The Occurrence and Preservation of Diatoms in the Palaeogene of The North Sea Basin

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ABSTRACT

The often widespread occurrence of diatoms in the marine sediments of the North Sea Palaeogene has long been recognised. They occur in abundance through a number of intervals where calcareous microfossils are absent (due to palaeoenvironmental conditions and subsequent dissolution). However, poor preservation has previously impeded the taxonomic identification of these diatom assemblages, with most specimens occurring as pyritised inner moulds (steinkerns). This study has involved the first detailed description of these assemblages, which was achieved through the use of electron microscopy combined with comparisons with well-preserved specimens, and a survey of original species descriptions held in the Natural History Museum. These techniques have enabled the identification of a total of 79 species, 40 of which have not previously been formally described in pyritised form.

Material analysed in this study (including samples from exploration wells and coeval onshore sections around the North Sea Basin) has led to the recognition of a number of diatom events which broadly form three major assemblages through the North Sea Palaeogene sequence. The lowermost is the most diverse, occurring within the volcaniclastic Sele and Balder formations and their onshore equivalents around the Paleocene/Eocene boundary interval. The relationship of abundant diatomaceous deposits to vulcanicity during this interval is discussed, together with other factors (including increased nutrient levels) encouraging the proliferation of diatoms. A later, less diverse assemblage in the mid Eocene includes more cosmopolitan species; above this is a distinctive Oligocene to mid Miocene assemblage.

The state of preservation of diatom assemblages varies markedly around the North Sea Basin; this has been discussed and microprobe analyses conducted. A number of taxonomic revisions of previously published species (both pyritised and non-pyritised) have also been carried out, including translations of descriptions into English (and their emendment where necessary). A new genus, *Cylindrospira* (consisting of two species, *C. simsi* and *C. homanni*) is described which has no living representatives, but has features found in both extinct and extant genera. It is palaeoenvironmentally significant, occurring in a brackish facies of the Fur Formation diatomite, age-equivalent to one of the main diatomaceous intervals in the North Sea. Prior to this study, only fully marine diatoms had been documented from the Paleocene.

Existing microfossil zonation schemes for the North Sea Palaeogene have been refined, by integrating diatom events with those of stratigraphically well-defined fossil groups such as foraminifera and silicoflagellates. This has ebabled their correlation with other sections, and an improved understanding of palaeocirculation changes through the North Sea Palaeogene.

"I do not know what I may appear to the world, but to myself I have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me."

SIR ISAAC NEWTON

"One does not go straight up the mountain. Not because it is too steep, but because the view of the whole task from the beginning is too daunting."

FLASH

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This work might be seen as the culmination of a long-held interest in the natural world, first encouraged by my mother (who took me to the Natural History Museum when I was all of seven years old), and continued by a number of influential teachers/tutors, especially Mr. Chris Brooks (St. Mary's Primary School, Lowestoft, Suffolk); Mr. Tony Philpin (formerly Kirkley High School, Lowestoft); and Dr. Andy Haggart (Department of Geography, London Guildhall University).

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PART I: BACKGROUND

1. INTRODUCTION

2. THE GEOLOGY OF THE NORTH SEA BASIN: PREVIOUS RESEARCH

3. MATERIALS AND METHODS

1: INTRODUCTION

1.1 Overview; history of diatom studies

Diatoms are siliceous-walled single-celled algae, belonging to the Division Bacillariophyta. They are abundant and diverse at the present day, occurring in all bodies of non-toxic water exposed to light, and these factors have greatly facilitated their study since the early years of the development of the microscope in the 18th Century. Early microscopists were attracted by the often highly elaborate structure and geometric precision of their delicate skeletons or *frustules*. Indeed, they were for many years the preferred test objects for microscope lenses.

The 19th Century saw a great expansion in the study of diatoms, mainly in the field of taxonomy, with workers such as Ehrenberg (1838; 1841; 1843; 1845) describing many species; Kützing (1844) erected a scheme of classification which remains basically sound to the present day. Round *et al.* (1990, pp. 1-4) give a review of the history of diatom studies during this period, which were largely of a purely descriptive nature. The diversity of form of the siliceous frustules for long diverted attention from other aspects of cell biology, which have only recently been addressed, mainly through advances in the fields of genetics and molecular biology (e.g. Cox 1993). Round *et al.* (1990, pp. 5-28) give an informative overview of diatom biology, with a detailed discussion on various aspects of cell biology, reproduction and ecology. It is pertinent to briefly describe those aspects of diatom biology which have a direct bearing on the present study, in particular the taxonomic section (Chapter 4).

1.2 Diatom life-cycle; survival strategies

Diatom reproduction involves alternating sexual (meiotic) and asexual (mitotic) stages (Figure 1.1, p. 18). The asexual stage results in progressive reduction in mean cell size, so that eventually a generation results which must find some means of size restitution if it is to continue to sustain itself. This is achieved by the process of

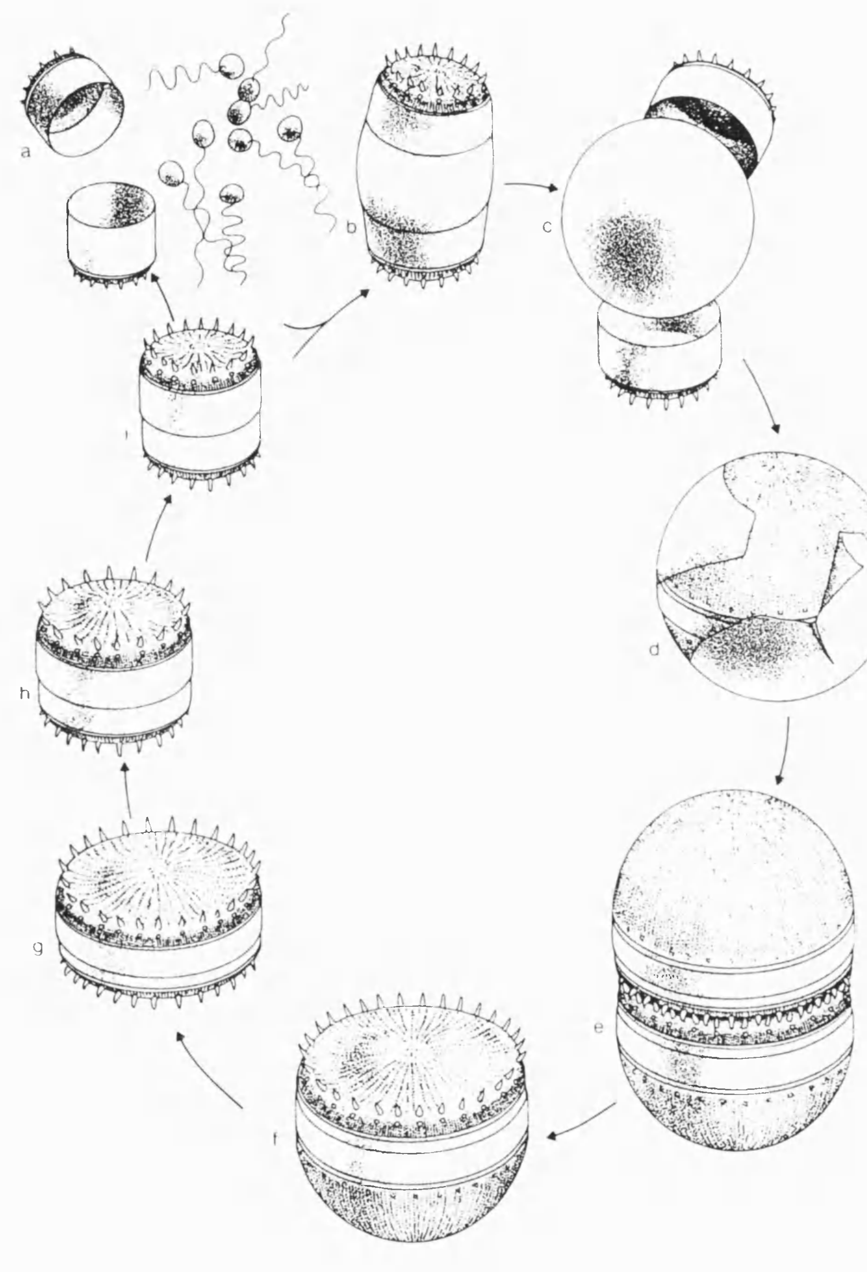


Fig. 1.1 Reproductive and survival strategies of diatoms.

Diatom life-cycle, involving sexual and vegetative phases: a) formation of motile gametes; b-c) formation of auxospore; d) auxospore breaking open to reveal initial cell; e) first division of initial cell; f) one of the cells from e) with a normal cell valve and an initial cell valve; g) a cell formed following several divisions of f); g) to i) vegetative size reduction.

From Round, Crawford & Mann 1990.

sporulation, resulting from the production and fusion of gametes from parent cells. An *auxospore* is formed (Figure 1.1) inside which new large, or *initial* cells develop. When mature, the auxospore divides and two new cells are produced. In this way the cell size increases and a new period of asexual reproduction can begin. Various stages in this reproductive cycle can be incorporated into the fossil record (see Chapter 4), and must be borne in mind when a taxonomic identification is attempted (the progressive size reduction referred to above has often caused confusion in taxonomy).

A further mechanism which helps to increase the likelihood of a population surviving is via the production of *resting spores* (Figure 1.2, p. 20). These are mainly formed in today's oceans by planktonic *centric* species, and take the form of thickly silicified cells which may or may not bear spines; three types have been observed (Fig. 1.2). Resting spores enable the diatom to sink through the water column and begin a phase of dormancy, which normally lasts until strong current action triggers the resuspension of the resting spore and the diatom cell can return to the photic zone. This phenomenon is a feature of populations which occur in upwelling zones along the western margins of the main ocean basins, and occurs in response to seasonal fluctuations in nutrient levels; but it is also characteristic of diatom populations in high latitudes which undergo strong seasonal variations in light intensity (R. Jordan, *pers. comm.* 1992). The viability of resting spores is a subject of much debate.

1.3 Geological and environmental applications

The geological and environmental applications of diatoms have been a relatively recent development. The recognition that they are sensitive to environmental changes has led to their application as monitors of changing water conditions, particularly in Holocene and Pleistocene sediments (e.g. Round 1957, 1961; Mackereth 1965; Haworth 1972; Flower & Battarbee 1983; Stager 1984; Jones *et al.* 1986; Battarbee 1988; Mitlehner 1992; Stabell 1993), whilst it has long been known that diatoms occur in rocks of Tertiary age. For many years it was thought that the oldest diatoms were from the latest Paleocene to earliest Eocene Moler (now renamed the Fur Formation, see Chapter 2) of northern Denmark (Heiberg 1863; Kitton 1871), which are preserved

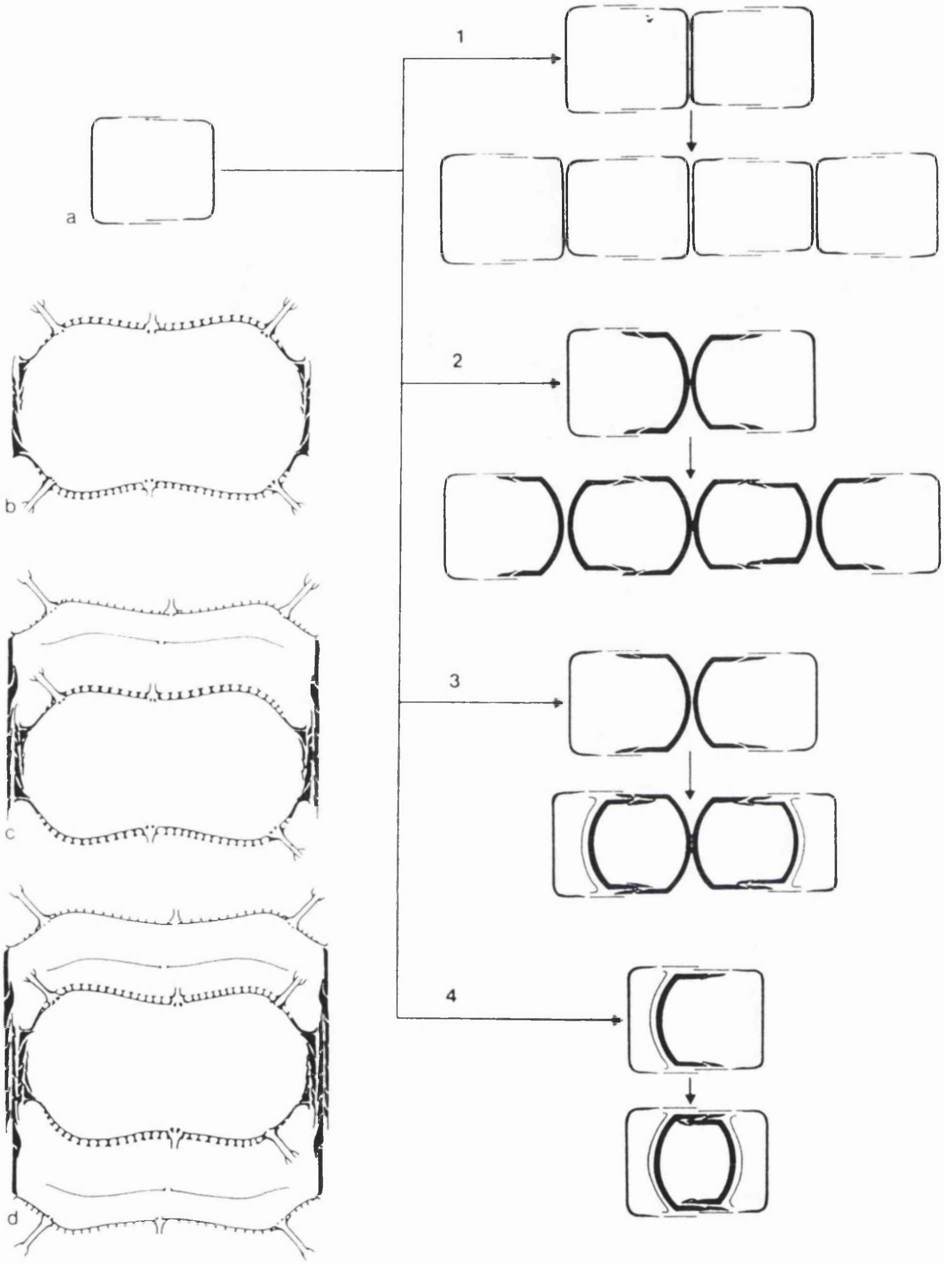


Fig. 1.2 Diatom survival strategies: the formation of different types of resting spore: 1. Normal equal vegetative division; 2-4 The formation of exogenous (2), semi-endogenous (3), and endogenous (4) resting spores; b-d sections through the 3 types of resting spores in the species *Thalassiosira nordenskioeldii*. From Round, Crawford & Mann 1990.

in glaciotectonically deformed strata containing other fossil remains. Later, deposits of pure diatomite in California were recognised by Hanna (1927b) as being of late Cretaceous age. In general, however, the use of diatoms as stratigraphic markers was hindered by their often sporadic occurrence in the fossil record; for example, only one horizon containing pre-Quaternary diatoms is known from onshore deposits in the British Isles (Shrubsole & Kitton 1881; Chapter 2). For a long time the ranges of many fossil species were a matter of speculation, as they often occur in deposits which are devoid of other, stratigraphically well-defined, fossil groups such as foraminifera.

1.4 Fossil diatoms in oceanic sediments: DSDP and ODP

Over the past 25 years, marine diatoms have become increasingly utilised for biostratigraphical correlation purposes, largely through the work of the Deep Sea Drilling Project (D.S.D.P.) and its successor the Ocean Drilling Program (O.D.P.). By detailed examination of cores through oceanic sediments which include both calcareous and siliceous microfossils, it has become possible to define the ranges of diatom species by calibrating these with the known ranges of other microfossils found in the same samples. Consequently, the fossil and evolutionary record of diatoms is now better known (Table 1.1, p. 22). Detailed zonation schemes have been erected for the open oceans using diatoms (see Fenner 1985) and these have been particularly successful for dating high-latitude sediments, and also those laid down below the carbonate compensation depth (CCD) where the more widely-used calcareous microfossils are not preserved due to dissolution. It has also been possible to use diatoms in the mapping of water masses through the Cenozoic (particularly after the mid Eocene) as marine diatom assemblages show strong latitudinal provinciality. Thus, the size and intensity of cold and warm water masses can be shown to have fluctuated markedly through the later Cenozoic, reflecting the step-wise cooling of the Earth's climate which culminated in the Quaternary glacial episodes (Barron & Baldauf 1989).

ERA	PERIOD/ SUBPERIOD		EPOCH/ STAGE	AGE Ma	MAJOR DIATOM EVENTS
CENOZOIC	QUATERNARY		Holocene	0.01	
			Pleistocene	1.65	< *Ethmodiscus* ooze accumulation, Pacific (19)
	TERTIARY	NEOGENE	Pliocene	3.4 5.2	<Generic composition same as at present day (18)
			Miocene	14.0 23.3	<Rapid evolutionary pulse, with over 100 new genera appearing (17) <Acme of marine pennate diatoms (16) ↑ Increased marine & freshwater diatomite production ↑ Step-wise cooling of oceans
		PALEOGENE	Oligocene	35.4	<Great floral turnover (15) <Oldest raphid pennate diatoms, Oamaru, New Zealand (14)
			Eocene	38.0 43.0	<Oldest non-marine diatoms, Wyoming (13) <Pyritised diatoms in Labrador Sea & Mackenzie Basin, Canada (12)
			Paleocene	56.0	**<Fur Formation diatomite, Denmark (11; This study)** **<Abundant pyritised diatoms in North Sea Basin (10; This study)**
MESOZOIC	CRETACEOUS		Maastrichtian	65.0 74.0	<K-T Boundary section, Seymour I., Antarctica (9)
			Campanian	83.0	<1st Araphid pennate diatoms (8) <Earliest diatomites: Urals (6), California (7)
			Santonian	86.6	<Oldest diatoms in North Sea Basin (5)
			Coniacian		
			Turonian	90.4	<Pyritised diatoms in Europe (4)
			Cenomanian	97.0	
			Albian	112.0	<Oldest well-preserved diatom assemblage, Weddell Sea, Antarctica (3)
			Aptian	125.0	
			Barremian	131.8	<Oldest pyritised diatoms, Carpathians (2)
			Hauterivian		
			Valanginian		
			Berriasian	145.6	
	JURASSIC		Tithonian	152.0	
			Kimmeridgian	154.0	(Age of main source-rock in North Sea)
			Oxfordian		
			Callovian		
			Bathonian		
			Bajocian		
			Aalenian	178.0	
			Toarcian	187.0	<Oldest reported diatoms, Boll shale, Germany (1)
			Pliensbachian		
			Sinemurian		
			Hettangian	205.0	

Table 1.1 Significant events in the fossil record of diatoms (timescale after Harland *et al.* 1989). Compiled from various sources, as follows:-
1) Rothpletz 1896; 2) Geroch 1978; 3) Harwood & Gersonde 1990; 4) Weisner 1936; 5) Copestake 1993; 6) Strel'nikova 1974; 7) Long, Fuge & Smith 1946; 8) Abbott & Harper 1982; 9) Harwood 1988; 10) King 1983; 11) Homann 1991; 12) Thomas & Gradstein 1981; McNeill 1990; 13) Lohman & Andrews 1968; 14) Schrader 1969; 15) Baldauf 1992; 16, 17 & 18) Barron 1985 ; 19) Mikkelsen 1977.

1.5 Diatoms in the Palaeogene of the North Sea

The Palaeogene sediments of the North Sea Basin include a number of sequences where calcareous microfossils are rare or absent. A function of both original environmental conditions and subsequent dissolution, this situation means that correlation of these sediments with those outside the North Sea is difficult (King 1983). Diatoms occur, often commonly, through these intervals, although the siliceous skeletons or frustules are frequently replaced by pyrite. The present study includes a detailed examination of these morphotypes (Chapter 4), which has facilitated both a more refined biozonation than exists at present (Chapter 5), and a greater understanding of environmental fluctuations during the Palaeogene in the NSB (Chapter 7).

1.6 Problems associated with this study

1.6.1 Geological and palaeoenvironmental factors

The conditions that have facilitated the generation and later preservation of hydrocarbons in the North Sea Basin, i.e. rapid infilling of the basin with organic-rich sediment; the localised development of sand bodies which form reservoirs, and deep burial and strong diagenesis which help to generate and seal in the accumulated hydrocarbons, have led to generally poor preservation of microfossils. Both the contemporaneous depositional environment and later subsidence and burial by younger sediments have encouraged widespread deformation through heat and pressure, and/or replacement of the original skeletons by mineralising fluids moving through the sediment. In the case of diatoms, this usually takes the form of pyritisation, which can greatly hinder identification to species level. The pyritisation process and its implications are discussed in Chapter 6.

A further palaeoenvironmental problem is that abundances of diatoms through North Sea Palaeogene sediments are generally spasmodic, and tend to be concentrated in intervals where calcareous foraminifera and nannofossils are not present (possible reasons for this are discussed in Chapter 7). The species diversity within these abundant assemblages is generally low, and tends to be dominated by the larger, more robust morphologies. This is a problem often encountered in fossil diatom assemblages, and needs to be considered when attempting quantitative biostratigraphical and palaeoecological analysis (Andrews 1972; Battarbee 1986). Between the abundance peaks diatom recovery is very poor, and so it has not been possible to recognise a continuous diatom zonation through the Palaeogene sequence.

1.6.2 Taxonomic problems

There are few published descriptions of Palaeogene diatoms, a situation which greatly hinders identification. With a few notable exceptions (e.g. Ross & Sims 1985, 1987; Sims 1989, 1990) publications include only light microscope photographs, and it is often difficult to compare 3-dimensional pyritised morphologies (which comprise the majority of North Sea Palaeogene diatoms) with light microscope photographs of near-transparent, well-preserved diatom valves (see plates in Homann 1991).

A review of diatom taxonomic literature reveals that much of the descriptive material is in the German language. This reflects the history of diatom studies, which has been largely dominated by German workers, from Ehrenberg and Grunow onwards. Although much of the more recent work has been published in English, this is not always the case. The monograph by Homann (1991) is entirely in German, and it was necessary to translate many of the species descriptions, some of which had been emended by Homann. This task was time-consuming, and necessitated the use of a technical German dictionary as much of the terminology is of a highly specialised nature. This problem also besets much of the work by Russian diatomists (e.g. Glezer *et al.* 1974), which is almost entirely in Russian and is extremely costly and time-consuming to translate. An additional problem is that diatom taxonomy is currently in a considerable state of flux (e.g. Cox 1993; Williams 1993) and concepts of species are the subject of much dispute. This is considered further in Chapter 4.

1.6.3 Sample provenance

Other problems concern the large amount of industrial interest in North Sea geology, related to hydrocarbon exploration. In many ways this is of great benefit scientifically, as a wealth of data now exist in the form of rock samples which have been recovered from the North Sea in the course of drilling. However, there are a few pitfalls associated with obtaining and utilising this information:-

i) Commercial confidentiality means that material from exploration wells cannot be released into the public domain for five years after a well has been drilled. This has hampered the examination of samples in this study, especially from wells known to contain diverse, relatively well-preserved diatoms, but which were unobtainable by the present author as they were in unreleased well material, owned jointly by a consortium of operators, some of which were reluctant to allow access (M.A. Charnock, *pers. comm.* 1992). In addition, samples from two of the wells obtained from British Petroleum were similarly unreleased, which means that data from these wells, although available for study, cannot be published for two years after thesis submission. Fortunately, this only forms a minor constituent of the material analysed.

ii) The past 10-20 years have seen the development of unpublished diatom zonation schemes by different exploration companies. In the almost complete absence of formal taxonomic literature on North Sea diatoms, many companies engaged in exploration have erected their own schemes. With a few exceptions, these include morphotypes which have been given reference numbers which are solely for in-house use. Consequently, considerable confusion exists as to the status of otherwise valuable biostratigraphic marker species, particularly as few of the morphotypes utilised in the various schemes have been photographed and published.

iii) A further problem with industrial well samples is that they are often rock chippings (cuttings), brought up by the drilling mud during drilling. These samples contain fragments from strata higher up in the well (including microfossils) and so are not as reliable as core samples. The latter are very expensive to drill, and consequently only available from certain intervals (Chapter 3).

1.7 Summary

Therefore, it can be seen that the present study was conducted within the constraints of a number of limiting factors, most of which are not normally associated with biostratigraphical and palaeoenvironmental analysis. However, despite this, a number of valuable discoveries have been made, some of which are of direct relevance to a refined knowledge of North Sea geology, and others which contribute to knowledge of diatom stratigraphy, palaeoecology, preservation and evolution.

1.7.1 Organisation of Thesis

The following is a brief review of the main body of the present work.

Chapter 2 gives a concise overview of the extant knowledge of North Sea geology, beginning with the underlying, pre-Cenozoic structure of the North Sea Basin, and continuing with a more detailed appraisal of the stratigraphy and sedimentology of the Cenozoic section, with particular emphasis on the Palaeogene. This leads onto a more detailed review of micropalaeontological investigations into the Palaeogene sections, including previous work on diatoms. The applications of this work are then considered with regard to the uses of biostratigraphical data in age-dating the Palaeogene, and their integration with other dating methods, including magnetostratigraphy. A review of Palaeogene diatoms in other areas outside the North Sea is then followed by an assessment of their correlation potential.

Chapter 3 is concerned with the derivation of sample material analysed in this investigation, including sample provenance, sampling procedure and a description of processing, diatom extraction and identification techniques.

Chapter 4 includes full taxonomic descriptions of all of the diatom species encountered in pyritised form in this study, including a review of diatom systematics, the rationale for description of pyritised specimens, and synonymy lists which comprise both pyritised and non-pyritised previous occurrences. Other species found in non-pyritised form only are then listed, along with other siliceous microfossils.

Chapter 5 includes the biostratigraphical age-determination of samples prepared from offshore wells, and the comparison of this biostratigraphy/ biozonation with existing biozonal schemes.

An assessment of the factors governing the preservation of diatoms is given in Chapter 6, including previous work on diatom dissolution, silica phase changes, and authigenic mineral infilling and replacement. Results are given of XRD microprobe analysis conducted on Palaeogene diatom specimens from different parts of the North Sea Basin, and interpretation of these results.

Chapter 7 is a discussion on the evidence gained from this and previous studies on palaeoenvironments during the North Sea Palaeogene, including the possible relationship of richly diatomaceous sediments to vulcanicity. Finally, a discussion is given on palaeoceanographic changes in and around the North Sea Basin.

Chapter 8 is a summary of the achievements of the present study, together with suggestions for further research.

2. THE GEOLOGY OF THE NORTH SEA BASIN: PREVIOUS RESEARCH

2.1 Geological evolution; Cenozoic depositional history

2.1.1 Introduction: history of exploration

Mainly as a result of extensive exploration for hydrocarbons since the first major discoveries of the 1960's and 1970's, a large amount of data has been amassed which has enabled a detailed appraisal of the geological evolution of the North Sea Basin to be made. Although most of the exploration activity has centred on the reservoirs occurring in Mesozoic sediments there have been a number of discoveries, including the enormous Forties Field, which are located in Palaeogene strata. The Norwegian sector in particular has yielded considerable areas of Palaeogene reservoir, which include the Balder, Cod and Heimdal fields (Bain 1993). As a consequence of the extensive exploration activity associated with these and other finds, there now exists a wealth of information allowing a reconstruction of both the structural framework and the depositional history of the North Sea Basin. The current (1994) state of knowledge of this history is summarised below.

2.1.2 Pre-Cenozoic structural development

Located on the continental shelf of the northeastern margin of the Atlantic Ocean, the North Sea Basin is part of a wider region of basins and narrower grabens which are separated by areas of more positive relief (Figure 2.1, p. 29). Although there is an apparently simple pattern of north-south subsidence along its central axis, this masks a structure which is far more complex, so that its later structural and stratigraphic development has been largely controlled by deeper structures from its earlier history (Glennie 1990, p. 34). This development is essentially the outcome of the following factors:-

1) A sequence of divergent, convergent and tangential plate movements.

2) Crustal subsidence and uplift resulting in basins and highs, and crustal shortening leading to orogenesis.

