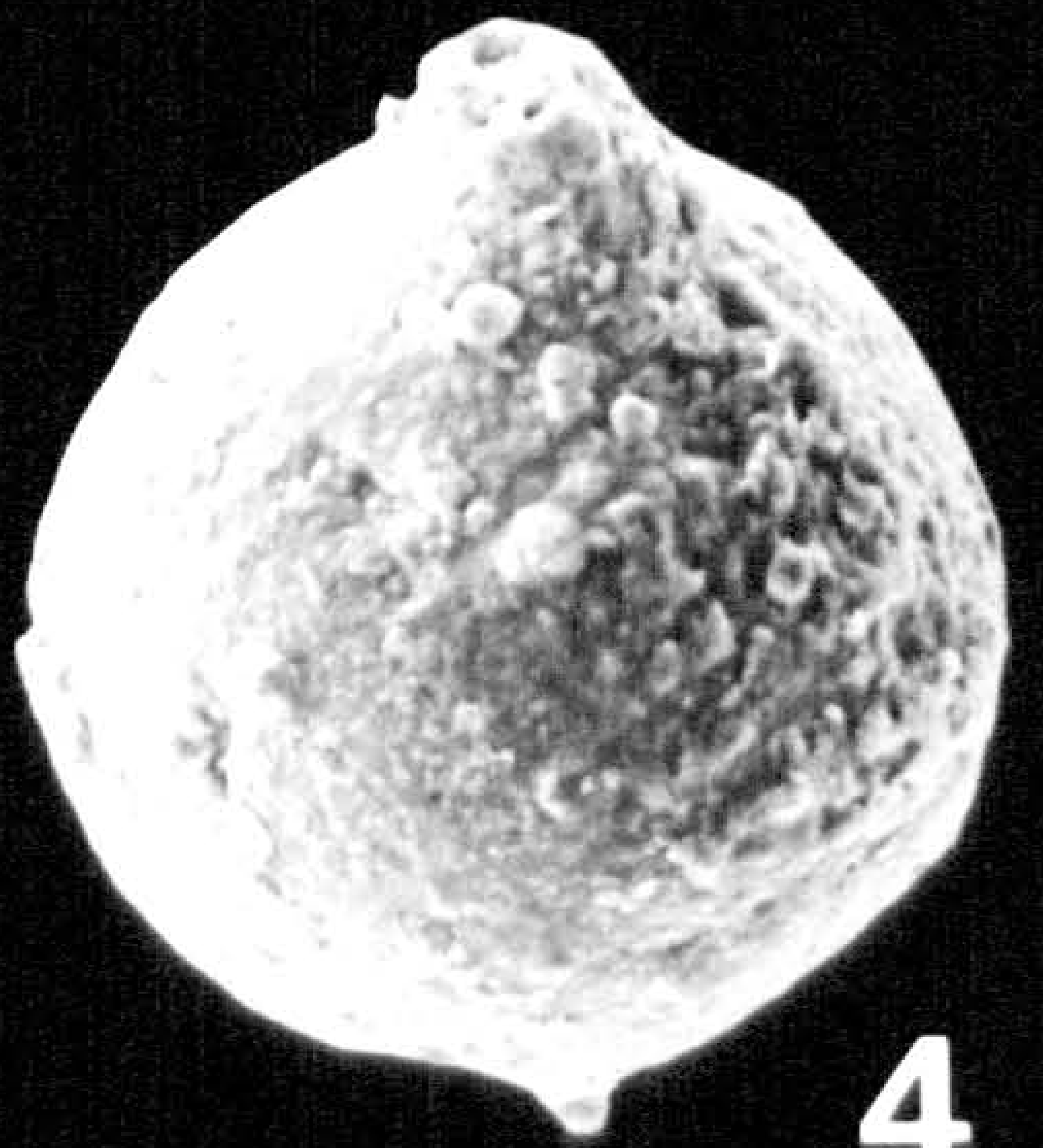
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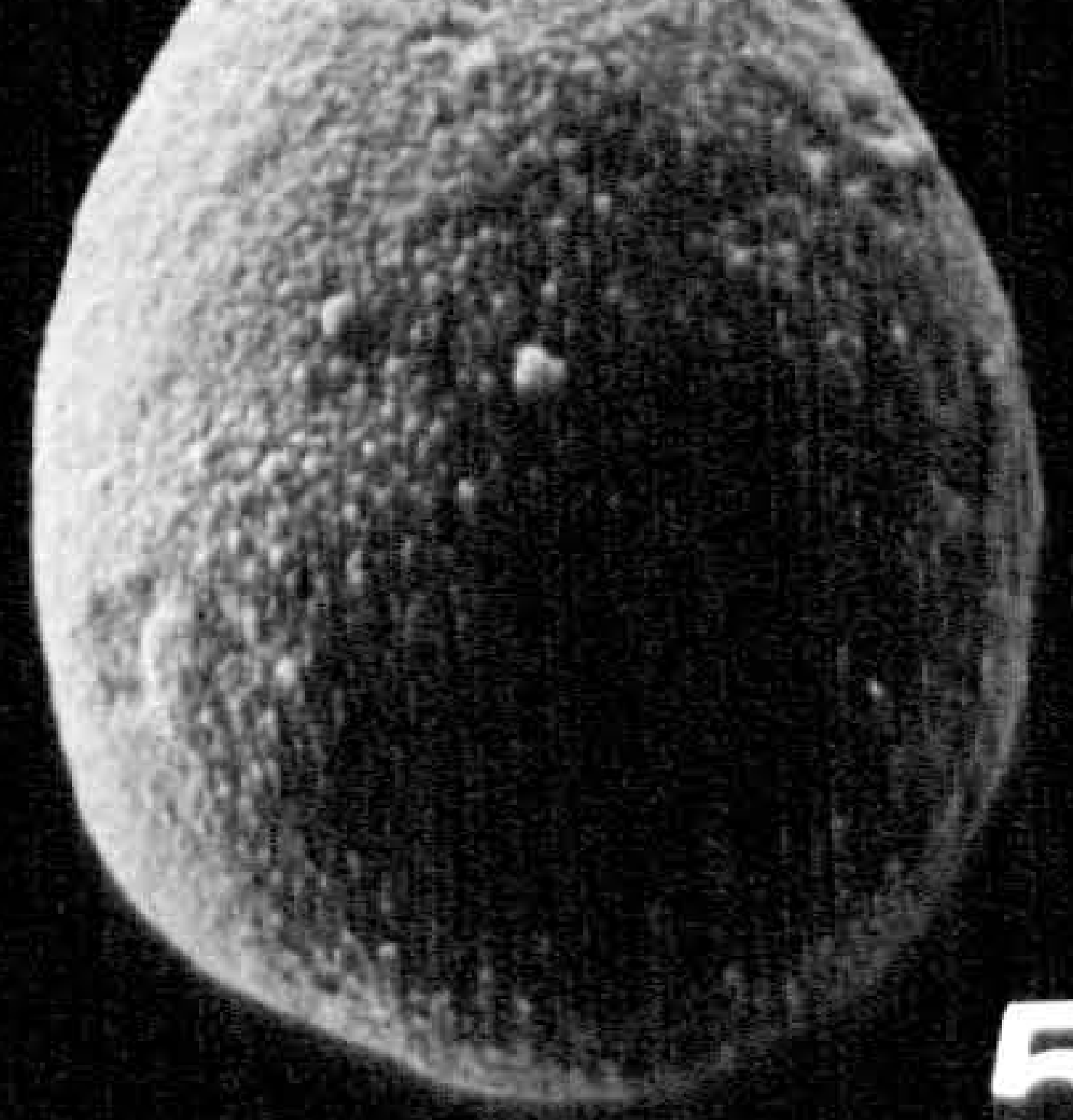
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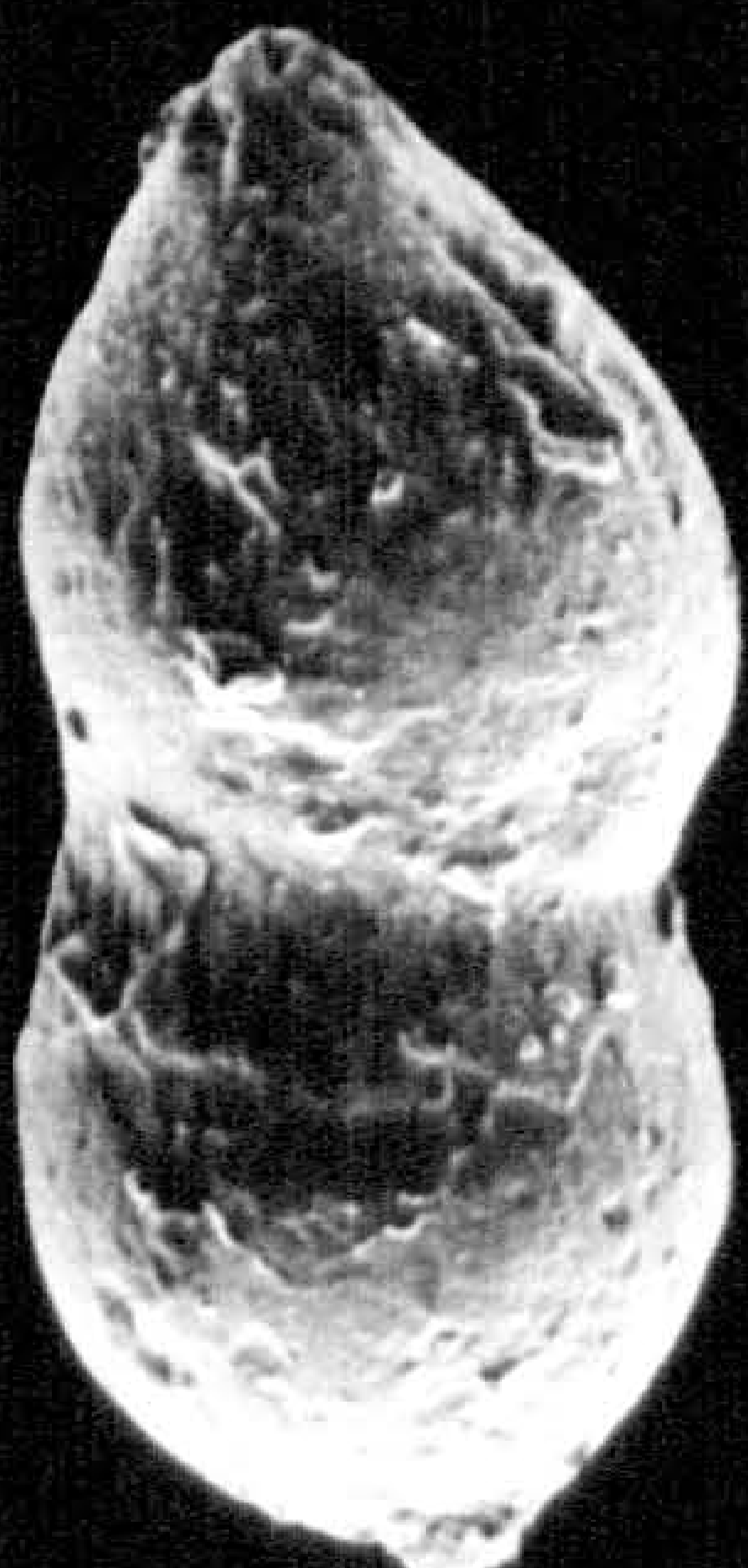
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PLATE 18

Figure 1. Palaeopolymorphina sp.
Maximum Length 391μm. Sample No. U13

Figure 2. Bullopora rostrata Quenstedt, 1858
Maximum Length 450μm. Sample No. GS20

Figure 3. Ramulina spandeli Paalzow, 1917
Maximum Length 296μm. Sample No. F11

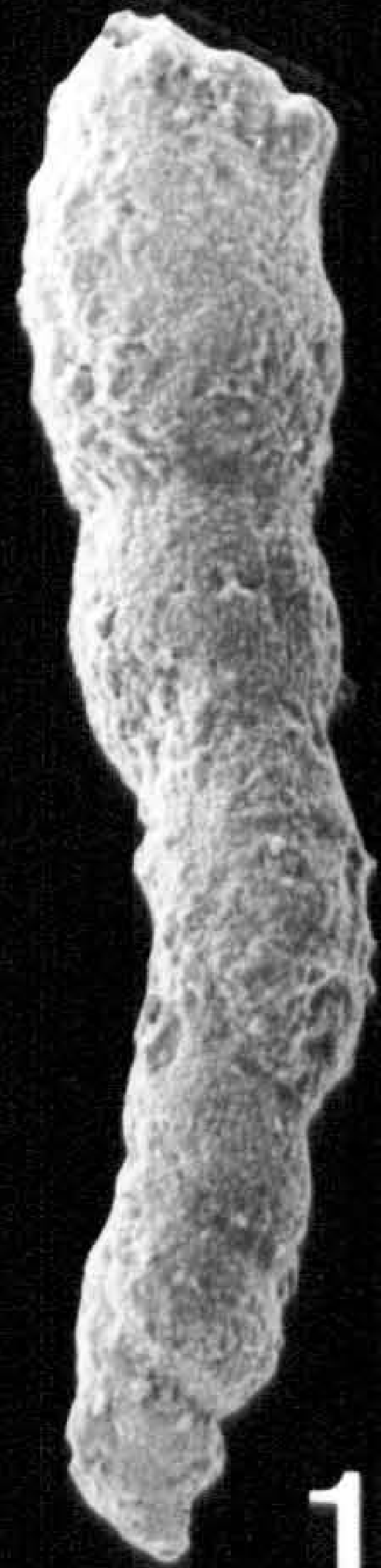
Figure 4. Epistomina sp. A
Maximum Diameter 330μm. Sample No. GS9

Figure 5. Epistomina sp. B
Maximum Diameter 339μm. Sample No. DC24

Figure 6. Epistomina mosquensis Uhlig, 1883
Maximum Diameter 497μm. Sample No. DC4

Figure 7. Epistomina ornata (Roemer), 1841
Maximum Diameter 182μm. Sample No. DC6

PLATE 18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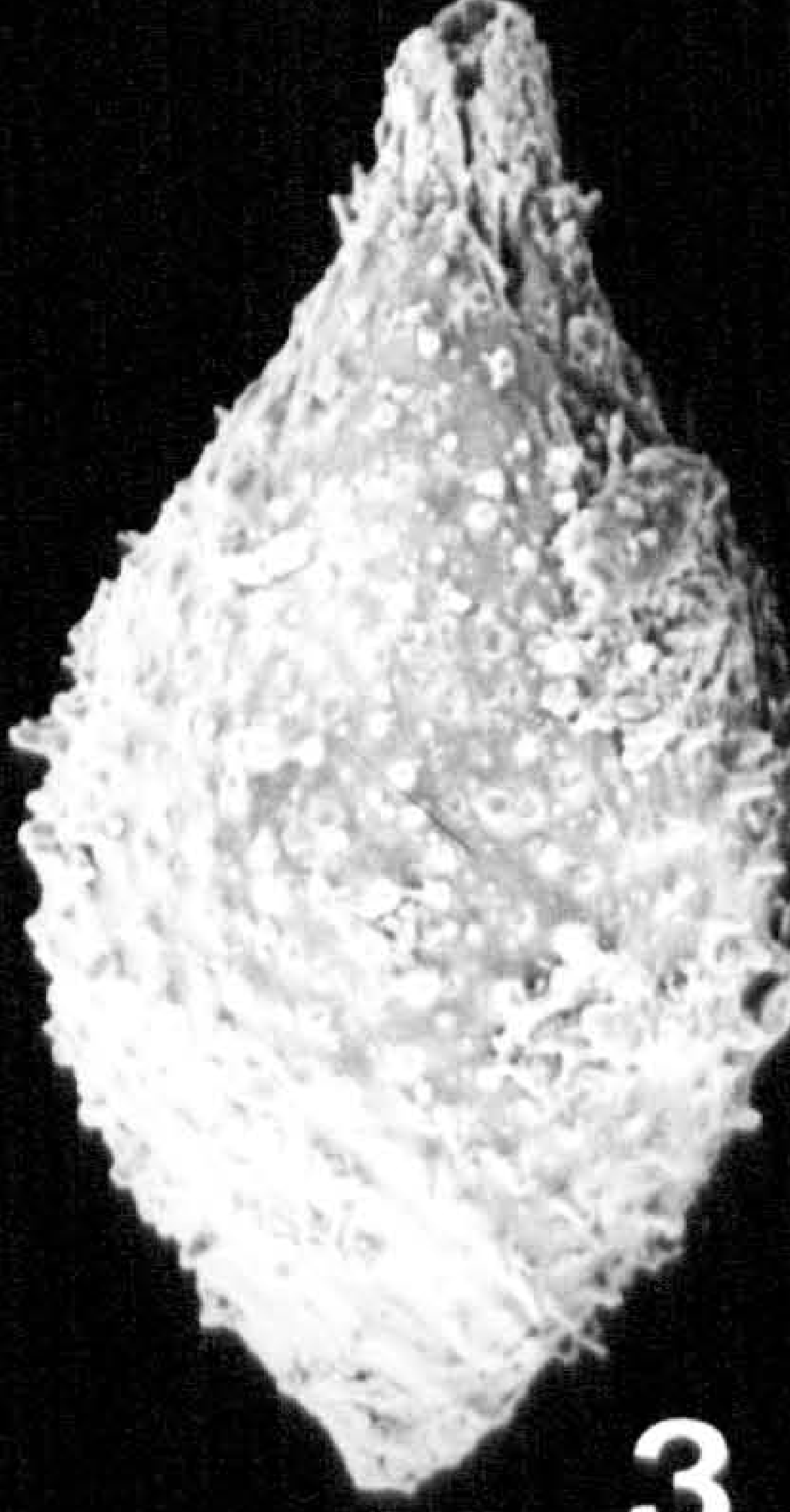
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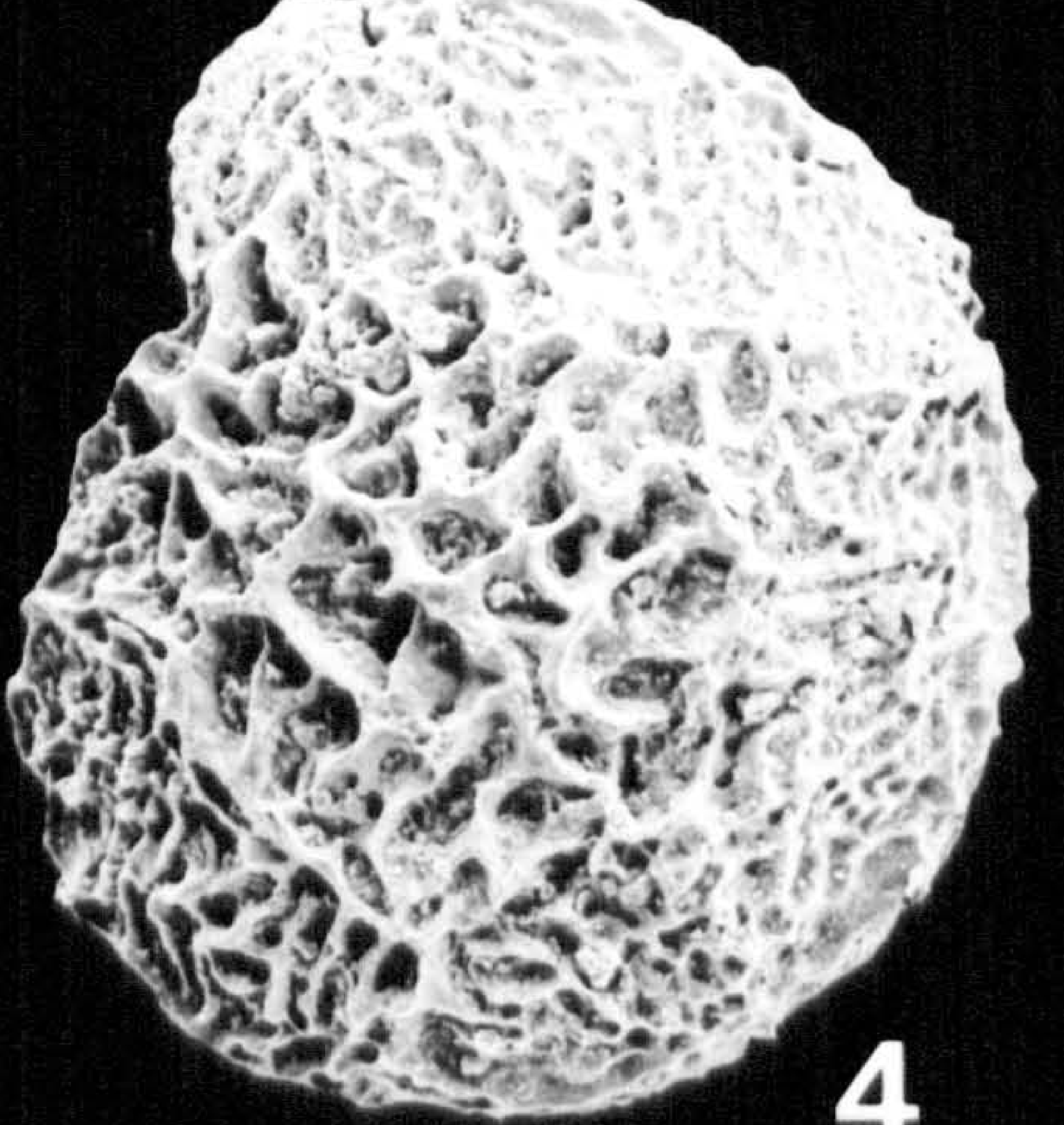
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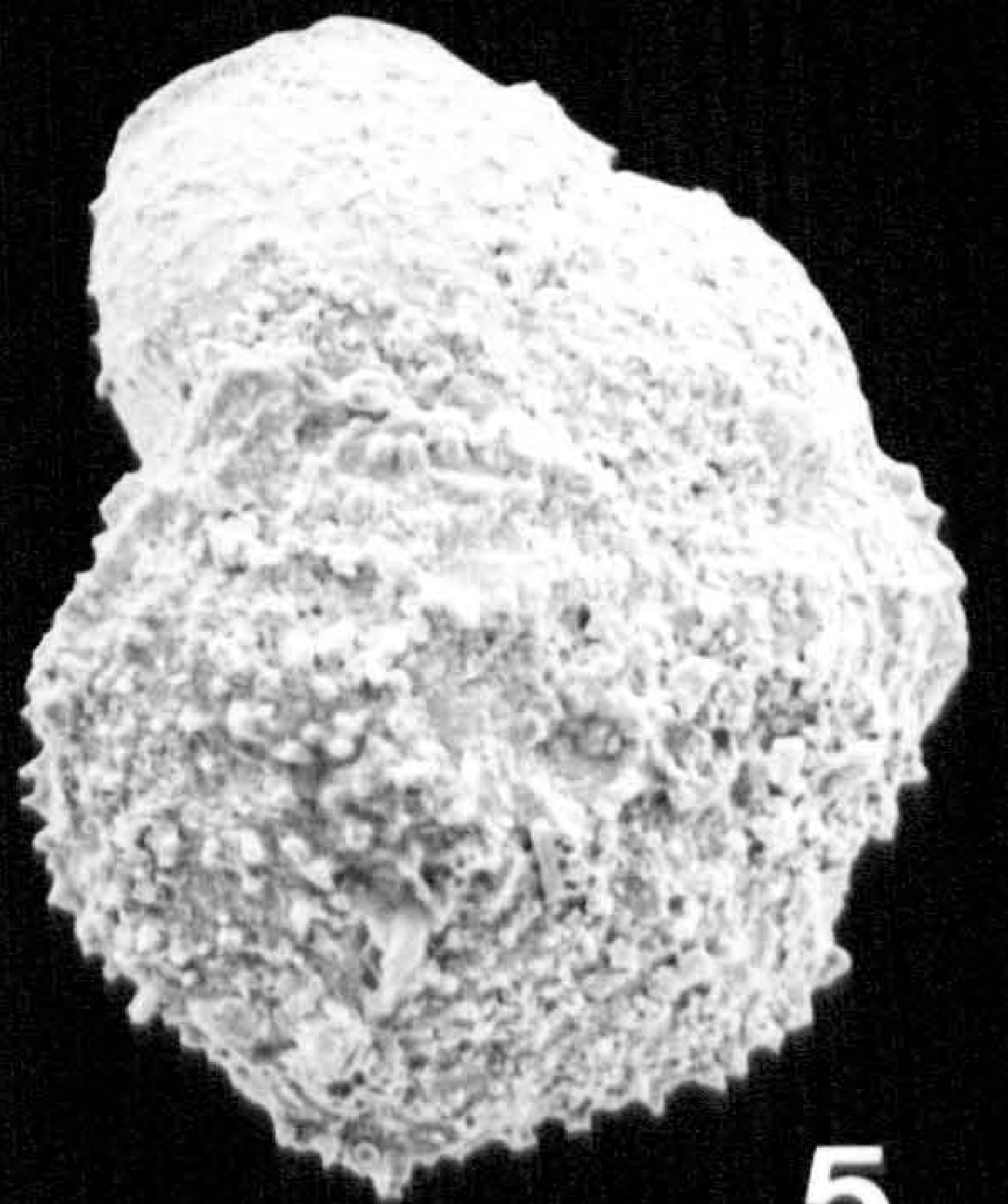
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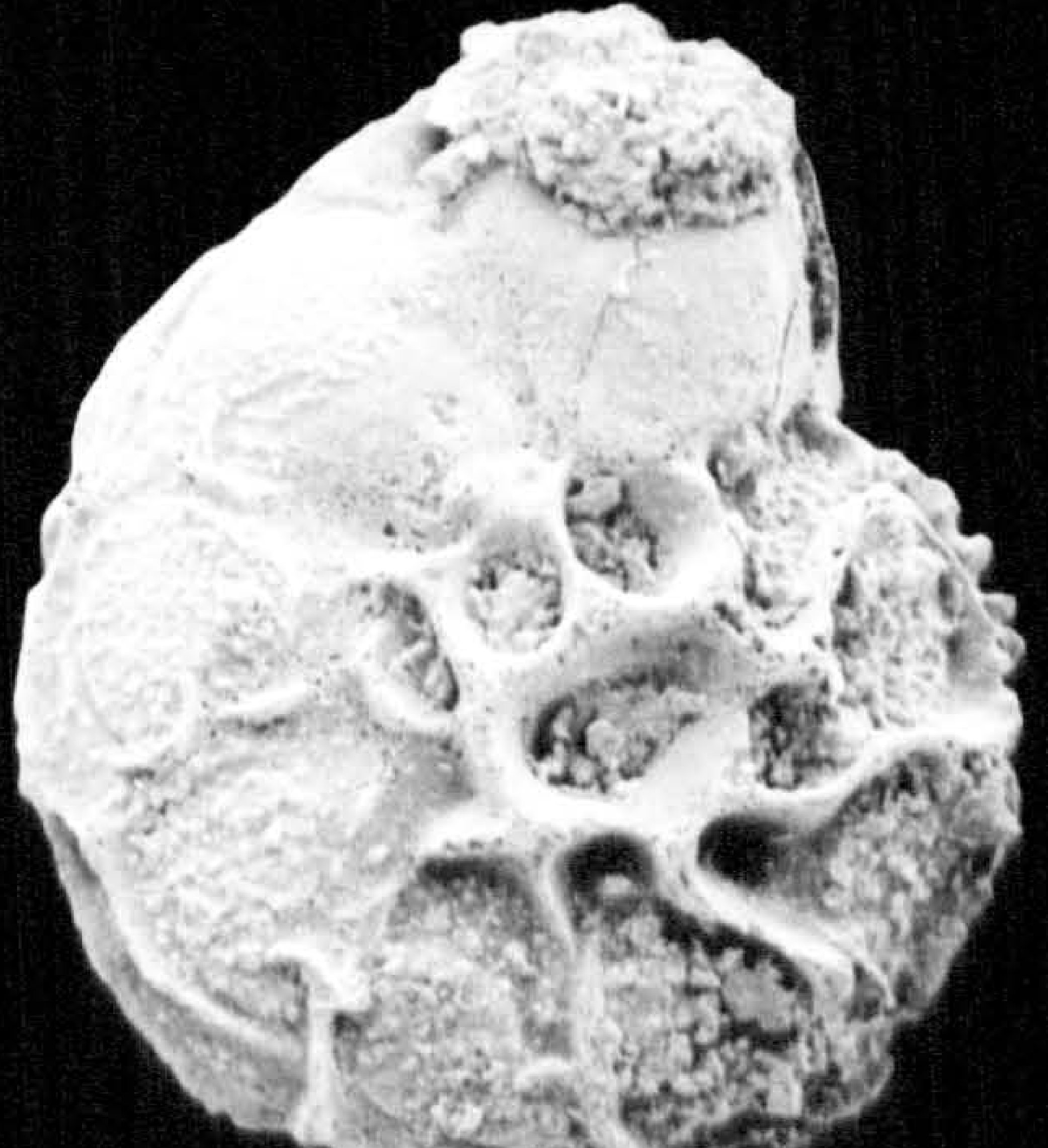
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PLATE 19

Figure 1. Epistomina parastelligera (Hofker), 1954
Maximum Diameter 246µm. Sample No. GS14

Figure 2. Epistomina stellicostata Bielecka & Pozaryski, 1954
Maximum Diameter 322µm. Sample No. GS2

Figure 3. Conorboides marginata Lloyd, 1962. Spiral View
Maximum Diameter 208µm. Sample No. DC9

Figure 4. Conorboides marginata Lloyd, 1962. Umbilical View
Maximum Diameter 160µm. Sample No. GS10

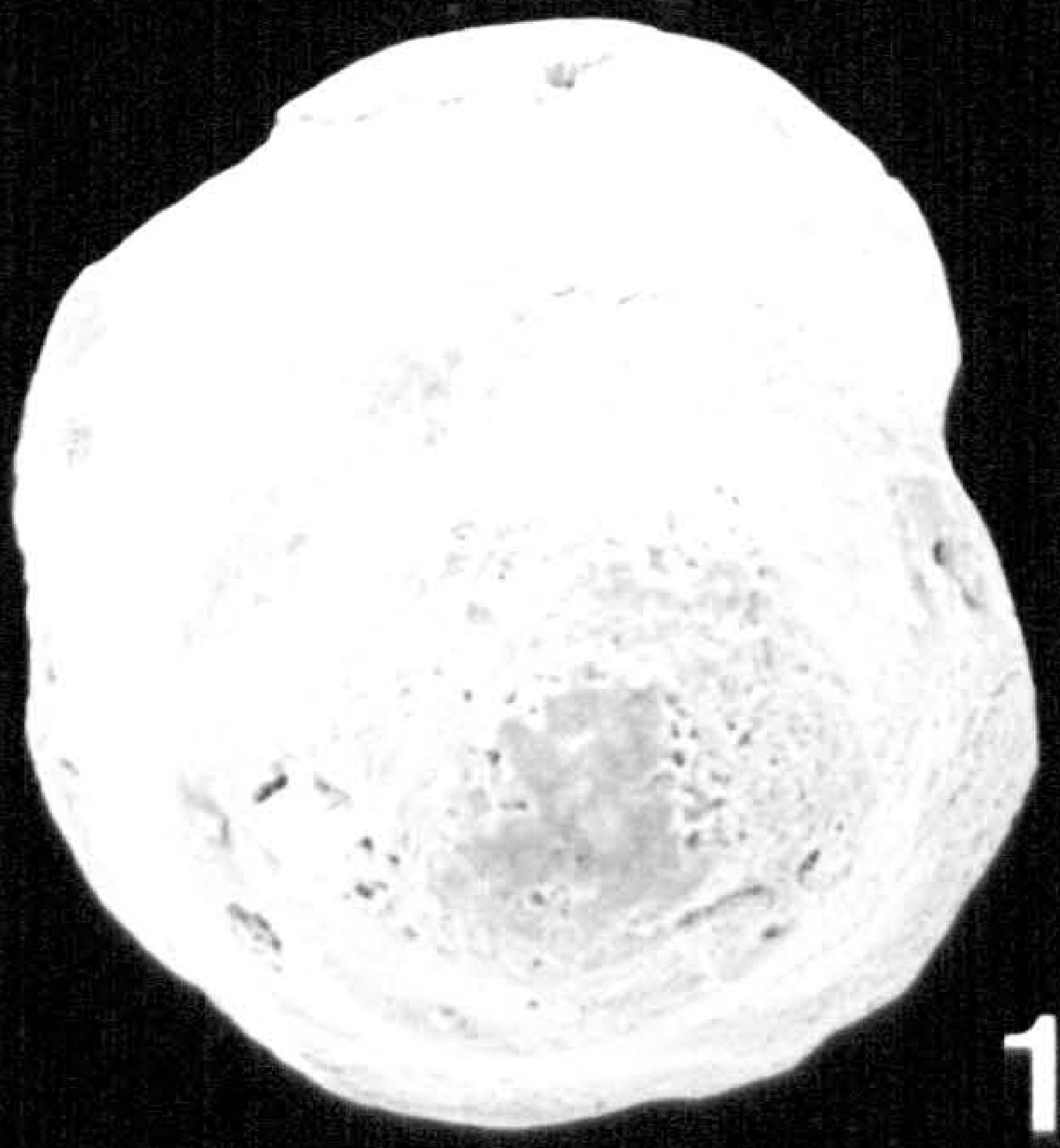
Figure 5. Conorboides pygmaea Cordey, 1962
Maximum Diameter 193µm. Sample No. DC4

Figure 6. Globuligerina oxfordiana (Grigelis), 1958
Maximum Diameter 131µm. Sample No. DC16

Figure 7. Paalzowella feifeli (Paalzow), 1932. Spiral View
Maximum Diameter 277µm. Sample No. DC8

Figure 8. Paalzowella feifeli (Paalzow), 1932. 'Umbilical' View
Maximum Diameter 312µm. Sample No. DC8

PLATE 19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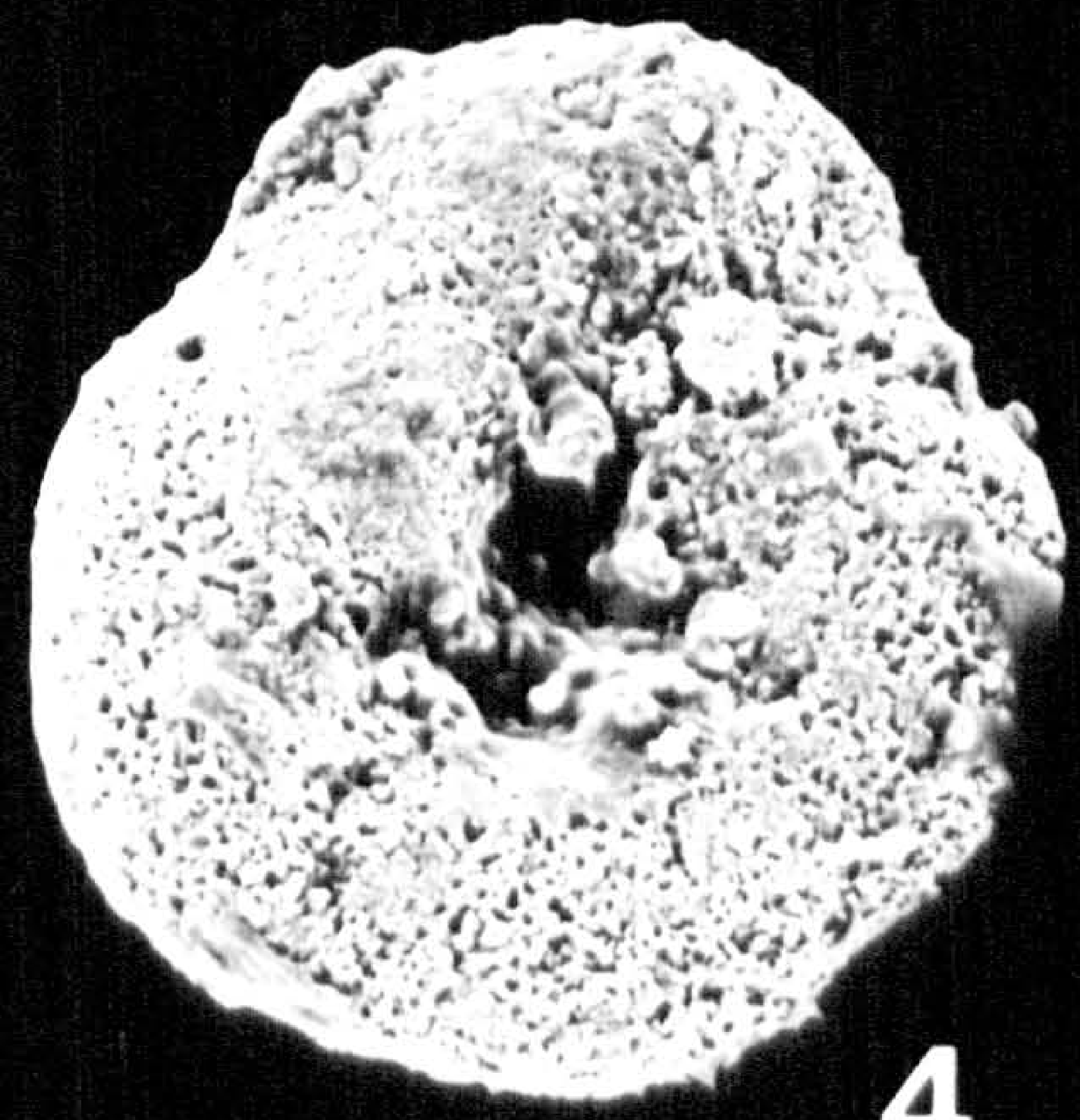
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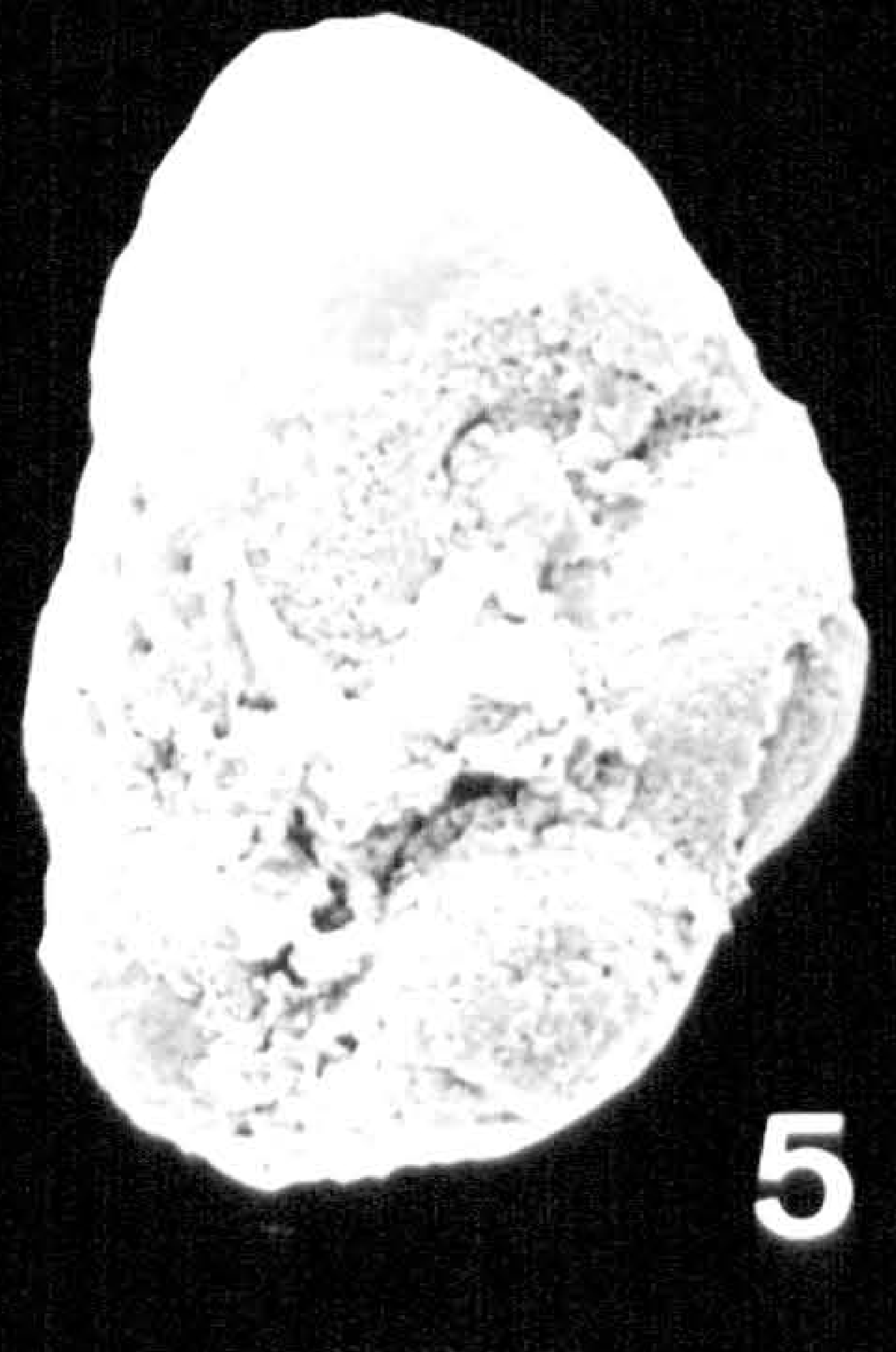
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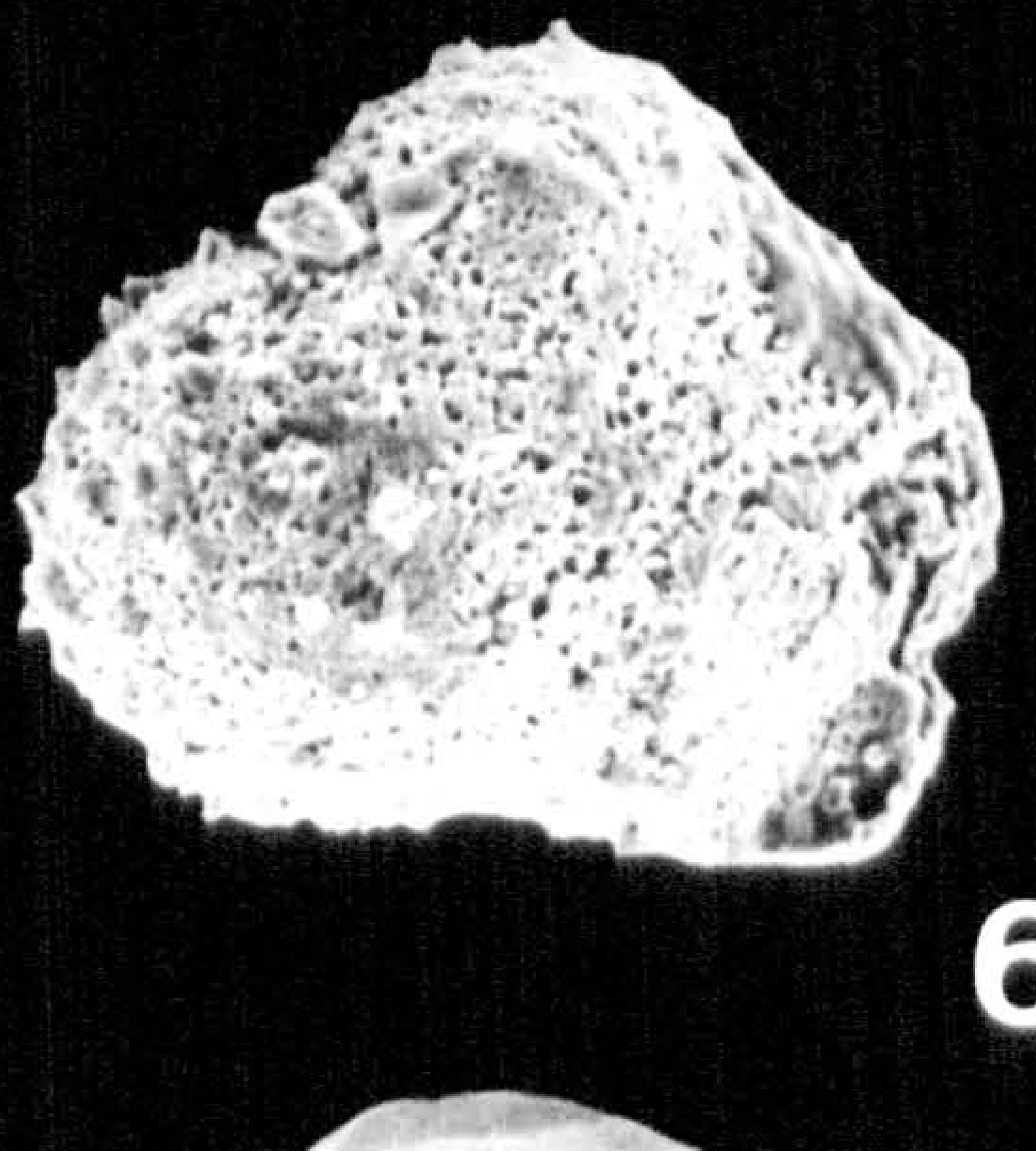
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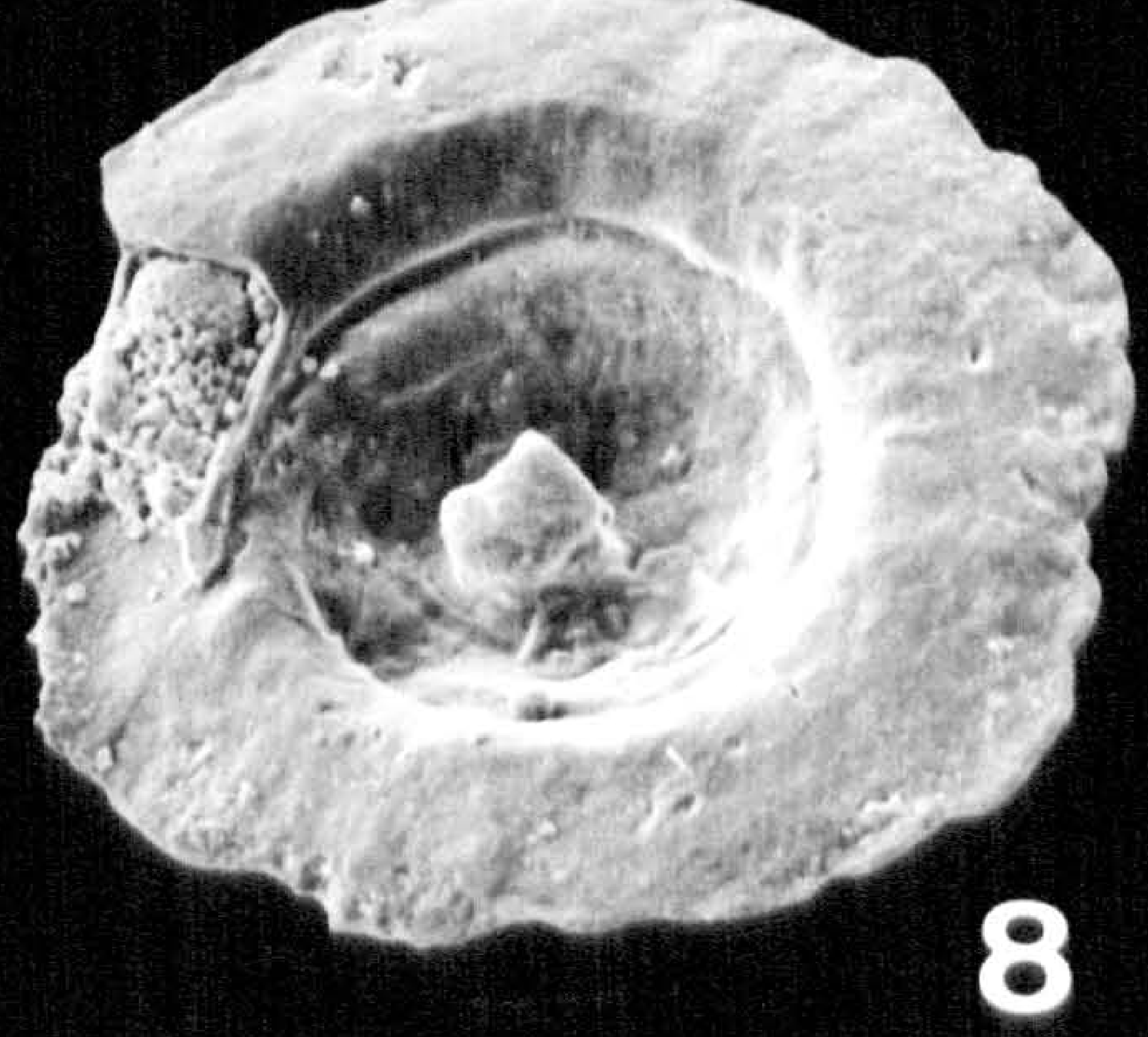
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PLATE 20