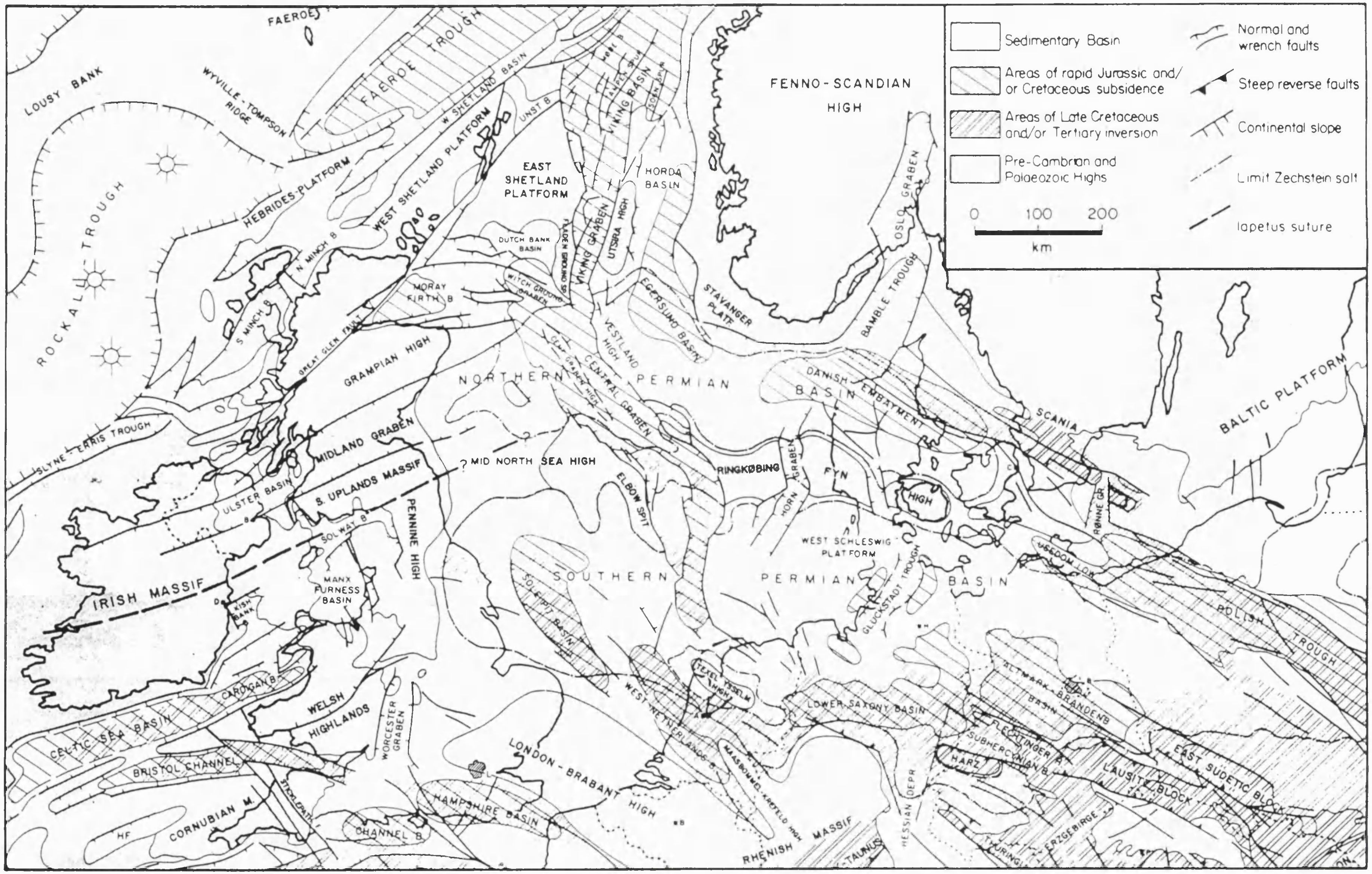


Fig. 2.1 North Sea Basin area, showing main structural features (from Glennie 1990)

3) Erosion leading to sedimentation in both marine and continental environments.

4) Changes in the rate of heat flow through the crust, commonly leading to uplift and igneous activity in areas of high heat flow; or to subsidence, commonly with no igneous activity, in areas of low heat flow.

2.1.3 Evolutionary outline

Table 2.1 (p. 31) gives a simplified historical sequence of events which are significant in the evolution of the North Sea area. These are briefly discussed below:-

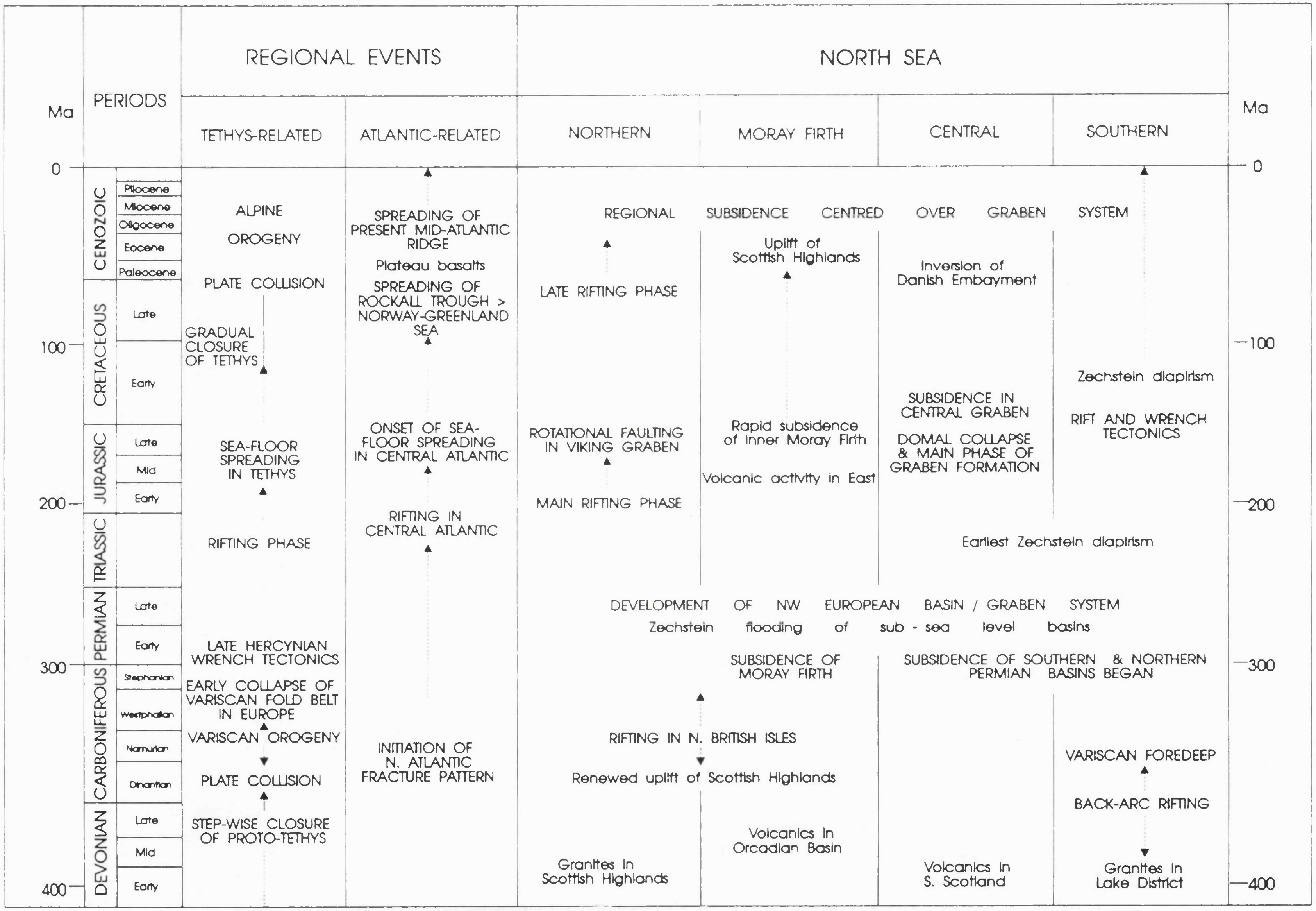
1) The combined Athollian and Caledonian Orogenies (Late Cambrian to Late Silurian) brought together parts of continental crust which would later form the North Sea. Prior to these events, the North Sea area comprised widely separated continental fragments in, and marginal to, different parts of the early Palaeozoic Iapetus Ocean and Tornquist Sea.

2) Rifting, which occurred during the Devono-Carboniferous, led to the development of structural relief which possibly resulted from adjustments between and along the margins of the formerly separate Laurentian and Scandinavian cratons. Examples of this are Devonian movement along the Great Glen Fault, and early Carboniferous structural relief.

3) The Variscan Orogeny during the early Carboniferous marked the closure of the southern Proto-Tethys Ocean and the creation of the supercontinent Pangaea. The widespread deposition of continental red beds, which are preserved over much of the North Sea area, occurred from this time until the late Triassic.

4) Early Permian subsidence of the Moray Firth and east-west trending Northern and Southern Permian Basins was followed by initiation of the north-south trending Viking and Central Graben system. The grabens began to subside rapidly during the Triassic (when development of the adjacent Stord and East Shetland basins was initiated) and reached their maximum structural development by the beginning of the Cretaceous as a result of **5**.

5) Mid-Jurassic domal uplift and widespread erosion was centred over the axis of especially the Central Graben; late Jurassic to earliest Cretaceous strike-slip movements and fault-block rotations within and adjacent to the Viking and Central Grabens probably coincided with the opening of the Central Atlantic and rifting



Ma	PERIODS		REGIONAL EVENTS: TETHYS-RELATED	REGIONAL EVENTS: ATLANTIC-RELATED	NORTH SEA: NORTHERN	NORTH SEA: MORAY FIRTH	NORTH SEA: CENTRAL	NORTH SEA: SOUTHERN	Ma
0	CENOZOIC	Pliocene							0
		Miocene	ALPINE	SPREADING OF PRESENT MID-ATLANTIC RIDGE	REGIONAL SUBSIDENCE CENTRED OVER GRABEN SYSTEM				
		Oligocene	OROGENY						
		Eocene		Plateau basalts		Uplift of Scottish Highlands			
		Paleocene	PLATE COLLISION	SPREADING OF ROCKALL TROUGH > NORWAY-GREENLAND SEA	LATE RIFTING PHASE		Inversion of Danish Embayment		
	CRETACEOUS	Late	GRADUAL CLOSURE OF TETHYS						
100		Early					SUBSIDENCE IN CENTRAL GRABEN	Zechstein diapirism	100
	JURASSIC	Late	SEA-FLOOR SPREADING IN TETHYS	ONSET OF SEA-FLOOR SPREADING IN CENTRAL ATLANTIC	ROTATIONAL FAULTING IN VIKING GRABEN	Rapid subsidence of inner Moray Firth	DOMAL COLLAPSE & MAIN PHASE OF GRABEN FORMATION	RIFT AND WRENCH TECTONICS	
		Mid				Volcanic activity in East			
200		Early		RIFTING IN CENTRAL ATLANTIC	MAIN RIFTING PHASE				200
	TRIASSIC		RIFTING PHASE				Earliest Zechstein diapirism		
	PERMIAN	Late			DEVELOPMENT OF NW EUROPEAN BASIN / GRABEN SYSTEM Zechstein flooding of sub - sea level basins				
		Early	LATE HERCYNIAN WRENCH TECTONICS			SUBSIDENCE OF MORAY FIRTH	SUBSIDENCE OF SOUTHERN & NORTHERN PERMIAN BASINS BEGAN		
300	CARBONIFEROUS	Stephanian	EARLY COLLAPSE OF VARISCAN FOLD BELT IN EUROPE						300
		Westphalian							
		Namurian	VARISCAN OROGENY	INITIATION OF N. ATLANTIC FRACTURE PATTERN	RIFTING IN N. BRITISH ISLES			VARISCAN FOREDEEP	
		Dinantian	PLATE COLLISION		Renewed uplift of Scottish Highlands			BACK-ARC RIFTING	
	DEVONIAN	Late	STEP-WISE CLOSURE OF PROTO-TETHYS			Volcanics in Orcadian Basin			
		Mid							
400		Early			Granites in Scottish Highlands		Volcanics in S. Scotland	Granites in Lake District	400

Table 2.1 Evolution of Tethys & Atlantic oceans related to some North Sea post-Caledonian structural events (after Glennie 1990).

between Iberia and Newfoundland. Thus the duration of an active Viking-Central Graben system coincided with the slow break-up of Pangaea into North America, Europe and Africa.

6) The end of North Sea Graben development was linked to the onset of sea-floor spreading in the North Atlantic Ocean. Initially this was along the line of the Rockall-Faeroes Trough but it shifted to its present axis in the mid-Tertiary. The latter coincided with an active igneous phase which left its imprint in the sediments of the North Sea Basin; this is discussed further below (2.1.4, p. 33 onwards).

Superimposed upon the changing pattern of crustal fragmentation and reunification was an overall slow northward passive drift of the continents. This movement took the southern North Sea area from south of the Equator prior to the Carboniferous to its present location roughly equidistant between the Equator and the North Pole (Lovell 1977). It had a latitudinal climatic effect on fauna and on sedimentation but cannot be considered of structural importance without relating this motion to other plate movements.

The combination of time- and latitude-related climatic changes, and the pattern of structural deformation, erosion and sedimentation referred to above, is responsible for oil and gas being in reservoirs whose ages range from Devonian to Tertiary (Oligocene). The bulk of the oil and gas in the central and northern North Sea basins is derived from just one source rock, the late Jurassic Kimmeridge Clay, whereas most of the oil of The Netherlands and northern Germany is from another source, the Early Jurassic Posidonia Shale. The gas reservoirs of the southern North Sea area, however, have been charged almost entirely from the Carboniferous Coal Measures.

The foregoing account demonstrates that the structural geometry of the North Sea area can be considered as the result of plate movements involving tension and compression in different directions at different times in its developmental history. A more detailed account of this history is given by Glennie (1990, Chapters 2-4).

2.1.4 Palaeogene depositional history

Beginning approximately 65 million years ago (Ma), the Palaeogene marks a period of significant changeover in the depositional environment of the North Sea Basin (see Lovell, in Glennie 1990). The pelagic chalks and marls of the Late Cretaceous and Danian (Early Paleocene) were superseded by a considerable thickness of submarine clastic gravity-flow sands and muds, followed by prograding deltaic fan wedges (Rochow 1981). The influx of clastics and the development of coastal systems is related to an episode of uplift affecting the Scottish mainland and much of the northwestern North Sea Basin. This uplift was related to the early Tertiary opening of the North Atlantic, which also saw the onset of a major volcanic phase affecting western Scotland and Northern Ireland, The Faeroes and eastern Greenland (the Brito-Arctic Igneous Province [B.I.P.] of Boulter & Kvacek 1989). This episode left its imprint in the sediments of the North Sea area, in the form of widespread pyroclastic ashes and tuffs (Jacqué & Thouvenin 1975; Knox 1984; Malm *et al.* 1984).

Knox & Morton (1988) recognise two main phases of Late Paleocene clastic sedimentation. The earliest phase (Montrose Group; Table 2.2, p. 34) occurred in open marine conditions, in both shallow and deep water environments, and is represented by claystones and sands. Much of the deposition is associated with submarine fan systems. A volcanic episode during this time ("Subphase 1" of Knox & Morton) is represented by tuffaceous beds in the northwest of the basin which interdigitate with marls and are grouped together as the Lista Formation. The later phase (represented by the Moray Group) mostly occurred in marginal marine and marine environments with restricted circulation (associated with a worldwide lowstand in sea-level, Mudge & Copestake 1992a). Deposits of the Moray Group include marine sands and silts of deltaic aspect, passing basinward into laminated shales; submarine fan sands occur deeper in the basin.

A second, more extensive, phase of volcanic activity at the end of the Paleocene is represented by volcaniclastic deposits which give a distinctive high gamma response on sonic logs, allowing correlation over large areas of the basin. Originally grouped together to form the Rogaland Group by Deegan & Scull (1977), these units are more extensive than the underlying, more restricted sands and muds and include two basin-

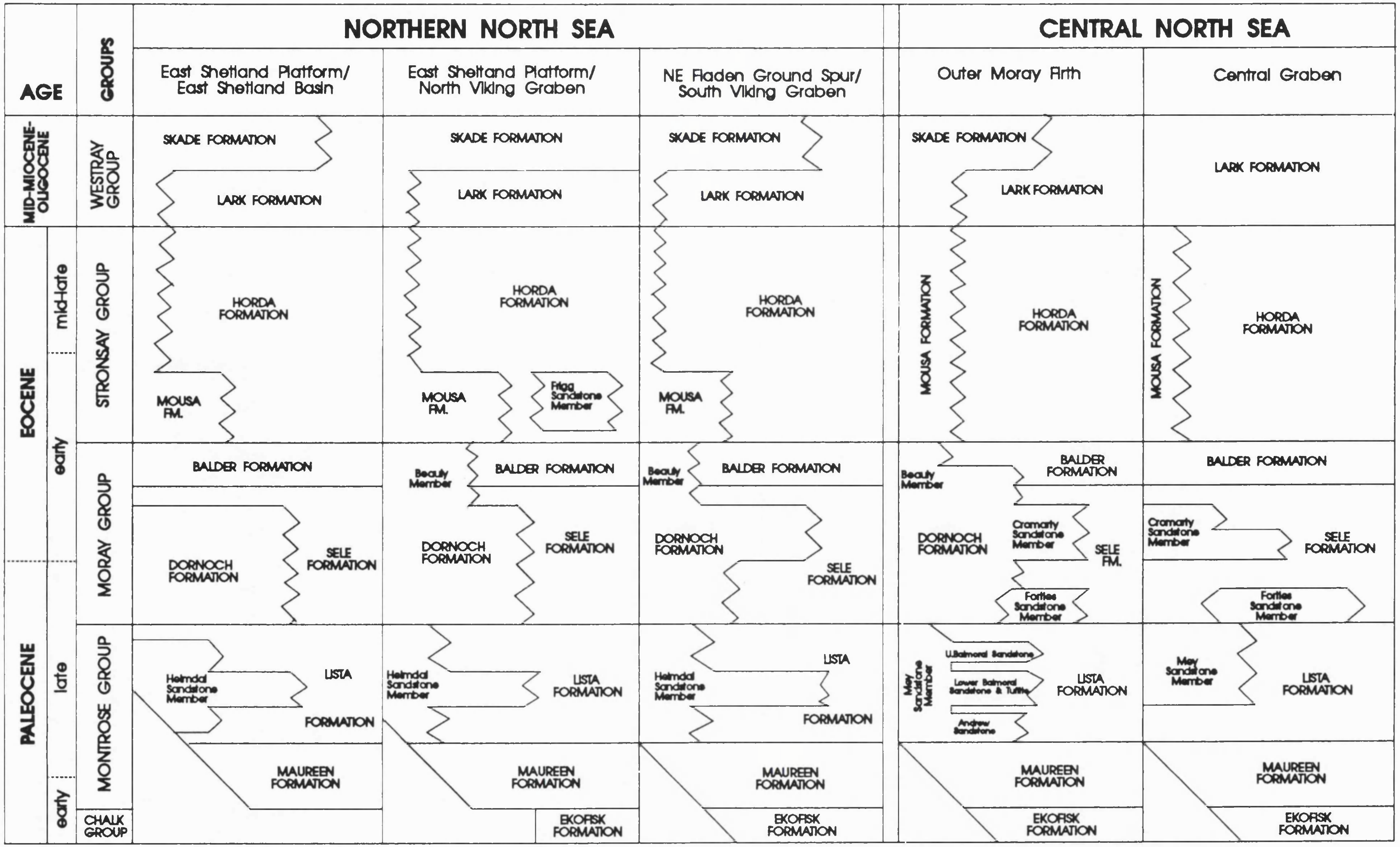


Table 2.2 Palaeogene lithostratigraphic nomenclature for the UK northern and central North Sea (after Knox & Holloway 1992).

wide formations, the Sele and Balder. More recently, these units have been placed within the upper part of the Moray Group (Knox & Holloway 1992; see Table 2.2, p. 34). This period of increased vulcanicity is divided into three subphases (Knox & Morton 1988), on the basis of differing rock thickness developments and geochemical characteristics:-

Subphase 2a

This period is marked by airfall ashes over a wide area of the North Sea, extending into Denmark, North Germany and Belgium (King 1990). Offshore, these form the main part of the Sele Formation; the various onshore equivalents are shown in Table 2.3 (p. 40). The mineral composition of the ash layers suggests partial derivation from the Faeroes-Greenland area of the B.I.P., with some input from western Scotland and Northern Ireland. Lithologically, the Sele Formation consists primarily of tuffaceous shales and distal turbidite deposits indicative of a deep basinal anoxic environment. Towards the top of this unit, the tuff becomes more pronounced and grades into the overlying Balder Formation.

Subphase 2b

This, the period of main ash and tuff accumulation in the North Sea Basin, is represented by a prominent marker interval offshore, known lithologically as the Balder Formation (Malm *et al.*, 1984; Table 2.2). It is characterised by very distinctive ash bands, and can be traced over virtually the whole of the North Sea, and onshore in the Fur and Ølst formations of northern Denmark (Heilmann-Clausen 1985b), in the basal London Clay in SE England (Jolley & Spinner 1991) and in the Ieper Formation of northern Belgium (King 1990). Geochemical and petrological analysis of this ash suggests that the focus of vulcanicity had shifted away from NW Britain, and was concentrated more in the Faeroes-Greenland area. The comparative violence of this activity is attested by the high proportion of volcanic glass present in the Balder Formation, and by the acidic composition of the ashes and tuffs. This is an enigmatic feature, as it is widely held that lavas originating in oceanic rifting sequences are of a more alkaline nature. Knox & Morton (1988) have suggested that this peculiar situation could have arisen from the reaction of seawater with the ash. The restricted nature of the North Sea at this time (Figure 2.2, p. 36) lends support to this hypothesis.

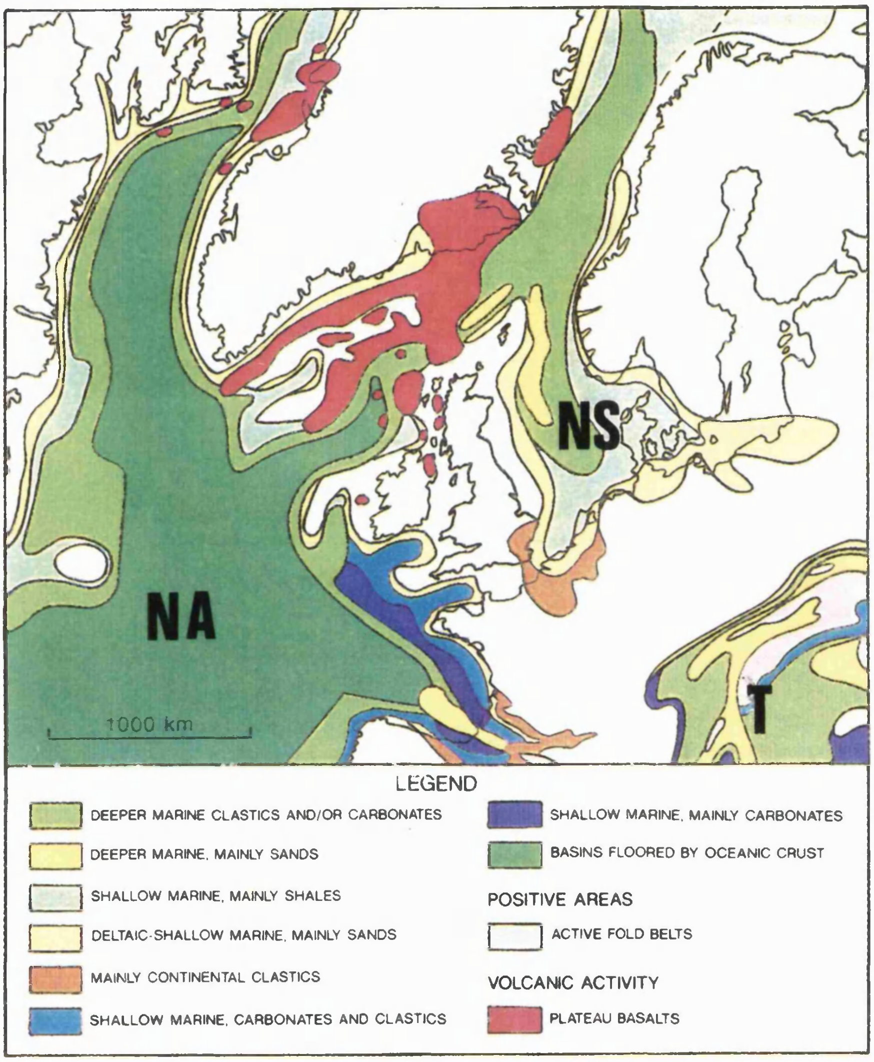


Fig. 2.2 Palaeogene palaeogeography of northwest Europe (from Vining *et al.* 1993, after Ziegler 1988). Note widespread vulcanicity in NW Britain, The Faeroes and Greenland; and relative isolation of the North Sea (NS)/Barents Sea/Arctic Ocean, from North Atlantic (NA) and Tethys (T).

Bonde (1979; Fig. 2.3, p. 38) suggested a circulation model for the North Sea Basin during this period, which envisaged a prolonged period of coastal upwelling along the coast of Norway driven by seasonal, monsoonal, northwesterly winds. This was held to account for both the increased siliceous productivity in the North Sea Basin, as well as the great thicknesses of volcanic ash and tuff, intercalated with laminated diatomite, preserved in the cliffs around the Limfjorden area of northern Denmark. Bonde's model was later refuted by Pedersen (1981) who conducted a detailed sedimentological study of the Fur Formation and found only sporadic laminations; it was proposed that any upwelling was more likely to have been sporadic, and restricted to the Limfjorden area. This matter is discussed further in Chapter 7.

Subphase 2c

In the northwest of the North Sea Basin and in the adjoining West Shetland Basin a further volcaniclastic unit has been detected via magnetic anomaly patterns obtained during exploration for hydrocarbons. Its geochemical signature suggests provenance from volcanoes present nearby. This is the evidence for most recent vulcanicity in North Sea sediments; hence its identification as subphase 2c, and from this time onwards the main focus of activity was the mantle plume which lies beneath Iceland at the present.

Above the Moray Group , the rest of the Tertiary sequence in the North Sea is divided into the Horda, Stronsay, Westray and Nordland Groups (Table 2.2, p. 34). The Horda Group consists mainly of marine shales with some thin limestone streaks and localised sand units, and records a deepening of the basin with improved circulation as a result of the Early Eocene transgressive phase (shown by widespread glauconite and influxes of calcareous foraminifera and nannoplankton), while the Nordland Group comprises a great thickness of monotonous marine shales and clays. The latter are only possible to correlate on the basis of their contained microfossils, as there are no lithological variations which can be mapped over any distance. However, recent work by Mudge & Bujak (1994) shows that it is in fact possible to subdivide the later Eocene sequence by calibrating high gamma ray peaks with a detailed dinocyst zonation.

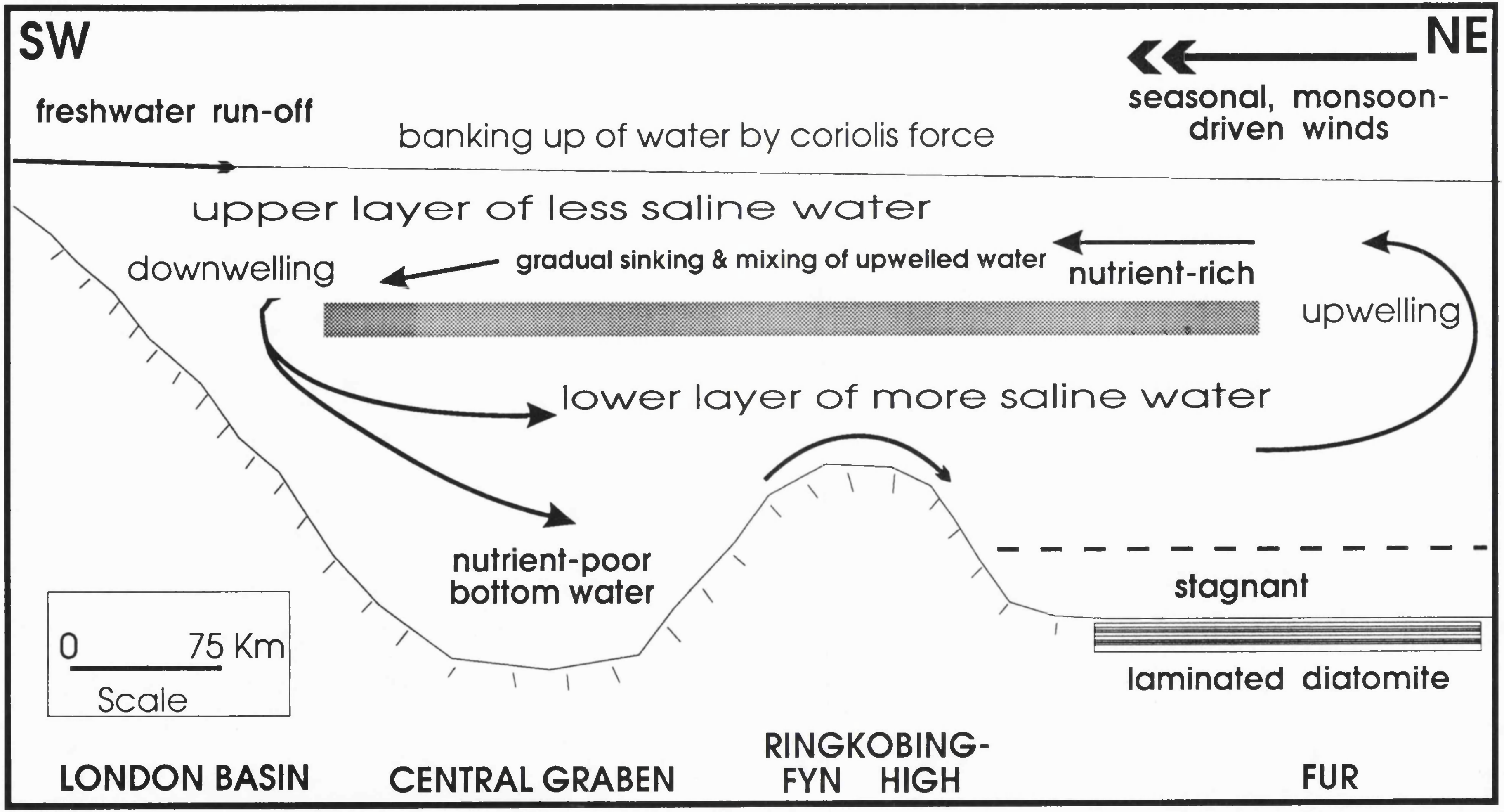


Fig. 2.3 Circulation model for the North Sea during the earliest Eocene (after Bonde 1979, with modifications). Note that the vertical scale is schematic.