Figure 1. Hsuum sp. 1 Dyer & Copestake, 1989
Maximum Length 178µm. Sample No. KW11

Figure 2. Parvicingula blowi Pessagno, 1977
Maximum Length 168µm. Sample No. E41

Figure 3. Parvicingula blowi Pessagno ssp. A Dyer & Copestake, 1989
Maximum Length 211µm. Sample No. E41

Figure 4. Parvicingula aff. jonsei Pessagno, 1977
Maximum Length 300µm. Sample No. E19

Figure 5. Parvicingula sp. A
Maximum Length 311µm. Sample No. E41

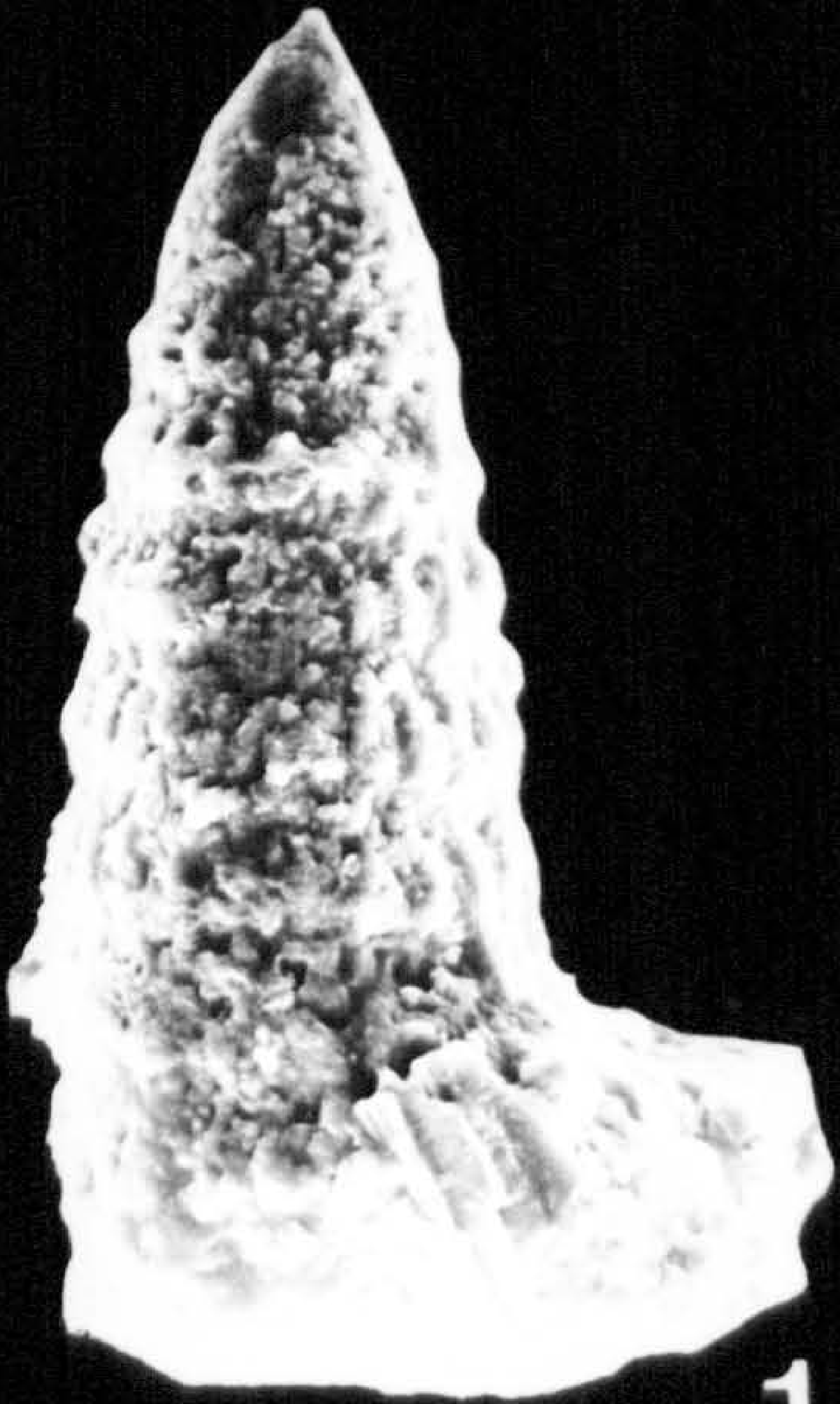
Figure 6. Multicytrid Nassellarian gen. & sp. indent.
Maximum Length 229µm. Sample No. BRS24

Figure 7. Multicytrid Nassellarian gen. & sp. indent.
Maximum Length 238µm. Sample No. BRS24

Figure 8. Stichocapsa devorata Rüst, 1885
Maximum Length 178µm. Sample No. F21

Figure 9. Stichocapsa sp. indent
Maximum Length 189µm. Sample No. DC2

PLATE 20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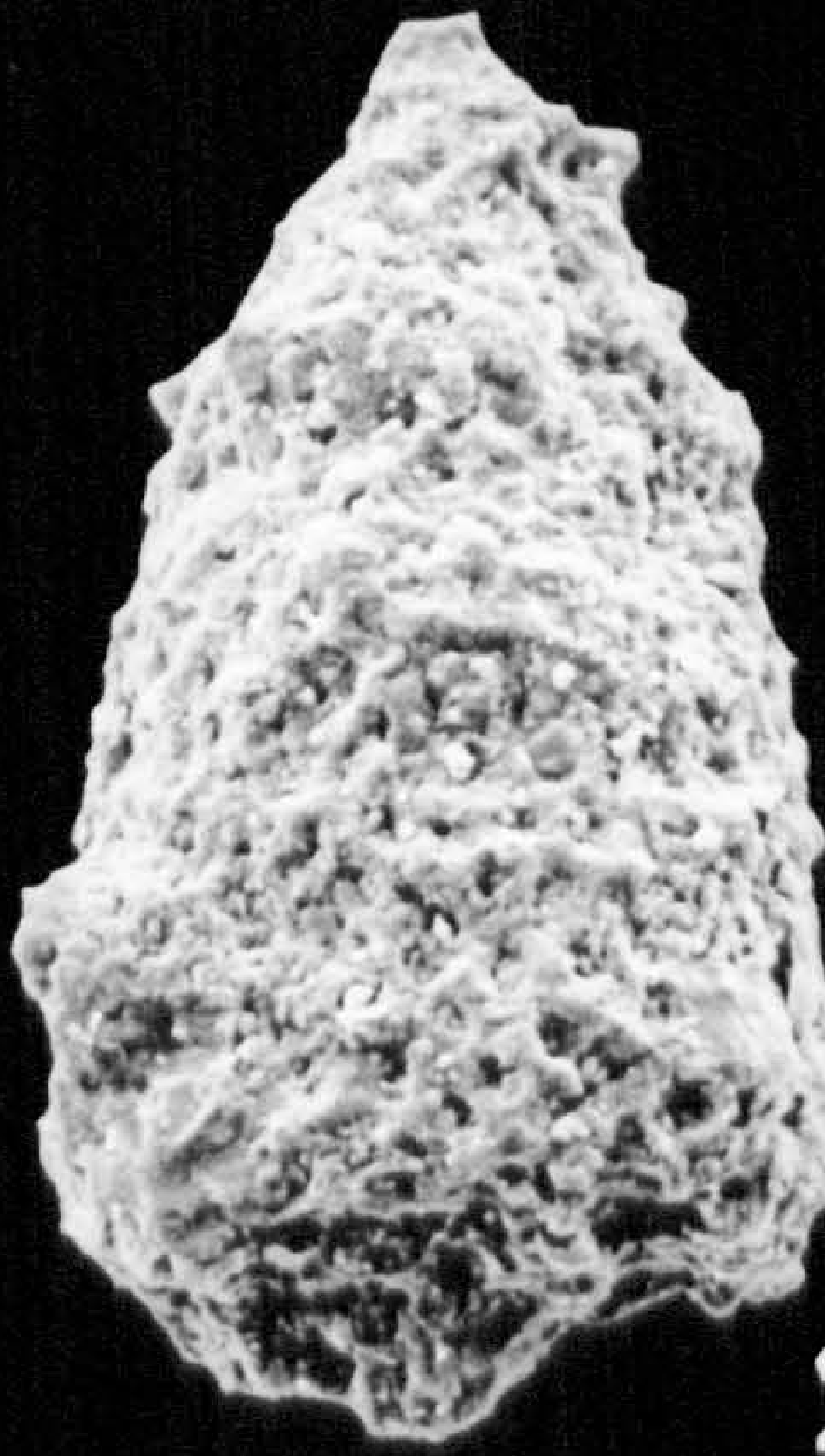
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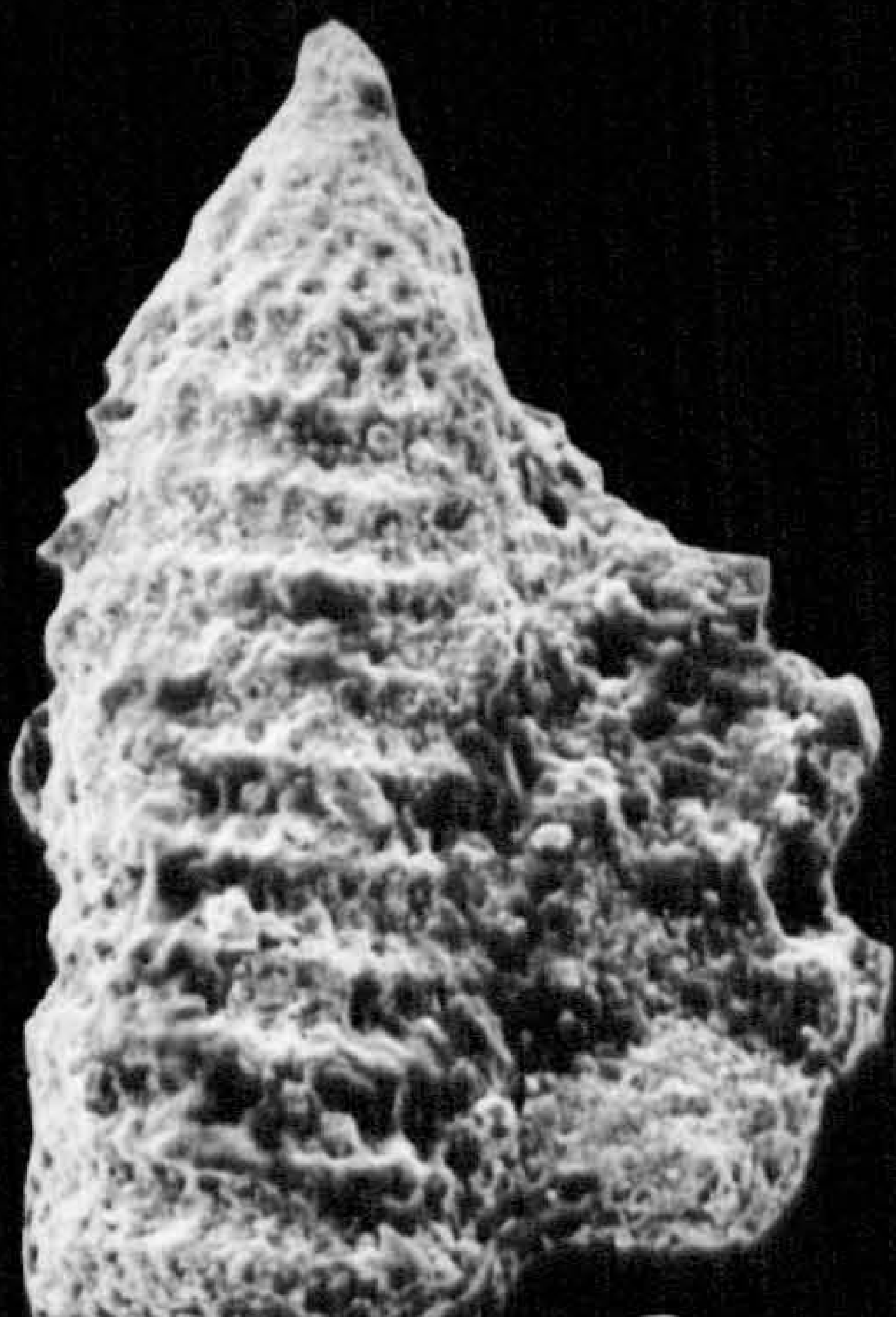
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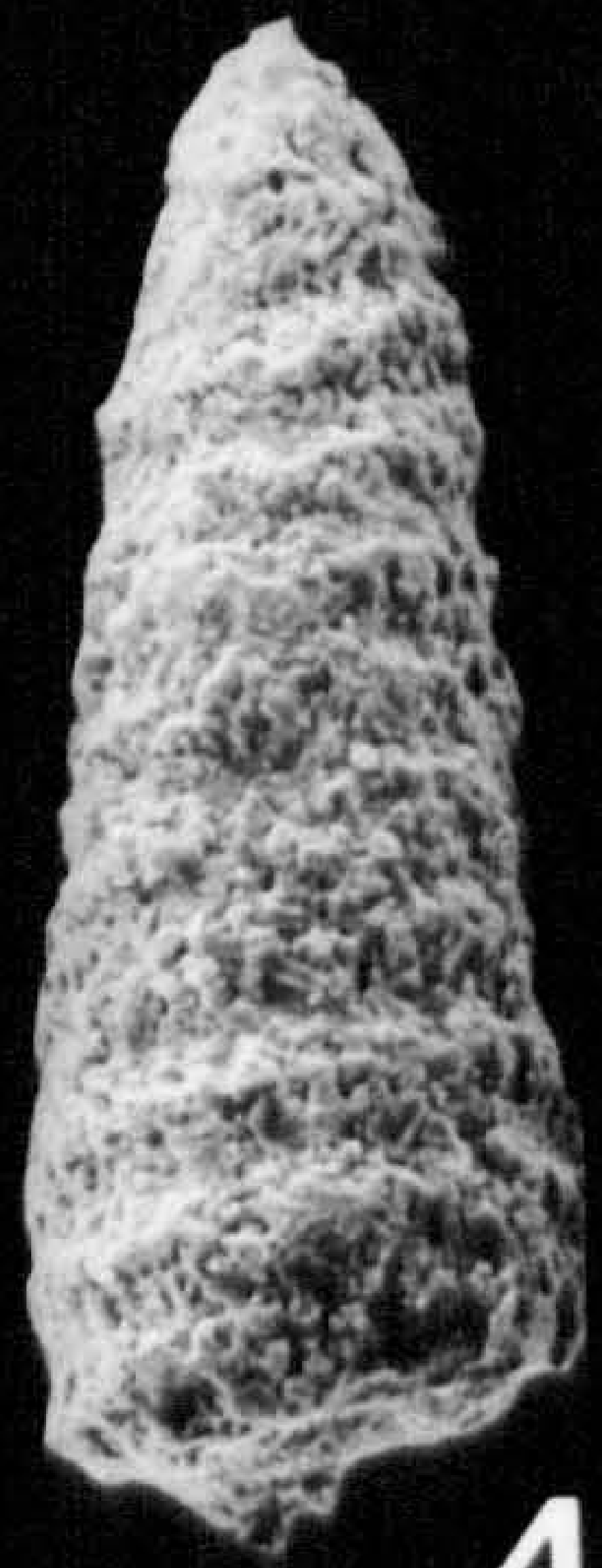
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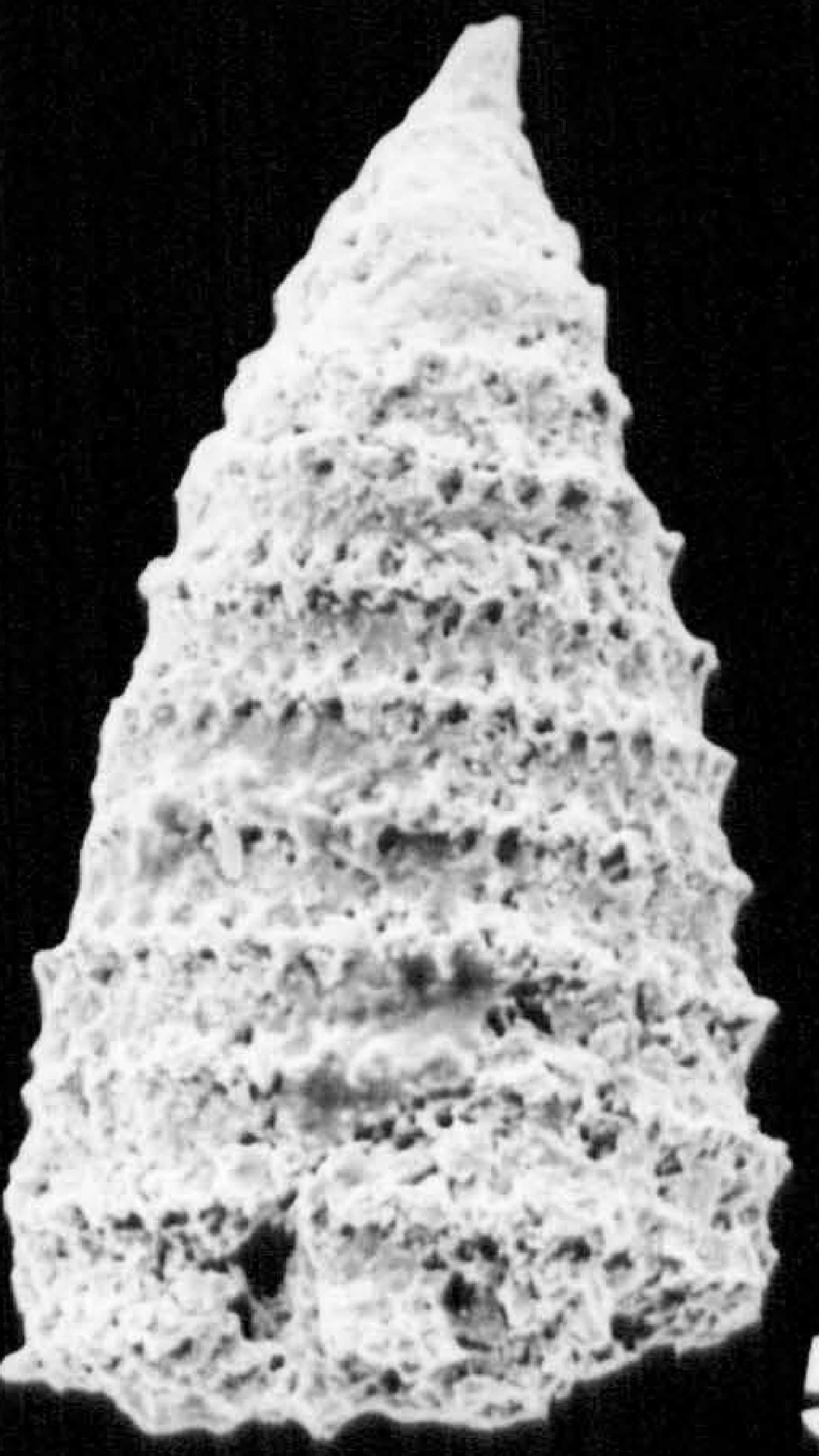
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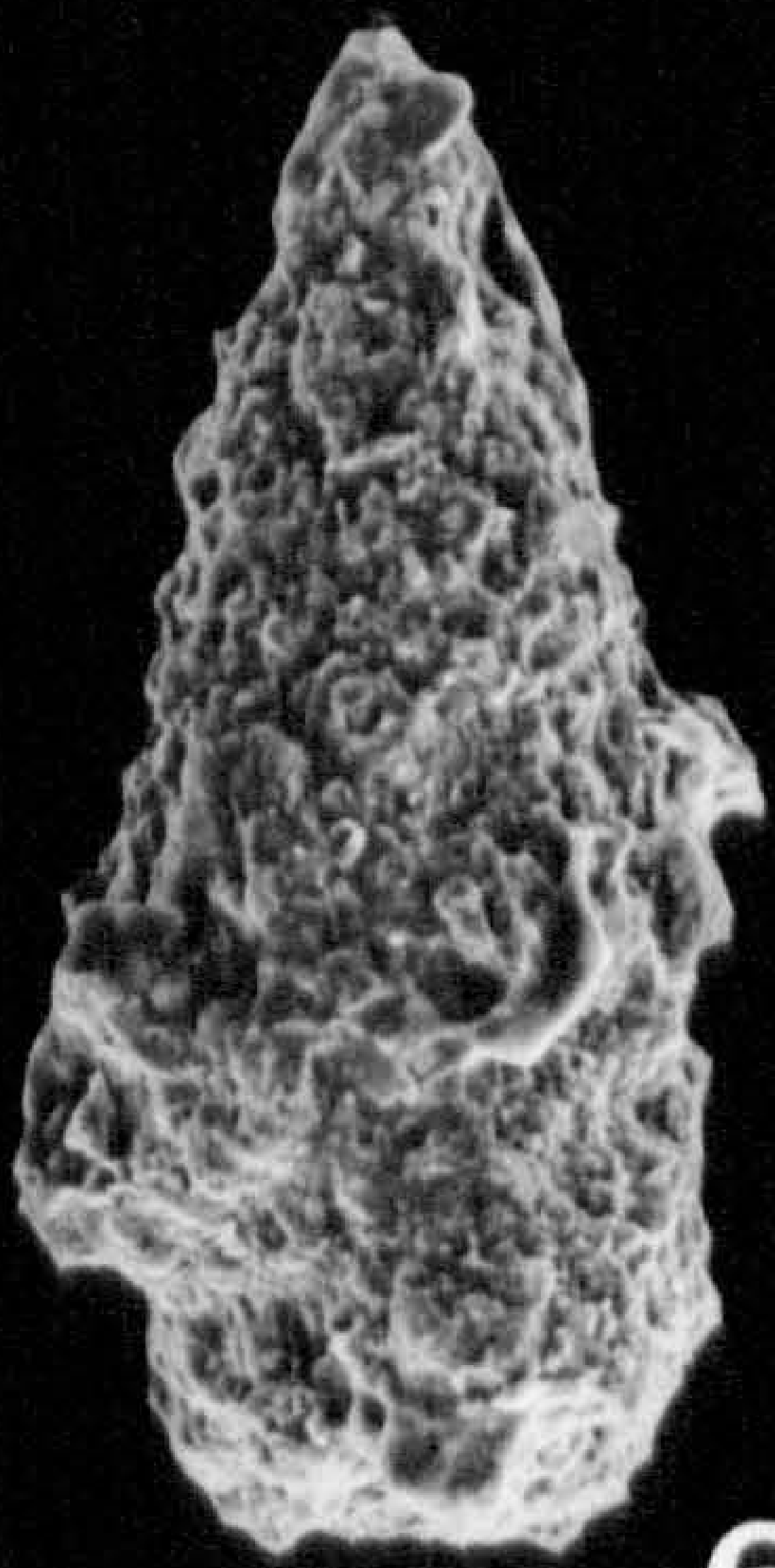
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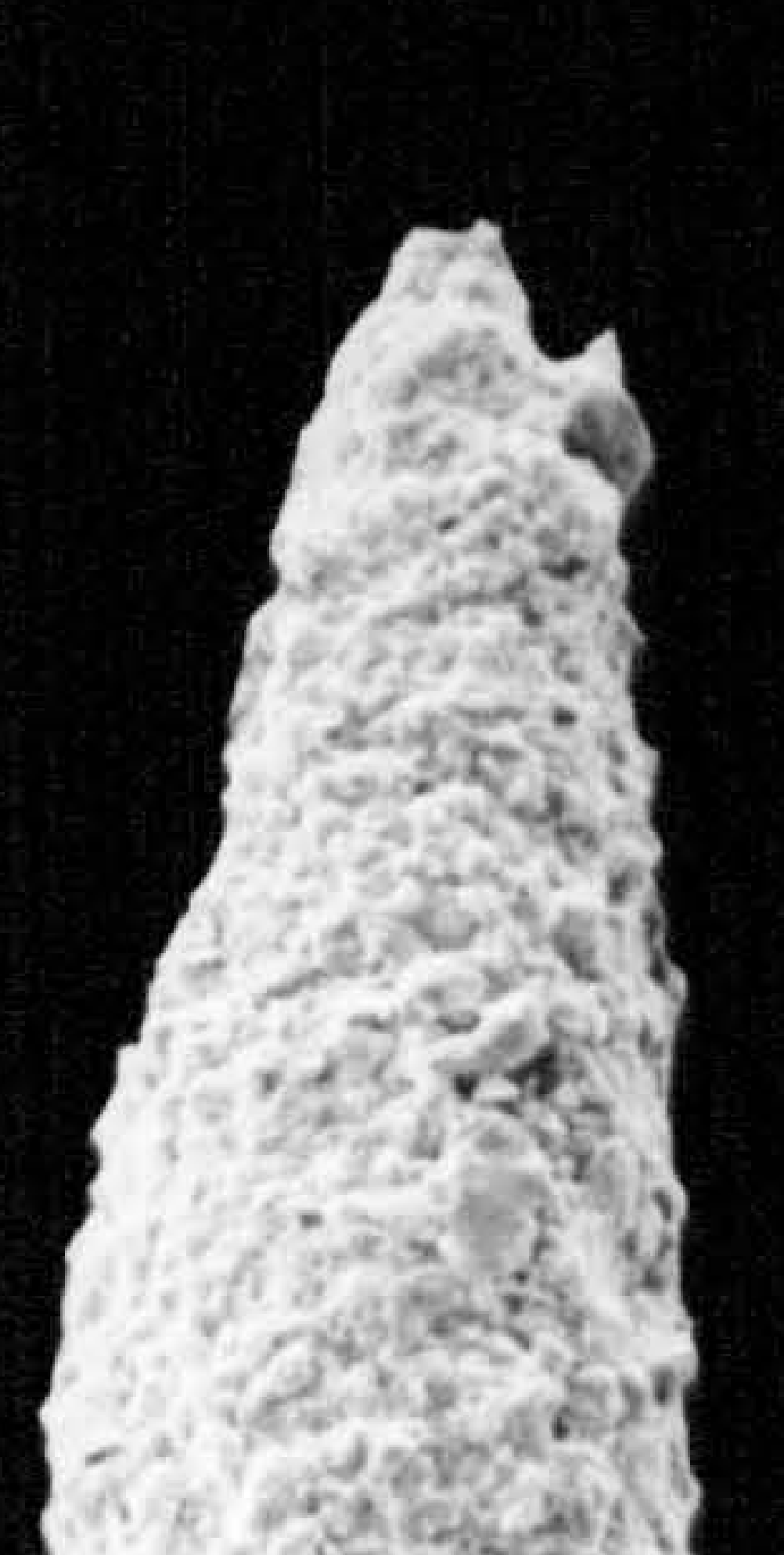
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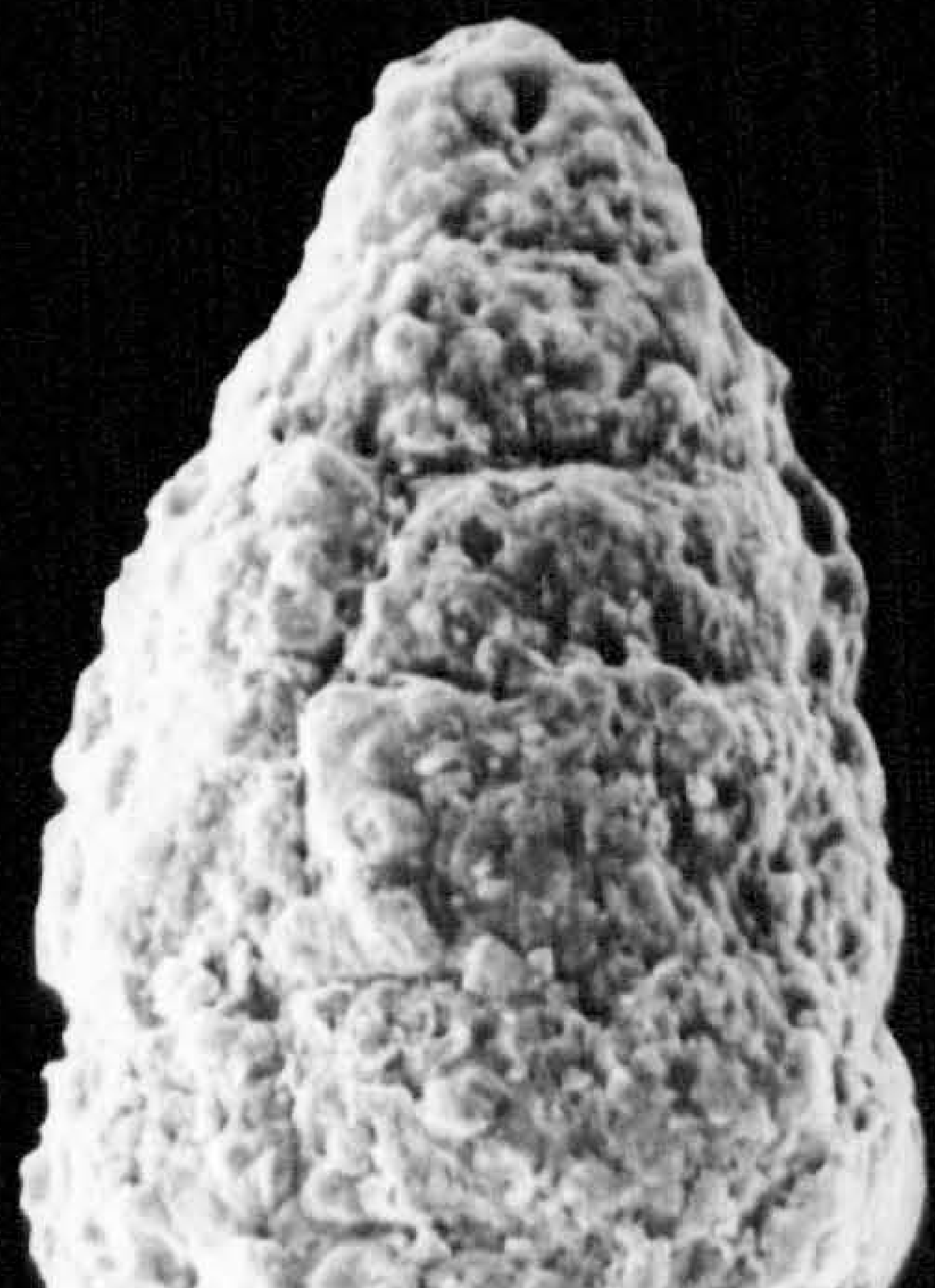
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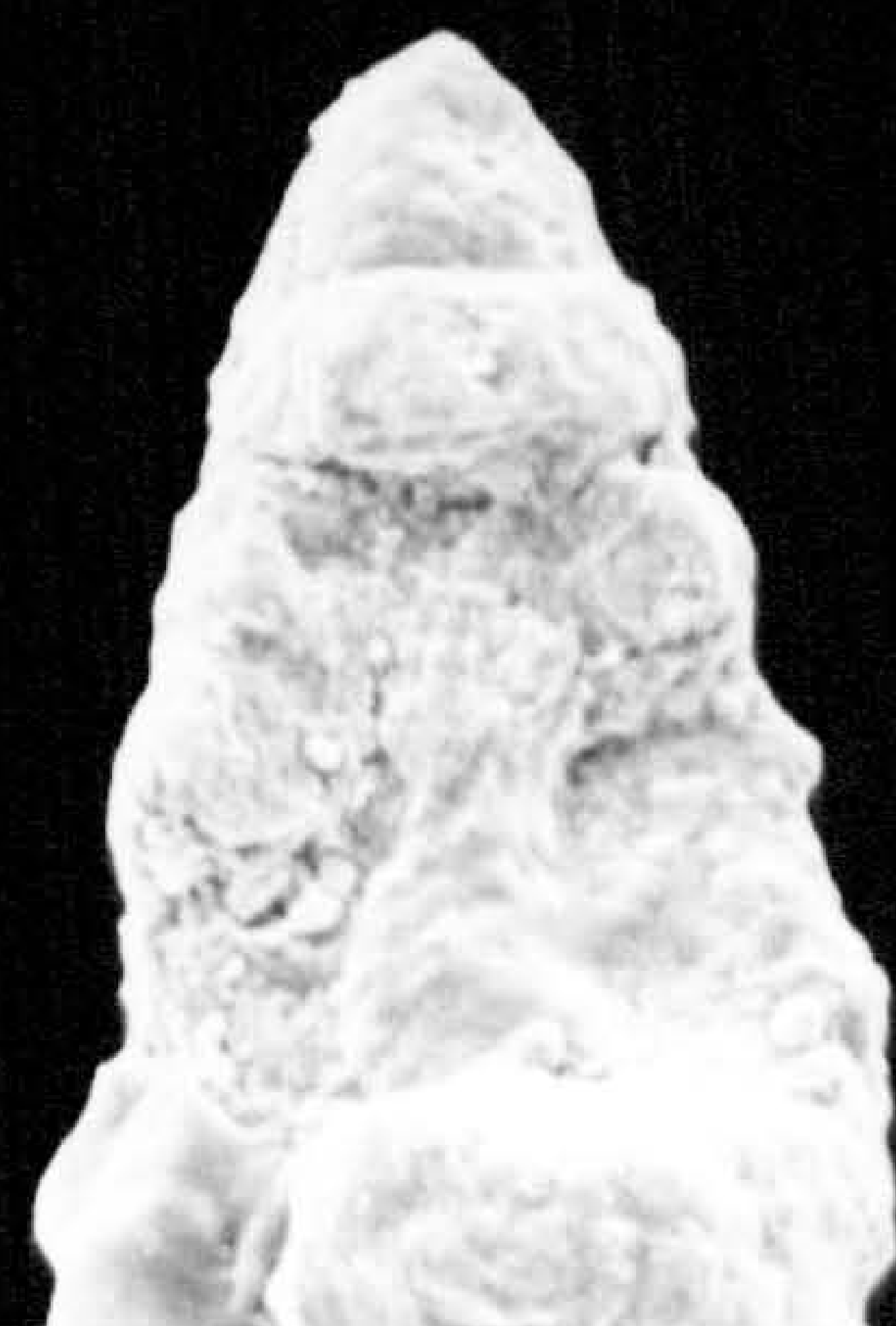
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PLATE 21

Figure 1. Tricolocapsa sp. A
Maximum Length 135µm. Sample No. DC2

Figure 2. Tricolocapsa sp. indent.
Maximum Length 163µm. Sample No. BRS21

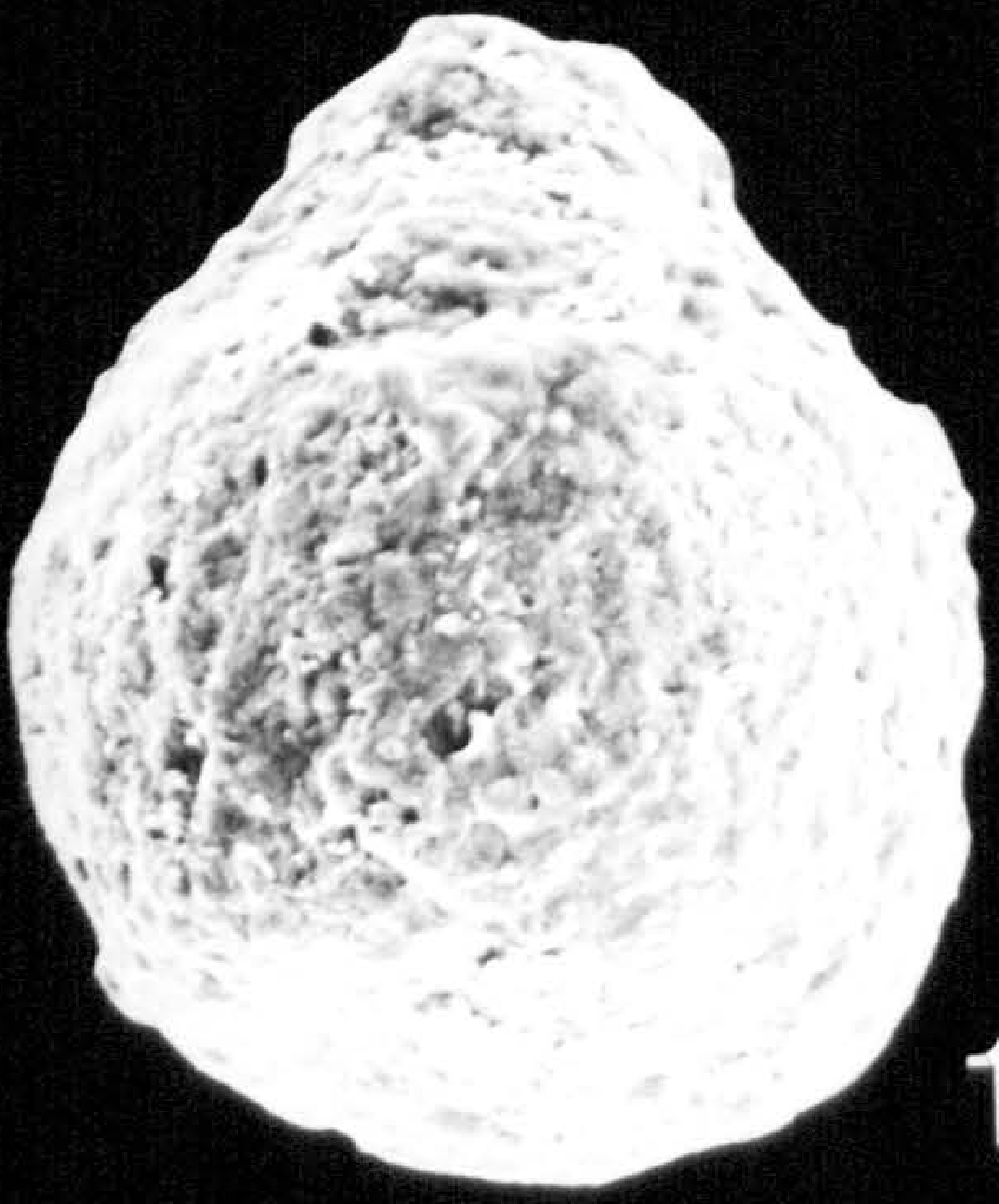
Figure 3. Paronaella pessagnoi Blome, 1984
Maximum Length 196µm. Sample No. BRS22

Figure 4. Crucella sp. indent
Maximum Length 191µm. Sample No. BRS24

Figure 5. Pseudocrucella plana Blome, 1984
Maximum Length 260µm. Sample No. DC5

Figure 6. Pseudocrucella sanfilippoae (Pessagno), 1977
Maximum Length 290µm. Sample No. E15

PLATE 21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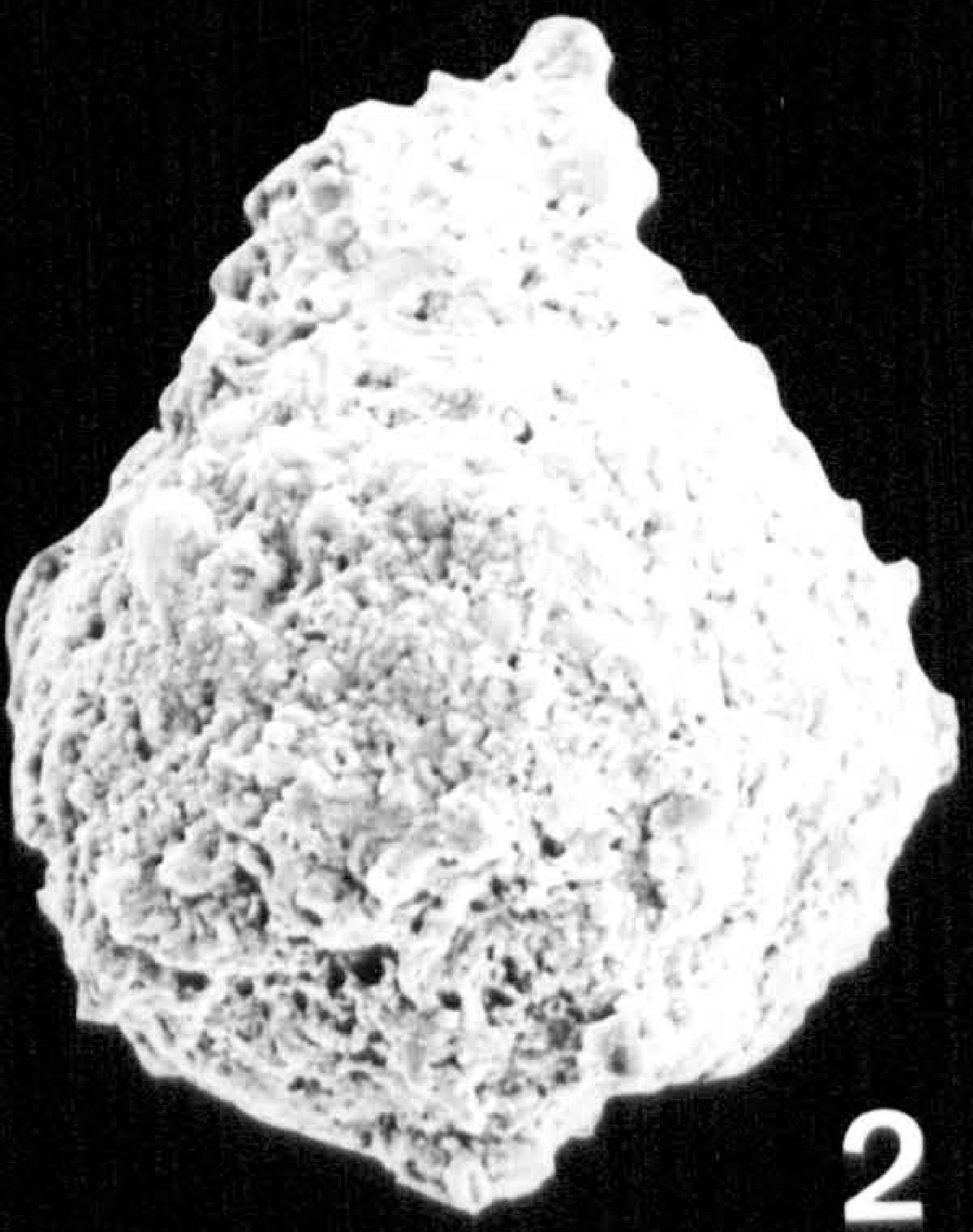
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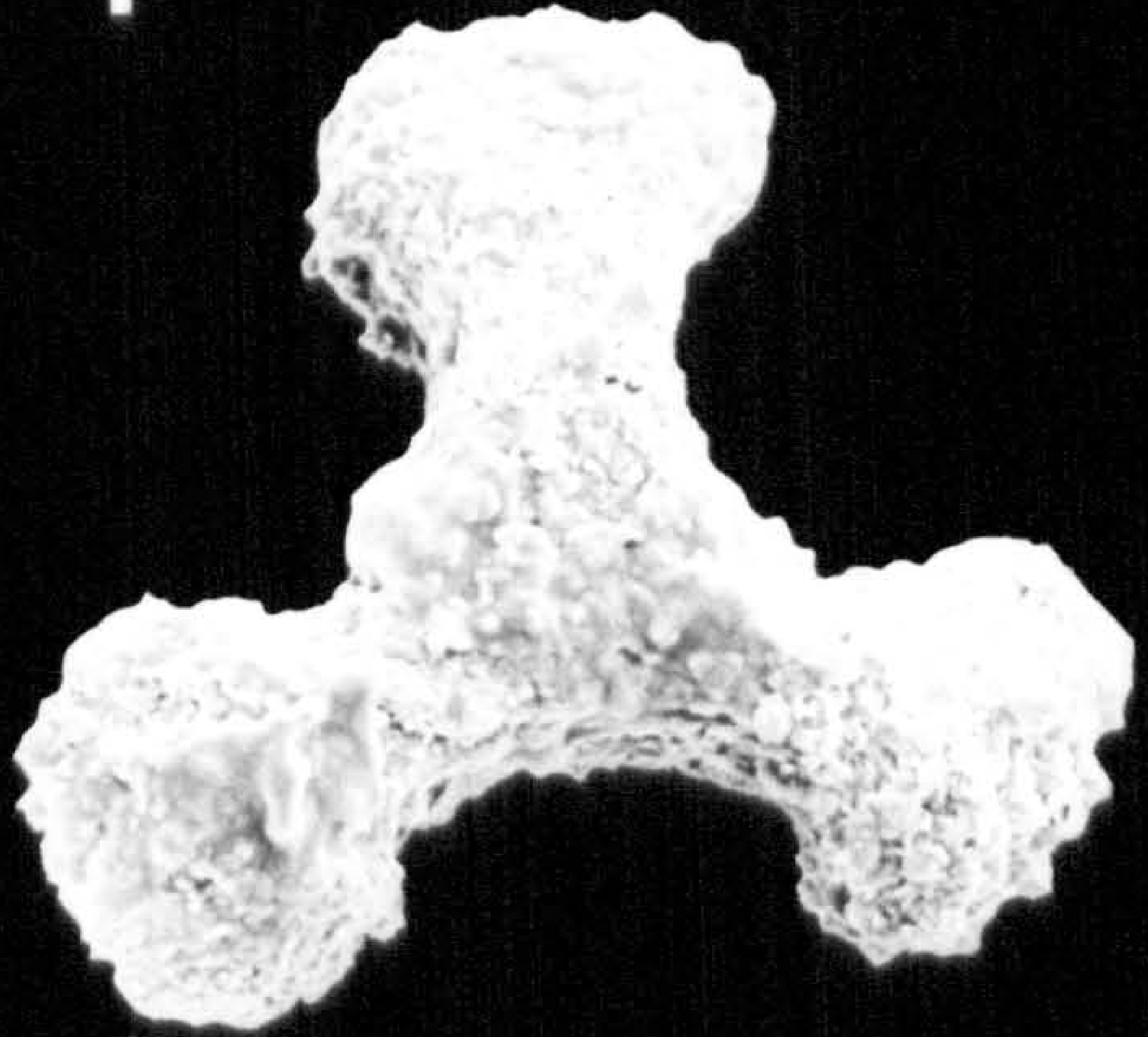
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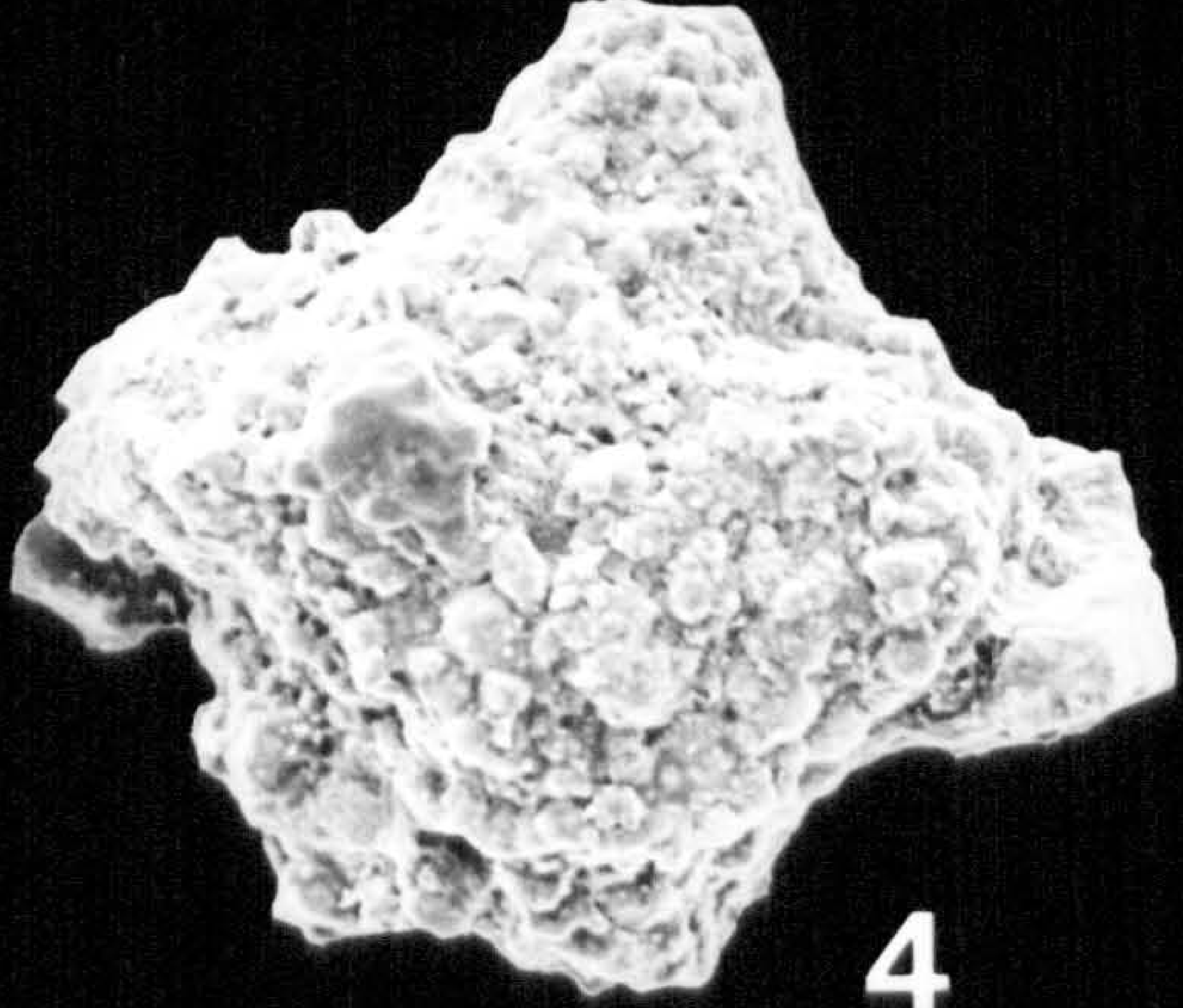
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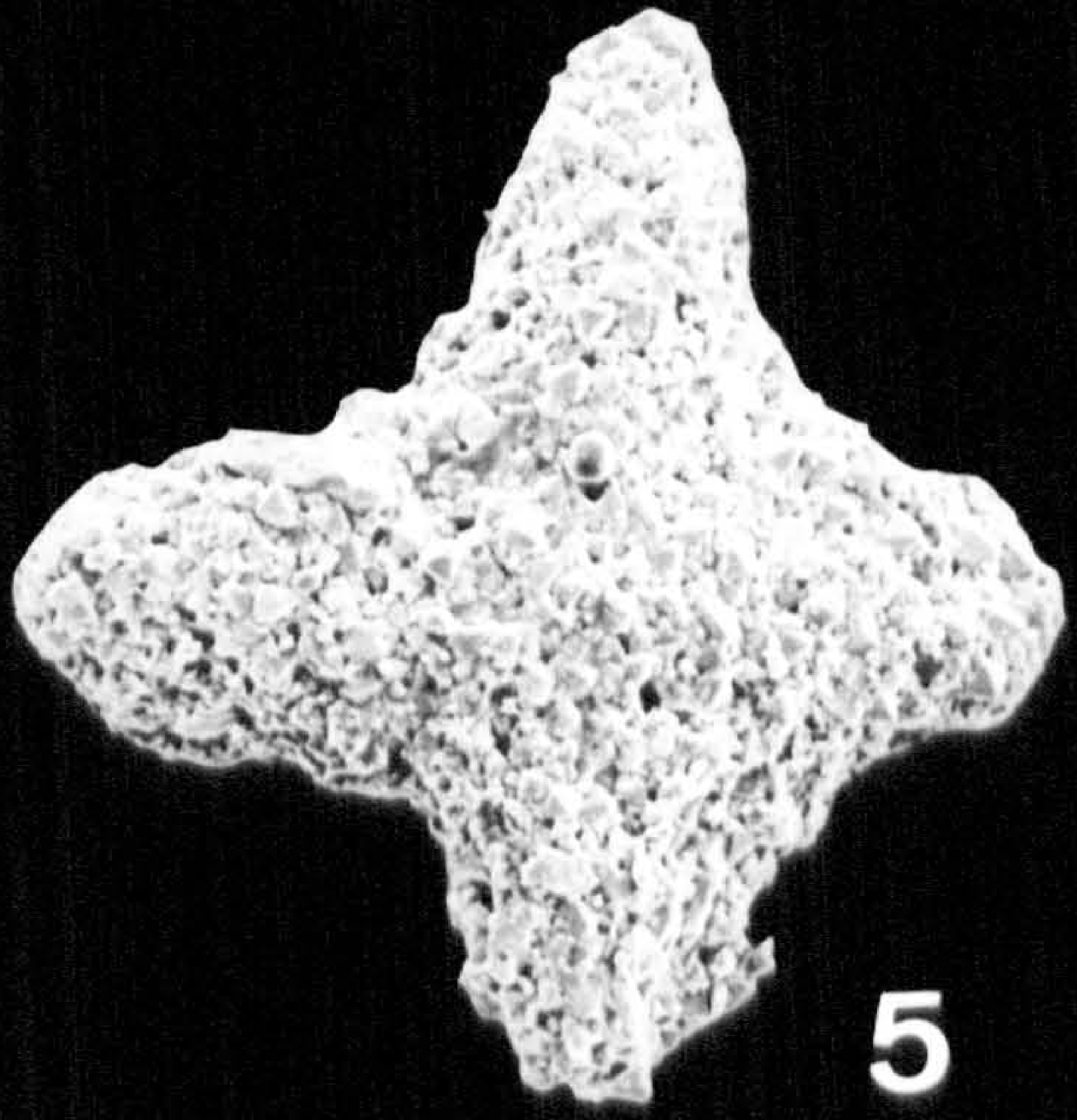
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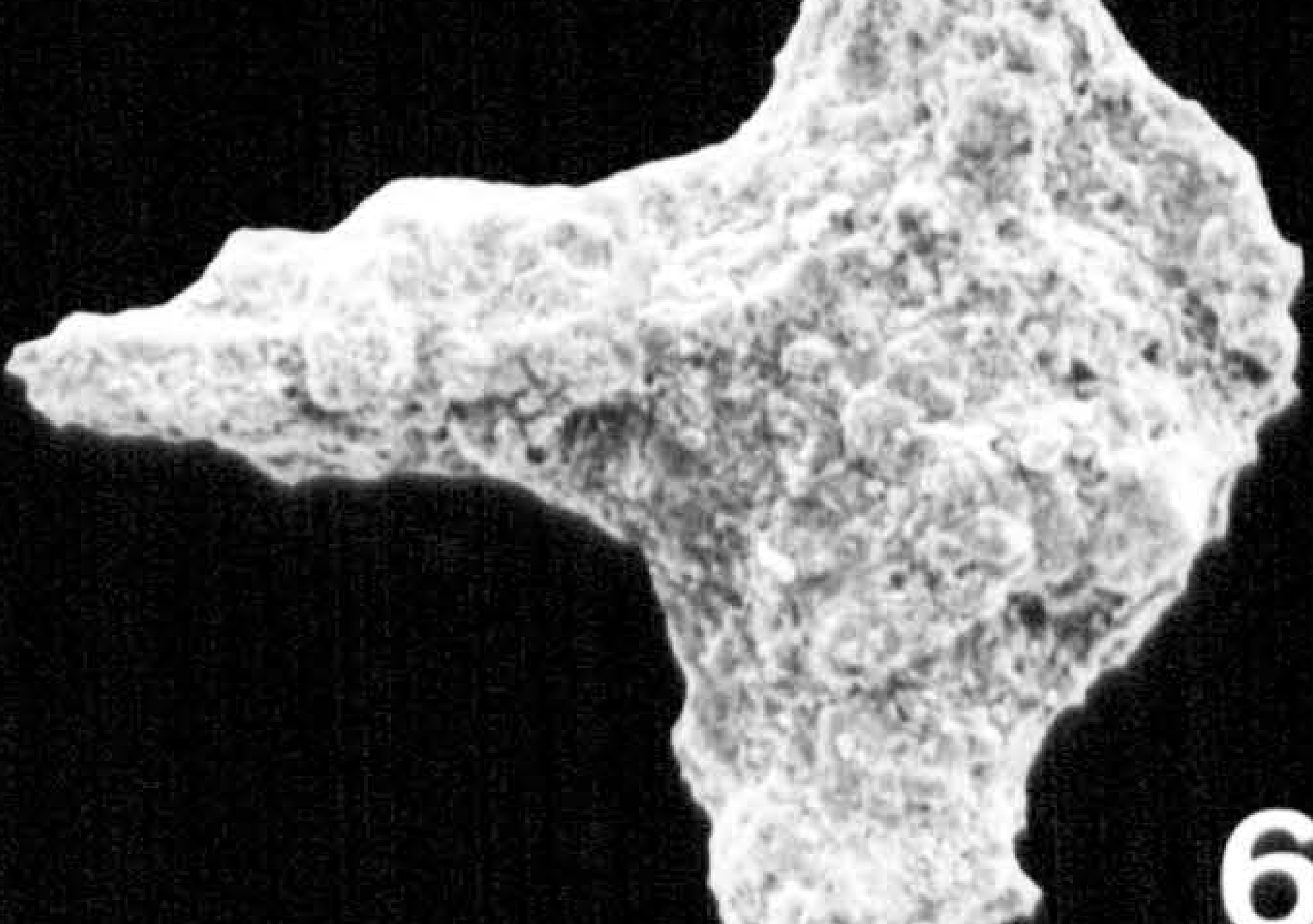
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PLATE 22