The Eocene and later deposits mark the continued subsidence of the North Sea Basin, which became more regular from mid Eocene times onwards (King 1983). Continued erosion of the Scottish mainland, the East Shetland Platform, and parts of Scandinavia, led to the deposition in some marginal areas of deltaic and coastal barrier sand units. Phases of marine transgression, which often truncate these regressive units, are marked by thin beds rich in glauconite or phosphatised faecal pellets and fish debris. The uppermost sediments of this group consist of uncompacted muds and these are usually overlain by glacial deposits.

2.2 Palaeogene Biostratigraphy

2.2.1 Overview: North Sea Micropalaeontology

In the past decade a large amount of micropalaeontological information has become available from the North Sea Basin, as previously confidential data have become released and subsequently published. This has enabled detailed biostratigrahic zonations to be drawn up (e.g. King 1983; Gradstein *et al.* 1988; Mudge & Copestake 1992a,b; Schröder 1992). The essential unifying feature about these schemes is that they feature a range of microfossil groups, a necessary consequence of the fact that there are a number of intervals in the Palaeogene section where one particular fossil group may be rare or absent (due to palaeoenvironmental conditions, subsequent dissolution, and diagenesis) so that other fossils present in that section are used instead. This is particularly evident in the micropalaeontological schemes, where foraminifera, diatoms and radiolaria are used in a single scheme (e.g. King 1983). More recently this situation has extended to include palynological data (e.g. Mudge & Copestake 1992a,b; Gradstein *et al.* 1992), so that a greater amount of information can be utilised in the assessment of a given section, in terms of palaeoenvironment, age resolution and changes in the circulation regime of the basin, than was previously possible. Table 2.3 (p. 40) gives a representative litho- and biostratigraphical scheme for part of the Palaeogene sequence in and around the North Sea Basin.

AGE	BIOZONATION (Diatoms & *Foraminifera*)	LITHOSTRATIGRAPHY			
		CENTRAL NORTH SEA	SOUTHERN ENGLAND	BELGIUM	DENMARK
EARLY EOCENE	*Globigerina linaperta*	HORDA FORMATION	LONDON CLAY FORMATION	**IEPER FORMATION**	ROSNAES CLAY FORMATION
	Coscinodiscus **sp. 1**	**BALDER FORMATION**	**HARWICH FORMATION**	(Absent)	① **OLST FORMATION** ② **FUR FORMATION**
LATE PALEOCENE	***Coscinodiscus*** **spp.**	**SELE FORMATION**	WOOLWICH/ READING FORMATIONS	LANDEN FORMATION	③
	Impoverished agglutinated foraminifera assemblage	LISTA FORMATION	THANET FORMATION		HOLMEHUS FORMATION
	Bolivinopsis spectabilis	MAUREEN FORMATION	(Absent)	(Absent)	KERTEMINDE FORMATION
EARLY PALEOCENE	*Globigerina simplicissima* *G. trivialis*	EKOFISK FORMATION		'MONTIAN'	DANSKE-KALKE FORMATION

① KNUDSHOVED MEMBER
② SILSTRUP MEMBER
③ KNUDEKLINT MEMBER

Table 2.3 Correlation of Lower Palaeogene stratigraphy of the Central North Sea with equivalent units around the basin margins. Diatoms and diatomaceous intervals shown in bold. Compiled from: Heilmann-Clausen 1985a; Mudge & Copestake 1992a; Ellison 1994.

2.2.2 Diatoms: North Sea and Onshore

Very little detailed taxonomic or biostratigraphic work has been published on the Tertiary diatoms of the North Sea, for three main reasons:-

1) Information which exists has been almost exclusively conducted within the confines of the oil companies and their ancillary service companies. Due to industrial secrecy, this information has remained "in-house" and consequently unavailable for wider scientific study.

2) The major drilling objectives have until relatively recently concentrated on the underlying Mesozoic strata (in particular Jurassic reservoir sands), so that there are few cored sections available for the Tertiary (i.e. diatomaceous) sequence. This situation has improved since the discovery of major reservoirs in the lower Palaeogene (e.g. the Forties, Balder and Gryphon fields) so that more cored sections are now available. However, few reservoirs have been discovered in sediments younger than the Lower Eocene (Bain 1993) and so the detailed stratigraphy of this interval is relatively poorly known.

3) Finally, the diatoms themselves are almost always poorly preserved, being replaced and/or infilled by pyrite (Jacqué & Thouvenin 1975; Hughes 1981; King 1983) and this has hindered their identification. As a result, species have remained in open nomenclature which, combined with proprietary restrictions, has meant little standardisation in North Sea diatom identification and zonation schemes.

The most easily available of the few published references to North Sea Tertiary diatoms is that of King (1983) which gives plates and short descriptions of the five most common morphotypes which have widespread stratigraphical significance. Of these, "*Coscinodiscus* spp. 1 & 2" are the most widely-documented as they occur, often in large numbers, within the volcaniclastic Balder and Sele Formations around the Paleocene/Eocene boundary (forming the *Coscinodiscus* sp.1, NSP 4 planktonic zone in the scheme of King, 1983). These, together with the triangular morphotype referred to as "*Triceratium* sp. 1" were first described from the Unter-Eozän of Northern Germany by Bettensteadt *et al.* (in Bartenstein *et al.* 1962). The other three morphotypes described by King (1983), "Diatom spp. 3, 4 & 5", have not been published elsewhere but are distinctive, widespread zonal markers in the upper Oligocene and Miocene of the North Sea sequence. No attempt was made by King to assign accurate taxonomic names to any of these taxa.

The best-preserved diatomaceous assemblage from offshore sediments to date is that of Malm *et al.* (1984). A plate and short descriptions were given of both unaltered and pyritised diatoms (and silicoflagellates, see 2.2.6) preserved in calcareous concretions in the Balder Formation (see 2.1.4, p. 35). This "snapshot" implies that the original diatom assemblage was rich and diverse, but has largely been destroyed by the effects of diagenesis in the sediment surrounding the nodules.

Onshore north-west European Tertiary diatomaceous sections have a long history of investigation (Grunow 1866; Kitton 1871; Shrubsole & Kitton 1881; Schulz 1927; Staesche & Hiltermann 1940; Bettenstaedt *et al.* 1962; Benda 1965, 1972; King 1981; Bignot 1983; Homann 1991). This is partly a reflection on their greater accessibility, and of the better preservation of many of the diatoms, so that over the years a large amount of material has been published on sites around the periphery of the North Sea. The most famous of these is the Fur Formation diatomite of northern Denmark (previously known as the "Moler" or "Mo-Clay", see Chapter 3). The earliest descriptions of diatoms from here were published as long ago as 1863 by Heiberg, and both he and other early workers, including Ehrenberg, described many diatom taxa from this deposit (see Homann 1991, pp. 147-157 for references). Although other sections are more poorly preserved, nevertheless these too have a long history of scientific investigation. Shrubsole & Kitton (1881) were the first to correctly identify a zone of curious, sub-microscopic shiny discs from the base of the London Clay as pyritised diatoms; whilst similar pyritised morphologies were described from the Unter-Eozän of northwest Germany by Staesche & Hiltermann (1940), and subsequently by Bartenstein *et al.* (in Bettenstaedt *et al.* 1962). More recently, Bignot (1983) documented similar forms from the age-equivalent Sparnacian beds of the Paris Basin. Diatoms in the basal part of the Ieper Clay of Belgium were included in the zonation scheme of King (1990). To the southeast of the North Sea Basin, Palaeogene diatoms have also been recovered from the lower Oligocene of the Carpathian flysch (Kaczmarska 1982).

2.2.3 Foraminifera: North Sea Basin

In contrast to diatoms, the Palaeogene foraminifera of the North Sea Basin are far better documented (e.g. Gradstein & Berggren 1981; Hughes 1981; King 1983, 1989; Gradstein *et al.* 1988; Charnock & Jones 1990). This is mainly because they are more abundant, and occur continuously through most of the Palaeogene section. Also, a great amount of information has been made available in the past decade from the oil companies and their ancillary service companies, as material from exploration wells has become released into the public domain. A detailed biostratigraphic zonation of the North Sea Palaeogene has been recognised, initially using foraminifera only, but more recently utilising a number of microfossil groups to form more integrated biozonation schemes (e.g. Mudge & Copestake 1992a,b; Table 2.3, p. 40).

After the initial period of early Palaeogene carbonate-dominated sedimentation, characterised by planktonic foraminifera such as *Globigerina* and *Globorotalia*, a change in sedimentation style which accompanied the mid-Paleocene tectonic activity (see section 2.1 above) led to the development of foraminiferal faunas dominated by agglutinating taxa in the centre of the basin (the "*Rhabdammina* biofacies" of King 1983), with calcareous benthic species in more littoral areas around the basin margins. This situation persisted from the Late Paleocene until the Late Miocene in some areas. King (1983) divided the Palaeogene sequence into 17 benthic foraminiferal (NSB) and 16 planktonic (NSP) zones, the latter based on the occurrence of planktonic foraminifera, or diatoms and radiolaria where planktonic foraminifera are not present. Sequences which include index species of both sets of zones are used to correlate the NSB and NSP zones. Boundaries of both zones are considered by King to be controlled mainly by environmental changes rather than evolutionary events, as there is a remarkable synchroneity between the zonal boundaries of most of the planktonic and benthic zones. King later refined this scheme to include NCA (non-calcareous agglutinated) zones (King 1989).

2.2.4 Calcareous nannoplankton

The environmental factors which dictate the occurrence and preservation of nannofossils in the North Sea Basin Palaeogene are largely the same as those governing the distribution of planktonic foraminifera, i.e. the mid-Paleocene changeover from pelagic to clastic sedimentation and later basin isolation, outlined above (see 2.1). Therefore, significant gaps occur in the record of these organisms, especially for Late Paleocene and Early Eocene time, which have caused difficulties in the detailed correlation of the North Sea Basin sequence with those elsewhere (see section 2.3). Gallagher (1989, 1990) conducted a detailed zonation of the North Sea Palaeogene using nannofossils and divided the sequence into 23 zones, based on the first downhole occurrence (FDO) of species. He also tentatively proposed a combined nannofossil/foraminiferal biozonation scheme, to include those sequences lacking nannofossils.

2.2.5 Palynology

The clastic, restricted marine nature of large parts of the North Sea Basin Palaeogene sequence (in particular the large reservoir-sand bodies) has led to the investigation of palynomorphs (microplankton, spores and pollen) as they have a more continuous record in these intervals (e.g. Heilmann-Clausen 1982, 1985a,b; Powell 1988; Schröder 1992). In some cases this information has been combined with that from other microfossil groups (e.g. Mudge & Copestake 1992a,b), to produce an integrated zonation. Schröder (1992) used time-significant pollen marker taxa from north-west continental Europe, combined with Shell's evaluation of central North Sea wells, to produce "PT zones" for the Late Paleocene interval. Four main, basin-wide zones were recognised based on microplankton assemblages, while for the central North Sea a further fourfold, mainly pollen-based, subdivision was erected. It was suggested that quantitative shifts in the Late Paleocene pollen spectrum may have been influenced by changes in climate, and that such shifts may represent "time-lines", with validity over a much wider area than the central North Sea.

2.2.6 Silicoflagellates

These siliceous microfossils are not utilised as much as the preceding groups, as their occurrence is of an extremely patchy nature, being mainly restricted to intervals of predominantly siliceous sedimentation, in upwelling zones (Loeblich *et al.* 1968; Harwood 1988). In addition, their fragile skeletons (which consist essentially of a ring of silica with various projections which facilitate taxonomic identification) are prone to dissolution. This precludes much of the post-Danian sequence in the North Sea Basin, except for the Fur Formation diatomite of northern Denmark (see 2.2.2). This deposit contains rich assemblages of diatoms, silicoflagellates, archaeomonads, ebridians and sporadic radiolaria, but calcareous fossils are absent and zonation has long proved problematic. However, the silicoflagellates exhibit definite changes in assemblage composition and it has thus been possible to divide the sequence into zones. This was first attempted by Martini (1974) who referred the Fur Formation to the *Dictyocha deflandrei* and *D. naviculoidea* Zones. A more refined scheme was later devised by Perch-Neilsen (1976) who placed it in the *Naviculopsis constricta* Zone, further subdividing this into five subzones. Samples from Fur examined by the present author for diatom taxonomic and palaeoecological purposes (Chapters 4, 5 & 6) were dated using the latter scheme. Sediments from deeper in the basin have been strongly affected by diagenesis (see 2.1) and the only occurrence of silicoflagellates from these are from calcareous concretions, recovered from a core in the Norwegian sector of the Viking Graben by Malm *et al.* (1984). In addition to unaltered diatoms, these concretions contained diagnostic silicoflagellates which enabled the authors to place the lower part of the Balder Formation within the *N. aspera* subzone of Perch-Nielsen (ibid.).

2.2.7 Radiolaria

At certain intervals in the North Sea Basin Palaeogene sequence there occur floods of poorly-preserved radiolaria. These are spumellarian forms, generally referred to *Cenosphaera* spp. (see King 1983, pl.1), and form important marker horizons, normally indicating a deepening of the basin. Other morphologies occur sporadically through the sequence, but bad preservation often precludes accurate identification. Entwistle (unpublished report, UCL. 1993) gave illustrations and descriptions of some of the more important forms encountered. Onshore, *Cenosphaera* sp. has been recorded in the Unter-Eozan of northern Germany (Bettenstaedt *et al.* 1962). The presence of rare but well-preserved radiolaria in the Fur Formation (in addition to other siliceous microfossils such as ebridians, archaeomonads and endoskeletal dinoflagellates) has been noted by a number of workers (see Perch-Nielsen 1976) but these had not been formally identified prior to this work.

2.3 Correlation with other areas

2.3.1 General Outline; Problems

Correlation of the Palaeogene sequence in the North Sea Basin with the standard Cenozoic timescale (Berggren *et al.* 1985; Harland *et al.* 1989) is hampered for several reasons:-

1) Microfossil species diversity is low in the relatively high-latitude North Sea Basin, compared with that in the tropical latitudes used in the main zonations. Many of the key marker species are not present in the North Sea Basin.

2) The tenuous connection of the North Sea with open oceanic areas during the early Cenozoic inhibited the influx of planktonic organisms into the basin. This is especially true for the Paleocene/Eocene boundary, Zone NP 10 time of Berggren *et al.* (1985) when calcareous plankton is absent in the basin. In the later Eocene, nannoplankton are sometimes rare or of restricted occurrence (Gallagher 1989, 1990).

3) In contrast to parts of the Mesozoic, sedimentation in the North Sea Basin during the Palaeogene was not continuous over wide areas and the sequence contains many hiatuses and restricted depositional settings (such as deltas) which are difficult to correlate precisely. It is only very recently that an accurate stratigraphy has been devised (Knox & Holloway 1992; Table 2.2, p. 34), and many of the microfossil zonation schemes have applicability over limited areas.

4) Preservation is often poor, particularly within the "*Rhabdammina* biofacies" (King 1983) which persisted over large areas of the basin during the Palaeogene, as conditions here did not facilitate either the production or preservation of calcareous fossils; where they do occur, they are often etched or overgrown (Gallagher 1990).

5) Many of the benthic foraminiferal taxa used in the North Sea zonation schemes are of little stratigraphic use outside the basin. However, progress has recently been achieved via the use of assemblages rather than single marker-species, which have been found to have a wider application in other areas (e.g. using the R.A.S.C. method of Gradstein *et al.* 1992). It has therefore been possible to extend benthic foraminiferal assemblage zones to areas such as the Barents Sea and Labrador Sea, where similar conditions existed during the Palaeogene (Pak & Miller 1992).

As a consequence of the above factors, it has only been possible to correlate accurately limited intervals of the North Sea Palaeogene with the standard marine plankton zonation schemes. Increasing use is made of schemes which combine microfossil groups (see 2.2.4, above), and several schemes have been proposed (Costa & Müller 1978; Aubrey 1985; Powell 1988; Gallagher 1990). Difficulties nevertheless remain concerning the definition of the problematic Zone NP 10, with the earlier recommendation of the appearance of the dinoflagellate *Wetzeliella astra* as its base (Pedersen & Surlyk 1983) being called into question by Ali *et al.* (1992). This and other stratigraphic problems are the subject of the current International Geological Correlation Programme (I.G.C.P.) Working Group 308, Paleocene-Eocene Boundary Events. Some workers, e.g. Knox (1984) have used indirect methods to correlate ash layers around the poorly-defined Paleocene-Eocene boundary with those preserved in the Goban Spur and Rockall areas of the North Atlantic. Unpublished data by Berggren suggest that ash layer -17 in the sequence preserved in Denmark and in the North Sea, also positively identified in the North Atlantic (Knox 1985), may be a candidate for the Paleocene-Eocene boundary level; whilst Ali *et al.* (1992) have refined the magnetostratigraphic calibration of the Early Eocene sequence in the southern part of the North Sea Basin, developing a high-resolution "event-stratigraphy" for the Ypresian deposits of this region (Fig. 2.4, p. 48). This was achieved by linking the magnetostratigraphy of the sedimentary sequence to the geomagnetic polarity timescale using biostratigraphic data from calcareous nannoplankton and dinoflagellates.

2.3.2 Worldwide Palaeogene diatom assemblages: correlation potential

Few continuous diatomaceous sections have been recovered from Palaeogene sediments globally. This contrasts with the relatively complete Neogene sequence, and is a reflection partly on the greater age, and consequent propensity for dissolution, of Palaeogene diatoms; and that there appear to have been fewer areas of upwelling (i.e. sites of diatom production, Barron 1993). This is partially offset by the apparently heavier silification of Palaeogene diatoms (although this may be a function of silica phase changes due to lithification), so that where sections do exist they are often very diverse (e.g. the Fur Formation). Diatom species used in the zonation schemes of the

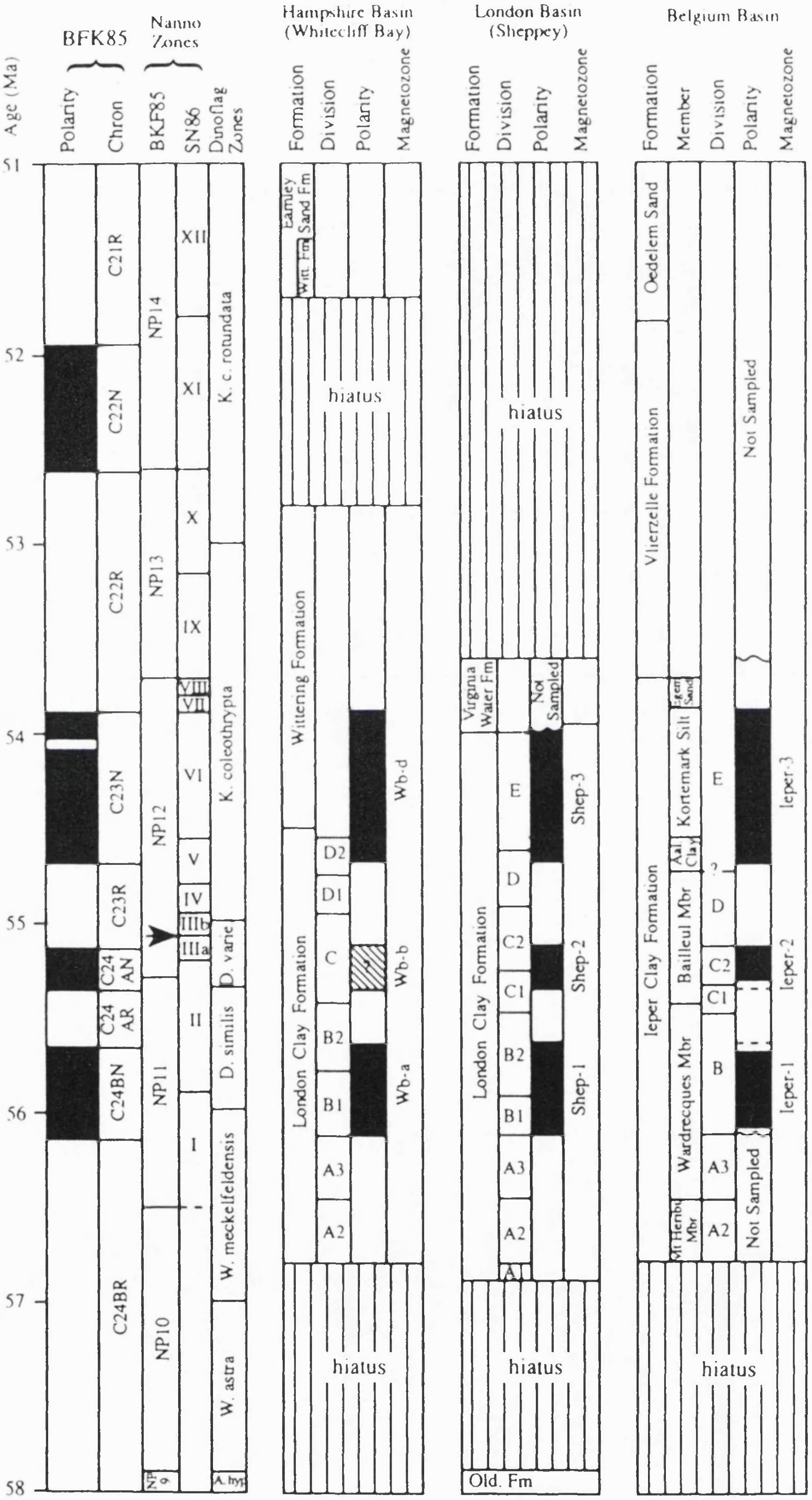


Fig. 2.4 Magnetostratigraphy of the Paleocene-Eocene boundary interval in the southern North Sea, with nannofossil and dinoflagellate zones (from Ali *et al.* 1992).

Deep Sea Drilling Project (DSDP) and its successor the Ocean Drilling Program (ODP) have mainly been recovered from sequences in the open oceans, in low and southern high latitudes (see Table 2.4, p. 50; Fig. 2.5, p. 51). Those from higher latitudes tend to have a patchy distribution, being restricted to certain sections of the Palaeogene sequence, as in the Norwegian Sea zonations of Schrader & Fenner (1976) and Dzinoridhze *et al.* (1978); and the Southern Ocean zonations of Gombos (1977, 1983, 1984) and Mukhina (1976). This makes inter-regional correlation difficult, if not impossible. However, recent work by Dell'Agnese & Clark (1994) suggests the close correlation of a richly siliceous interval (containing diatoms, silicoflagellates, archaeomonads and ebridians) from the lower Eocene in the central Arctic Ocean, with the Fur Formation. This suggests at least an intermittent connection of the restricted North Sea Basin and Barents Sea with the Arctic Ocean during the early Eocene.

Increasing provinciality of diatom floras from the middle Eocene onwards restricts inter-regional correlation from this time onwards (Barron 1993). This provincialism reflects the increased latitudinal segregation of water masses, a function of the change of the ocean circulation pattern of the World Ocean during this period from a relatively sluggish regime driven by salinity gradients (which characterised the World Ocean during the Mesozoic and Early Cenozoic, Parrish & Curtis 1982), towards a more vigorous circulation pattern characterised by steep equatorial and polar thermal gradients. This led in turn to the increased incidence of upwelling and the related accumulation of siliceous, organic-rich deposits, including diatomites, around the margins of ocean basins in which new, provincially endemic diatom taxa flourished (Barron & Baldauf 1989).

Onshore sections from the former Soviet Union have yielded well-preserved diatom floras from the Urals and the Volga Basin (e.g. Proshkina-Lavrenko 1949; Glezer *et al.* 1974), which show affinities both with the assemblages from north Denmark (Fur) and the Norwegian Sea. This suggests at least some connection across the Russian Platform during this period, probably in the form of a shallow, epicontinental sea (Barron 1987). Unfortunately, much of the Tertiary sequence is missing in the intervening area and in Fennoscandia, having been eroded during subsequent uplift and by continental ice sheets during the Quaternary (Miller 1979). A further problem inhibiting accurate correlation is that many diatom specimens from Russian localities

Europe: Onshore & Offshore	**Others: Northern Hemisphere (incl. former Soviet Union)**	**Others: Southern Hemisphere (incl. Indian Ocean)**
Kitton 1871 (1); **Shrubsole & Kitton 1881** (2); Schulz 1927 (3); **Staesche & Hiltermann 1940** (3); **Bettenstaedt *et al.* 1962** (3); **Benda 1965** (3), 1972 (1); **Jacqué & Thouvenin 1975** (4); Schrader & Fenner 1976 (5); Dzinoridze *et al.* 1978 (5); **Hughes 1981** (4); **Kaczmarska 1982** (6); **Bignot 1983** (7); **King 1983** (4); Baldauf 1984 (8); **Malm *et al.* 1984** (4); Homann 1991 (1)	Grunow 1884 (9); Proshkina-Lavrenko *et al.* 1949 (10); Jousé 1951 (11); Paramonova 1965 (12); Sheshukova-Poretskaya & Glezer 1964 (13); Glezer 1966 (14); Shibkova 1968 (15,16); Glezer *et al.* 1974 (10,13,17,18) Strel'nikova *et al.* 1978 (19); Sims & Ross 1988 (20,29); Ehrlich & Moshkovitz 1982 (21); Hanna 1927a (22); Kanaya 1957 (22); Hanna & Brigger 1964 (23); Fenner 1981 (24); **Thomas & Gradstein 1981** (25); Gombos 1982 (26); Fenner 1985 (27); Kitchell *et al.* 1986 (28); Baldauf & Monjanel 1989 (30); **McNeill 1990** (31); Dell'Agnese & Clark 1994 (28)	Schrader 1969 (32); Gombos 1977 (33); Hajos 1976 (34); Mukhina 1976 (35); Fenner 1977 (36); Ross 1976 (37); Gombos 1983 (38); Gombos & Ciesielski 1983 (39); Gombos 1984 (40); Harwood 1988 (41); Sims & Ross 1988 (42,43); Desikachary & Sreelatha 1989 (32); Fenner & Mikkelsen 1990 (44); Edwards 1991 (32); Fenner 1991 (45,46); Fourtanier 1991 (47,48); Harwood & Maruyama 1992 (49)

Table 2.4 Published records of Palaeogene diatoms. Figures in parentheses refer to localities in Figure 2.5, p. 51 (pyritised assemblages shown in bold).

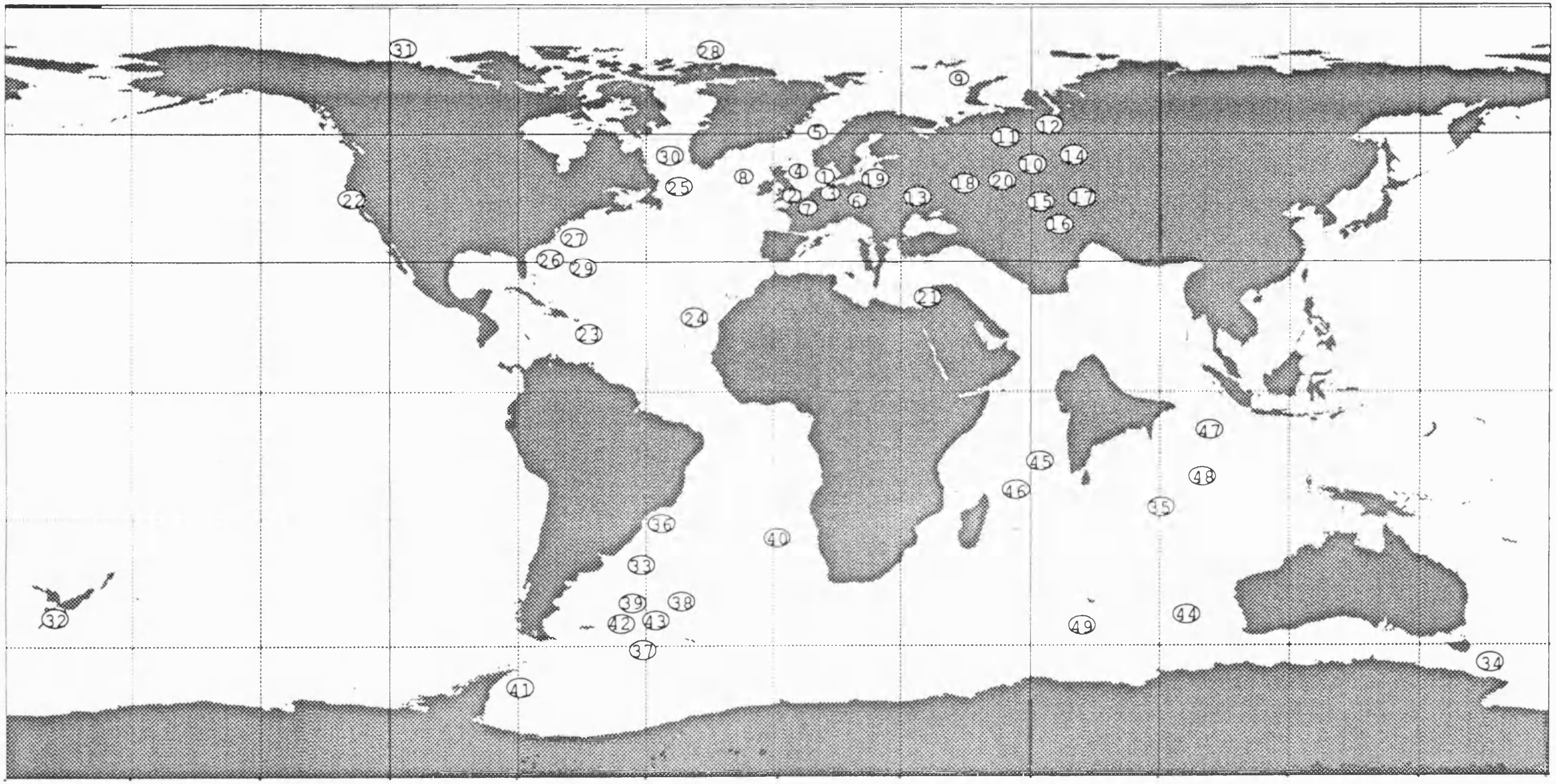


Fig. 2.5 Palaeogene diatom localities (configuration of continents at latest Paleocene, 56 Ma. Reconstruction by ATLAS, Cambridge). Figures refer to references in Table 2.4.

housed in the Natural History Museum were collected in the last century and inadequately labelled in terms of locality or stratigraphical position, and so they are of negligible value for precise correlation (Ross & Sims 1985, pp. 279-282).