Figure 1. Orbiculiforma sp. A
Maximum Diameter 268µm. Sample No. E42

Figure 2. Orbiculiforma sp. A. Side View
Maximum Diameter 268µm. Sample No. E42

Figure 3. Orbiculiforma sp. B
Maximum Diameter 265µm. Sample No. DC5

Figure 4. Orbiculiforma sp. B. Side View
Maximum Diameter 265µm. Sample No. DC5

Figure 5. Orbiculiforma iniqua Blome, 1984
Maximum Diameter 305µm. Sample No. BRS29

Figure 7. Orbiculiforma iniqua Blome, 1984
Maximum Diameter 305µm. Sample No. BRS29

Figure 6. Orbiculiforma lowreyensis
Maximum Diameter 206µm. Sample No. F19

Figure 8. Orbiculiforma lowreyensis. Side View
Maximum Diameter 206µm. Sample No. F19

PLATE 22


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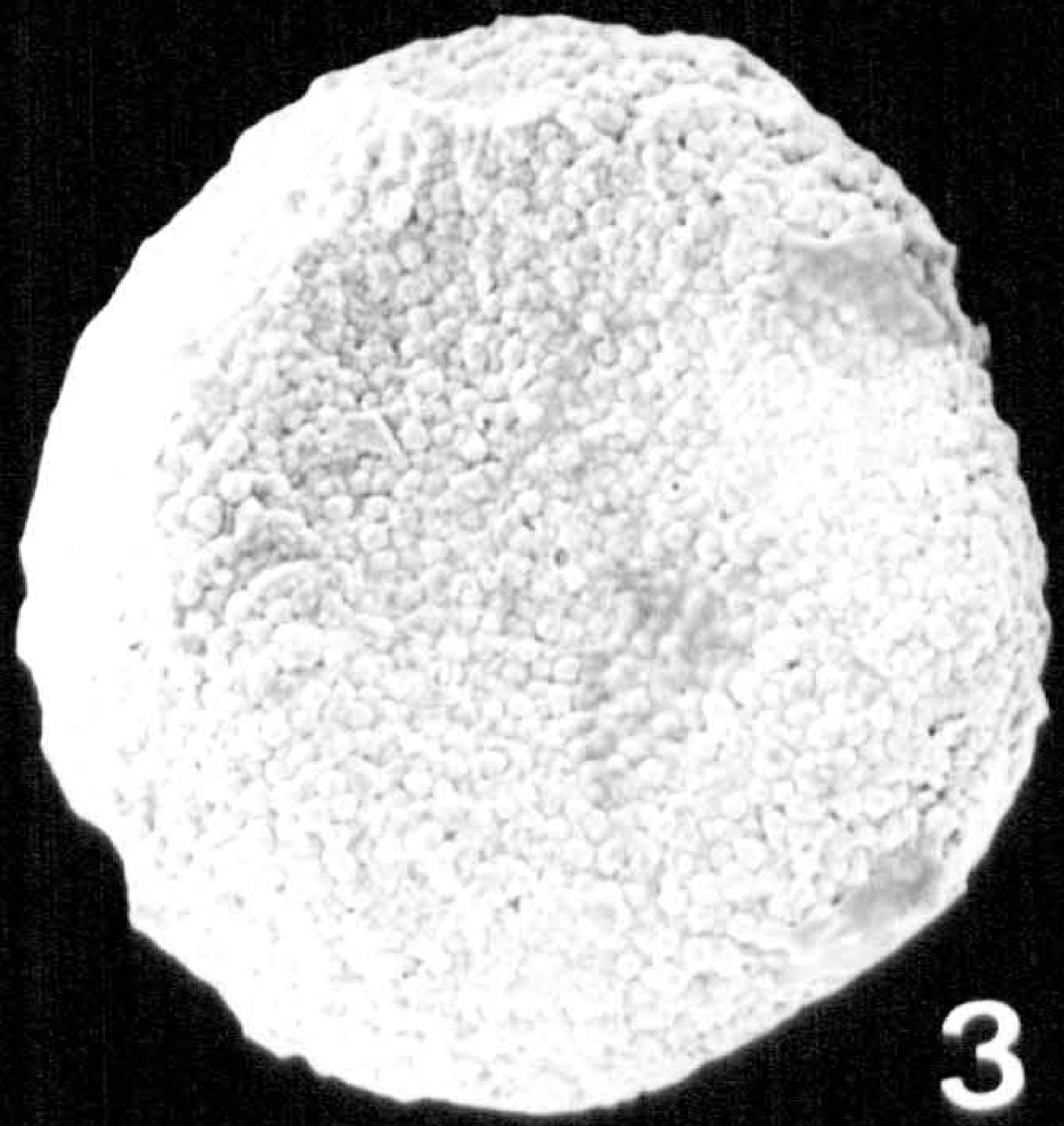
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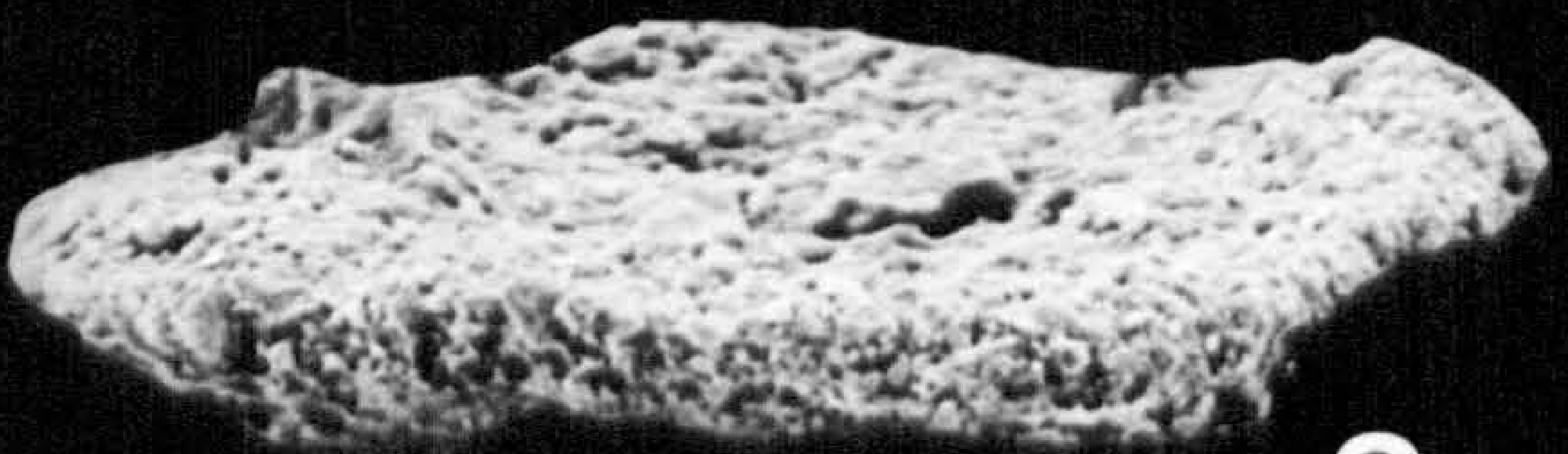
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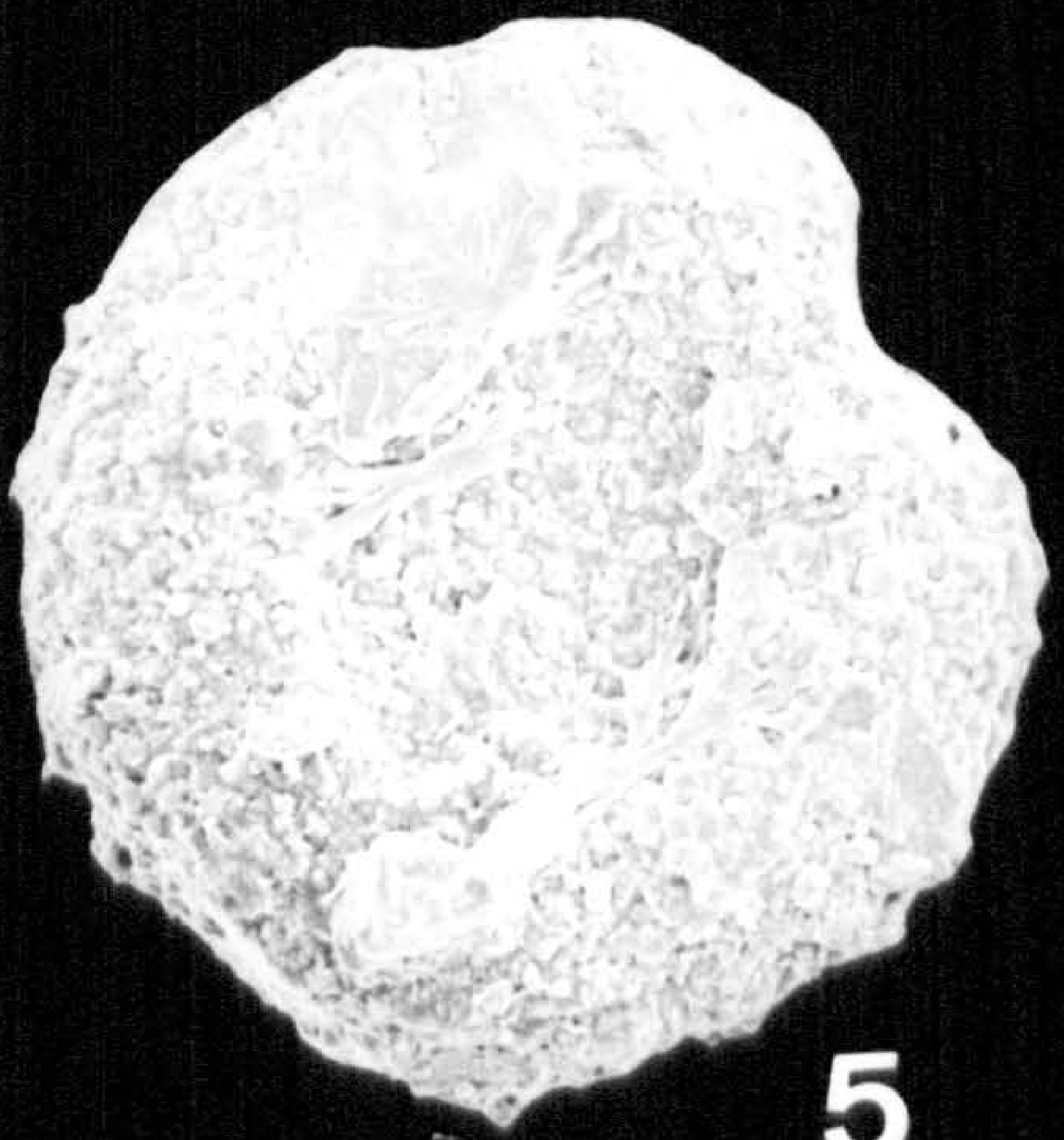
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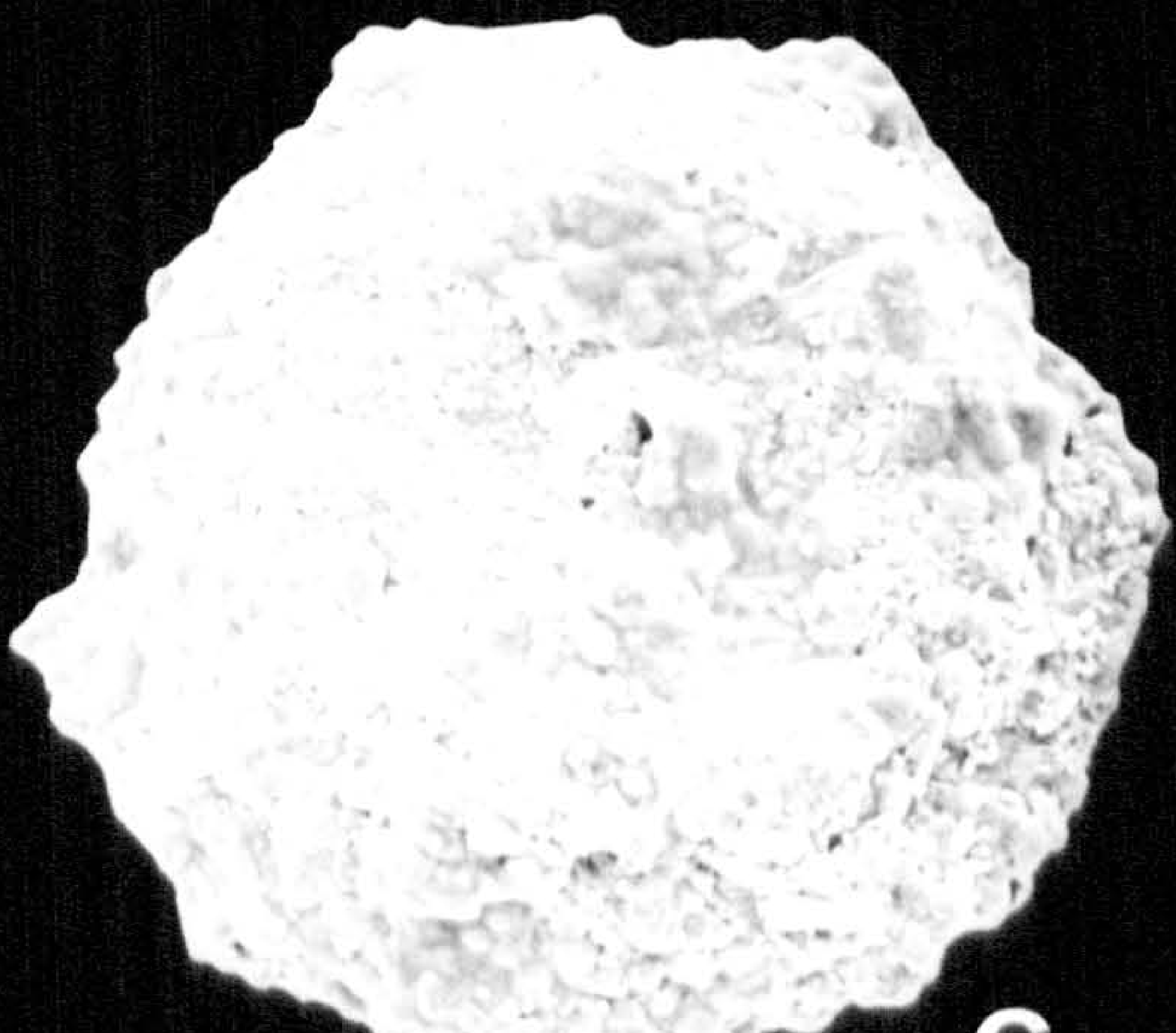
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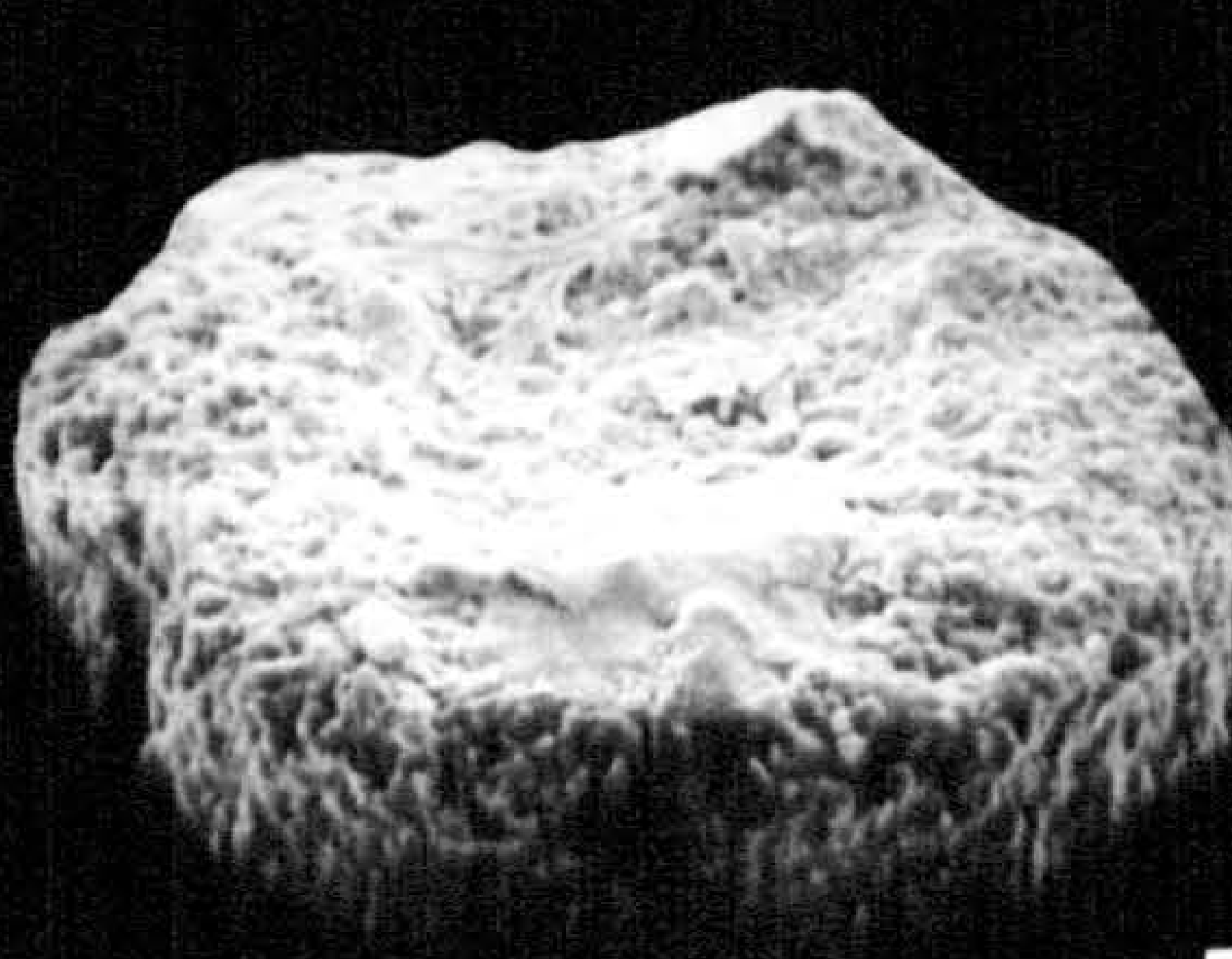
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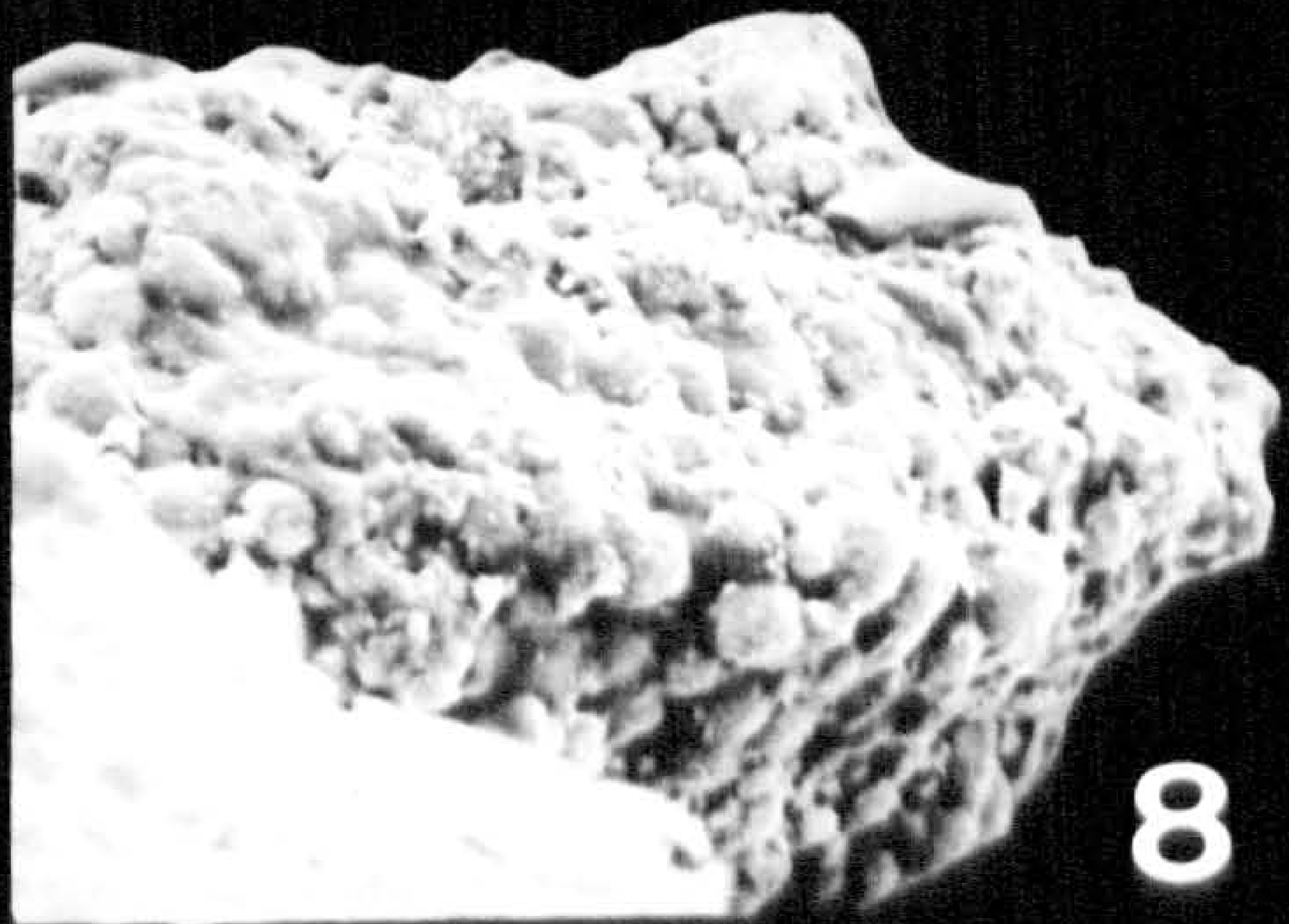
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PLATE 23

Figure 1. Orbiculiforma mclaughlini Pessagno, 1977
Maximum Diameter 205μm. Sample No. F18

Figure 2. Cavaspongia sp. A
Maximum Length 158μm. Sample No. DC5

Figure 3. Spongodiscus sp. 4 Dyer & Copestake, 1989
Maximum Diameter 203μm. Sample No. E20

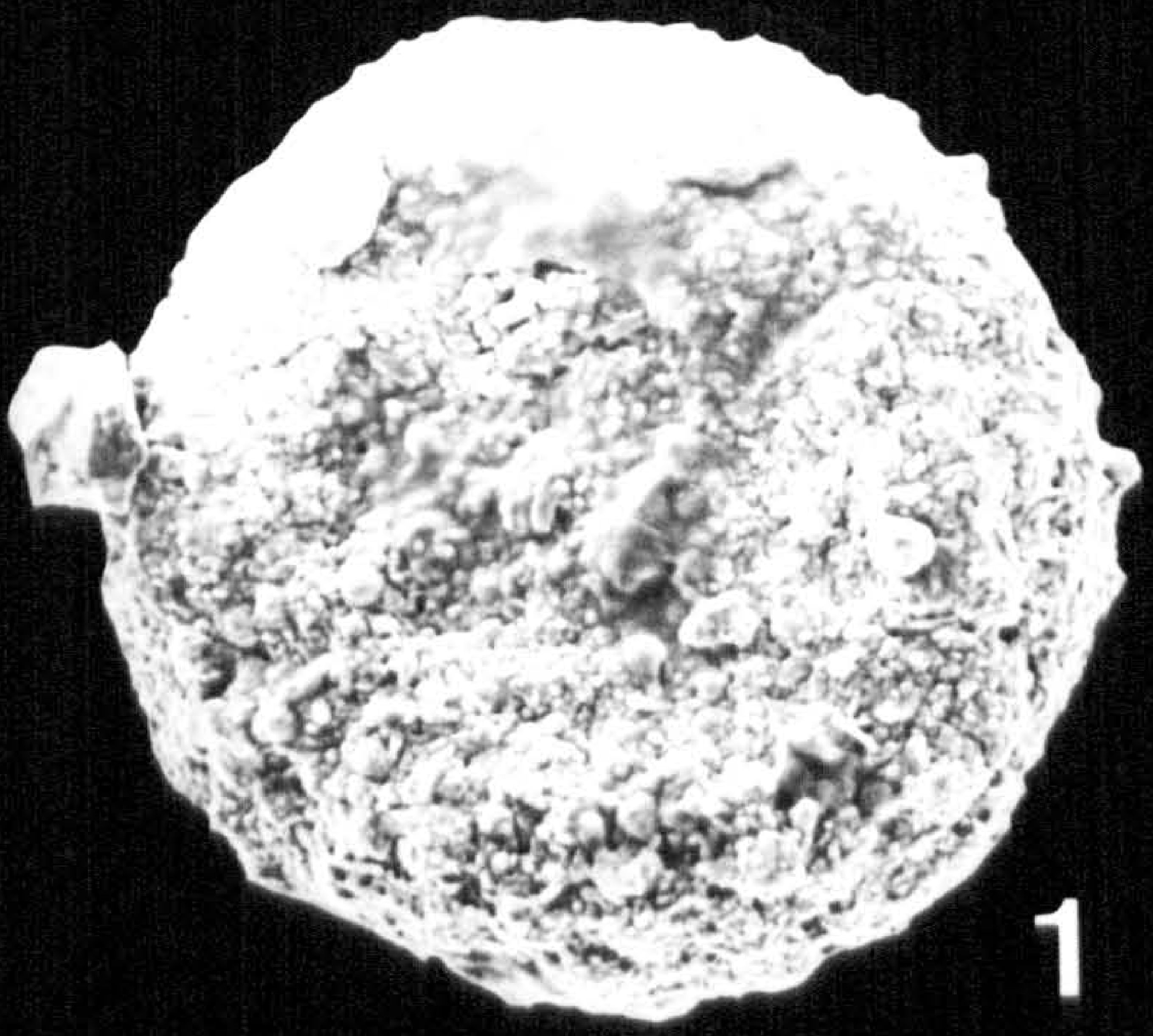
Figure 4. Praeconocaryomma sp. 1 Dyer & Copestake, 1989
Maximum Diameter 138μm. Sample No. E14

Figure 5. Praeconocaryomma hexagona (Rüst), 1898
Maximum Diameter 103μm. Sample No. E14

Figure 6. Cenodiscus sp. A
Maximum Diameter 252μm. Sample No. E42

Figure 7. Cenodiscus sp. A. Side View
Maximum Diameter 252μm. Sample No. E42

PLATE 23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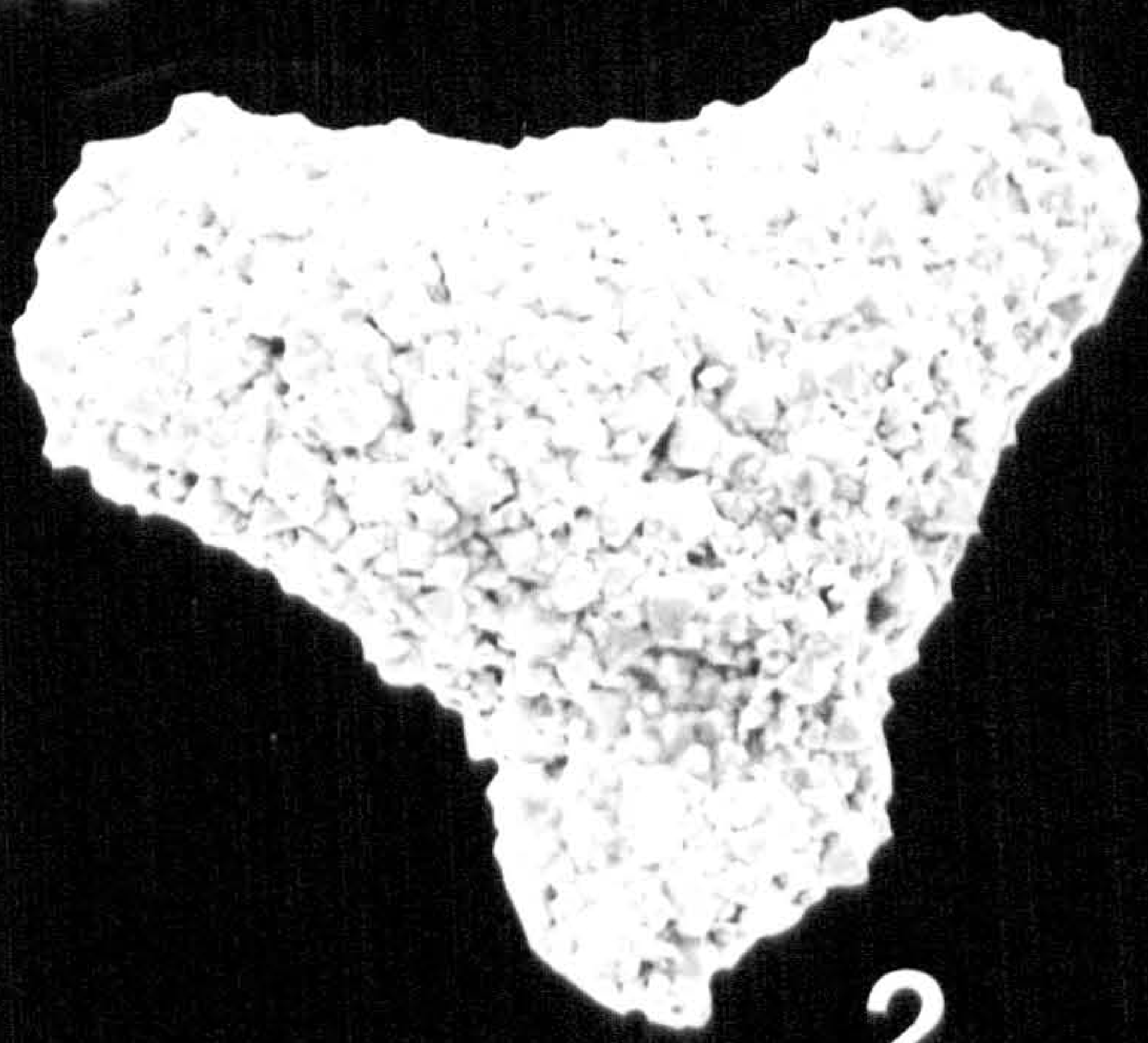
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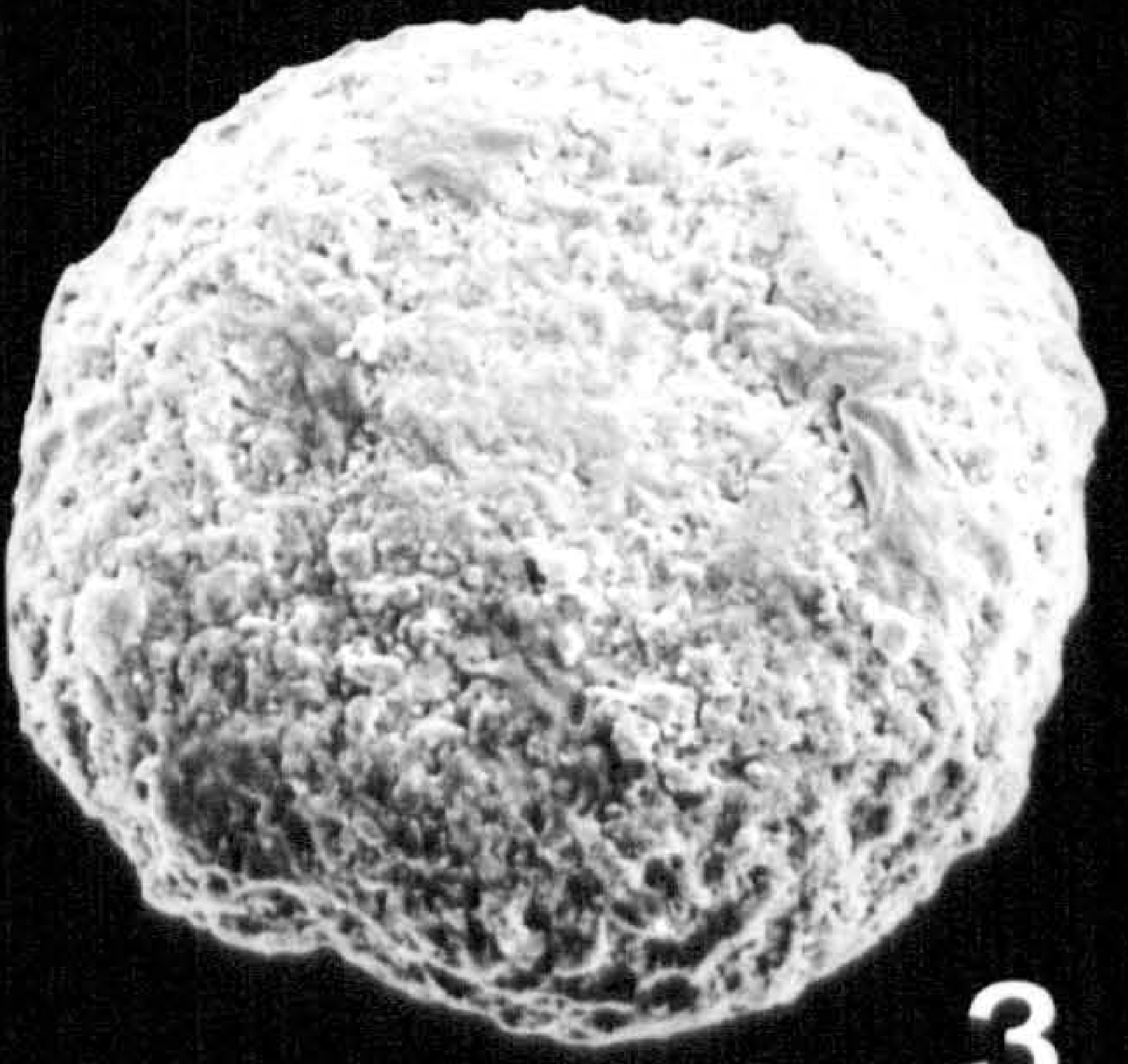
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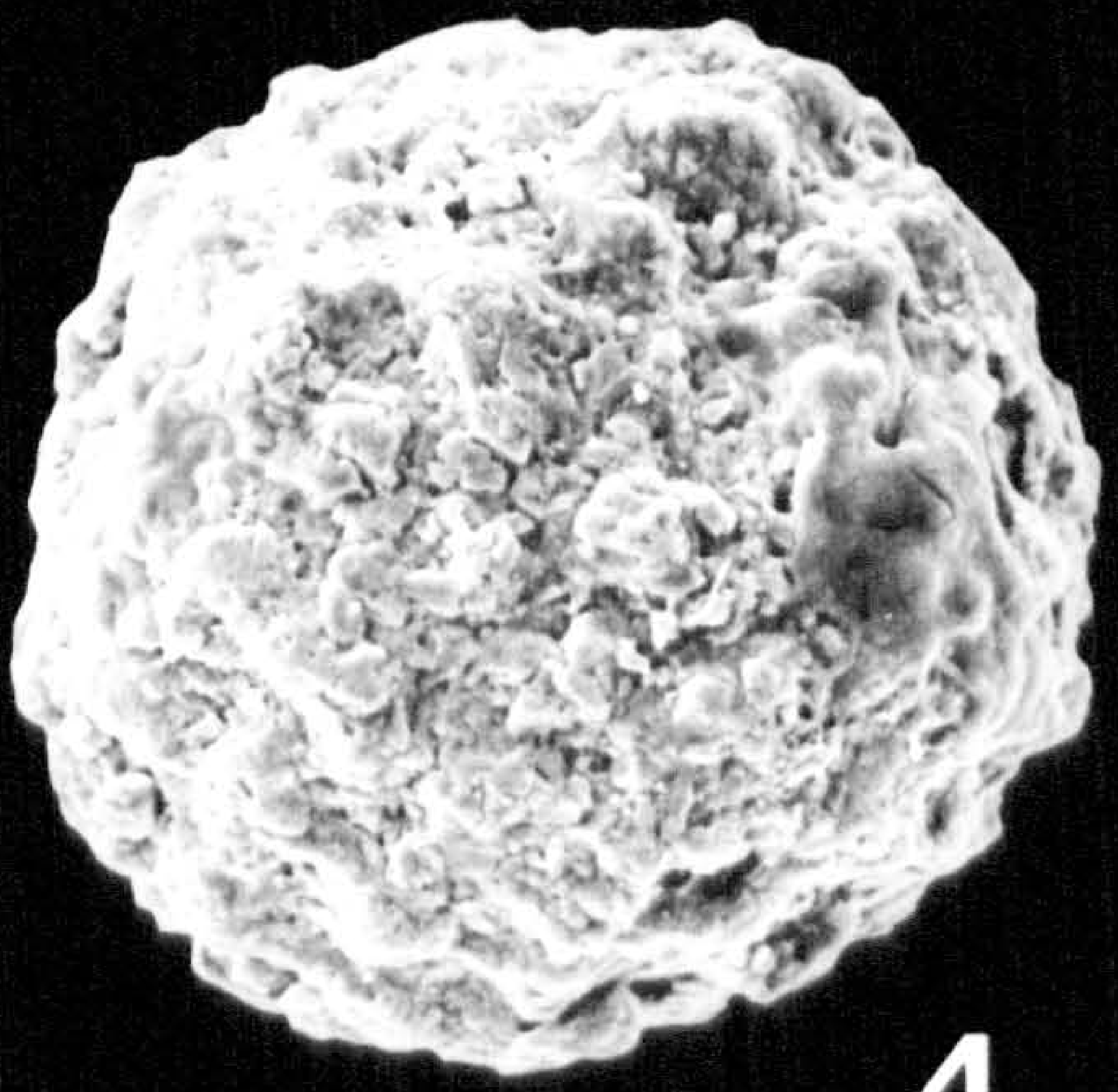
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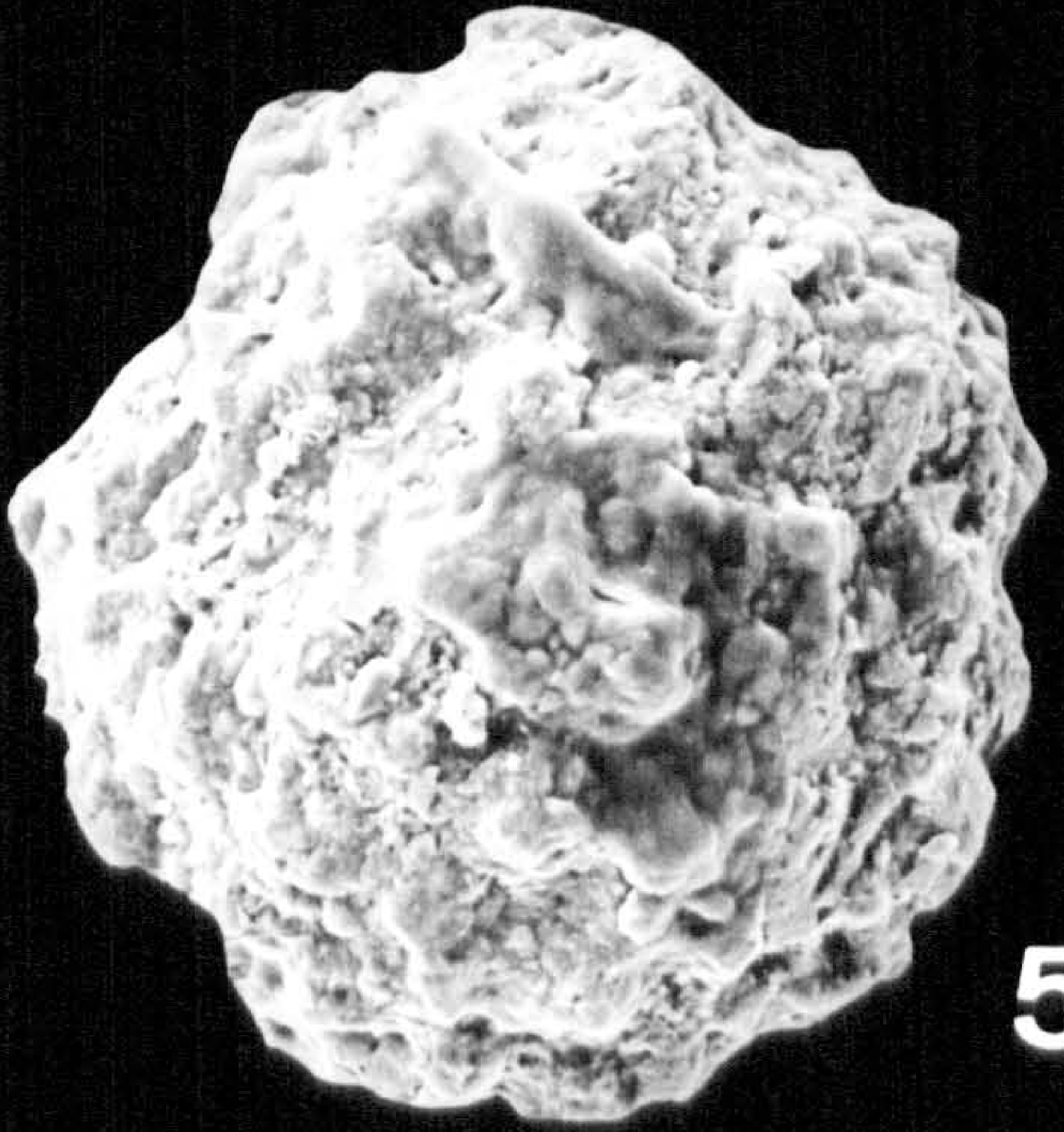
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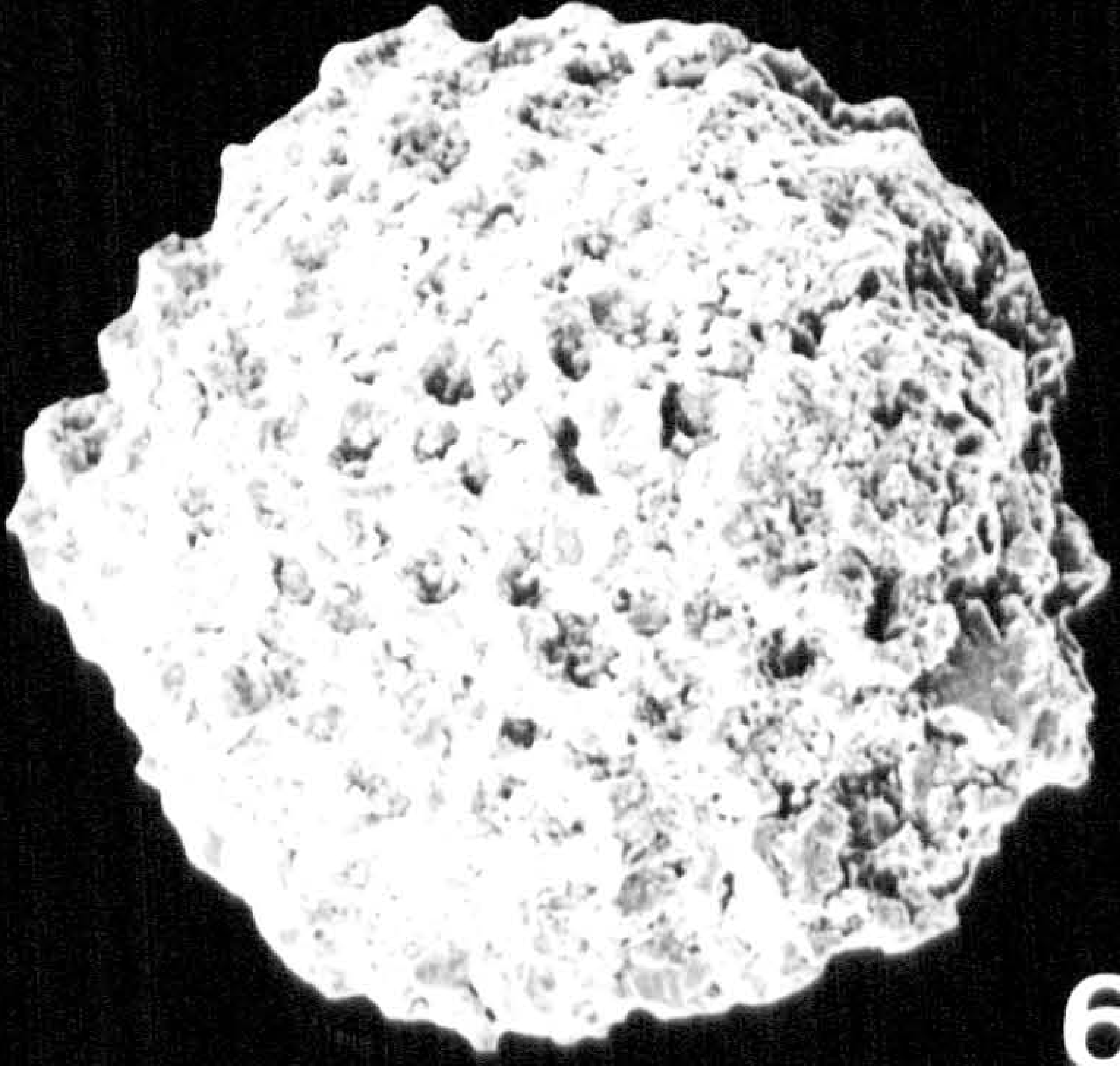
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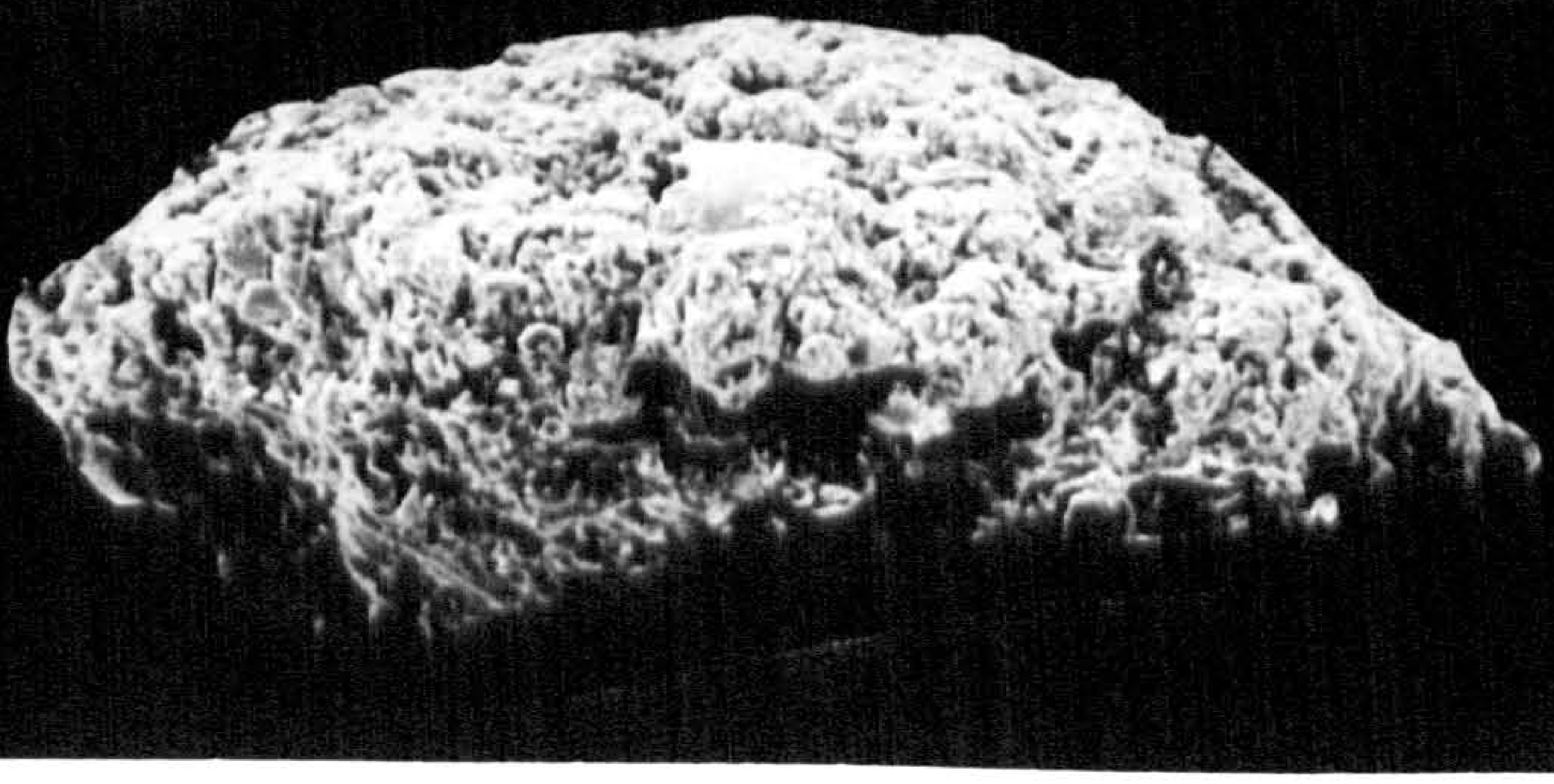
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PLATE 24