Pyritised diatom assemblages have been recovered from Palaeogene sections in other areas outside the North Sea, in particular the Labrador Sea (Thomas & Gradstein 1981) and the Beaufort-Mackenzie basin (McNeil 1990). In both cases, the assemblages were found during drilling for hydrocarbons, from basinal settings similar to the North Sea. Some of the morphotypes described show similarities to those from the North Sea Basin, and are discussed further in Chapter 5. Closer to the North Sea Basin, recent work shows that pyritised diatoms are also abundant in the West Shetland Basin (Copestake 1993) and in the Barents Sea (M.A. Kaminski, *pers. comm.* 1993), at similar intervals to the main abundance peak in the North Sea (uppermost Paleocene to lowermost Eocene). To date, no detailed taxonomic study has been carried out on these assemblages.

3. MATERIALS AND METHODS

3.1 Study Material

Samples from various localities in and around the North Sea Basin, and further afield, were analysed for this study. Offshore samples from hydrocarbon exploration wells were provided by British Petroleum Development Ltd, from their core stores in Glasgow; whilst comparative material, used for correlation and taxonomic purposes, came from a number of sources outlined below.

3.1.1 Offshore sample material

Samples from exploration wells (Figure 3.1, p. 54) were selected according to the following criteria:-

1) Where possible, the well should be "released"- i.e. completed more than 5 years ago and available to the public under UK law. Where a well or wells had not been released, an agreement was reached whereby information obtained from these is to be kept on restricted access for two years after thesis submission. In practice, very little useful data were obtained from such boreholes (see 5.2.3, Chapter 5).

2) As full a stratigraphic sequence as possible should be present through the Paleogene sequence. Unfortunately, this proved impracticable due to the many hiatuses and complex sedimentary regimes present in the North Sea Tertiary sequence (Chapter 2).

3) Ideally, a continuous core through the whole of the Tertiary sequence should be analysed. However, due to the expense of coring, only cores from sand bodies (potential reservoirs) were available. As the majority of these occur within the upper Paleocene and lower Eocene, samples from the higher Tertiary are subject to caving (see 3.1.3).

The first wells to be analysed were 15/28a-3 (N58° 07' 6.52"; E01° 55' 7.10"), and 21/9-1 (N57° 42' 20"; E00° 46' 05"). These wells helped to define the diatomaceous intervals in the Tertiary sequence, and experience with them influenced the selection of further wells, in particular two core sections from the south Viking Graben, 16/13a-4 (approximately N59° 38' 0"; E01° 05' 0") and 16/13a-5 (approximately N59° 39'

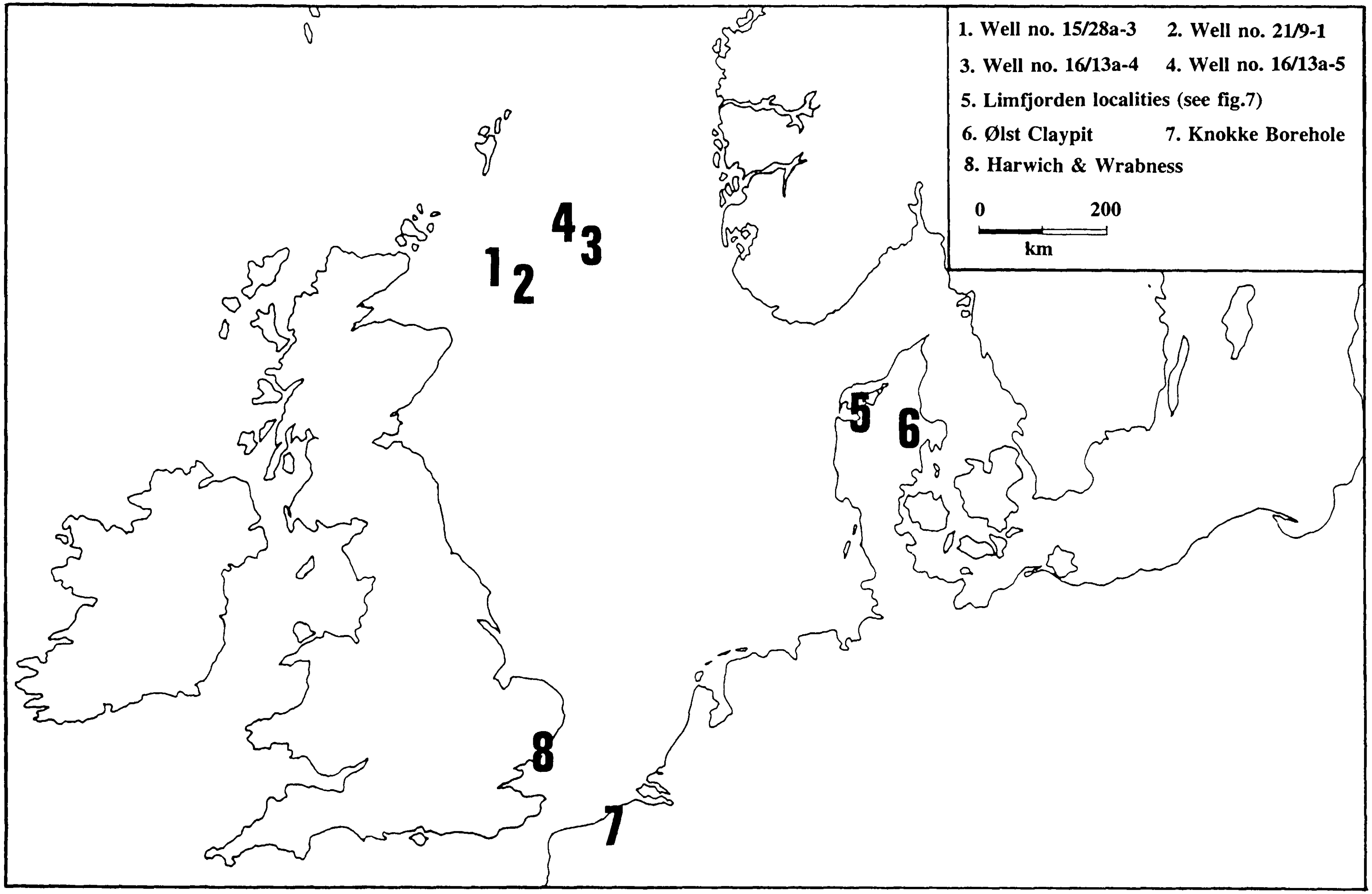


Fig. 3.1 Sample localities in and around the North Sea Basin.

0"; E01° 05' 10"). These are located in an area where diverse assemblages of relatively well-preserved diatoms had been recovered by workers in service companies (M.A. Charnock, *pers. comm.* 1992). Unfortunately, it transpired that other wells in this area were not available for study, as they were still on restricted access (the area being a productive oil field, see above).

Obtaining well-preserved, abundant diatom samples proved to be a problem during this study (see Chapter 1) and eventually it was decided, on consultation with and on the approval of Mr S. Payne (BP Petroleum Development Ltd., Glasgow), that the BP collection of diatom morphotypes would be made available for study to try to ensure the fullest taxonomic coverage possible. This consists of cavity slides containing diatoms from a number of wells in the North Sea, and collected on an informal basis over a period of years during routine picking for foraminifera (the predominant microfossil group used in North Sea biostratigraphy, see Chapter 2). On receipt of these slides, it was discovered that the precise stratigraphic interval of some samples had not been recorded. Nevertheless, a number of slides were examined for taxonomic purposes and electron micrographs taken of the better-preserved specimens. In doing so, it became apparent that it was possible to determine the taxonomic status of a number of diatom morphologies which had previously been in open nomenclature or assigned morphotype numbers by the various exploration companies.

3.1.2 Comparative material

Samples from onshore localities around the North Sea Basin and further afield were analysed in addition to the well material, so that taxonomic and stratigraphic problems could be addressed. These localities are as follows:-

3.1.2.1 Limfjorden region, Jutland, North Denmark

Samples from a number of localities in this area (including the islands of Fur and Mors, see Figure 3.2, p. 56) were examined, most of which are in the collections of the Natural History Museum, London. Some of the slides were prepared in the last century, and unfortunately their precise localities and stratigraphic intervals were not properly recorded. This is a problem with some of the older fossil diatom collections in the museum (especially those from the former Soviet Union, see below). It was

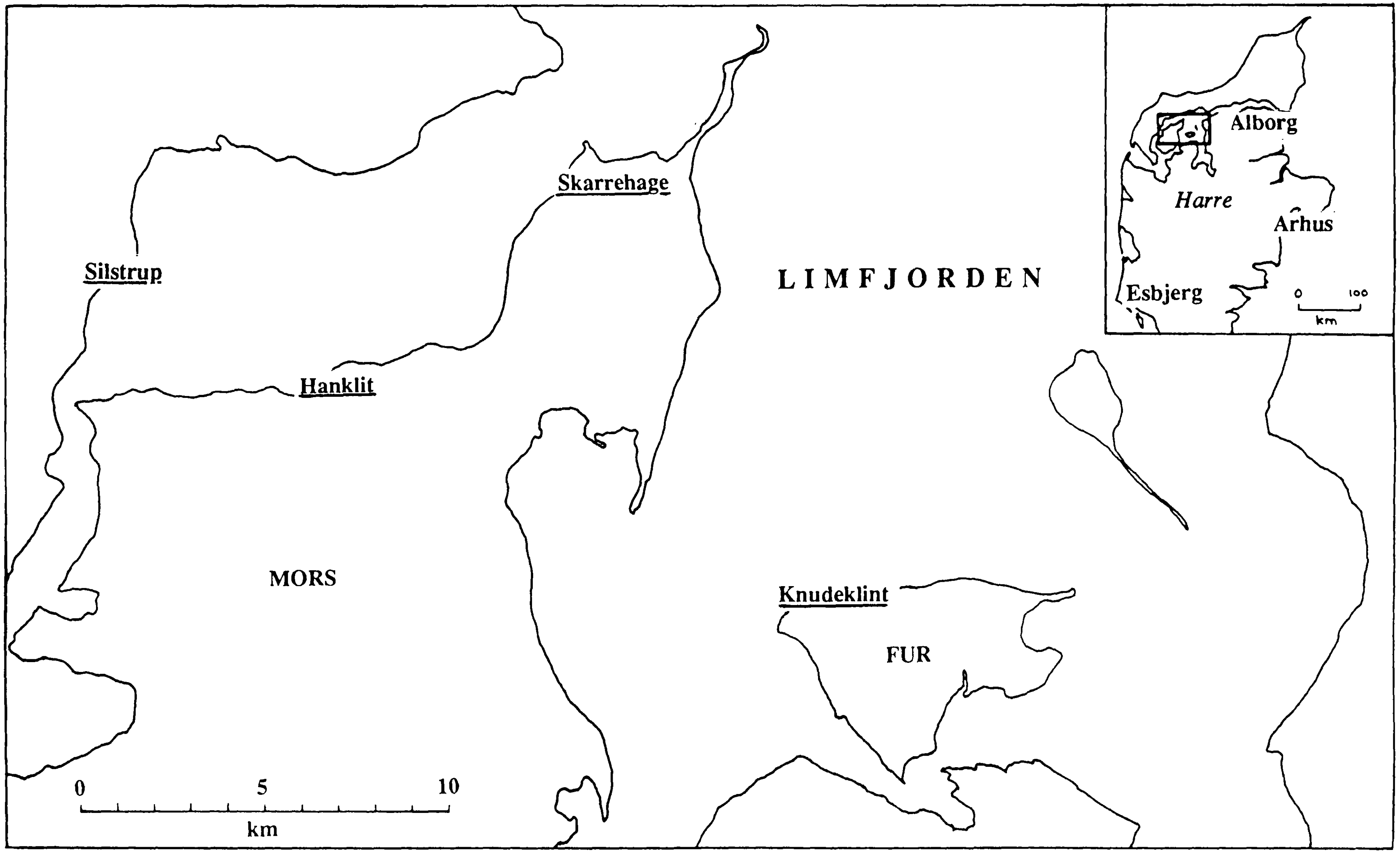


Fig. 3.2 Localities around the Limfjorden area, north Denmark. Underlined place names indicate sample localities. *Harre*: samples from here analysed by J. Fenner (unpublished data).

therefore fortuitous that some diatom samples from this area were sent to the museum during the period of this study by Dr. Marion Homann. These samples were subjected to SEM analysis, for comparison with NSB specimens, and additional smear slides were made up in order to examine any quantitative assemblage changes in the diatom flora through the samples (see 3.1.4.1) which had been collected from precisely-determined intervals. Dr. Homann's material came from the latest Palaeocene/ earliest Eocene age Fur Formation (formerly Moler or Mo-Clay) which crops out at several places in the Limfjorden region, and is held to be the lateral equivalent of the Sele and lowermost Balder formations in the North Sea (Pedersen & Surlyk 1983). Containing rich assemblages of diatoms and silicoflagellates, this long-renowned deposit held great potential for the elucidation of the diatom species found in equivalent units around the NSB, as well as providing vital stratigraphic information for the poorly-defined Palaeocene/Eocene boundary. Accordingly, it was decided that a visit to some key localities in Denmark would be of great use and after discussion with Dr. C. Heilmann-Clausen the following localities were visited:-

3.1.2.1.2 Islands of Fur and Mors, Limfjorden

Several of the type localities of the Fur Formation were visited by the present author, in order to understand better the spatial and sequential distribution of the calcareous concretions from which Dr. M. Homann's samples had been taken (see above). Samples were also collected from several localities, for possible investigation at a later date. Figures 3.4 (p. 58) and 3.5 (p. 59) show parts of the sections visited.

3.1.2.2 Ølst claypit, near Århus, Jutland

This claypit, situated 10 kilometres north of Århus (Fig. 3.2), is the type locality of the Ølst Formation (Heilmann-Clausen 1985b). Lithologically and palynologically identical to the Sele and Balder formations, the sequence here is the lateral equivalent of the Fur Formation. It contains the same ash-bands, and can therefore be correlated with great precision. Dr. Heilmann-Clausen had seen fragments of diatoms in palynological preparations from this locality, and further samples were taken by the present author (see Fig. 3.4, p. 58).

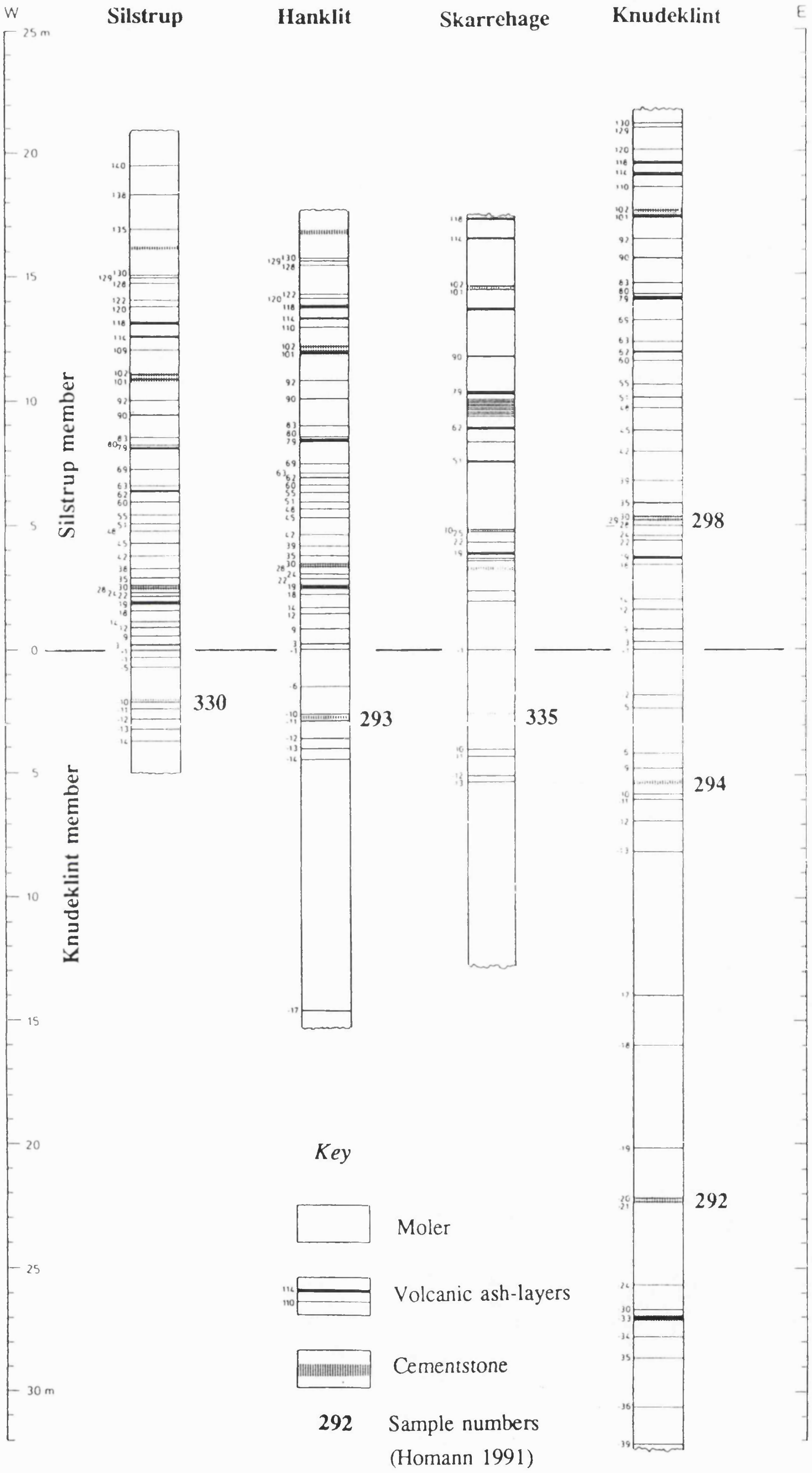


Fig. 3.3 Position of samples within the sequence of ash layers (numbers assigned by Bøggild 1918) preserved in the Fur Formation.

Fig. 3.4 a) View of the cliff section at Knudeklint, Island of Fur. Greyish-white layers of diatomite, intercalated with darker bands of volcanic ash. Note: the prominent thick ash-layer in the middle distance (arrow) is Layer +19 in the sequence of Bøggild (1918).

Fig. 3.4 b) View of part of the section at Ølst. The prominent light-coloured band in the foreground has been identified as ash-layer +19 (see Fig. 3.3) by C. Heilmann-Clausen.

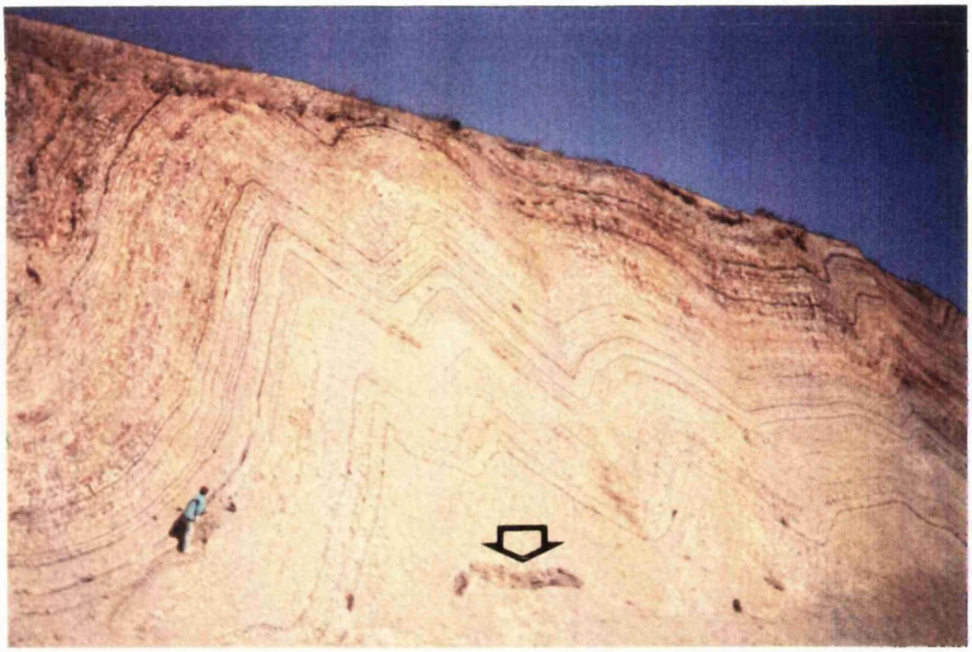


Fig. 3.5 a) Section through the Silstrup Member of the Fur Formation at Ejerslev, near Skarrehage. Note: 1) figure marks position of Ash-layer +19; 2) arrow marks cementstone layer: calcareous concretions, from which well-preserved fossils, including fish, plants and diatoms, have been recovered.

Fig. 3.5 b) Calcareous concretion from the Silstrup Member, Ejerslev, with fossil fish (identified as an Argentinoid by Dr. N. Bonde). Note: laminae within the groundmass contain abundant diatom valves and frustules.

3.1.2.3 Knokke no.1. well, West-Vlaanderen, Belgium

In December 1991 a meeting of the International Geological Correlation Programme (I.G.C.P.) Project 308 (Paleocene/Eocene Boundary Events) was held in Brussels. The present author attended and visited various localities in Belgium. Most of these were in lithologies from continental or marginal marine environments, and therefore unsuitable for the occurrence and/or preservation of Palaeogene diatoms (only fully marine species had evolved at this time, see Table 1.2, Chapter 1), but samples were examined from the lowermost Ieper Clay (the lateral equivalent of the London Clay), of the Knokke no.1 well, kept in the core store of the Service Géologique de Belgique, Brussels. A detailed account of the micropalaeontology of this well was published by King (1990) and so the diatomaceous intervals in the well were easily located and sampled.

3.1.2.4 Harwich and Wrabness, Essex, England

The cliff sections at these localities together form the type section for the Harwich Member of the London Clay (King 1981). This has been found to contain the degraded equivalent of the ash-bands present at this interval throughout the North Sea Basin (see 2.1.4, Chapter 2), and is known to contain an easily-correlatable horizon of pyritised diatoms, recognised since the last century (Shrubsole & Kitton 1881). This is the only known pre-Quaternary diatomaceous interval in the onshore succession of the British Isles. Samples from both sections were collected and donated by M.A. Charnock.

3.1.2.5 Diatom samples from the former Soviet Union

A number of diatom slides were examined from the collections of the Natural History Museum, London which had originated from various localities in the former Soviet Union. As with the slides from Denmark discussed above, the precise localities and stratigraphic horizons from which these samples were taken are poorly recorded. Ross & Sims (1985, pp. 279-282) discussed the possible provenance of a number of these samples, including those from "Kamichev", "Simbirsk", "Carlovo" and "Kuznetzk". Only the latter has been identified with certainty, and is located in the area of Penza, in the Volga Basin (No. 13 in Fig. 2.4, p. 51). It is considered to be late Eocene in age, based on silicoflagellates. Ross & Sims (q.v.) regard all of these localities as being situated within the general region of the Volga Basin, as both early and late Eocene diatomites outcrop there. Recently, attention has focused on the Mesozoic radiolaria from this region, but little work has been carried out on the precise stratigraphy of diatoms from here. Almost all published material is in Russian (e.g. Glezer *et al.* 1974) and in any case does not give detailed descriptions of outcrops. This situation is unfortunate, as specimens from these localities are well-preserved, and would allow comparisons to be made with the Eocene and Oligocene diatoms found sporadically in samples from the North Sea.

3.1.3 Sampling of Study Material

Material from exploration wells consisted of three types of sample:-

1) Cores: these normally consist of continuous rock cylinders. They are extremely expensive to drill, as the whole of the drill-string needs to be recovered at the surface in order to bring up the intact core (a "round trip"), which causes a considerable delay in drilling. Consequently, they are normally only taken through intervals held to be potential hydrocarbon reservoirs. They are therefore most commonly taken in sandstones and limestones, and often contain few microfossils other than palynomorphs. However, where fossils do occur they are obviously *in situ* and of great use for correlation.

2) Side Wall Cores (SWC): a miniature core, of approximately 25mm x 75mm, is taken from the side wall of an exploration well by firing a hollow "bullet casing" into the rock. The depth of these is accurate to within 0.5 metres. As with cores, any contained fossils are *in situ.*

3) Ditch Cuttings (DC): these, the most widely available samples from exploration wells, consist of rock chippings which are returned to the surface in the drill mud after the drill head has penetrated a particular stratum. They are accurate to between 3 and 10 metres depending on the speed of drilling and casing levels. Unlike cores and SWC, DC may contain chippings from higher levels in the hole (cavings) brought up in the drilling mud, which can cause confusion when trying to ascertain the age of a

given sample which may be compounded by the effects of mud contamination. Therefore, only the first downhole occurrence (FDO) or "top" of a particular microfossil is recorded when using DC samples, in order to minimise the effects of caving. The main advantage of these samples is that they represent a variety of lithologies covering a wide interval. Ideally, the study of a particular well would include all three types of sample, but in practice this is rarely possible.

3.1.3.1 Sample selection

The selection of number of samples and their position within a well was initially decided after consultation with staff at British Petroleum Development Ltd., Glasgow. Diatoms occur only sporadically within the North Sea Tertiary sequence, and by directing processing towards intervals known to contain diatom assemblages valuable processing time was saved and more attention could be focussed on detailed taxonomic and preservational problems via electron micrography. After the successful recovery of these assemblages in the first wells analysed (and the careful noting of the characteristic formations and lithologies containing diatoms), samples from further wells could be selected with relative confidence. A lack of suitable wells available (see above) meant that the study was extended to a survey of the BP diatom reference collection. The total number of samples analysed from each well is listed in Table 3.1 (p. 64).

3.1.4 Preparation of Study Material

3.1.4.1 Diatom Recovery

Initially, the standard procedures for diatom preparation (including the use of Hydrogen peroxide, Battarbee 1986) were conducted on DC samples from BP wells 15/28a-3 and 21/9-1. However, it quickly became apparent that the vast majority of diatoms recovered were replaced or infilled with pyrite. As Hydrogen peroxide has an adverse effect on pyrite, an alternative technique was implemented (Table 3.2, p. 65).

WELL NUMBER	DC	CORE	SWC	TOTAL
15/28A-3	58	0	0	58
21/9-1	43	16	0	59
16/13A-4	0	16	0	16
16-13A-5	0	16	0	16
*3/30A-4	4	0	0	4
*16/16A-3	2	0	0	2
*22/6-1	0	2	0	2
*22/6A-2	2	0	0	2
*208/15-1	1	0	1	2
*21/10-1	1	0	0	1
*22/6A-6	0	0	1	1
	111	**50**	**2**	**163**

* = Samples from BP diatom reference collection

Table 3.1 Offshore sample provenance

Stage 1	Dry sample is boiled in water and sodium hydroxide ($NaOH$) to disaggregate the sediment.
Stage 2	Sample plus water is wet-sieved through a 63-micron sieve to remove the finest clay. Care is required to ensure that any heavy particles are retained from the <63 micron fraction, in order to recover any small pyritised diatoms.
Stage 3	Residues are oven-dried, and dry-sieved into different size-fractions.
Stage 4	Each size fraction is spread onto a picking tray and picked under a Wild incident-light microscope, using a fine brush. A maximum of four trays is picked per sample. Very small diatoms (<45µm) are picked using a pig's eyelash, affixed to a piece of wooden dowelling with araldite glue (Sims 1989).
Stage 5	Picked diatoms are placed in microfaunal slides, each morphology being placed into a numbered grid square.

Table 3.2 Processing techniques used in this study

Despite early reservations regarding possible corrosion of any residual silica preserved on the pyritised moulds, it was found that this procedure was the most effective for maximum recovery of diatoms. To test whether any corrosion was occurring, it was decided to carry out a control, involving boiling a duplicate sample in water without the $NaOH$. SEM examination of diatoms from the 2 differently-processed samples revealed no evidence of dissolution or corrosion, and so it was decided to continue the processing technique outlined above.

Samples from BP cores 16/13a-4 and 16/13a-5, Viking Graben (see above) were also processed for diatoms. Containing highly-indurated, well-laminated claystones (with lignite and fish-debris) intercalated with ash-bands and with carbonate concretions, these cores held good potential for recovery of both pyritised and non-pyritised diatoms as a similar lithology from the Norwegian Sector had yielded a well-preserved diatom assemblage (Malm *et al.* 1984). Initial smear slides taken from the most promising intervals (i.e. concretionary layers) revealed no preserved diatoms, and so the samples were subjected to more prolonged processing.

Due to the highly-indurated nature of the core samples, and the fragility of any non-pyritised diatoms which may be present, it was decided to break down the rock fragments by freeze-thaw, a technique used successfully by J. Hinchey (*pers. comm.* 1993). This involved soaking the rock in water for 24 hours, then placing it in a freezer for a further 24 hours, and finally dropping the frozen sample into boiling water. While this proved effective in breaking down the sample, examination of the broken-down residue revealed only a few, poorly-preserved pyritised diatoms. Subsequent processing with hydrogen peroxide produced no further diatoms.