Figure 1. Cenodiscus sp. indent.
Maximum Diameter 135µm. Sample No. BRS29

Figure 2. Cenodiscus sp. indent. Side View
Maximum Diameter 135µm. Sample No. BRS29

Figure 3. Cenosphaera sp. 1 Dyer & Copestake, 1989
Maximum Diameter 137µm. Sample No. E41

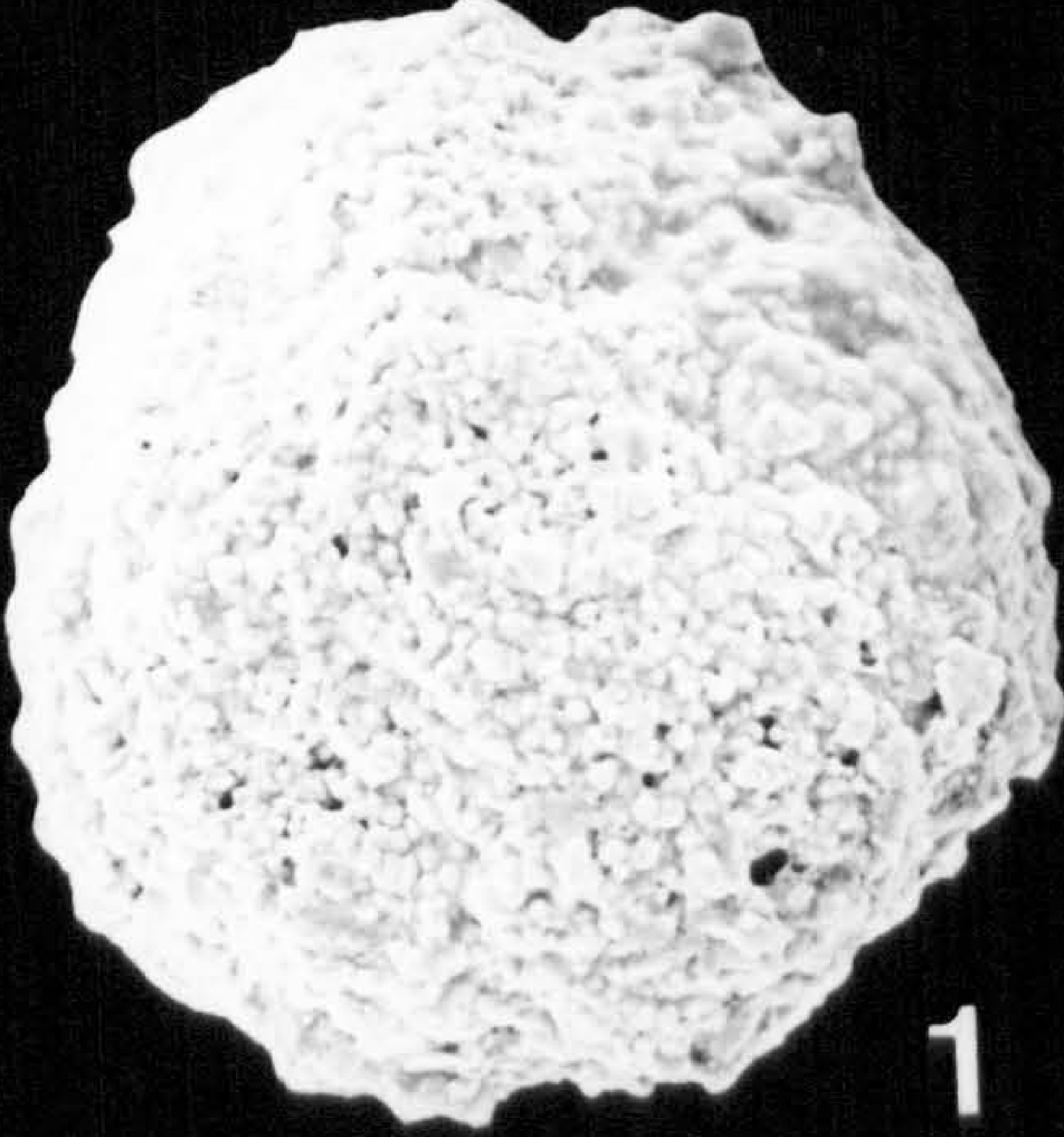
Figure 4. Cenosphaera sp. 2 Dyer & Copestake, 1989
Maximum Diameter 231µm. Sample No. E41

Figure 5. Cenosphaera sp. A
Maximum Diameter 100µm. Sample No. E11

Figure 6. Cenosphaera sp. indent
Maximum Diameter 135µm. Sample No. BRS27

Figure 7. Spherical Sponge Spicule
Maximum Diameter 120µm. Sample No. BRS25

PLATE 24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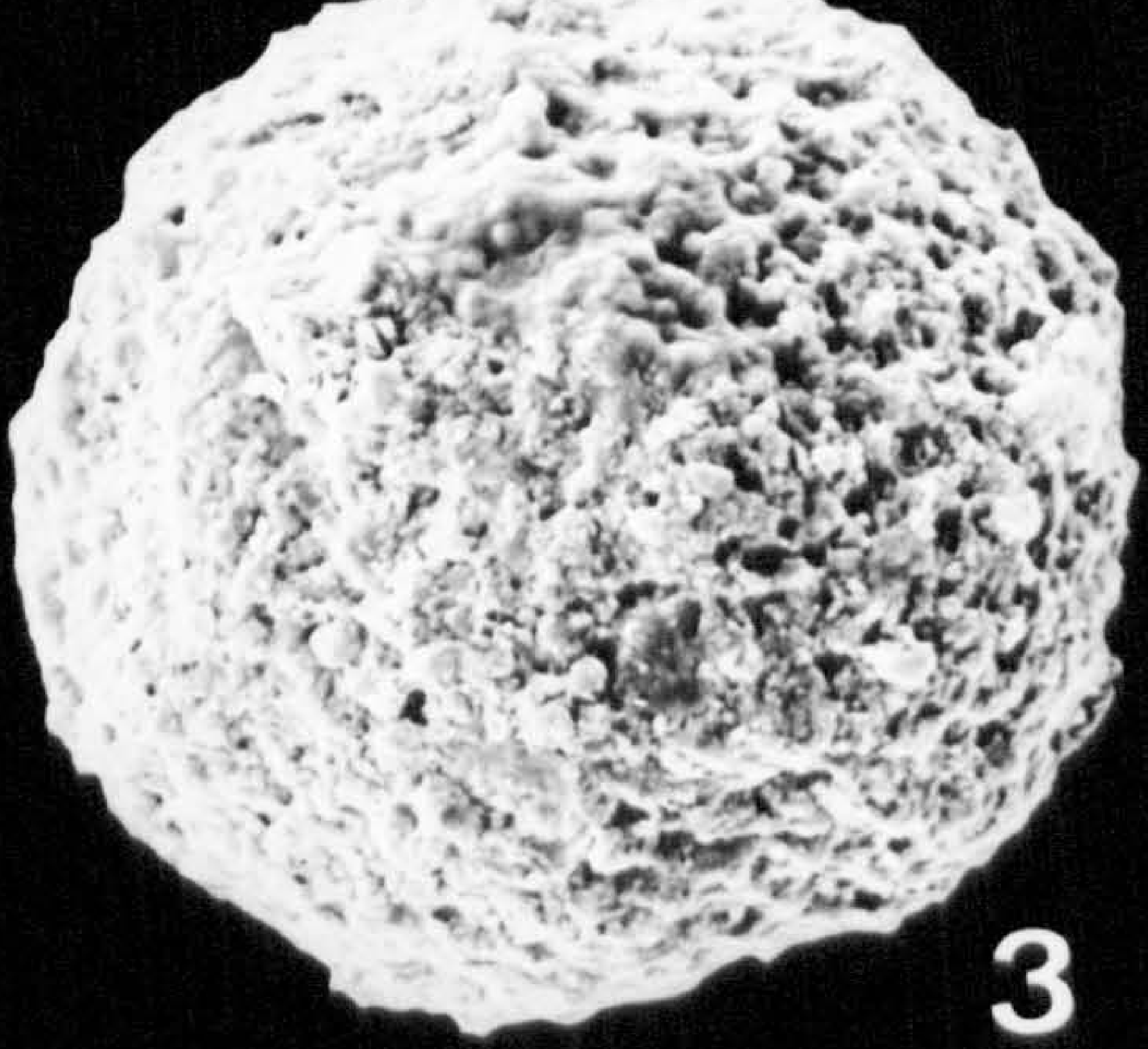
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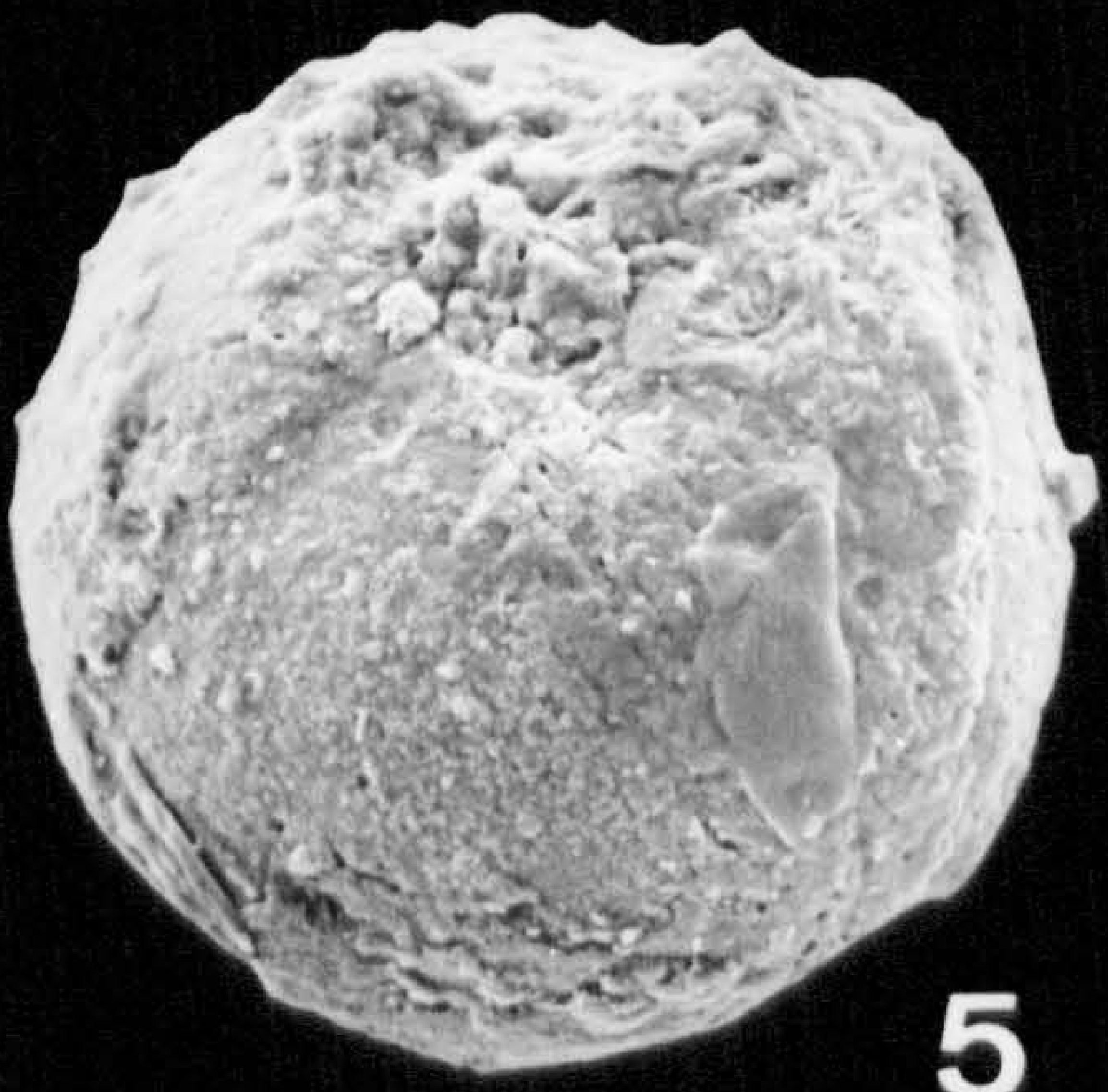
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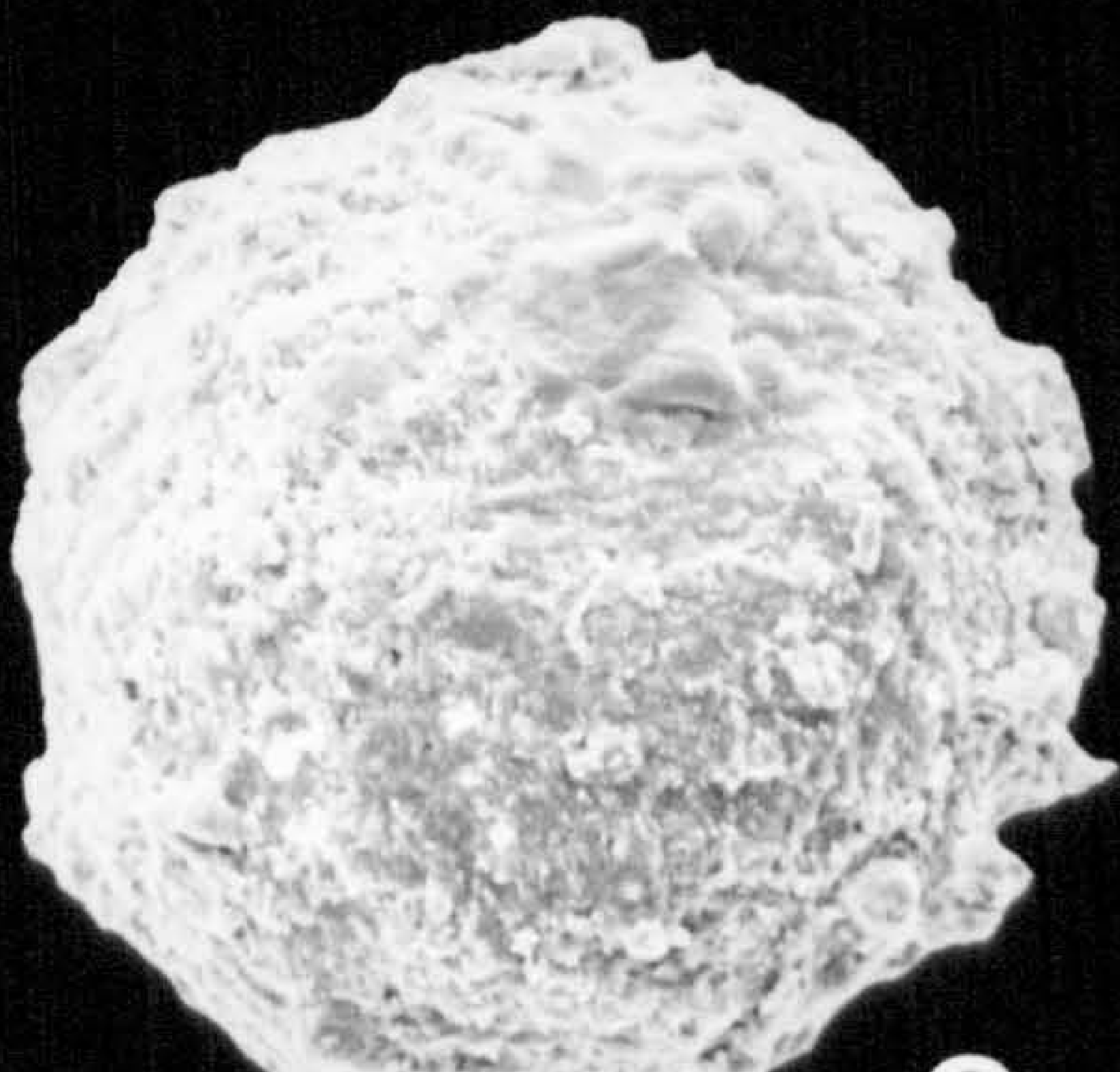
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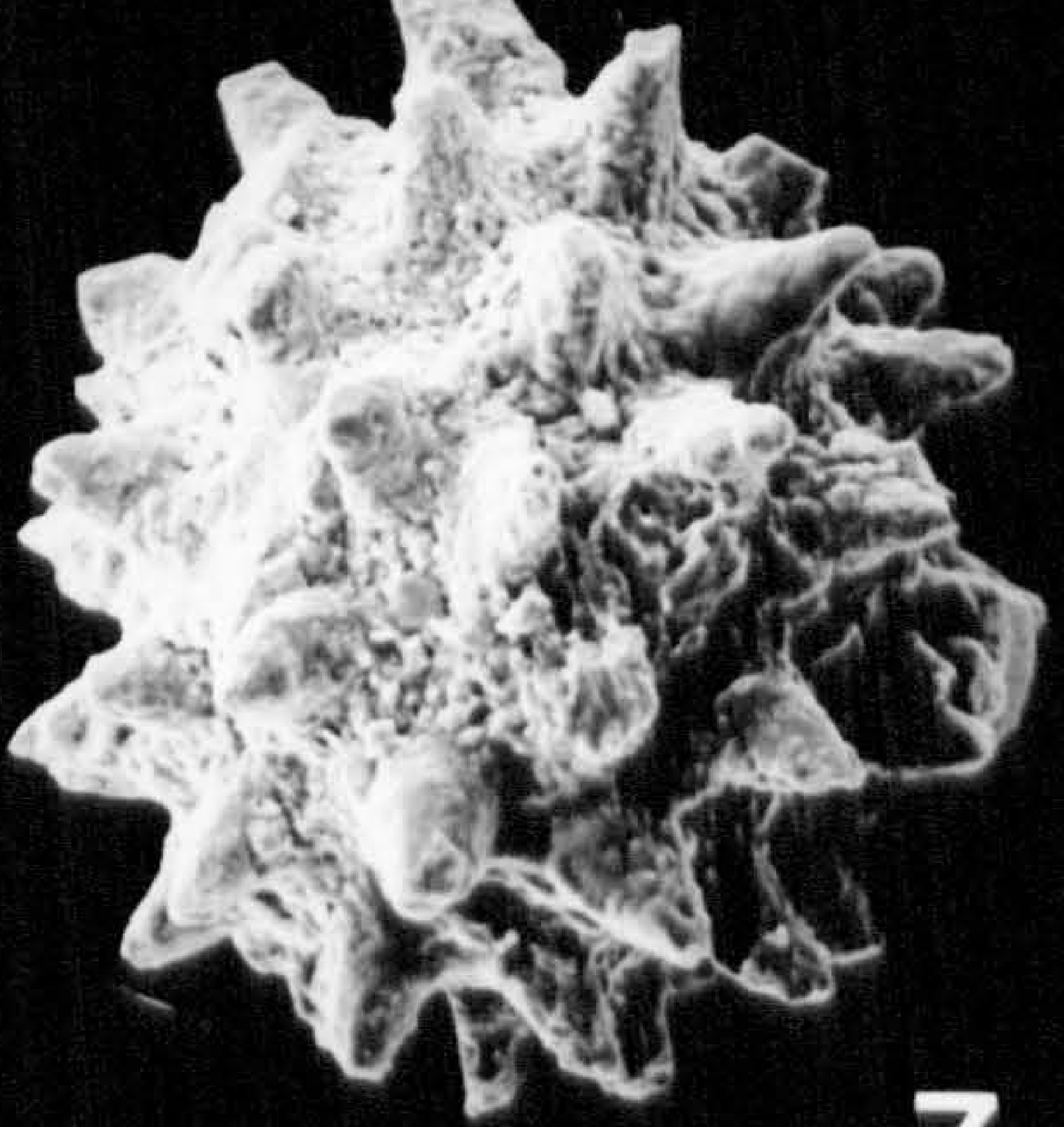
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PLATE 25