Strewn slides containing well-preserved, non-pyritised diatoms (as well as silicoflagellates, ebridians, radiolaria and archaeomonads) were also examined from the Fur Formation, Denmark (see above). These were sent to the Natural History Museum by Dr. M. Homann, and had been previously processed and cleaned. In any case, the extreme purity of many of the layers of diatomite from which these samples came meant that minimal processing was required (Homann 1991, p. 13). Therefore, it was only necessary to take a pipetted sample from each phial and dry it at on a mica strip at normal room temperature, before picking and/or coating the sample for SEM examination. Strewn slides from each sample provided by Dr. Homann were mounted by K. Childs, and are now housed in the diatom collections at the Natural History Museum, London. A minimum of four hundred specimens were counted from each of these slides, and in addition silicoflagellates and radiolaria were included and logged (Chapter 5).

Electron micrographs of specimens from all localities were taken using the JEOL T-200 Scanning Electron Microscope (SEM) and its successor the Zeiss DSM 940 at U.C.L., as well as the Hitachi S-800 field emission SEM at the Natural History Museum. Some specimens in the strewn slides from Fur, Denmark were also photographed via the transmitted light camera microscope, under phase-contrast light in order to illustrate the differential silicification of some of the diatom taxa. Due to the extreme opacity of both the pyritised and calcified diatoms which formed the majority of specimens examined, it was not decided to photograph these in transmitted light. Identification of diatoms was helped by the publication, during the course of the present study, of a monograph on the diatoms of the Fur Formation by Homann (1991). However, whilst of undeniable value this publication only included light microscope photographs of diatoms, and it often proved difficult to determine the status of the 3-dimensional, pyritised morphologies from the North Sea using this reference alone. Therefore, it was decided to photograph specimens from strewn slides sent by M. Homann (see above) via the SEM, and this approach proved extremely effective in determining the identity of the North Sea morphotypes, many of which only had fragmentary remains of the original characters used for species level taxonomy. In the course of this work it became necessary to emend some of Homann's species designations. This was facilitated by referring to the original species descriptions and illustrations (e.g. Heiberg 1863; Grunow 1884; Schmidt 1874-1959) and, where possible, the holotypes. Unfortunately, many of the original specimens housed in the Natural History Museum were mounted in canada balsam, and so SEM observation of these was not possible. Nevertheless, some of Homann's descriptions were found to be invalid and these are discussed in Chapter 4.

Silicoflagellates, found in the samples from Fur, were identified by reference to Perch-Nielsen (1976 & 1985). These proved of great biostratigraphical use, and allowed the accurate placing of samples within Perch-Nielsen's (1976) scheme.

3.1.4.2 Differential Preservation: Microprobe Analysis

SEM observation of diatom specimens from different localities around the North Sea showed considerable variations in preservational style, with many specimens replaced and/or infilled with pyrite and other authigenic minerals. However, the degree of pyritic replacement and the identity of the mineral encrusting the specimens were not known, and as it was felt that this would give valuable information about palaeoenvironments and diagenetic history, it was decided to subject selected specimens to energy-dispersive X-ray microprobe analysis (EDX). This was conducted using a Link An-10000 EDX Microanalysis System in the Mineralogy Department of the Natural History Museum, London under the supervision of Dr. T. Williams. Specimens were selected from the central part of the North Sea Basin (BP well 15/28a-3) and from the basin margin (Knokke no.1 well), with an unpyritised diatom frustule from the Fur Formation used as a control. The results of this investigation are discussed in Chapter 6.

PART II: RESULTS AND DISCUSSION

4. TAXONOMY

5. BIOSTRATIGRAPHY

6. PRESERVATION OF DIATOMS IN NORTH SEA PALAEOGENE SEDIMENTS

7. DIATOMS AND PALAEOENVIRONMENTS DURING THE PALAEOGENE IN THE NORTH SEA BASIN

8. CONCLUSIONS

4: TAXONOMY

4.1 Introduction

The vast majority of diatom morphologies which occur in the Palaeogene sediments in and around the North Sea Basin have never been formally identified. This is due to a) preservational problems related to both original palaeoenvironmental regime and strong diagenesis; and b) a lack of detailed SEM study (with the notable exception of the Fur Formation of northern Denmark, see Homann 1991). Consequently, workers in the oil industry who encounter these microfossils have tended to assign **morphotype numbers** to the diatom morphotypes, many of which are of stratigraphical importance (see King 1983; Knox & Holloway 1992; Mudge & Copestake 1992a, b; Copestake 1993). Unfortunately, there exists no standardised scheme and so there is a considerable amount of confusion regarding the status of the majority of these morphotypes. The few published sources refer to the widespread occurrences of *Coscinodiscus* spp. 1 and 2 (Bettenstaedt *et al.* 1962) and a few other forms (see King 1983) whose taxonomic status is uncertain. In most cases, any large, circular diatom encountered is placed within the "dustbin" genus *Coscinodiscus* (a common practice among marine diatom workers, even where well-preserved specimens are available).

To date, the only published occurrence of well-preserved Palaeogene diatoms from the North Sea is by Malm *et al.* (1984), who recovered a remarkably preserved, partially unpyritised, North Sea diatom assemblage from calcareous concretions in the Balder Formation, which gives an insight to the original species composition prior to diagenesis. Certain age-diagnostic silicoflagellates indicate that this assemblage correlates with the upper part of the Fur Formation (Silstrup Member, Pedersen & Surlyk 1983; Chapter 3), which is further borne out by the close similarity of the diatom species composition from both localities.

4.2 Taxonomy of pyritised diatoms: rationale

During the course of the present investigation it has become apparent that, although extremely badly preserved specimens are often encountered, it is nevertheless possible to identify accurately a number of taxa using high-resolution electron microscopy. A large percentage of the specimens recovered occur as pyritised inner moulds (**steinkerns**, see McNeill 1990), on which the original structure of the inside of the valve is often preserved. Thus, it is possible to identify a number of taxa whose valves are known to possess characteristic internal features such as labiate processes, whilst the general pattern of areolae may often be observed. Sometimes, there may be complete replacement of the siliceous frustule by pyrite, in which case the external features can be distinguished, often with a surprising degree of clarity (for example, many of the specimens recovered from the Ieper Formation, Belgium and the Ølst Formation, Denmark). Occasionally, a veneer of original silica is preserved on the surface of an otherwise pyritised specimen which greatly facilitates identification. This phenomenon tends to affect only the more heavily-silicified taxa, such as *Fenestrella antiqua* (Grunow) Swatman and *Stellarima microtrias* (Ehrenberg) Hasle & Sims, and its presence is usually indicated by an iridescent "sheen" on the specimen when first observed during routine picking.

An additional feature of steinkerns is that they preserve the original shape of the whole diatom frustule. Non-pyritised fossil diatoms are usually encountered as isolated valves (exacerbated by the cleaning process), and it is often impossible to ascertain the size and positioning of girdle bands in relation to the valve margin (which may vary between vegetative cells and auxospores). In this study, it has therefore been possible to emend species descriptions, to include the frustule dimensions (e.g. *Fenestrella antiqua* (Grunow) Swatman).

4.2.1 SEM versus LM: identification of valid characters

There is at present much debate regarding the viability of using characters present on the inside of the diatom valve to distinguish between certain species (see Round *et al.* 1990, p. 120-1 for an overview). This is especially true of the genus *Coscinodiscus*, a notoriously difficult genus to identify to species level even when well-preserved specimens are available. Often the SEM is necessary to resolve differences which cannot easily be distinguished in the LM (although many features can be seen in well-preserved specimens). Consequently, certain species encountered during biostratigraphical and environmental studies are often left in open nomenclature. This situation is far from ideal, especially if the species involved are of particular stratigraphic importance. Fortunately the use of the SEM has become more widespread, and is now more of a routine tool as models have become cheaper and more portable. However, for the present study it was decided not to concentrate on features which are less than 5 μm in diameter (many of which are not preserved in pyritised specimens). Species descriptions from taxonomic monographs are therefore presented in abridged form, to include those features which can easily be identified on moderately preserved specimens.

The SEM has proved invaluable during the present work, as it has enabled the taxonomic identification of poorly preserved specimens which are opaque when observed via LM. The SEM has also enabled the matching of species with gross morphologies so that taxa may be identified during later routine picking. This is particularly successful for the larger species, but is of limited use for some of the smaller (30-80μm) centric species, many of which have very similar valve morphologies. Fortunately, these normally form only a minor constituent of assemblages and are long-ranging, and consequently of little stratigraphical value.

Many of the taxa described herein are found in the aforementioned Fur Formation diatomite, which contains a rich and varied flora of diatoms preserved in original biogenic silica (or possibly its phase-change equivalent, see Chapter 6) and described in some detail in the monograph by Homann (1991). She emended a number of taxa, many of which had been previously described in the last century (e.g. Heiberg 1863; Grunow 1884; Schmidt 1874-1959). However, all specimens in Homann's monograph were photographed at LM level only. During the course of present study, specimens of some of these taxa were examined via SEM for comparison with morphotypes from the North Sea, and it was found that some of Homann's descriptions had to be re-emended. SEM examination of the comparative material also revealed the presence of a new diatom genus (see 4.6.2). This may have been overlooked by Homann as it was found in a sample containing a large amount of siliceous debris, which obscures most of the valve when viewed in the LM.

4.3 Diatom Taxonomy: a state of flux

"With no absolute guide to the size of discontinuity for separation [of diatoms] at a given rank, and no universally applicable, objective criteria for the delimitation even of species....we must admit that our taxonomy is never likely to be free from bias and distortion. However, in many cases the data make it obvious that taxonomic revision is necessary" (Round *et al.* 1990, p. 120).

A number of authors have commented on the relatively chaotic present state of diatom taxonomy (Round *et al.* 1990, pp. 117-123; Nikolaev 1990; Edwards 1991; Cox 1993; Williams 1993). This situation is a function of the often conflicting criteria used to distinguish taxa, both at species level and variation within species. For example, the use of the concept of sub-species has not gained universal acceptance among diatom workers, who use the terms **variety** and **forma** to distinguish intraspecific morphological variation, which is displayed by many diatoms. Some taxa have been split into a bewildering number of varieties and formas. In the case of chain-forming diatoms (such as *Paralia* and *Trinacria* in the present work) this is due to a lack of study of complete chains, as the valves at the ends of these chains (**separation valves**, see Crawford *et al.* 1990) have different features to those within the chain itself (**linking valves**).

The term **forma** should ideally be retained only for variations within a given population of a diatom species which are due to environmental stress, i.e. teratological or ecophenotypic variations. This variation usually takes the form of distortion, in alignment of areolae and sometimes valve shape. Ecophenotypic variation can be demonstrated in living populations, but can only be inferred in fossil assemblages.

By contrast, the term **variety** in diatom (and other botanical) nomenclature is analogous to **subspecies** in zoological taxonomy, and signifies that a change in the genetic make-up of a taxon is occurring (P.A. Sims, *pers. comm.*), i.e. a feature is seen consistently in specimens from different localities. This is the case with a number of taxa in the present study, which it has been necessary to divide into varieties (e.g.

Coscinodiscus morsianus (Grunow) Sims; *Aulacodiscus aemulans* Hustedt).

4.4 Diatom Systematics

As discussed above, there is considerable confusion at present in the world of diatom systematics; the arguments for and against different concepts of classification (e.g. Williams 1993) are outside the scope of the present work. Round *et al.* (1990, pp. 125-9) attempted to resolve some of the difficulties by reviewing and revising the fundamental relationships between different sub-orders of diatoms. Whilst there are some reservations surrounding their scheme, it is the first comprehensive appraisal of diatom systematics for some years, superceding the earlier scheme of Simonsen (1979) and taking into account new advances gained through the greater use of the SEM. An abridged version of the classification of Round *et al.* 1990 is shown in Table 4.1 (p. 74).

4.5 Diatom Nomenclature

The terminology used to describe gross morphological features of the diatom frustule follows that in Hustedt (1930); Anonymous (1975); Barber & Howarth (1981); whilst ultrastructural features, observable via SEM, are given in Ross & Sims (1970); Ross & Sims (1985, 1987); Round *et al.* (1990).

4.6 Location of material

Specimens are housed in the following locations:

a) Micropalaeontology Unit, University College London.
Included here are all pyritised specimens described herein. Catalogue numbers are given in the plate descriptions.

b) Diatom Section, Botany Department, Natural History Museum, London.
Included here are all specimens from the Homann collection (see plate descriptions); in addition to specimens labelled "Fur Nykøbing".

Division BACILLARIOPHYTA

NB: Typefaces used for each classification are as follows:

CLASS SUBCLASS *ORDER* Family *Genus*

COSCINODISCOPHYCEAE (Centric diatoms)

THALASSIOSIROPHYCIDAE

COSCINODISCOPHYCIDAE
- *MELOSIRALES*
  - Stephanopyxidaceae
    - *Stephanopyxis*
  - Hyalodiscaceae
    - *Hyalodiscus*
- *PARALIALES*
  - Paraliaceae
    - *Paralia*
- *COSCINODISCALES*
  - Coscinodiscaceae
    - *Coscinodiscus, Brightwellia*
  - Stellarimaceae
    - *Stellarima, Fenestrella*
  - Aulacodiscaceae
    - *Aulacodiscus*
  - Heliopeltaceae
    - *Actinoptychus*
- *ASTEROLAMPRALES*
  - Asterolampraceae
    - *Asterolampra*
- *ARACHNOIDISCALES*
  - Arachnoidiscaceae
    - *Arachnoidiscus*

BIDDULPHIOPHYCIDAE
- *TRICERIATIALES*
  - Triceratiaceae
    - *Triceratium, Odontella, Cerataulus*
- *HEMIAULALES*
  - Hemiaulaceae
    - *Hemiaulus, Trinacria*

LITHODESMIOPHYCIDAE

CORETHROPHYCIDAE

CYMATOSIROPHYCIDAE
- *CYMATOSIRALES*
  - Rutilaraceae
    - *Rutilaria*

RHIZOSOLENIOPHYCIDAE
- *RHIZOSOLENIALES*
  - Rhizosoleniaceae
    - *Rhizosolenia*

CHAETOCEROPHYCIDAE

Table 4.1 Diatom classification (after Round, Crawford & Mann 1990; with the addition of the family Stellarimaceae Hasle & Sims 1990). NB: only orders and families represented in the present study are included here.

FRAGILARIOPHYCEAE (Araphid, pennate diatoms)

FRAGILARIOPHYCIDAE
  RHAPHONEIDALES
    Rhaphoneidaceae
      Rhaphoneis, Sceptroneis

BACILLARIOPHYCEAE (Raphid, pennate diatoms)

EUNOTIOPHYCIDAE

BACILLARIOPHYCIDAE

Table 4.1. Diatom classification (continued)

4.7 List of diatom species identified during this study, with page reference

NB. Species marked with an asterisk (*) were only identified in non-pyritised form, in samples from the Fur Formation. Their full taxonomic descriptions are found in Homann (1991); it was not considered necessary to emend these, although comments have been made on some of the more significant species encountered (see 4.8.2).

Species	**Page**
Actinoptychus senarius (Ehrenberg) Ehrenberg, emend. Andrews & Abbott	114
Actinoptychus senarius resting spores	115
**Arachnoidiscus indicus* Ehrenberg	151
Asterolampra insignis A. Schmidt	118
Asterolampra marylandica Ehrenberg	119
Asterolampra sp.	120
Aulacodiscus allorgei Chenevière	105
Aulacodiscus heterostictus Barker & Meakin	106
**Aulacodiscus hirtus* Barker & Meakin	151
Aulacodiscus insignis Hustedt, emend.	107
Aulacodiscus insignis var. *aemulans* (Hustedt) Mitlehner MS	108
Aulacodiscus insignis var. *quadrata* (King) Mitlehner MS	109
Aulacodiscus singiliewskyanus Barker & Meakin	110
Aulacodiscus subexcavatus Hustedt	112
Aulacodiscus suspectus A. Schmidt	113
Brightwellia spiralis Glezer	92
Brightwellia? sp.	93
Cerataulus ?weissflogii Pantocsek	124
**Coscinodiscus* ex gr. *argus* Ehrenberg *sensu* Homann	151
Coscinodiscus morsianus var. *morsianus* comb. nov.	88
Coscinodiscus morsianus var. *moelleri* Mitlehner MS	89
**Coscinodiscus moelleri* A.Schmidt	151
**Coscinodiscus radiatus* Ehrenberg	151
Coscinodiscus ?radiatus	91

Species	**Page**
Cylindrospira simsi Mitlehner, sp. nov. MS	148
Cylindrospira homanni Mitlehner, sp. nov. MS	150
Fenestrella antiqua (Grunow) Swatman, emend.	99
Fenestrella antiqua auxospores	101
Fenestrella antiqua initial cells	102
Fenestrella antiqua resting spores	103
**Goniothecium odontella* var. *danica* Grunow	151
**Hemiaulus* cf. *H. curvatulus* Strel'nikova	151
**Hemiaulus danicus* Grunow	151
**Hemiaulus elegans* (Heiberg) Grunow, emend. Homann	151
Hemiaulus ?elegans (Heiberg) Grunow, emend. Homann	126
**Hemiaulus februatus* Heiberg	151
**Hemiaulus hostilis* Heiberg	152
**Hemiaulus kittonii* Grunow	152
**Hemiaulus mitra* Grunow, emend. Homann	152
**Hemiaulus muticus* Strel'nikova	152
**Hemiaulus polymorphus* Grunow	152
**Hemiaulus polymorphus* var. *morsiana* Grunow	152
**Hemiaulus proteus* Heiberg	152
**Hemiaulus pungens* Grunow, emend. Homann	152
Hemiaulus? sp.	126
**Hyalodiscus* ex gr. *laevis/subtilis* sensu Grunow	152
Odontella heibergii Grunow	122
Odontotropis carinata Grunow	137
Odontotropis cristata Grunow	138
**Odontotropis hyalina* Witt, emend. Homann	152
**Omphalotheca jutlandica* Grunow, emend. Homann	146
*"*Paralia ornata*" Grunow	152
Paralia siberica (A. Schmidt) Crawford & Sims	83
**Paralia siberica* var. *laevis* Crawford	152

4.8 Systematic Palaeontology

4.8.1 Morphologies found in pyritised form during the present study

General remarks. A number of the featured taxa are illustrated and described in the major floras (e.g. Pantocsek 1886-1905; Schmidt 1874-1959; Hustedt 1927-1966). However, few descriptions are in the English language and so it was decided to include the generic descriptions given in Round, Crawford & Mann (1990); these give clear, concise summaries of defining characteristics, and include features observable in the SEM. Other species-level descriptions were translated directly from German, e.g. Benda (1965); Homann (1991).

Terminology. A number of the taxa described here have been revised in recent years, to take into account SEM observations. These are referred to under "*Revised diagnosis & description*". In addition, it has sometimes been necessary to further emend descriptions, as pyritised morphotypes usually preserve the original frustule shape with girdle bands intact, a feature not often observed in non-pyritised specimens which are usually preserved as isolated valves. Any further revision is referred to under "*Emended diagnosis (herein)*".

"*Dimensions.*" Dimensions given refer to size ranges.

The following abbreviations are used:

LM = light microscope

MS= Manuscript name. Species described or emended herein, but not formally published.

SEM = scanning electron microscope

SPT = Simon Petroleum Technology (formerly Robertson)

? = referrable to a described genus and/or species, but all the diagnostic features in the original diagnosis are not clear in specimens seen in the current study, due to poor preservation.

Bold =pyritised form

4.8.1 TAXONOMIC DESCRIPTIONS OF PYRITISED DIATOMS

Division BACILLARIOPHYTA

Class COSCINODISCOPHYCEAE Round & Crawford, in Round *et al.* 1990
Subclass COSCINODISCOPHYCIDAE Round & Crawford, in Round *et al.* 1990
Order *MELOSIRALES* Crawford, in Round *et al.* 1990

Family STEPHANOPYXIDACEAE Nikolaev, 1983

Remarks. One of a number of diatom families represented by a single genus.
Included genus: Stephanopyxis Ehrenberg
Stratigraphic Range. Lower Cretaceous (Albian) to Recent (Harwood & Gersonde 1990).

Genus STEPHANOPYXIS Ehrenberg, 1845

Type Species: Stephanopyxis aculeata (Ehrenberg) Grunow, 1884

Description "Cells cylindrical to almost spherical, joined by processes into long filaments. Valves domed, hemispherical to discoid; without obvious distinction into valve face and mantle. areolae large, hexagonal, opening outwardly by large foramina in shallow chambers Areolae more regularly arranged towards the valve centre. A ring of tubular processes is present; in some fossil forms additional processes occur at the centre. The processes arise as extensions of the walls of the areolae and articulate with those of the sibling valve" Round *et al.* 1990, p. 158.
Remarks. P.A. Sims (*pers. comm.* 1992) refers to the shallow chambered areolae as pseudoloculae.

A very distinctive diatom genus, whose documented range extends from the Albian stage of the Cretaceous (and possibly earlier, Harwood & Gersonde 1990) to Recent. It exhibits a wide variation in morphology, even within species. A common marine planktonic genus, mainly tropical in distribution but carried into colder waters by currents. Common in fossil deposits where more species are documented, some of which may be resting spores; as with many long-ranging genera, fossil species are more heavily-silicified than extant taxa.

Stephanopyxis ?*turris* (Greville & Arnott) Ralfs

Pl. 1, figs. 2-3.

1981 "Spherical diatom" HUGHES: pl. 15.3, fig. 9.

?1991 *Stephanopyxis turris* (Greville & Arnott) Ralfs var. *cylindrus* Grunow. HOMANN: 57, pl. 38, figs. 1-11.

Number of specimens recovered: 1 (pyritised)

Description. Valve domed, hemispherical with no distinction into valve face and mantle. Areolae large (3 in 10 µm), hexagonal, arranged more regularly towards valve centre, and bounded by distinctive nodes (pseudoloculae). No processes are distinguishable due to poor preservation, and only tentative species determination is possible.

Dimensions. Valve diameter 55 µm.

Remarks. Only one specimen recovered from offshore well samples, preserved on a pyritised specimen of *Trinacria regina*. The latter is very abundant in the sample and is also common in the coeval Fur Formation, and so the *in situ* nature of this taxon is not in doubt. It may have been common in the original assemblage (see Malm *et al.* 1984, fig. 8), although this predominantly neritic species may not have been abundant in the more central, deeper parts of the North Sea Basin.

Occurrence (this work). BP well 21/9-1, central North Sea, top Balder Formation.

Stratigraphic range (literature). Middle Eocene: North Sea (Hughes 1981).

Order *PARALIALES* Crawford, in Round *et al.* 1990

Family PARALIACEAE Crawford 1988

Remarks. Centric, chain-forming diatoms characterised by robust valves with radial markings on the valve face.

Included genera: Paralia, Ellerbeckia.

Stratigraphic Range. Upper Cretaceous (Campanian) to Recent.

Genus PARALIA Heiberg, 1863

Type species. Paralia marina (W. Smith) Heiberg, 1863

Description (abridged). "Cells shortly cylindrical, linked to form straight chains. Valves robust, circular, with radial markings on the valve face. Valve face and margins sharply differentiated. Sibling valves within chains linked via well-developed interlocking ridges and grooves, and by marginal spines; cameo (relief) and intaglio valves occur. The relief valves have stepped mantles. At the ends of each chain are separation valves, with reduced ridges and no marginal spines. Copulae numerous, open" (Round *et al.* 1990, p. 166).

Remarks. Paralia is a chain-forming diatom, with species common in the fossil record and in coastal environments today. It is characterised by having a very complex valve morphology (see the taxonomic revision of *P. sulcata* by Crawford, 1979). As with other chain-forming genera (see *Trinacria regina* in the present study), a number of forms have been illustrated which are in fact different valves within a chain.

Paralia siberica (A. Schmidt) Crawford & Sims

Pl. 1, figs. 4-6.

1893 *Melosira siberica* A. SCHMIDT: Taf. 177, figs. 12-22.

1990 *Paralia siberica* comb. nov. CRAWFORD *ET AL.*: 246, figs. 1-30.

var. *siberica*

1893 *Paralia sulcata* var. *siberica* sensu A. SCHMIDT 1892-3, Taf. 175, figs. 9, 15 **non** (Grunow) Grunow.

1893 *Paralia sulcata* var. *siberica* forma *coronata* sensu A. SCHMIDT 1892-3, Taf. 175, fig. 11 **non** Grunow.

1893 *Paralia sulcata* var. *siberica* forma *radiata* GRUNOW ex A. SCHMIDT 1892-3, Taf. 175, figs. 12-14 pro parte, quoad fig. 13.

1991 *Paralia sulcata* (Ehrenberg) Cleve var. *siberica*. HOMANN: 53, Pl.

var. *laevis* Crawford, 1990

1882 *Melosira sulcata* var. *siberica* GRUNOW in VAN HEURCK, Pl. 91, fig. 22.

1884 *Paralia sulcata* var. *siberica* (Grunow) GRUNOW: p. 94.

1884 *Paralia sulcata* var. *siberica* forma *coronata* GRUNOW: p. 95, Taf. 5 (E), fig. 36.

1882 *Melosira sulcata* var. *biseriata* forma *coronata* GRUNOW in VAN HEURCK, Pl. 91, fig. 24.

1884 *Paralia sulcata* var. *biseriata* forma *coronata* (Grunow) GRUNOW: p. 94.

1892 *Paralia rossica* sensu A. SCHMIDT, Taf. 175, fig. 10, non Pantocsek.

1984 *?Brightwellia* sp. 1. MALM *ET AL.*: 158, fig. 8m.

1990 *Paralia siberica* var. *laevis* Crawford, var. nov. CRAWFORD *ET AL.*: 246, figs. 7-24.

1991 *Paralia sulcata* (Ehrenberg) Cleve var. *biseriata*. HOMANN: 52, Pl. , figs.

Number of specimens recovered: 9 (pyritised); 4 (non-pyritised, Fur Formation)

Revised diagnosis & description. Crawford *et al.* 1990, p. 248.

Dimensions. Valve diameter 40-80 µm. Length of chains variable, from 40-100 µm.

Remarks. Crawford *et al.* (1990) conducted a thorough taxonomic revision of *Melosira siberica*, moving it to *Paralia* and distinguishing it from the extant species *P. sulcata.* Both are closely related, but exhibit a number of contrasting features at SEM level which are described in Crawford *et al.* (*ibid.*, p. 248). The stratigraphic ranges of the species are different, *P. sulcata* ranging from Miocene to Recent whereas P. siberica is restricted to Paleocene and Eocene (and possibly Oligocene) sediments. Therefore, all of the morphotypes of *Paralia* encountered in North Sea Palaeogene sediments can be assigned to *P. siberica.*

Chains and individual valves of *P. siberica* are found sporadically through the Palaeogene of the North Sea, as pyritic infillings. Although surface details, such as radial markings on the valve surface, are not normally preserved, the separation valve (see Crawford *et al.* 1990, fig. 19) at the end of the chain is identifiable due to its raised central area. In addition coarse ribs, which correspond to the edges of each valve within a chain, can also be recognised.

Two varieties of *P. siberica* were described by Crawford *et al.* (1990), *laevis* and *siberica*. Unfortunately the feature which distinguishes these, i.e. the presence or absence of papillae on the surface of the valves (see figs. 25-30 in Crawford *et al.* 1990) could not be identified in pyritised specimens, and so it was not possible to place these within the varieties. A further variety was figured by Homann (1991) as *Paralia ornata* Grunow, and also by Malm *et al.* (1984) as *?Brightwellia* sp. This has not been formally placed, but is certainly a variety of *P. siberica*.

P. siberica is known informally under various morphotype numbers, e.g. "*Coscinodiscus*" sp. 19 (Haliburton); "Diatom spp. 64 & 66" (SPT).

Occurrence (this work). BP well 15/28a-3, central North Sea: Sele, Balder, Horda and Lark formations. Fur, Denmark: Fur Formation.

North Sea range (unpublished). Paleocene to Oligocene (SPT).

Range (literature). Paleocene: Russia, Ulyanovsk oblast ("Ananino", "Simbirsk", see Crawford *et al.* 1990).

?Eocene: Russia, Sverdlovsk oblast ("Kamischev", Crawford *et al.* 1990).

Order: *COSCINODISCALES* Round & Crawford, in Round *et al.* 1990

Family COSCINODISCACEAE Kützing, 1844

Remarks. The largest family of diatoms. All forms are solitary, planktonic and often large (up to 300 µm in diameter).

Extensive ultrastructural studies have recently led to the splitting away of the genera *Stellarima* and *Fenestrella*, formerly included in the Coscinodiscaceae into the new family Stellarimaceae (Sims & Hasle 1990). Both genera have been found to be abundant in the Palaeogene of the North Sea, and are described in detail under the relevant entry below.

SEM studies undertaken during the present work have confirmed the suggestion by Sims (1989) that the genus *Craspedodiscus* is invalid, and is herein considered to be a variety of *Coscinodiscus* sensu stricto. This is discussed further under the entry for *Coscinodiscus morsianus*.

Included genera: Coscinodiscus, Craspedodiscus, Brightwellia, Palmeria.
Stratigraphic Range. Upper Cretaceous to Recent.