Figure 1. Rhaxella perforata Hind, 1893
Maximum length 110μm. Sample No. BRS29

Figure 2. Sponge Spicule; Triad Axon
Maximum Length 480μm. Sample No. HE7

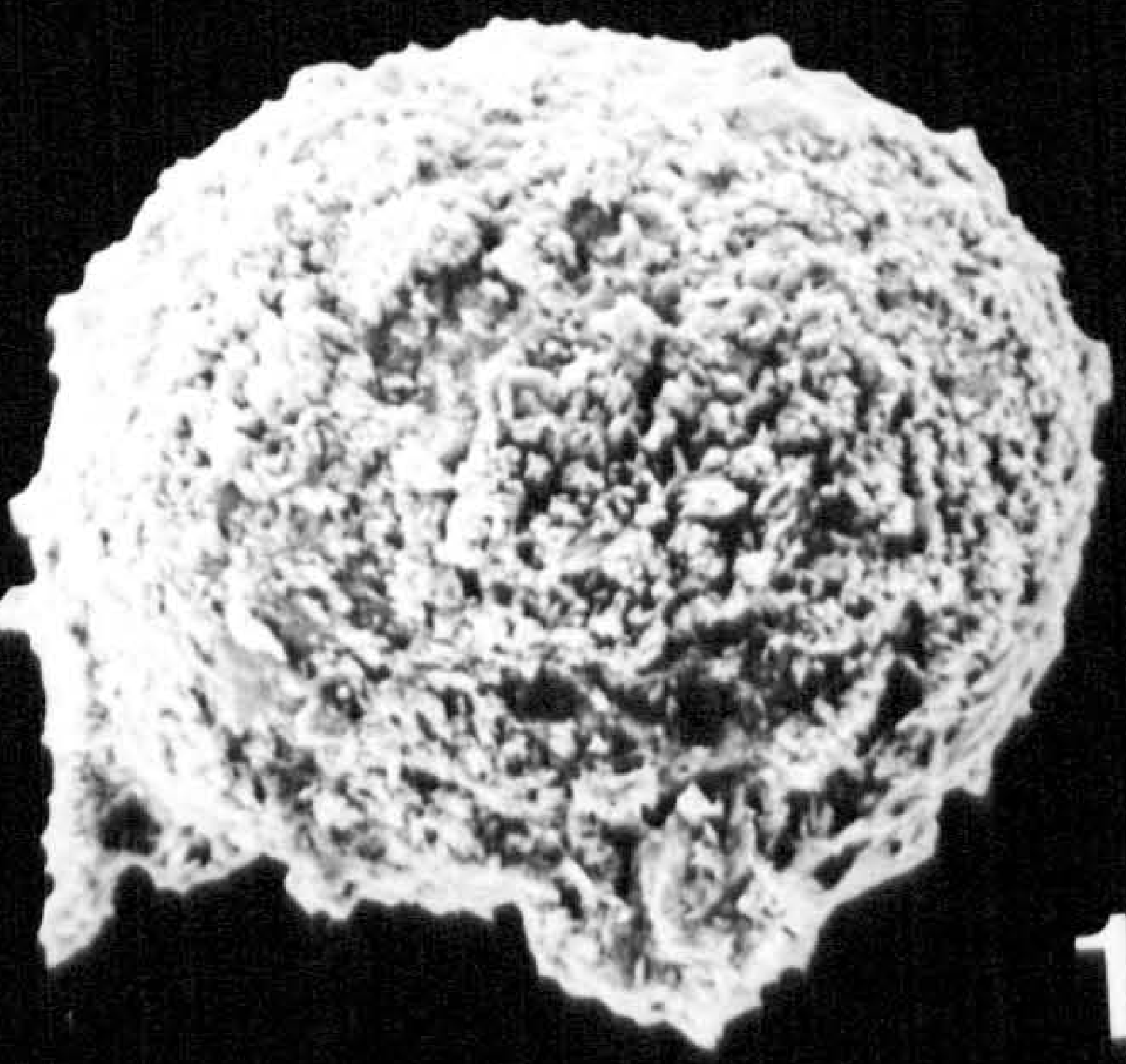
Figure 3. Sponge Spicule; Tetrad Axon
Maximum Length 303μm. Sample No. HN1

Figure 4. Sponge Spicule; Axon
Maximum Length 550μm. Sample No. HN1

Figure 5. Sponge Spicule; Axon
Maximum Length 600μm. Sample No. GM7

Figure 6. Sponge Spicule; Axon
Maximum Length 1.13mm. Sample No. GM19

PLATE 25



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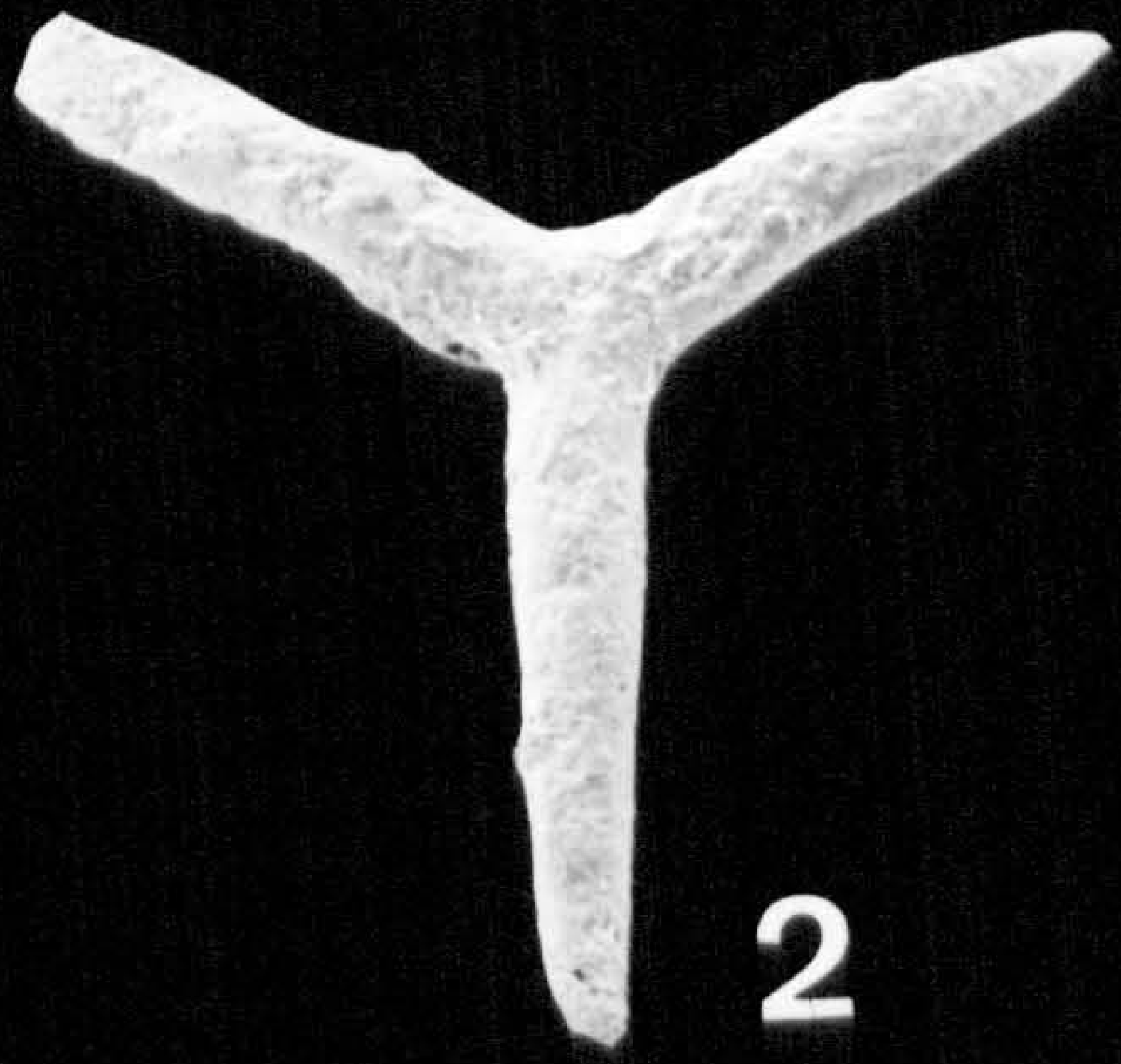

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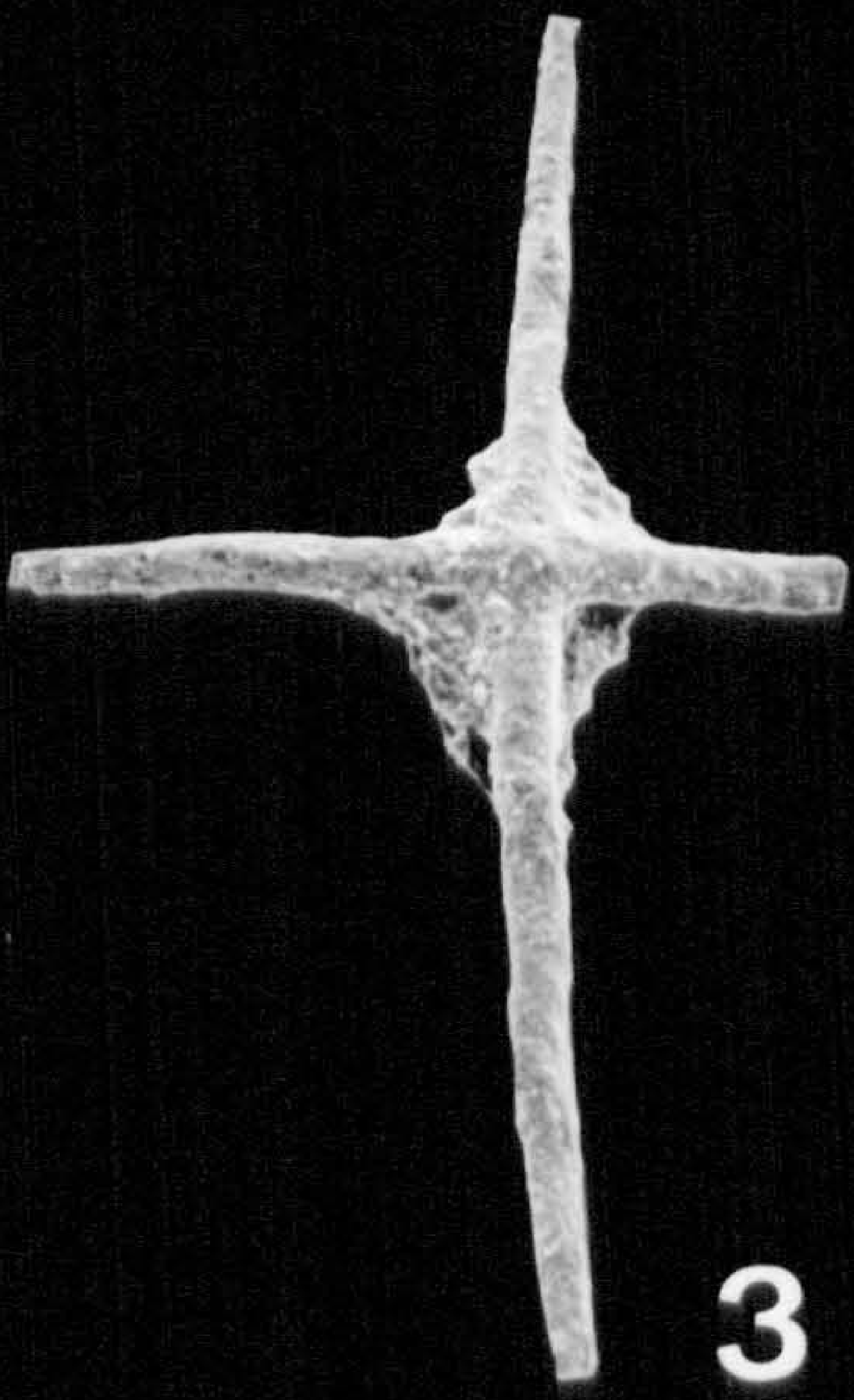

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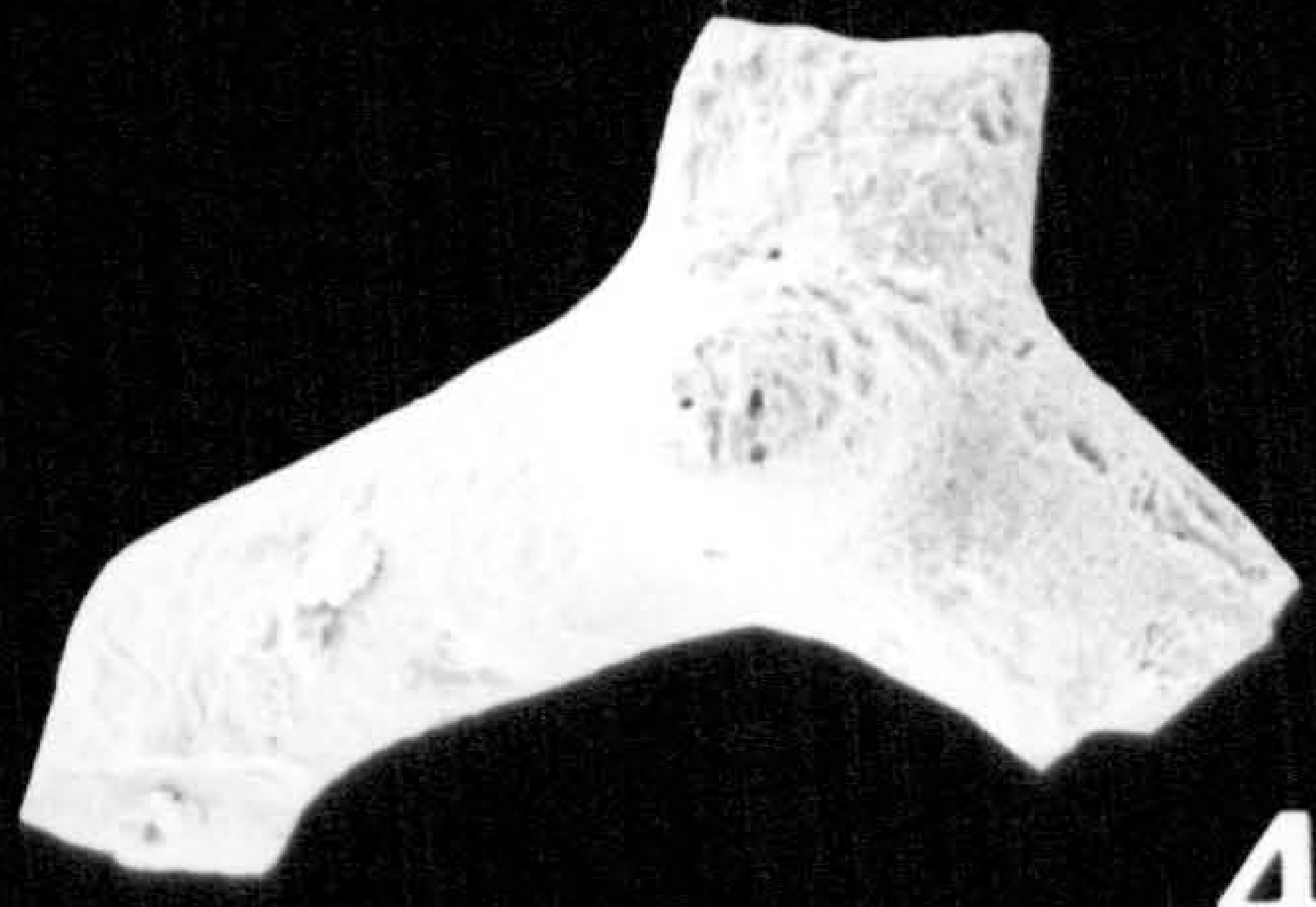

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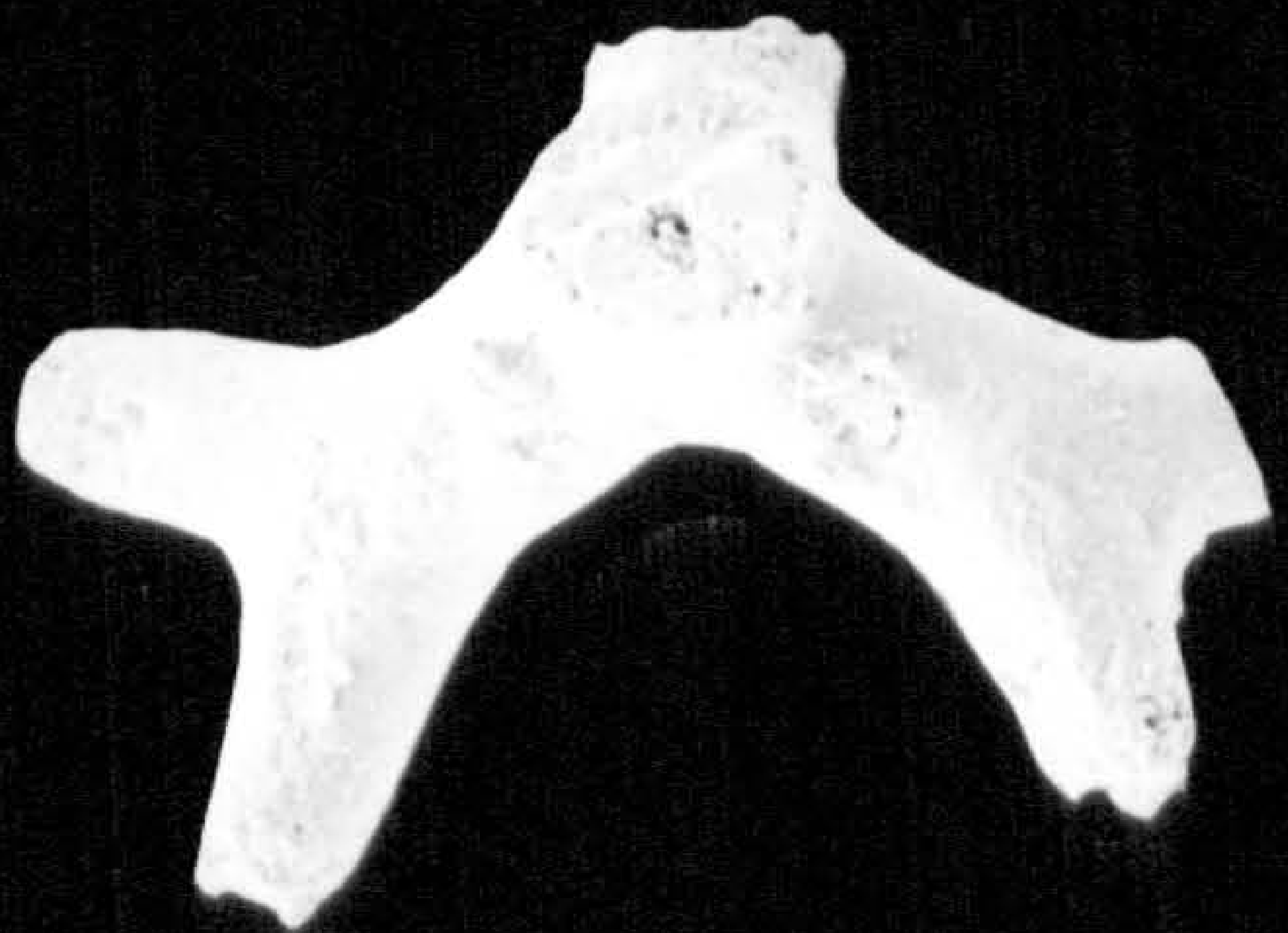

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