Genus COSCINODISCUS Ehrenberg, 1838

Type species. Coscinodiscus argus Ehrenberg, 1838

Revised description. "Cells discoid or drum-shaped. Numerous parietal discoid chloroplasts. Cells solitary. Cingulum consisting of a wide collar-shaped valvocopula and mostly two narrower bands, all with regular rows of small areolae. Valves usually circular, flat or more or less convex. A central hyaline area or a central rosette of areolae present or absent. Loculate areolae with external vela and internal foramina in radial and sometimes, secondary spiralling rows. One marginal ring of labiate processes including two larger ones, sometimes a second ring on the valve mantle and one or more irregular rings on the valve face. All processes projecting internally but not externally" (Hasle & Sims 1986b, p. 316).

Remarks. Approximately 400 species of *Coscinodiscus* have been described, mainly from Recent material. A genus into which many large, discoidal diatoms are "dumped" by workers unsure of correct taxonomic status. Some revisions have taken place, with species being moved to newly-erected genera such as *Azpeitia, Fenestrella* and *Stellarima.* Other species have been moved to the genus *Thalassiosira.*

Few studies have been carried out on pre-Neogene species of *Coscinodiscus.* Sims and others have recently shown that a number of Cretaceous and Palaeogene species in fact belong to other genera (Hasle & Sims 1986a; Sims 1990). This has been found to be the case with a number of the morphologies from North Sea Palaeogene sediments, hitherto assigned to *Coscinodiscus.*

However, it should be noted that *Coscinodiscus* is a notoriously difficult genus to identify at species level, as many of the features used to distinguish between species are often only readily identifiable via SEM. Comparative studies undertaken during the present work have shown that some of the species designations of Homann (1991) are incorrect (see below), whilst others are probably valid.

Coscinodiscus morsianus (Grunow) Sims, emend.

Pl. 1, figs. 7-11; pl. 2, figs. 1-5.

1940 *?Coscinodiscus* (bikonkav). STAESCHE & HILTERMANN: 15, Pl. 6, fig. 4.
1943 *Coscinodiscus* sp. (bikonkav). WICK: 5, pl. 1, figs. 67-89.
1962 *Coscinodiscus* sp. 2 Bettenstaedt *et al.* in SIMON & BARTENSTEIN: 358, pl. 20, fig. 20 a-b.
1975 Coscinodiscus sp. 2. JACQUÉ & THOUVENIN: 462, pl. 2, fig. F.
1981 *Coscinodiscus* sp. 2, Bettenstaedt et al. 1962. HUGHES: 191, pl. 15.3, fig. 12.
1981 *Coscinodiscus sp. 4*. THOMAS & GRADSTEIN: 19, Pl. 3.1, figs.13-16.
1983 *Coscinodiscus* sp. 2 Bettenstaedt *et al.* 1962. BIGNOT: 17, pl. 1, figs. 1-4.
1983 Coscinodiscus sp. 2 Bartenstein and others. KING: 20, pl. 1, fig. 3.
1984 *Coscinodiscus* sp. 2. MALM *ET AL.*: 158, fig. 8f.
1989 *Coscinodiscus morsianus* (Grunow) Sims, stat. nov. SIMS: 354, figs. 8-15, 68.

Number of specimens recovered: 140 (pyritised); 70 (non-pyritised, Fur Formation)

Original diagnosis & description. "The valves are circular, 130-320 μm in diameter. Small specimens have a flat valve face, while larger specimens have raised and rounded marginal rims. The areolae are in radial rows with many incomplete rows extending to all areas of the valve face, producing the irregularly branched pattern seen under LM (see fig. 68, Sims 1989). At the beginning of each incomplete radial row is a larger areola (noted as a useful taxonomic character by Fryxell & Ashworth 1988). A circle of much larger, often elliptical areolae is present at the valve centre (the character used by Grunow (1884) to place the species in *C. oculus-iridis* Ehrenberg). There are 3 rows of areolae in 10 μm; the areolae are loculate, with 3 areolae in 10 μm along the rows at mid-radius, and 4 in 10 μm at the centre and margin." (Sims 1989, p. 354).

Emended description. It is herein proposed that specimens of *Coscinodiscus morsianus* (Grunow) Sims possessing a corrugated valve surface be referred to *C. morsianus* var. *moelleri*, whilst those with a more uniform concave or flattened valve face be referred to as *C. morsianus* var. *morsianus*.

Remarks. Both the descriptions in Homann (1991) and SEM observations during the present study confirm that the areolar arrangement and structure of *Craspedodiscus moelleri* (Schmidt) Homann are identical to those of *Coscinodiscus morsianus* (Grunow) Sims. Sims (1989, p. 356), considers that "the separation of *Craspedodiscus* from *Coscinodiscus* rests solely on differences in the contour of the valve face, and is thus no more marked than that between Groups 1 and 2 of *Coscinodiscus*".

Coscinodiscus morsianus has a widespread occurrence in Palaeogene sediments in and around the North Sea Basin. In pyritised form, it is preserved as a discoidal (=single valve) or biconcave (=frustule) internal mould. Specimens from the basal Ieper Formation of N. Belgium are commonly completely replaced by pyrite, preserving the external morphology with surprising clarity. Although whole cribra have not been observed in pyritised specimens, the attachment points are clear in some specimens in both the Belgian and North Sea samples (compare fig. 10, Sims 1989). Two varieties, *morsianus* and *moelleri*, are here described formally.

var. *morsianus*

Pl. 1, figs. 7-11.

1884	*Coscinodiscus oculus-iridis* var. *morsianus*. GRUNOW: 77.
1889	*C. oculus-iridis* var. *morsiana*. RATTRAY: 561.
1965	*Coscinodiscus oculus-iridis* Ehrenberg v. *borealis* (Bailey) Cleve. BENDA: 169, pl. 21, fig. 10, 11.
1981	***Coscinodiscus* sp. 4. THOMAS & GRADSTEIN: 19, Pl. 3.1, figs. 13-16.**
1989	*Coscinodiscus morsianus* (Grunow) Sims. SIMS: 354, figs. 9-15, 68.
1991	*Coscinodiscus* ex gr. *oculus-iridis* Ehrenberg. HOMANN: 43, pl. 13, figs. 1-5.

Number of specimens found: 126 (pyritised); 52 (non-pyritised, Fur Formation)

Original diagnosis & description. As for the species (Sims 1989, p. 354, see above).
Emended diagnosis. Specimens of *Coscinodiscus morsianus* (Grunow) Sims with a concave or flattened valve face, with no surface corrugation.
Dimensions. Valve diameter 80-250 µm.

Remarks. The referral of this taxon to *Coscinodiscus* ex gr. *oculus-iridis* in the monograph by Homann (1991) is considered invalid in the light of the detailed study, at LM and SEM level, of Sims (1989). A similar taxon, called *Coscinodiscus* ex gr. *argus* by Homann, was not positively identified in pyritised form during the present study. Well-preserved specimens of *C.* ex gr. *argus* were examined, however, which portray differences in the valve centre which may or may not be valid characters (Fryxell & Ashworth 1988).

North Sea range. Upper Paleocene to Lower Eocene (King 1983; Mudge & Copestake 1992a & b).

Occurrence (this study). BP wells 15/28a-3 & 21/9-1, central North Sea, upper part of the Balder Formation; Knokke borehole, base of the Ieper Formation, Belgium; Wrabness, Essex, Walton Member of the London Clay; Knudeklint, Hanklit, upper part of the Knudeklint Member, Fur Formation; Ølst, Ølst Formation.

North Sea Range (unpublished). Upper Paleocene to Lower Eocene (SPT).

Range (literature). Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Heiberg 1863; Grunow 1884; Schmidt 1874-1959; Rattray 1889; Benda 1972; Sims 1989; Homann 1991); North Sea (King 1983; Malm *et al.* 1984; Mudge & Copestake 1992a,b).

Lower Eocene: U-Eozän, North Germany (Schulz 1927; Benda 1965); London Clay, England (Shrubsole & Kitton 1881; King 1981); Ieper Formation, Belgium (King 1990); Sparnacian, Paris Basin (Bignot 1983).

Lower Eocene to Miocene: Offshore Eastern Canada (Thomas & Gradstein 1981).

Mid Eocene: Southern North Sea (Hughes 1981).

var. *moelleri* Mitlehner, nom. nov. MS

Pl. 2, figs. 1-5.

1884 *Coscinodiscus annulatus.* GRUNOW: 74, pl. 5, fig. 57.

1893 *Craspedodiscus Mölleri.* SCHMIDT 1874-1959: pl. 184, fig. 3.

1893 *Craspedodiscus Klavsenii.* GRÜNDLER in A. SCHMIDT 1874-1959: pl. 184, fig. 5.

1949 *Craspedodiscus Moelleri.* PROSHKINA-LAVRENKO: vol. 1, pl. 5, fig. 11; vol. 2: pl. 83, fig. 3.

1965 *Craspedodiscus moelleri* A.Schmidt. BENDA: pl. 1, fig. 1.

1981 *Coscinodiscus* sp. 2. THOMAS & GRADSTEIN: 19, Pl. 3.1, figs. 5 & 6.

1989 *Coscinodiscus morsianus* (Grunow) Sims. SIMS: 354, fig. 8.

1991 *Craspedodiscus moelleri* (Schmidt) emend. Homann. HOMANN: 47, pl. 17, 1-5.

Number of specimens found: 14 (pyritised); 18 (non-pyritised, Fur Formation)

Published description. "Valves circular, relief concentric with a corrugated appearance. The central area is either flat or convex, and grades into an annular depression which slopes upward towards the valve margin. Outside of this depression is a thick, broadly convex "ringwall", which is raised above the level of the central area. The width of the "ringwall" is variable, between 20 and 50% of the radius. Central area small, with a distinct rosette. Areolae in radial rows, with a secondary spiral arrangement. Areolae on the "ringwall" are arranged in an enclosed, polygonal network. Areolae in mid-valve depression are more rounded. Central area of the valve with enclosed areolae, 3-4 in 10μm. Isolated areolae may or may not extend around the central rosette ("*Klavsenii*-type"). Distinct sieve membranes often extend around the areolar margins (9-12 puncta in 10 μm)" (translated from Homann 1991, p. 47).

Emended description (herein). SEM studies during the present work have revealed that all areolae have hexagonal walls with a rounded surface, a feature found in all true species of *Coscinodiscus.*

Dimensions. Valve diameter 120-250 μm; areolae 6-10 in 10 μm. Height of mantle at valve margin 10 μm.

Remarks. Homann's (1991) description was at LM level only. As a consequence, it failed to take into account that the areolar shape varies with depth of field, being rounded at the surface but more hexagonal with depth through the valve, so that there will be an apparent variation in areolar shape on any undulating specimen when viewed in the LM. The corrugation of the valve is therefore the only feature separating *C. morsianus* var. *moelleri* from *C. morsianus* var. *morsianus.*

C. morsianus var *moelleri* has a similar distribution to *C. morsianus* var. *morsianus*, but is less common in samples from the deeper parts of the North Sea, being more abundant in neritic assemblages such as the Ieper Formation of northern Belgium. *C. morsianus* var. *moelleri* has a similar distribution in sediments of the same age from offshore Eastern Canada (Thomas & Gradstein 1981).

Occurrence (this work). BP wells 15/28a-3 & 21/9-1, central North Sea: Sele and Balder formations; Belgium: Ieper Formation (base); Wrabness, Essex: London Clay (base); Denmark: Knudeklint Member of the Fur Formation.

North Sea range. As for var. *morsianus* (above), but less common in sections from deep in the basin. Known as "*Coscinodiscus* sp. 77" by SPT.

Range (literature). Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Schmidt 1874-1959; Grunow 1884; Benda 1972, Homann 1991).

Lower Eocene: England, base of London Clay (Shrubsole & Kitton 1881); North Germany (Schulz 1927).

Lower Eocene to Miocene: Offshore Eastern Canada (Thomas & Gradstein 1981).

Coscinodiscus ?radiatus Ehrenberg

Pl. 2, fig. 6.

?1991 *Coscinodiscus radiatus* Ehrenberg *sensu* Grunow. HOMANN: 45, pl. 16, figs. 1-3.

Number of specimens found: 101 (pyritised)

Description. Valves large, circular, flattened. Areolae in radial rows, often infilled.

Dimensions. Diameter of valve 80-120 µm.

Remarks. A number of specimens of flat, centric diatoms have been recovered from Paleocene to Oligocene sediments during the present study. Superficially, they resemble small specimens of *Coscinodiscus morsianus*, but poor preservation precludes accurate species determination. However, the radial alignment of areolae is strongly suggestive of *C. radiatus*, a species common in marine waters at the present day.

This morphotype is known as "*Coscinodiscus* cf. sp. 2 (Bartenstein *et al.* 1962)" in the zonation of SPT.

North Sea range (unpublished). Paleocene to Oligocene.

Occurrence (this study). BP well 15/28a-3 central North Sea: Sele, Balder, Horda, Lark formations.

Genus BRIGHTWELLIA Ralfs in Pritchard, 1861

Type species. Brightwellia coronata (Brightwell) Ralfs

Revised description. Valves round, shallow and saucer-like,with a ring of radially elongate (oval) openings externally separating a central zone of areolae from a marginal zone. Areolae loculate, opening internally by ribbed foramina and externally through cribra. The cribra have large central pores surrounded by a ring of smaller pores. The pores form curving rows. A small plain central area is present" (Round *et al.* 1990, p. 182).

Remarks. An exclusively fossil genus, occurring only in the Eocene and Oligocene. A number of species form important stratigraphic markers (e.g. *B. hyperborea*, Gombos 1977, 1982).

Brightwellia spiralis Glezer

Pl. 2, figs. 10-11.

1964 *Brightwellia spiralis*. GLEZER in SHESHUKOVA-PORETSKAYA & GLEZER: 82-4, Pl. 3, fig. 3.

1983 *Brightwellia spiralis* Glezer. GOMBOS & CIESELSKI: 600, pl. 23, figs. 1-30.

1986 *Brightwellia spiralis* Glezer. ANDREWS: 130, fig. 4.

Number of specimens found: 1 (pyritised)

Description. Valve round. Valve face with numerous pores, extending in a spiral arrangement away from the valve centre. Hyaline central area small, rounded. A groove extends around the valve, at approximately 15 µm from the valve margin.

Dimensions. Valve diameter 120 µm. Width across central area 60 µm. Pores 8-10 in 10 µm.

Remarks. Only one specimen recovered, probably caved, as the first occurrence of this genus is recorded as Mid Eocene (Andrews 1986). The groove referred to above marks the ring of elongate openings on the surface of the valve (Round *et al.* 1990, p. 182, figs. a-f). The hyaline central area and spiralling array of pores are well preserved in the specimen examined.

Occurrence (this work). BP well 21/9-1, lower Balder Formation.
North Sea range. Not known.
Range (literature). Upper Eocene: Ukraine (Glezer 1964).
Lower Oligocene: Southwest Atlantic (Gombos & Cieselski 1983); USA, California (Andrews 1986).

Brightwellia? sp.

Pl. 2, fig. 9.

Number of specimens found: 1 (pyritised)

Description. Valve round, inflated. A clear groove extends around the valve, at approximately 2/3 of the valve diameter. Inside this groove, the valve surface is highly domed. Surface details not clear due to poor preservation.
Dimensions. Valve diameter 80 µm.

Remarks. One specimen recovered. Although species assignment is not possible (due to secondary pyrite overgrowth over the entire valve), the groove extending around the valve face is a feature characteristic of *Brightwellia*.

Occurrence (this study). BP well 15/28a-3, central North Sea, Lark Formation.

Family STELLARIMACEAE Nikolaev ex Sims & Hasle, 1990

Remarks. A recently defined family, comprising two genera formerly included within the Coscinodiscaceae. Nikolaev (1983, p. 1124) introduced the name "Stellarimaceae Nikolaev, nom. nov" for a monotypic family but did not formally publish the name. Sims & Hasle (1990, p. 207) subsequently made a formal designation for the new family. As both of the included genera feature prominently in North Sea Palaeogene assemblages and have been described in detail only recently (but not in pyritised form), it is necessary to include herein comprehensive descriptions of each. In addition, specimens from both genera have been recovered which represent stages in the diatom life-cycle and are thus important from a palaeoecological viewpoint.

"A survey of *Stellarima* and *Fenestrella* show that the characters they have in common are overall shape, lack of a distinct central area, labiate processes that are identical in shape and structure and that are neither marginal, rarely central but usually positioned in a ring on the valve face. Both genera also have loculate areolae with cribra lying flush with the valve surface and specialised areolae scattered between them. The valvocopulae of the two genera also appear to be similar in structure" (Sims 1990, p. 287).

Included genera: Fenestrella, Stellarima.

Stratigraphic Range: Upper Cretaceous (Campanian) to Recent.

Genus STELLARIMA Hasle & Sims, 1986

Type species. Stellarima microtrias (Ehrenberg) Hasle & Sims, 1986b

Emended diagnosis. "Cells single or forming short filamentous colonies. Frustules discoid or lenticular. Valves weakly to strongly convex. Areolae loculate with a cribrum externally and a foramen internally, arranged in fascicles. A small hyaline area at the centre of the valve with a single labiate process or a group of labiate processes" (Hasle & Sims 1986b, p. 111).

Remarks. A recently erected genus, comprising a number of taxa formerly assigned to *Coscinodiscus* and *Symbolophora.* Distinguishing features include a central array of internal labiate processes or rimoportulae (one or more in number), fine areolae (striae) arranged radially (fasciculate in resting spores), and the lack of a distinct valve mantle or marginal rimoportulae. All known species form resting spores (see Hasle & Sims 1986a; Sims & Hasle 1987; Hasle *et al.* 1988).

Hasle & Syvertsen (1985) reviewed *Coscinodiscus wittianus* (Pantocsek), a large (120-250 µm diameter) diatom found in the Paleocene of the North Sea (informally named "Coscinodiscus N 11" by BP; "Coscinodiscus sp.4" by Shell; "Coscinodiscus sp. 25" by Haliburton), and found that it has sufficient diagnostic features to warrant the erection of a new genus, *Thalassiosiropsis*. However, Hasle & Sims (1986a) subsequently created the genus *Stellarima*, whose diagnostic features (i.e. one or more central labiate processes and fasciculate areolae) are present in *Thalassiosiropsis* (which therefore needs further revision, Sims *pers. comm.* 1994).

Stellarima microtrias (Ehrenberg) Hasle & Sims
Pl. 4, figs. 6-11.

1844 *Symbolophora? Microtrias/Tetras/Pentas/Hexas* EHRENBERG: 205.

1884 *Coscinodiscus symbolophorus* GRUNOW: 82, pl. 4, figs. 3-6.

1930 *Coscinodiscus stellaris* Roper var. *symbolophora* (Grun.) Jørgensen. HUSTEDT: 396.

1949 *Cos. stellaris* var. *symbolophora*. PROSHKINA-LAVRENKO: vol. 1, pl. 2b, fig. 23; pl. 4a, fig. 3.

1976 *Coscinodiscus symbolophorus* Grunow. HAJOS: DSDP 35: 826, pl. 20, figs. 11, 12.

?1981 *Coscinodiscus* sp. B HUGHES: 191, pl. 15.3, figs. 10, 11.

1981 *Coscinodiscus* sp. 3. THOMAS & GRADSTEIN: 19, Pl. 3.1, figs. 7-12.

1983 *Coscinodiscus* sp. 1 Bartenstein and others 1962, small variety. KING: 20.

1983 *Symbolophora furcata* (Karsten) NIKOLAEV: 1124, pl. 1, figs. 8, 9.

1986a *Stellarima microtrias* Hasle *et* Sims comb. nov. HASLE & SIMS: 111, figs. 18-27.

1991 *Symbolophora microtrias* Ehrenberg. HOMANN: 61, pl. 40, figs. 1, 2, 4, 5.

Number of specimens recovered: 202 (pyritised); 87 (non-pyritised, Fur Formation)

Revised diagnosis & description (abridged). "The cells in girdle view are more or less rectangular to quadrate with curved corners. The valves vary in shape from almost flat to slightly convex. The species has the process pattern common to the genus, i.e. lacking marginal processes but having a number of labiate processes at the valve centre. *S. microtrias* has 2-8 labiate processes in the vegetative cells and 3-5 in the resting spores. The labiate processes are usually associated with a hyaline area which follows the line of opening and extends to the valve centre so that a few areolae are sometimes enclosed. The number of areolae in 10 µm are 11-15 and 12-16 along a radius and a tangent respectively" (Hasle *et al.* 1988, p. 196).

Dimensions. Valve diameter variable, from 40-95 µm. Areolae fine, arranged in radial lines, 10-12 in 10µm.

Remarks. The central group of labiate processes on the valves of *S. microtrias* form an impression in pyrite-infilled specimens, usually only observable via SEM (although these are clearly visible via LM in unpyritised specimens). The overall valve shape of *S. microtrias* is similar to that of *Fenestrella antiqua* (Grunow) Swatman, and a raised marginal rim around the edge of the valve is a feature common to both taxa. Industrial micropalaeontologists working on the North Sea Palaeogene have consequently often classed *S. microtrias* as a smaller variant of *Coscinodiscus* sp. 1 (*sensu* Bettensteadt *et al.* 1962), the previously published name for the pyritised form of *F. antiqua.* However, pyritised specimens can be distinguished via LM by the markedly smaller size of *S. microtrias* and by the fact it occurs throughout the Palaeogene in the North Sea, whereas *F. antiqua* is restricted to the Upper Paleocene and Lower Eocene. Hughes (1981) figured two specimens from the Oligocene of the southern North Sea bearing a superficial resemblance to *S. microtrias*, but no central labiate processes could be distinguished in either case due to low magnification and poor preservation.

Occurrence (this work). Sporadically, often in large numbers, at various levels through the Palaeogene sequence in wells 15/28a-3 & 21/9-1, central North Sea. Especially abundant in the Sele & Balder formations; Denmark: Fur Formation.

North Sea range (unpublished). Upper Cretaceous (Campanian) to Upper Oligocene (P. Copestake, *pers. comm.* 1994). Known as "*Coscinodiscus* cf sp. 1" by SPT.

Range (literature). Upper Cretaceous (Campanian): Russia, western Siberia (Strel'nikova 1965, 1974; Glezer *et al.* 1974).

Paleocene: Russia, locality uncertain (Proshkina-Lavrenko 1949).

Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Kitton 1871; Grunow 1884; Schmidt 1874-1959; Rattray 1889; Stolley 1899; Tempere & Peragallo 1915; Schulz 1927; Benda 1972; Homann 1991).

Lower Eocene: North Germany (Schulz 1927; Benda 1965); London Clay, England (Stolley 1899).

Eocene to Pliocene: Offshore Eastern Canada (Thomas & Gradstein 1981).

Middle Eocene to Lower Oligocene: Central equatorial Pacific (Fenner 1984, DSDP 75).

Middle Eocene: SW Atlantic (Gombos 1983, DSDP 71/2).

Upper Eocene: California (Hanna 1931); Russia, eastern Urals (Proshkina-Lavrenko 1949).

Lower Oligocene: SW Pacific (Hajos 1976, DSDP 35).

Miocene: Hungary (Pantocsek 1903-5); Vienna Basin (Rehakova 1967); Japan (Sawamura 1963); California (Hanna 1932).

Recent: Antarctic pack-ice (Hasle & Sims 1986a).

Stellarima sp.

Pl. 4, fig. 12.

Number of specimens recovered: 25 (pyritised)

Description. Valve shape biconvex with a marginal rim, distinguished from *S. microtrias* by possessing a more markedly convex outline, with a depression at the centre of each valve face.

Dimensions. Valve diameter 50-150 μm.

Remarks. Poor preservation hinders accurate identification of these morphotypes. Hasle & Sims (1986a) illustrate and document resting spores of *S. microtrias* from Present-day pack-ice offshore Antarctica, and these show similar features to specimens of *Stellarima* sp. recovered from the North Sea.

Pyritised diatom auxospores which clearly belong to the genus *Stellarima* have been documented from the Middle Eocene of the Beaufort-Mackenzie Basin, Canada (McNeill 1990). They exhibit labiate processes ("endocorona" of McNeill) which are positioned at the centre of the valve face, a diagnostic feature of *Stellarima.* No species designation was attempted by McNeill, due to poor preservation.

Stellarima sp. is known under various morphotype numbers by oil companies, e.g. "*Coscinodiscus* sp. 17" and "*Coscinodiscus* sp. 68" (SPT).

Occurrence (this work). Sporadically in the Paleocene, Eocene, Oligocene and Miocene in well 15/28a-3, central North Sea.
North Sea range (unpublished): Upper Cretaceous (Campanian) to Lowermost Oligocene (N. Hume, *pers. comm.* 1994).

Genus FENESTRELLA Greville, 1864

Type species. Fenestrella barbadensis Greville, 1864

Original diagnosis. "Frustules free, disciform: disc with a minute, radiant cellulation, interrupted by in the middle by linear bands, composed of parallel lines of cellules, each band terminating in a flat ocellus" (Greville 1864, vol. 9: 67 [80]).

Remarks. "Chief diagnostic characters are the lack of a distinct central area (unusual in a centric diatom) and the presence of two "ocelli" [actually labiate processes] lying opposite and mid-way between the valve centre and margin" (Sims 1990, p. 278).

A hitherto rarely recorded fossil genus (ranging from Paleocene to Miocene), described accurately only recently (see above). Two species are known, one of which, *F. antiqua*, has been found to form a major component of diatom assemblages in the Lower Eocene Balder Formation of the North Sea and its onshore equivalents. Its common occurrence as a pyritised steinkern may explain why this large, otherwise very fragile diatom is so frequently encountered therein, the pyrite infilling having preserved the shape of the frustule.

Fenestrella antiqua (Grunow) Swatman, emend.

Pl. 3, figs. 1-10; pl. 4, figs. 1-5.

1882 *Janischia antiqua.* GRUNOW in VAN HEURCK: pl. XCV bis, figs. 10, 11.

1890 *Coscinodiscus ludovicianus* Rattray. RATTRAY: 596.

1940 *?Coscinodiscus* sp. (bikonvex). STAESCHE & HILTERMANN: 15, pl. 6, fig. 3.

1943 *Coscinodiscus* sp. 1 (bikonvex). WICK: 5, pl. 1, figs. 47-66.

1948 *Fenestrella antiqua* (Grunow) Swatman comb. nov. SWATMAN: 53, pl. 2, figs. 10, 11.

1962 *Coscinodiscus* sp. 1 Bettenstaedt *et al.* in SIMON & BARTENSTEIN: 357, pl. 2, figs. 18, 19.

1972 *Janischia antiqua* Grun. BENDA: pl. 2, fig. 10, 11.

1975 Coscinodiscus sp. 1. JACQUÉ & THOUVENIN: 462, pl. 2, figs. A-E.

1983 Coscinodiscus sp. 1 Bettenstaedt *et al.* 1962 BIGNOT: 17, pl. 1, figs. 5, 6 & 8.

1983 *Coscinodiscus* sp. 1 Bartenstein and others. KING: 20, figs. 1, 2.

1984 *Coscinodiscus* sp. 1. MALM ET AL.: 158, fig. 8a.

1990 *Fenestrella antiqua* (Grunow) Swatman. SIMS: 179, figs. 1-14, 22.

1991 *Fenestrella antiqua* (Grunow) Swatman. HOMANN: 48, pl. 18, figs. 1, 2, 4, 5.

Number of specimens recovered (vegetative cells): 112 (pyritised); 106 (non-pyritised, Fur Formation)

Revised diagnosis & description (abridged). "Valves circular, weakly domed, fragile and golden in colour. A ring of well-spaced labiate processes present at approximately 1/3 of the distance from the valve margin to the valve centre, these more densely aggregated in two opposite areas to form rows of processes (the ocelli of Greville 1864). These rows of closely packed processes vary in length and, on most valves, lie parallel to the valve margin, slightly within the ring of well-spaced or individual processes. The number of processes in each patch varies from 5 to over 50, and there is apparently no close relationship between valve diameter and number of processes. No obvious central area to the valve is present. Rows of areolae arranged in fascicles extend to the valve margin. The fascicles that include the patches of labiate processes are much wider than those over the rest of the valve. These narrower fascicles are regular in size and each bifurcates so that an individual process lies at the centre of each bundle. Fine hyaline rays can often be seen positioned between the individual processes defining the fascicles" (Sims 1990, p. 279).

Emended diagnosis (herein). Outline of frustule biconvex in girdle view, with prominent, heavily-silicified girdle bands which form an angle with the valve margin (only observed in pyrite-infilled specimens). The girdle bands are of the "open" or "split" variety (Round *et al.* 1990, p. 48). Non-pyritised specimens are preserved as isolated valves, usually broken with girdle bands detached. The areas of packed labiate processes are normally only seen via SEM, under low magnification, in pyritised specimens and take the form of indentations.

Dimensions. Valve diameter 150-360 µm. Areolae 11-14 in 10µm.

Remarks. Sims (1990, p. 279, figs.1-14, 22) gave plates, both LM and SEM, of this taxon. Her descriptions were of well-preserved, non-pyritised specimens.

The largest diatom in Palaeogene sediments from the North Sea Basin, the pyritised biconvex frustules of *F. antiqua* have hitherto been identified as *Coscinodiscus* sp. 1 (Bettenstaedt *et al.* 1962, see above). A variety of gross morphologies of *F. antiqua* have been revealed via SEM observations during the present study. The distinctive labiate processes described above are preserved as indentations in pyritised specimens, thus forming an impression of the inside of the valve; these are normally only visible in the SEM in pyritised specimens, although they are clearly visible in the LM in non-pyritised valves. A veneer of original silica is preserved on the pyrite steinkerns of some specimens found in the Balder Formation, which gives the appearance of a prominent iridescent sheen to the specimen. The varieties observed in frustule shape, and their stratigraphical significance, warrant separate descriptions as they represent stages in the life-cycle of *F. antiqua*.

Occurrence (this work). BP wells 15/28a-3 & 21/9-1, central North Sea, Sele and Balder formations; Knudeklint, Denmark, Fur Formation; Ølst, Denmark, Ølst

Formation.

North Sea range. Upper Paleocene to Lowermost Eocene (Bettenstaedt *et al.* 1962; Jacqué & Thouvenin 1975; King 1983; Malm *et al.* 1984; Mudge & Copestake 1992a,b).

Range (literature). Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Rattray 1889; Schulz 1927; Benda 1972; Sims 1990; Homann 1991).

Lower Eocene: North Germany (Schulz 1927); Russia (Glezer *et al.* 1974); Paris Basin (Bignot 1983); Belgium (King 1990).

?Upper Eocene: Russia, "Kamischev" (Chenevière 1934, see also Ross & Sims 1985).

Fenestrella antiqua auxospores

Pl. 4, figs. 1-2.

Number of specimens recovered: 16 (pyritised)

Description. Shape cylindrical due to a very wide girdle, often with distinct cingula. The valves are highly domed, and do not exhibit the pronounced angle with the girdle seen in vegetative cells. Rows of labiate processes not always clear due to poor preservation, but distinguishable in some specimens.

Dimensions. Valve diameter 120-300 µm, width of cell 300-500 µm.

Remarks. A variant of *F. antiqua* commonly found in the volcaniclastic Sele Formation, central and northern North Sea. The unusually thickened girdle is strongly suggestive of an *auxospore* (see Round *et al.* 1990, p. 85), reflecting a period of vegetative reproduction with new, smaller diatom cells forming beneath the protective girdle band.

Unpublished data from oil exploration and service companies allude to the widespread occurrence of this distinctive morphology in large enough numbers to form a marker for the upper part of the Sele Formation (uppermost Paleocene) in proprietary zonation schemes. Known under various morphotype in the informal diatom zonations of different companies, e.g. "*Coscinodiscus* sp. 8" (SPT); "*Coscinodiscus* sp. 16" (British Petroleum). Informally named "Coscinodiscus barreliformis" by M.A. Charnock and others.

Occurrence (this work). BP wells 15/28a-3 & 21/9-1, central North Sea, Sele Formation.
North Sea range (unpublished). Upper Paleocene (SPT).
Range (literature). The only published account of pyritised diatom auxospores is from the Middle Eocene of the Beaufort-Mackenzie Basin, Canada (McNeill 1990). However, these clearly belong to the genus *Stellarima* as they exhibit labiate processes ("endocorona" of McNeill) that are positioned at the centre of the valve face, and not nearer to the valve margins as in *Fenestrella*, or around the inside of the margin itself, as in *Coscinodiscus.*

Fenestrella antiqua initial cells

Pl. 3, figs. 6-7.

Number of specimens recovered: 6 (pyritised)

Description. A morphological variant of *F. antiqua* characterised by having one valve more markedly domed than the other. In addition, the valve/girdle junction varies on either valve, with that formed by the less highly domed valve showing a clear angle. The rows of packed labiate processes characteristic of *F. antiqua* are clearly visible on specimens unaffected by diagenetic recrystallisation.
Dimensions. Valve diameter 120-280 µm.

Remarks. The heterovalvar shape of this diatom is at first suggestive of a resting spore. However, SEM observation reveals that this is a combination of two valves, one being that of an *F. antiqua* vegetative cell, the other that of an *F. antiqua* auxospores, and therefore represents the *initial cell* stage in the diatom life-cycle, with the highly-domed auxospore valve on one side of the girdle and a vegetative cell valve on the opposite side (Round *et al.* 1990, p. 34). This form often occurs in association with resting spores of *F. antiqua.* Known as "*Coscinodiscus* sp. 13" by SPT.

Occurrence (this work). Wells 15/28a-3 & 21/9-1, central North Sea, Balder Formation.

Range (literature). No published account exists for this morphotype. It is often found in cuttings and core in the central and northern North Sea in the Balder Formation (N. Hume, *pers. comm.* 1993).

Fenestrella antiqua resting spores

Pl. 4, figs. 3-5.

Number of specimens recovered: 23 (pyritised); 38 (non-pyritised, Fur Formation)

Description. Cells large (120-280 µm diameter), with no girdle band so that the frustule resembles a discus when seen in girdle view. Specimens are commonly very smooth, with a thickened frustule which carries fine areolae. The areas of packed labiate processes are much shortened by comparison to those of the normal cells, and do not curve with the valve face but are straighter, or curve slightly away from the valve margin. The rows of enlarged pores, which connect the two areas of packed labiate processes on the normal cells, are absent.

Remarks. A morphological variant of *F. antiqua* which is a resting spore, formed as a response to adverse environmental conditions (Round *et al.* 1990, p. 56). This is a common feature of diatom assemblages in both open ocean and coastal upwelling situations, and is a response to a depletion in nutrients and/ or light intensity. Resting spores are of widespread occurrence in the Upper Paleocene and Lower Eocene diatom assemblages in and around the North Sea Basin.

Occurrence (this work). BP wells 15/28a-3 & 21/9-1, central north Sea, Sele and Balder formations, more abundantly in the Sele Formation. Isolated valves also observed in samples from the Fur Formation, Denmark, at the top of the Knudeklint Member.

Range (literature). There is no published description of this morphotype, but it is often encountered in ditch cuttings and cores from the central and northern North Sea in the

Sele & Balder formations. It is normally referred to as "*Coscinodiscus* sp. 7" (British Petroleum/Britoil, SPT) or "*Coscinodiscus* sp. 9" (Haliburton).
North Sea range. Uppermost Paleocene (Mudge & Copestake 1992b).
Range (literature). Mudge & Copestake (1992b) refer to the abundance of this morphotype at the top of the Sele Formation in the northern North Sea.

Family AULACODISCACEAE (Schütt) Lemmermann, 1903

Remarks. A single genus represents this family, which is distinguished by its distinctive marginal processes (see Round *et al.* 1990, p. 188).

Included genus: Aulacodiscus
Stratigraphic range: Upper Cretaceous to Recent

Genus AULACODISCUS Ehrenberg, 1844

Type species. Aulacodiscus crux Ehrenberg

Description (abridged). "Cells solitary, circular in valve view with conspicuous marginal processes. Valve with a conspicuous hyaline area at the centre from which rows of loculate areolae radiate. The valve surface is often corrugated and the valve mantle is not differentiated from the rest of the valve. The areolae are closed by cribra externally and open internally by large foramina. Rimoportulae marginal, complex" (Round *et al.* 1990, p. 188).
Remarks: A very large, mainly fossil genus, ranging from Upper Cretaceous to Recent. Difficulties in distinguishing species were commented on in the extensive review of Burke & Woodward (1963-74), in particular the fact that some species possess dissimilar valves which has caused considerable taxonomic problems where whole frustules are not preserved intact. Also, a number of species have hitherto been documented only from the "Diatom Complexes" of European Russia (Glezer *et al.* 1974). The precise localities and stratigraphic positions of much of this material are not known, and so the exact age of species is often conjectural (see Ross & Sims

1985).

A number of species of *Aulacodiscus* occur in the Palaeogene of the North Sea Basin, some of which form useful stratigraphic markers.

Aulacodiscus allorgei Chenevière

Pl. 5, figs. 3-4.

1934	*Aulacodiscus allorgei.* CHENEVIÈRE: Pl. 8, fig. 2.
1947	*Aulacodiscus allorgei* Chenevière. BARKER & MEAKIN: 175, pl. 24, fig. 2.
1970	*Aulacodiscus allorgei* Chenevière. ROSS & SIMS: 54, pl. 4, figs. 18-22.
1971	*Aulacodiscus allorgei* Chenevière. BURKE & WOODWARD 1973-74: 322-3.
1981	***Coscinodiscus* sp. 1. THOMAS & GRADSTEIN: 19, Pl. 3.1, figs. 1-4.**

Number of specimens recovered: 2 (pyritised)

Original diagnosis & description (abridged). "Valve circular. Surface with a flat marginal zone thence sloping sharply to a more or less elevated large polygonal (usually quadrate) central zone with slightly convex sides, rounded angles somewhat distant from the margin, and sometimes a slight central depression. Processes 4, rarely 5, broad, ligulate, projecting radially outwards from dilated clear areas at the angles of the polygonal elevation, with the outer part nearly horizontal and extending generally as far as the margin of the valve. Markings small polygonal cellules, 5-6 in 10 µm" (Barker & Meakin 1947, p. 175).

Dimensions. Valve diameter 100-150 µm.

Remarks. Ross & Sims (1970) conducted an SEM study of *A. allorgei*, and described the fine structure of the valve. Burke & Woodward (1963-74, p. 323) commented on the variation between specimens of the outline of the central elevation, which may be straight, convex or concave. They also remarked on the general difficulty in distinguishing *A. allorgei* from *A. hirtus* Barker & Meakin, with which it often co-occurs in the "Kamischev" deposit (?Paleocene to Upper Eocene).

Pyritised specimens are often badly preserved, and sometimes only the central elevation and corner processes can be distinguished. Nevertheless, these are sufficiently diagnostic for species designation. Thomas & Gradstein (1981) figured specimens of *A. allorgei* (as "*Coscinodiscus* sp. 1") from Palaeogene sediments offshore Eastern Canada. In the North Sea, specimens are known variously as "Diatom sp. 28" (SPT); "Diatom sp. P", "*Coscinodiscus* N5" (British Petroleum). A similar morphology, which Haliburton refer to as "*Coscinodiscus* sp. 10" and SPT call "Diatom sp. 53", is restricted to the Paleocene in the North Sea; this is likely to be *A. hirtus*.

Occurrence (this work). BP well 16/16a-3 (central North Sea) and 3/25-1 (northern North Sea), both from the BP collection of diatom morphotypes.
North Sea range (unpublished). Lower Oligocene (SPT).
Range (literature). Eocene: Russia, "Kamischev", Sverdlovsk oblast (Chenevière 1934; Barker & Meakin 1947; Burke & Woodward 1963-74, pp. 323-4).
Upper Eocene to Pliocene: Offshore Eastern Canada (Thomas & Gradstein 1981).

Aulacodiscus heterostictus Barker & Meakin
Pl. 5, fig. 2

1943 *Aulacodiscus heterostictus.* BARKER & MEAKIN: 251, pl. 38, fig. 2.
?1974 *Aulacodiscus schmidtii* Witt. GLEZER *ET AL.*: pl. XIV, figs. 3, 4.

Number of specimens recovered: 1 (pyritised)

Original diagnosis & description (abridged). "Valve circular. Processes 3, with a slender stem and an enlarged head. Surface depressed at the centre, rising gently to the processes, and descending to a flat border level with the centre. Markings different in three concentric zones: (1) a small rounded central zone with a few conspicuous rounded areolae scattered irregularly on a faint areolate network; (2) a large median zone with radiating rows of rounded areolae in translucent furrows, the areolae being closer together in the outer half of the row and remotely spread in the inner half; (3) the border with radiating rows of confluent quadrate cellules extending more or less over the edge of the raised surface" (Barker & Meakin 1943, p. 251).

Dimensions. Valve diameter 150 µm.

Remarks. Barker & Meakin (1943) comment on the similarity of *A. heterostictus* to *A. schmidtii* Witt and *A. septus* A. Schmidt, from which it is distinguished by the markings of the median zone and the rounded instead of triangular central zone. One of the specimens of *A. schmidtii* figured by Glezer *et al.* (1974, pl. XIV, fig. 3) appears very similar to *A. heterostictus*; the species may be conspecific as both appear in the same material ("Singiliewsky"). Only detailed SEM study of all morphological variants within this assemblage can resolve this problem.

Found in the Middle Eocene in the North Sea. Known informally as "Sp. CN 22" (British Petroleum).

Occurrence (this work). BP well 16/16a-3, central North Sea (in BP collection of diatom morphotypes).

North Sea range (unpublished). Middle Eocene (British Petroleum).

Range (literature). Eocene: Russia, "Singiliewsky", presumed to be Volga Basin (Burke & Woodward 1963-74, p. 241).

Aulacodiscus insignis Hustedt, emend.

Pl. 5, figs. 5-6, 10-12.

var. *aemulans* Mitlehner, nom. nov.

1944 *Aulacodiscus insignis.* HUSTEDT in A. SCHMIDT 1874-1959: Pl. 458, figs. 3-6.

non 1947 *Aulacodiscus aemulans.* BARKER & MEAKIN: 176, pl. 24, fig. 1.

1971 *Aulacodiscus insignis* Hustedt. BURKE & WOODWARD 1963-74: 332.

1983 Diatom sp. 4. KING: 20, pl. 1, figs. 5, 6.

1983 Diatom sp. 5. KING: 20, pl. 1, figs. 5, 6.

var. *quadrata* Mitlehner, nom. nov.

?1886 *Amphitetras subrotundata* JANISCH in A.SCHMIDT 1874-1959: pl. 99, fig. 24.

1983 Diatom sp. 3. KING: Plate 1, fig. 4.

Number of specimens recovered: 12 (pyritised)

Revised diagnosis & description (abridged). "Valve circular, with a narrow hyaline margin. Surface with a large polygonal elevation, angles usually 4, rounded, extending nearly to the margin, and sides arcuate, with steep slopes to the margin. Processes short stout tubular, projecting outwardly from small clear areas at the angles of the elevation. Markings on top of the elevation subcircular or polygonal cellules, 2.5 in 10 µm, disposed in radiating lines. The larger cellules have a central eyespot and puncta, 20 in 10 µm" (Barker & Meakin 1947, p. 175).

Emended diagnosis (herein). Valves round in outline, or quadrate with convex sides. Processes four or five. Cellules with internal pores, forming a pseudoloculate structure. These internal pores are arranged in horizontal lines.

Dimensions. Valve diameter 125-250 µm.

Remarks. Barker & Meakin (1947) appear to have been unaware of Hustedt's (1944) original description for *A. insignis*. Accordingly, Burke & Woodward (1971, p. 332) referred to Hustedt's original name. *A. aemulans* Barker & Meakin is therefore a junior synomym, and is here rejected in favour of *A. insignis* Hustedt.

Detailed SEM studies of specimens of *A. insignis* during the present work have revealed that it is necessary to erect two varieties, *aemulans* and *quadrata.*

var. *aemulans* Mitlehner, nom. nov. MS

Pl. 5, figs. 5-6

Number of specimens recovered: 9 (pyritised)

Original diagnosis & description. As for *A. insignis* (see above). The following descriptions were given by King (1983) for the pyritised forms:-

1) Form with four processes: "Circular in valve view, very thin and slightly convex in girdle view. Four equally spaced small projections are present near the valve margin (only present on one valve)" (King 1983, p. 20).

2) Form with five processes: "Similar to Diatom sp. 4, but with five small equally

spaced projections near the valve margin" (King 1983, p. 20).

Emended description (herein). Valve round. The large, polygonal elevation on the valve face may have four or five angles. Processes four or five. Cellules often indistinct, with only a meshwork of small areolae visible, 5-6 in 10 µm.

Description. As for *A. aemulans* (see above).

Dimensions. Valve diameter 100-200 µm.

Remarks. Both the four and five angled forms of *A. insignis* var *aemulans* commonly occur in the Oligocene and lower Miocene of the central North Sea, the form with four processes ranging through the upper Oligocene and Miocene whereas the form with five processes is restricted to the lower part of the Upper Oligocene. Although always found in pyritised form, the position of the peripheral angles and the dissimilar valves are sufficiently diagnostic for recognition. Only the form with four processes was encountered during the present study.

Occurrence (this study). BP well 16/16a-3, northern North Sea, in the BP collection of diatom morphotypes, Lark Formation.

North Sea range (unpublished). Upper Oligocene to Lower Miocene (SPT).

Range (literature). Sufficiently widespread in the North Sea to form a zonal marker for Zone NSP 10 in the zonation of King (1983).

?Upper Eocene: Russia, Volga Basin, "Carlovo" and "Kamischev" (Barker & Meakin 1947; Burke & Woodward 1963-74).

var. *quadrata* (King) Mitlehner, nom. nov. MS

Pl. 5, figs. 10-12.

Number of specimens recovered: 5 (pyritised)

Original description. "Quadrate in valve view, rectangular in girdle view. Prominent "knobs" occur at the corners of each valve" (King 1983, p. 20).

Emended diagnosis (herein). Valves quadrate. A clear angle of approximately 95 degrees occurs between the sides, to form developed corners. Mantle narrow, with a distinct flange which extends around the valve circumference. Four processes, clearly produced, project at an inward angle of 45 degrees, at each corner, these only present on one valve. Areolae large, hexagonal, 5-6 in 10 µm.

Dimensions. Valve diameter 120-180 µm.

Remarks. A. insignis var. *quadrata* has never encountered in non-pyritised form (P. Copestake, *pers. comm.* 1994). However, a remarkably similar form was illustrated in Schmidt's Atlas (1874-1959). It was collected during the *Gazelle* Expedition of 1874-8 by A. Janisch, who figured a drawing of *A. subrotundata* in a set of plates, distributed privately in 1904, and without any text; it cannot therefore be considered a valid name. In addition, other diatom taxa depicted from the same expedition have a distinctly modern aspect to them (although it is possible that the highly robust frustules were reworked from older sediment, as some species recorded from the same expedition are also known from the Upper Eocene of Barbados, Rattray 1889). In the absence of an accurate description, it was decided to formally erect a new variety.

Occurrence (this work). BP well 15/28a-3: 4180', 4330'; BP well 21/296-7, 5280'; BP well 21/10-1, 5060'.

Stratigraphic range (literature). This highly distinctive diatom has a sufficiently widespread occurrence in the Oligocene of the central and northern North Sea to form a zonal marker (Zone NSP 9) in the North Sea zonation of King (1983). NB larger specimens (e.g. plate 5, fig. 12) are restricted to the lower Oligocene; smaller specimens range throughout the Oligocene.

Aulacodiscus singiliewskyanus Barker & Meakin

Pl. 5, fig. 7.

1943 *Aulacodiscus singiliewskyanus.* BARKER & MEAKIN: 251, pl. 38, fig. 3.

1970 *Aulacodiscus singiliewskyanus* Barker & Meakin. ROSS & SIMS: 57, pl. 6, figs. 33-34.

Number of specimens recovered: 1 (pyritised)

Original diagnosis & description (abridged). "Valve circular. Processes 5, rarely 4 and 6, projecting from small circular clear areas on broad radial inflations extending to the border from the angles of a polygonal elevation. Primary rays distinct, extending from the clear areas on the inflations to the sides of a small roughly outlined polygonal clear area at the centre of the surface. Markings small rounded granules, close together in radial rows, confused near the centre. In the compartments between the processes, the surface near the border is depressed and then rises into an inwardly curved narrow mound" (Barker & Meakin 1943, p. 251).

Dimensions. Valve diameter 150 µm.

Remarks. Only one specimen recovered in the present study, pyritised but with all of the features described by Barker & Meakin (1943) clearly visible except for the primary rays, which extend along the inflations in unpyritised specimens.

Barker & Meakin (1943) and Ross & Sims (1970) commented on the close resemblance of this species to *A. tuberculatus* Pantocsek, a form found in the same material, from Singilei in the Volga Basin, Russia. Ross & Sims (q.v.) considered that the two may be end-members of a continuous series, a phenomenon often found in diatom populations. A third species, *A. archangelskianus* Witt is also very similar, but has only been documented in Upper Cretaceous deposits (Hanna 1934; Long, Fuge & Smith 1946), although it may extend into the Mid Paleocene (Haliburton, unpublished data). *A. singiliewskyanus* is known under various informal names, e.g. "Coscinodiscus N16" (British Petroleum); "Diatom sp. 38" (SPT).

Occurrence (this work). BP well 208/15-1, 1315 m, northern North Sea, in BP collection of diatom morphotypes, Horda Formation.

North Sea range (unpublished). Apparently restricted to a narrow range in the Mid Eocene (SPT).

Range (literature). Eocene: Russia, Volga Basin, Sengilei (Barker & Meakin 1943; Ross & Sims 1970).

Aulacodiscus subexcavatus Hustedt

Pl. 5, fig. 1.

1944	*Aulacodiscus subexcavatus.* HUSTEDT, pl. 460, figs. 3-13.
1965	*Aulacodiscus subexcavatus* Hustedt. BENDA, 171, pl. 22, figs. 6-7; **non** pl. 23, fig. 1.
?1974	*Craspedoporus actinoptychoides.* GLEZER *ET AL.*: pl. XXXII, fig. 10.

Number of specimens recovered: 1 (pyritised)

Revised description (abridged). "Forms with 3 radial elevations, at the summits of which are processes. Valve margin has small radial striae, central area plain. Surface with radial rays of round, free pores, 5-6 in 10 µm. This morphology has gross similarities with *A. excavatus* A. Schmidt. It is distinguished by its more prominent valve relief (strongly indented between the elevations) and the situation of its large, pear-shaped processes. The latter are positioned close to the valve margin" (translated from Benda 1965, p. 171-2).

Dimensions. Valve diameter 85-120 µm.

Remarks. A. subexcavatus appears to be conspecific with *Craspedoporus actinoptychoides* Glezer. The latter was figured from the Eocene of Russia by Glezer *et al.* (1974), but not described in detail. Glezer's figured specimen is strongly suggestive of *A. subexcavatus*, the type specimen of which came from the area of the Volga Basin (Hustedt 1944).

One specimen examined, remarkably well-preserved. Found sporadically in the Eocene of the North Sea, known informally as: "*Coscinodiscus* N18" (British Petroleum/Britoil); "*Coscinodiscus* sp. 8" (Haliburton); "Diatom sp. 29" (SPT).

Occurrence (this work). BP well 208/15a-1, 1220 m., Horda Formation (from BP collection of diatom morphotypes).

Range (literature). Upper Paleocene to Lower Eocene: Denmark, Fur Formation (Benda 1972).

Lower Eocene: North Germany (Benda 1965).

Eocene: Russia, "Kamischev", Sverdlovsk oblast (Hustedt 1944; Glezer *et al.* 1974).

Aulacodiscus suspectus A. Schmidt

Pl. 5, figs. 8-9.

1876 *Aulacodiscus suspectus* A. SCHMIDT 1874-1959: pl. 36, figs. 17, 18.
1884 *Aulacodiscus imperfectus* GRUNOW: 69.
1884 *Coscinodiscus josefinus* GRUNOW: 69.
1930a *Coscinodiscus josephinus* Grunow. HUSTEDT: p. 429, fig. 232 (*sic.*).
1972 *Coscinodiscus josefinus* Grunow. BENDA: pl. 2, fig. 12.
1991 *Aulacodiscus suspectus* A. Schmidt. HOMANN: p. 37, pl. 6, figs. 1-5; pl. 7, figs. 1-3, 5.

Number of specimens recovered: 3 (pyritised); 6 (non-pyritised, Fur Formation)

Description. "Valve outline circular, flat or slightly convex. Central area poorly defined, with no central rosette. Areolae polygonal, arranged in radial lines away from the centre" (Translated from Homann 1991, p. 38).

Description. Shape flattened, discoidal with a low mantle. Central area hyaline. Areolae arranged radially in rows, 4-7 in 10 µm near the valve centre, declining markedly in size at the margin (9-10 in 10 µm). No secondary spiralling observed. An area of larger areolae occurs mid-valve. Between 2 and 6 hyaline rays are visible between the rows of areolae, at the end of each is a labiate process. Micro-labiate processes are sometimes visible both at the valve margin and on the valve face.

Dimensions. Valve diameter 35-125 µm.

Remarks. Pyritised specimens often exhibit prominent raised "bosses" or papillae, arranged radially over the valve surface. This is a useful feature for identification during picking. Other features, such as the labiate processes, are only observable via SEM.

Occurrence (this work). BP wells 15/28a-3 and 21/9-1, central North Sea in the Sele and Balder formations; Knudeklint, Denmark, Fur Formation.

Range (literature). Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Grunow 1884; Stolley 1899; Tempere & Peragallo 1915; Benda 1972; Homann 1991); Barents Sea (Grunow 1884).

Family HELIOPELTACEAE H.L. Smith, 1872

Remarks. The Heliopeltaceae include genera characterised by prominent elevations and depressions on the valve surface, usually forming sectors.

Included genera: Actinoptychus, Glorioptychus, Lepidodiscus.

Stratigraphic range: Upper Cretaceous to Recent.

Genus ACTINOPTYCHUS Ehrenberg, 1841

Type species: Actinoptychus senarius (Ehrenberg) Ehrenberg, emended Andrews & Abbott, 1985.

Description (abridged): "Cells discoid, solitary. Valves sectored so that alternate sectors are elevated or depressed. Central area plain or granulate. Areolae in radiate striae, opening by simple pores to the outside but over much of the surface the silica is corrugated or pitted, delimiting groups of areolae. External tubes of rimoportulae prominent, usually located at distal points on radii of elevated sectors. Margin of valve face often produced into a thickened rim or marked with special ornamentation below which the distinctively patterned valve mantle extends. The valve mantle often has spines, wart-like outgrowths, siliceous outgrowths, etc., and the edge is produced into a smooth flange" (Round *et al.* 1990, p. 200).

Remarks: A highly distinctive genus, common in the fossil record and in modern assemblages (over 150 possible valid species according to Van Landingham 1978). Some species range from the Upper Cretaceous. All extant species are exclusively marine and indicative of neritic waters.

Actinoptychus senarius (Ehrenberg) Ehrenberg, emend. Andrews & Abbott

Pl. 6, figs. 1-4.

1837 *Actinocyclus senarius* EHRENBERG: 61 (*nom. nud.)*

1841 *Actinocyclus (Actinoptychus) senarius* EHRENBERG: p. 137, pl. 4, fig. 1.

1941 *Actinoptychus senarius* (Ehrenberg) Ehrenberg. LOHMAN: p. 80, pl. 16, fig. 9.

1971 *Actinoptychus senarius* (Ehrenberg) Ehrenberg. WORNHARDT: 1280, pl. 8, figs. 1-12; pl. 9, figs. 1-12.

1985 *Actinoptychus senarius* (Ehrenberg) Ehrenberg. ANDREWS & ABBOTT: 70, pl. 6, figs. 14, 15; pl. 12, figs. 1, 2.

1991 *Actinoptychus senarius* (Ehrenberg) Ehrenberg, emend. Andrews & Abbott. HOMANN: p. 34, pl. 2, figs. 5, 7, 8; pl. 3, figs. 1-5.

Number of specimens recovered: 2 (pyritised); 21 (non-pyritised; Fur Formation)

Description. "Valve outline circular, relief radial, undulating with between 6 and 8 sectors. Low valve mantle and girdle band" (translated from Homann 1991, p. 34). This species is well described and illustrated in Andrews & Abbott (1985, p. 70, pl. 6, figs. 14, 15; pl. 12, figs. 1, 2).
Dimensions: Valve diameter 20-75 µm. 18-22 areolae in 10 µm on valve surface.

Remarks. The undulating, sectored surface of this species makes it easily recognisable, both in unaltered and pyritised form. Its other distinguishing features, such as tubular rimoportulae on alternating sectors, are not clear in pyritised specimens. A common species in neritic sediments today, occurring attached to algae.

Known under the various informal names in the proprietary zonations of exploration companies, e.g. "*Coscinodiscus* sp. 8" (Haliburton); "Diatom sp. 48" (SPT).

Occurrence (this work): Only one pyritised specimen recovered, from the Horda Formation in BP well 21/9-1. Common in the lower part of the Knudeklint Member of the Fur Formation, Denmark.

North Sea range (unpublished). Sporadically through the Palaeogene. An abundance peak occurs in the Lower Oligocene (SPT).

Range (literature): Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Kitton 1871; Moller 1891; Homann 1991).

Lower Oligocene: Western equatorial Pacific (Fenner 1984, DSDP 75).

Miocene: Georgia, USA (Andrews & Abbott 1985).

Recent: Worldwide, in coastal assemblages (Round *et al.* 1990, p. 200).

Actinoptychus senarius resting spores

Pl. 6, fig. 4.

1886 *Debya insignis* PANTOCSEK: 5, Pl. 29, fig. 298.

1896 *Actinoptychus (Debya) undulatus* Pantocsek, 1886 (non Rattray) VAN HEURCK: 495, fig. 233.

Number of specimens recovered: 1 (pyritised)

Description. Valve circular, with three equally-sized sectors. Each sector is separated from the next by a prominent ridge which splays out at the valve margin. These rays meet at the centre of the valve. Surface morphology unclear due to poor preservation.

Dimensions: Valve diameter 90 µm.

Remarks: A curious morphology, bearing strong similarities to *Debya insignis*, a form described from the Miocene of Hungary by Pantocsek (1886). Similar forms were documented by Van Heurck (1896) from Recent sediments around the North Sea, within cells of *Actinoptychus undulatus*. It therefore seems reasonable to assume that this is a resting-spore genus of *Actinoptychus*. This morphotype is known informally as "*Coscinodiscus benzi*" in the informal catalogue of BP.

Occurrence (this work): BP well 5406/30b-1, Viking Graben, Lark Formation.

North Sea range. Sporadically through the Oligocene and Miocene.

Range (literature). Miocene: Hungary (Pantocsek 1886).

Order: *ASTEROLAMPRALES* Round & Crawford, in Round *et al.* 1990

Family: Asterolampraceae H.L. Smith, 1872

Remarks. The Asterolampraceae include centric species with radiating raised rays, alternating with areolate areas. All species are marine, planktonic.

Included genera: Asterolampra, Asteromphalus.
Stratigraphic Range. Middle Eocene to Recent (Gombos 1980).

Genus ASTEROLAMPRA Ehrenberg, 1844

Type species. Asterolampra marylandica Ehrenberg, 1844

Description (abridged). "Valves watch-glass (saucer-) shaped, without a distinct valve mantle but with a radiating system of raised rays which expand to touch each other in the centre (modern species) or stop short of the centre, which is then areolate (fossil species). The elevations are unperforate. Between the rays the valve is areolate, each areola being loculate and opening to the outside by simple pores" (Round *et al.* 1990, p. 210).

Remarks. Easily distinguishable by its radiating system of raised rays separating compartments of areolae, this genus includes three morphologies which have been found in basal Eocene cutting samples from the central North Sea. Their occurrence at this level is probably due to caving, as *Asterolampra* is not considered to have evolved until the Middle Eocene (Gombos 1980). Unfortunately, no specimens were found in cores during the present study, and so their early occurrence in the North Sea cannot be substantiated. Although some species of *Asterolampra* are useful worldwide zonal indicators (see Fenner 1984), specimens were only rarely encountered in the Eocene to early Oligocene assemblages of the Norwegian Sea by Schrader & Fenner (1976, Fig. 40); their usefulness as zonal indicators in the more restricted North Sea is highly doubtful. Some of the diatom morphotypes in the scheme of SPT are strongly suggestive of species of *Asterolampra* (e.g. "*Cyclotella* sp. 87"); none of these were found during this study.

Asterolampra insignis A. Schmidt

Pl. 6, figs. 7, 10-11.

1889 *Asterolampra insignis.* A. SCHMIDT 1874-1959: pl. 137, figs. 1-3.
1984 *Asterolampra insignis* A. Schmidt. 1889. FENNER (DSDP 75): 1258.
1989 *Asterolampra insignis* Schmidt. DESIKACHARY & SREELATHA:
1991 *Asterolampra insignis* Schmidt. EDWARDS: pl. 8, fig. 90.

Number of specimens recovered: 8 (pyritised)

Description. Valve circular. Rays short and straight. Central area coarsely areolate; central areolae large (2 in 10 um), pentagonal or hexagonal, with variation in the number and arrangement. Central portion extends out to a distance of one third to one half of the valve radius. Marginal compartments small, areolate (5 in 10 um), the marginal areolae slightly larger than the rest.
Dimensions. Valve diameter 45-90µm. Rays 11-13.

Remarks. Specimens found tend to be partially encrusted with secondary pyrite, however enough detail is present for species recognition. Some specimens have longer rays, and correspondingly larger marginal compartments but the diagnostic features are consistent. Known under various morphotype numbers, e.g. "*Coscinodiscus* sp. 12" (British Petroleum/Britoil); "*Cyclotella?* sp. 86" (SPT).
Occurrence (this work). BP well 21/9-1, base Balder Formation, probably caved.
North Sea range (unpublished). Mid to Upper Eocene (SPT).
Range (literature). Upper Eocene to Lower Oligocene: Barbados, Oceanic Beds (Gombos 1980); Central equatorial Pacific (Fenner 1984, DSDP 75); New Zealand, Oamaru diatomite (Grove & Sturt 1887; Desikachary & Sreelatha 1989; Edwards 1991).

Asterolampra marylandica Ehrenberg

Pl. 6, figs. 5-6.

1844 *Asterolampra marylandica* EHRENBERG, 76, fig. 10.

1930 *Asterolampra marylandica* Ehrenberg HUSTEDT: 485-487, fig. 271.

1976 *Asterolampra marylandica* Ehrenberg, 1844. SCHRADER & FENNER (DSDP 38).

1978 *Asterolampra marylandica* Ehrenberg. DZINORIDZE *ET AL.* (DSDP 38, supplement).

1984 *Asterolampra marylandica* Ehrenberg, 1844. FENNER (DSDP 75): 1258.

1989 *Asterolampra marylandica* Ehrenberg. DESIKACHARY & SREELATHA: pl. 17, figs. 3-6.

1991 *Asterolampra marylandica* Ehrenberg. EDWARDS: pl. 8, fig. 90.

Number of specimens recovered: 9 (pyritised)

Description. "Characteristic of this species is the conical outline of the areolated marginal segments. No central areolae are present. The hyaline ridges connecting the centre of the valve with the nearest point of the areolate marginal segments are straight" (Fenner 1985, p. 727).

Dimensions. Valve diameter 110 µm. 7-8 rays. Areolae in outer compartments 8 in 10 µm.

Remarks. An important marker species for the Mid to Upper Eocene (Fenner 1985). Only one specimen recovered during the present study, the identity of which is not in question as all diagnostic features are preserved.

Known as "Diatom sp. 109" by SPT.

Occurrence (this work). BP well 21/9-1, central North Sea, Balder Formation, caved.

North Sea range (unpublished). Mid to Upper Eocene (SPT).

Range (literature). Middle Eocene: Norwegian Sea (Dzinoridze *et al.* 1978, DSDP 38, supplement).

Middle Eocene to lowermost Upper Eocene: Worldwide, forming the *A. marylandica* zone in the low-and mid-latitudes (Fenner 1985); Norwegian Sea (Schrader & Fenner 1976, DSDP 38).

Upper Eocene: Western Equatorial Pacific, forming a zonal marker (Fenner 1984, DSDP 75).

Upper Eocene to Lower Oligocene: New Zealand, Oamaru diatomite (Grove & Sturt 1887; Desikachary & Sreelatha 1989, Edwards 1991); Offshore Philippines, Benham Rise (Fenner 1984, DSDP 75).

Asterolampra sp.

Pl. 6, figs. 8-9, 12.

?1989 *Asterolampra wisei* sp. nov. DESIKACHARY & SREELATHA: pl. 17, fig. 2.

Number of specimens recovered: 1 (pyritised)

Description. Valve circular. 8 rays, central areolae 2 in 10 µm. Compartments appear to reach 1/2 the radius, unclear through poor preservation. Edge of valve not preserved, precluding positive identification.

Dimensions. Valve diameter 60 µm.

Remarks. One specimen observed, which appears to have some features in common with *A. wisei* Desikachary & Sreelatha (1989, pl. 17 fig. 2). It has a markedly smaller areolated central area than *A. insignis.*

Occurrence (this work): BP well 21/9-1, base Balder Formation, probably caved.

Subclass BUDDULPHIOPHYCIDAE Round & Crawford, in Round *et al.* 1990

Order *TRICERATIALES* Round & Crawford, in Round *et al.* 1990

Family TRICERATIACEAE (Schütt) Lemmermann, 1899

Remarks. The Triceratiaceae are characterised by their ocelli, which are raised above the valve surface.

Included genera. Triceratium, Odontella, Lampriscus, Sheshukovia, Pseudoauliscus, Eupodiscus, Pleurosira, Amphitetras, Cerataulus, Auliscus.
Stratigraphic range: Upper Cretaceous (Campanian) to Recent.

Genus TRICERATIUM Ehrenberg, 1838

Type species: Triceratium favus Ehrenberg, 1841

Description (abridged). "Valves triangular or sometimes square, shallow, often ornamented with simple or branched spines. Valve face flat or slightly convex; mantles very shallow. Areolae loculate, opening externally via foramina. Corner elevations present, ending in ocelli" (Round *et al.* 1990, p. 218).
General remarks. A relatively common coastal marine diatom, occurring worldwide at present.

Over 400 species of *Triceratium* were recognised by Van Landingham (1978). More recently this genus has undergone extensive revision, with some taxa being moved to genera such as *Sheshukovia* and *Trigonium* (Round *et al.* 1990); more revision is necessary before a confident assessment of the true number of species in this genus can be made.

Many of the *"Triceratium"* morphologies described from North Sea Palaeogene sediments have been found to be species of *Trinacria.* True species of *Triceratium* possess apical ocelli and small areolae, and lack the linking processes characteristic of *Trinacria.*

Triceratium sp.

Pl. 7, figs. 7-8.

Number of specimens recovered: 3 (pyritised)

Description. Valve triangular. Valve face convex, with a central sulcus. Valve margin prominent, perpendicular to valve face. Areolae fine, arranged in radial rows away from valve centre. Ocelli not clear in specimens observed, but the valve margin continues uninterrupted around the apices.
Dimensions. Valve diameter 80 µm. Areolae 5-6 in 10 µm.

Occurrence (this work). Knokke borehole, Belgium, 283 metres depth (base of Ieper Formation).

Genus ODONTELLA Agardh, 1832

Type species: Odontella aurita (Lyngbye) Agardh, 1832

Description (abridged). "Valves elliptical or lanceolate, with no separation into valve and mantle. Valve face plain or with fine granules, spinules or spines; sometimes with two ridges running on either side delimiting an elliptical area in the centre. At each end there is an elevation, sometimes low and blunt, elsewhere horn-like, which bears an ocellus. Wall loculate, with fine external pores and round internal foramina. The edge of the valve mantle is sometimes recurved so that a groove runs around just above the free edge. The spines, which are very variable in length, are actually the exit tubes of the rimoportulae, and are placed in the centre of the valves or close to the bases of the elevations, diagonally opposite each other" (Round *et al.* 1990, p. 220).

Odontella heibergii Grunow

Pl. 7, figs. 1-5.

1884 *O. heibergii.* GRUNOW: 58.

1899 *Denticella Heibergii* Grunow. STOLLEY: 121.

1981 "*Biddulphia*" sp. HUGHES: pl. 15.3, figs. 14, 15.

1991 *Odontella heibergii* Grunow. HOMANN: 97-8, pl. 27, figs. 1-4, 6.

Number of specimens recovered: 1 (pyritised); 6 (non-pyritised, Fur Formation)

Revised diagnosis & description (abridged). "Cell outline oval to round/oval. Poles drawn out into points. Valve surface convex. Valve edge marked by an acute line. At each pole a long, thin ocellus, somewhat thickened at the free end. Valve mantle high, shaped distinctly outwards from the base. Areolae proceeding from an apical midline in radial rows, increasingly curved towards the poles. Areolae rounded on the valve face, becoming more distinctly polygonal towards the mantle, 13-14 areolae in 10 µm. Valve mantle with pervalvar rows of areolae in distinct secondary slanting rows. Valve margin similarly areolar. Minute spines are irregularly distributed over the valve face and mantle, somewhat longer along the valve margin. Between 4 and 6 extremely long processes occur, irregularly arranged between the poles" (translated from Homann 1991, p. 98).

Dimensions. Length of valve 100 µm.

Remarks. Only one specimen recovered from offshore samples, as a pyritised steinkern. Very few areolae are preserved on the specimen found, except for a prominent area on the valve mantle which allows a comparison with Homann's description. These areolae form distinct polygons, arranged in rows down the mantle, 15-18 in 10 µm. Long labiate processes extend from the apical ocelli in Homann's specimens, in addition to smaller spines which protrude from the transapical lines. These features were observed in a specimen from the Fur Formation, photographed for comparative study. *O. heibergii* has been referred to as "Diatom sp. 46" in the informal diatom zonation of SPT.

Occurrence (this study). BP well 21/9-1, uppermost Balder Formation, central North Sea. Knudeklint, Fur Formation.

North Sea range (unpublished). Upper Paleocene to Upper Eocene (SPT).

Range (literature). Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Grunow 1884; Stolley 1899; Benda 1972; Homann 1991).
Middle Eocene: Southern North Sea (Hughes 1981).

Genus CERATAULUS Ehrenberg, 1841

Type species: Cerataulus turgidus (Ehrenberg) Ehrenberg, 1843

Description (abridged). "Valves elliptical or circular and twisted, with large ocelli on short elevations pointing in opposite directions. The torsion varies between slight and extreme and makes the valve margin non-planar. Surface of valve with spines or granules, especially on the mantle. Areolae radiate from the centre. Areolae loculate. Ocelli with wide plain margins and porelli in sectors. Found amongst the plankton, but strictly a benthic genus" (Round *et al.* 1990, p. 234).

Cerataulus ?weissflogii Pantocsek

Pl. 7, fig. 6.

?1892 *Cerataulus weissflogii* PANTOCSEK: Pl. XII

Number of specimens recovered: 1 (pyritised)

Description. Valve elliptical. Valve surface with a prominent ridge extending around the valve circumference, which breaks the valve slope. At opposite ends of this ridge two prominent ocelli project, which point in opposite directions. Ocelli orientated in different plane on opposite valve.
Dimensions. Greatest width of valve 90 µm.

Remarks. One specimen recovered from offshore samples, as a pyritised steinkern. Although the surface morphology is obscured by secondary pyrite growth, its prominent ocelli clearly place it within *Cerataulus*. The valve shape and size, and the positions of the prominent ocelli, are suggestive of *Cerataulus weissflogii* Pantocsek, a species described by Pantocsek (1892) from the Middle Miocene of Hungary.

Occurrence (this study). BP well 15/28a-3, Lark Formation, 4330' depth.

Order *HEMIAULALES* Round & Crawford, in Round *et al.* 1990

Family HEMIAULACEAE Heiberg, 1863

Remarks. Members of the Hemiaulaceae are characterised by the possession of prominent elevations, at the ends of which are linking processes which interlock with sibling valves in a cell and with adjacent cells to form long chains. Many fossil genera and species are placed in this family, the majority occurring in the Upper Cretaceous and Palaeogene.

Included genera: Hemiaulus, Trinacria, Eucampia, Cerataulina, Abas, Briggera, Keratophora, Kittonia, Strelnikovia, Baxteriopsis, ?Solium.
Stratigraphic Range: Upper Cretaceous (Campanian) to Recent.

Genus *Hemiaulus* Ehrenberg, 1841

Type species: Hemiaulus antarcticus Ehrenberg, 1845

Description (abridged). "Valves elliptical with long thin processes linking by apical spines. Valve face curved, merging imperceptibly with the deep mantles. Areolae large elliptical to rectangular holes closed by complex cribra or simple round pores. Copulae more finely areolate than the valves, split with pointed ends" (Round *et al.* 1990, p. 260).
Remarks. There are few living species of *Hemiaulus*. Round *et al.* (1990, p. 260) consider that selection pressure through time has eliminated many of the more robust, heavily-silicified species characteristic of the Upper Cretaceous and Palaeogene, leaving only the more delicate, lightly silicified forms.

Hemiaulus elegans? (Heiberg) Grunow, emend. Homann

Pl. 7, fig. 9.

?1991 *Hemiaulus elegans* (Heiberg) Grunow, em. Homann. HOMANN: 83, pl. 21, figs. 1-13.

Number of specimens recovered: 4 (pyritised)

Description. Valve trapezoidal, two of the ends produced to form pointed horns. Areolae round, pseudoloculate, 10-12 in 10 µm, arranged in regular lines.
Dimensions. Length between horns 80 µm.

Remarks. Certain, trapezoidal, diatoms recovered from the Ølst Formation, Denmark bear a superficial resemblance to *Hemiaulus elegans.* Although specimens are completely pyritised and individual valves cannot be distinguished, areas of areolae are often preserved and these show a similar style and arrangement to those on smaller specimens of *H. elegans* (Homann 1991, p. 84). This form is identical to a morphotype occurring in the lowermost Eocene of the North Sea, known as "*Isthmia* sp. 14" in the zonation of SPT.

Occurrence (this work). Ølst, Ølst Formation.
North Sea range (unpublished). Lowermost Eocene (SPT).

Hemiaulus? sp.

Pl. 7, fig. 12.

Number of specimens recovered: 32 (pyritised)

Description. In samples from the Sele Formation, central North Sea, there occur a number of small (40-60 µm) morphologies which are too poorly preserved to allow taxonomic identification. Their overall shape is reminiscent of the Hemiauliaceae, however, and often apical horns of unequal size can clearly be distinguished. In some

cases, two valves appear joined (cf. Homann 1991, pl. 23, fig. 10).
Dimensions. Width 40-60 µm.

Occurrence (this study). BP wells 15/28a-3 & 21/9-1, central North Sea. Fairly common in the fine fraction (<63 µm) of samples from the Sele Formation. Rare specimens are found in the base of the overlying Balder Formation, but this may be due to reworking.

Genus TRINACRIA Heiberg, 1863

Type species. Trinacria regina (Heiberg) Homann, 1991

Description. "Cells tri- (quadr-) angular, attached in chains by the extended apices. Valves elevated at the corners, where short and a longer spine(s) occur and interlock neatly with adjacent cells. Valve face raised in the centre and variously ornamented; ridged along the valve face/mantle junction, the ridges running up the elevations; valve mantle shallow. Areolae radiating from the centre, cribrate; continuing down the valve mantle and becoming smaller up the elevations" (Round *et al.* 1990, p. 268).
Remarks. A very characteristic triangular or quadrate genus, often confused with *Triceratium,* from which it is distinguished by its corner spines, larger size and radial areolae. A fossil genus, with species ranging from the Upper Cretaceous (Maastrichtian) to Upper Miocene (Sims & Ross 1988).

Trinacria excavata Heiberg

Pl. 9, figs. 3-6.

1863	*Trinacria excavata* n. sp. HEIBERG: 51, pl. 4, fig. IX (1-4).
1871	*Trinacria excavata* (Heiberg). KITTON: 101, pl. 3, fig. 6-9.
1884	*Tr. excavata* Heiberg. GRUNOW: 67.
1886	*Trin. excavata* Heiberg. A. SCHMIDT 1874-1959: pl. 96, figs. 6-8; pl. 97: figs. 6-10.
1905	*Trinacria excavata* Heiberg. var. *producta.* PANTOCSEK 1903-05: vol. 3, 115,

pl. 13, fig. 203.

1930 *Trinacria excavata* Heiberg. HUSTEDT: 887, pl 532.

1949 *Trinacria excavata* Heiberg. PROSHKINA-LAVRENKO: vol. 2, 193, pl. 74, fig. 2; pl. 96, fig. 4.

1965 *Trinacria excavata* Heiberg. BENDA: 177, pl. 24, fig. 11.

1972 *Trinacria excavata* Heiberg. BENDA: pl. 3, figs. 23, 24.

1975 *Trinacria excavata* Heiberg. HAJOS & STRADNER (DSDP 275)

1977 *Trinacria excavata* Heiberg. FENNER (DSDP 39): 535.

1977 *Trinacria excavata* Heiberg. GOMBOS (DSDP 36): 599, pl. 37, fig. 6.

1983 *Trinacria excavata* Heiberg, 1863. GOMBOS & CIESELSKI (DSDP 71): 605, pl. 17, fig. 8.

?1984 *Trinacria excavata* Heiberg, 1863. GOMBOS (DSDP 73): pl. 2, figs. 1, 2.

1988 *Trinacria excavata* Heiberg. HARWOOD: 89, fig. 21, 15 & 16.

1991 *Trinacria excavata* Heiberg. HOMANN: 119, pl. 46, figs. 1-8; pl. 47, figs. 1-6.

Number of specimens recovered: 6 (pyritised); 173 (non-pyritised, Fur Formation)

Revised diagnosis & description (abridged). "Valves tripolar, outline and relief variable. Sides strongly concave, more or less drawn out towards the poles, with rounded ends produced into points; sometimes partly expanded near the poles. Straight, relatively high elevations project perpendicular to the valve face, the summits ending in spines, some of which exhibit one or two minute clasps. Spines indented, interlocking with adjacent cells. Valve centre more or less convex, arched, becoming broadly flattened near to the poles. Both valves and adjacent cells differ in the height of the elevations and arching of the valve centre. Valve outline low, alar, with wings drawn up towards the elevations. Valve mantle low, extending over the valve base. Cells linked in chains. Areolae round, arranged in radial lines away from a large central areola, increasing in size towards the valve margin, 2-5 in 10 µm. Small, irregular puncta occur dispersed over the valve face. Girdle bands seldom seen attached to frustule" (translated from Homann 1991, p. 119).

Dimensions. Length between poles 70-150 µm.

Remarks. A long-ranging species, commonly occurring in marine sediments from

Upper Campanian to Oligocene age.

Rarely encountered in pyritised form in North Sea offshore and onshore samples, but this is probably a function of preservation as it is a relatively delicate form. Areolae unclear in pyritised specimens, but the valve shape and outline are sufficient for species designation. Well-preserved specimens are common in the upper part of the Fur Formation, Denmark. Known as "Trinacria sp. 32" in the zonation of SPT.

Occurrence (this study). BP well 15/28a-3, Balder Formation. Ølst, Denmark, Ølst Formation. Knudeklint, Denmark, Fur Formation.

North Sea range (unpublished). Upper Paleocene to Lower Eocene (SPT).

Range (literature). Upper Cretaceous (?Senonian): Baltic, Danzig Bay (Schulz 1935).

Upper Cretaceous (Campanian): Russia, eastern Urals (Strel'nikova 1974); USA, California (Hanna 1927b); Campbell Plateau, southwest Pacific (Hajos & Stradner 1975, DSDP 275).

Upper Cretaceous (Campanian) to Lower Paleocene (Danian): Seymour Island, Antarctica (Harwood 1988).

Paleocene: Russia, Sverdlovsk oblast (Proshkina-Lavrenko 1949); Barents Sea (Grunow 1884).

Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Heiberg 1863; Kitton 1871; Stolley 1899; Tempere & Peragallo 1915; Benda 1972; Homann 1991).

Lower Eocene: North Germany (Schulz 1927; Benda 1965); England, London Clay (Shrubsole & Kitton 1881).

Middle Eocene: Southern Atlantic (Fenner 1977, DSDP 39).

Upper Eocene: Southwest Atlantic (Gombos & Cieselski 1983, DSDP 36).

Upper Eocene to Lower Oligocene: Russia, Tyumen'sk oblast (Strel'nikova 1960).

Trinacria regina (Heiberg) Homann

Pl. 8, figs. 1-11.

1863 *Trinacria regina* n. sp., HEIBERG: 50, pl. 3.

1871 *Trinacria Regina* (Heiberg). KITTON: 101, pl. 2, figs. 1-7.

1884 *Tr. Regina* Heiberg. GRUNOW: 67.

1886 *Trinacria Wittii* SCHMIDT 1874-1959: pl. 96, fig. 1; pl. 97, fig. 2, 2a.

1893 *Trinacria Jordani* SCHMIDT 1874-1959: pl. 204, fig. 6.

1905 *Trinacria antiqua* PANTOCSEK 1903-05: Vol. 3, 115, pl. 32, fig. 456.

1930 *Trinacria regina* Heiberg. HUSTEDT: 884, fig. 528.

1949 *Trinacria regina* Heiberg. PROSHKINA-LAVRENKO 1949-51: Vol. 1, pl. 5, fig. 16; Vol. 2, p. 193, pl. 60, fig. 6.

1962 *Triceratium* sp. 1 Bettensteadt *et al.*, *in* SIMON & BARTENSTEIN: 358, pl. 20, fig.

1972 *Trinacria regina* Heiberg. BENDA: 256, pl. 1, figs. 8, 9.

1972 *Trinacria wittii.* A. Schmidt. BENDA: 256, pl. 4, fig. 38.

1981 *Triceratium* sp. HUGHES: 191, pl. 15.3, fig. 5.

1983 *Triceratium* sp. 1. Bettenstaedt *et al.* 1962. BIGNOT: 117, pl. 1, figs. 9, 10, 11.

1984 *Trinacria regina* Heiberg, 1863. GOMBOS: 501, pl. 3, fig. 1.

1984 *Trinacria* aff *wittii.* MALM *ET AL.*: 158, fig. 8i.

1984 *Trinacria wittii.* MALM *ET AL.*: 158, fig. 8j.

1991 *Trinacria regina* Heiberg, em. Homann. HOMANN: 124-6, pl. 50, figs. 1-7; pl. 51, figs. 1-7.

Number of specimens recovered: 165 (pyritised); 734 (non-pyritised, Fur Formation)

Description (abridged). "Valve tripolar, with more or less concave, rarely almost straight sides with broadly rounded poles, drawn out into a short, narrow point. Valve centre flat to highly convex, specimens with the latter sometimes having a concave depression at the top; rare teratological specimens with an eccentric curvature; central elevation substantially lower than the elevations which project from the corners. Elevations straight, narrow, usually tall but sometimes very short. Occasionally the apices of the elevations have a thickened, rounded top. Horn apices with two to three short, strengthened spines, ca. 8-15 µm long; these interlock with similar spines on adjacent cells to form an enclosed, interlocking chain. Valve margin sharply pronounced, distinctly alar (=winged), proceeding more or less parallel to the base of the valve mantle. The "wings" are drawn up to the height of the elevations. Valve mantle low, 5-25µm high, shaped around the base of the valve. The sharp edge of the mantle, combined with the extended alar mantle, often gives the impression of a "double edge" when seen in valve view." (translated from Homann 1991, p. 124-5).

Dimensions. Length between poles variable, from 60-230 µm. Areolae 3-6 in 10 µm, becoming smaller up the elevations.

Remarks. The "alar" projections of Homann are more properly termed marginal ridges (P. A. Sims, *pers. comm.* 1994).

Trinacria regina displays considerable morphological variation, in both valve shape and ornament. The extensive and varied synonymy for this species reflects this, and it is only recently that these variations have been studied in detail. Homann (1991) considered that specimens with an eccentric central areolation (cf. Homann 1991, Pl. 50, fig. 7) should be regarded as teratological (i.e. ecophenotypic) variants, whilst other morphologies formerly assigned species names (*"jordani; punctulata; wittii"*), are now regarded as variants of *T. regina.* Detailed SEM study of well-preserved, unpyritised specimens from the Fur Formation during the present study shows that many of the varieties of this species discussed by Homann are in fact different valves which interlock within a chain (see pl. 8, figs. 10-11). In addition, some of the areolae are seen to be ornamented with small spines (see Round *et al.* 1990, p. 269, fig. h).

This species is one of the most abundant taxa in offshore samples studied (dominating assemblages at the top of the Balder Formation), usually pyritised or calcified. Only the bases of the spines are normally preserved (although complete spines have been observed on pyritised specimens recovered from the Ølst Formation). Other fine detail (such as rimoportulae) is not clear in pyritised specimens. Some valves are deeply concave, which on closer inspection are separation valves, which are found at the terminal ends of each chain. In most cases the edge of the mantle is very prominent, appearing slightly concave in some specimens (cf. Homann 1991, Pl. 51, fig. 6). Some specimens exhibit fine, radial striae on the valve face, which Homann calls "Typ *jordani*" (Homann 1991, Pl. 51, fig. 5); others exhibit three radial, hyaline rays which are termed "Typ *witti"*. Malm *et al.* (1984, fig. 8j) figure the latter variant from an offshore well in the Norwegian Sector of the North Sea. In the coeval Fur Formation of Denmark, *T. regina* is extremely abundant in certain samples; this may be due to localised blooms (J. Fenner, *pers. comm.*, 1993).

Pyritised specimens have hitherto been designated as *Triceratium* sp. 1 Bettenstaedt *et al.* 1962. Other morphotypes are variants of *T. regina* (e.g. "Triceratium spp. 30, 31, 55, 58" of SPT).

Occurrence (this study). BP wells 15/28a-3 and 21/9-1, Sele and Balder formations; Base of Ieper Formation, Knokke borehole, Belgium; Ølst Formation, Denmark; Upper part of the Knudeklint Member, Fur Formation, Denmark.
North Sea range (unpublished). Upper Paleocene to Lower Eocene (SPT).
Range (literature). Paleocene: Cape Basin, South Atlantic (Gombos 1984, DSDP 73); Indian Ocean (Mukhina 1976); Volga Basin, Russia (Glezer *et al.* 1974).
Upper Paleocene to Lower Eocene: Barents Sea (Grunow 1884); Fur Formation, Denmark (Benda 1972; Homann 1991); Kerteminde Marl, Denmark (Bignot 1983); North Sea, Balder Formation (King 1983; Malm *et al.* 1984).
Lower Eocene: England, London Clay (Shrubsole & Kitton 1881; King 1981); Northern Germany, Unter-Eozan (Benda 1965); Northern France, Sparnacian (Bignot 1983).
Lower Middle Eocene: Russia, various localities (="Diatom Complex", Glezer *et al.* 1974). Middle Eocene: Southern North Sea (Hughes 1981).

Trinacria regina var. *tetragona* Grunow

Pl. 9, fig. 1.

1884	*Trinacria Regina* Heiberg Var. *tetragona* GRUNOW: 67.
1888	*Trinacria Regina* v. *tetragona* Grunow SCHMIDT 1874-1959: Pl. 152, fig. 22.
1972	*Trinacria regina* f. *tetragona* Grunow BENDA: pl. 3, fig. 22.
?1984	*Trinacria excavata* f. *tetragona* Schmidt, 1890. GOMBOS (DSDP 73): 501, pl. 5, figs. 7-9.
1991	*Trinacria regina* Heiberg var. *tetragona* Grunow. HOMANN: 126, pl. 49, figs. 10, 11.

Number of specimens recovered: 3 (pyritised)

Description. "A variant of *Trinacria regina* sensu stricto with four poles. Central area flat. Areolae small, relatively fine with 46 areolae in 10 µm, arranged in radial rows. Valve margin vertical, recurved between poles" (translated from Homann 1991, p. 126).

Dimensions. Valve diameter 80 µm.

Remarks. A relatively rare, possibly ecophenotypic, variant of *Trinacria regina.* Only one pyritised specimen observed in the present study, with surface morphology obscured due to poor preservation. However, the shape alone is sufficient for species identification. Referred to as "Buddulphia? sp. 57" in the zonation of SPT.

Occurrence (this study). BP well 22/6a-2, 2160 metres depth (from BP collection of diatom morphotypes).

Range (literature). Upper Paleocene: Cape Basin, South Atlantic (Gombos 1984, DSDP 73).

Upper Paleocene to Lower Eocene: Fur Formation, Denmark (Grunow 1884; Schmidt 1874-1959; Stolley 1899; Tempere & Peragallo 1915; Benda 1972; Homann 1991). Informally named "Trigonium N 1" by BP.

Genus SOLIUM Heiberg, 1863

Type species: Solium exsculptum Heiberg, 1863

Description. Ross & Sims 1987, p. 271-2.

Remarks. A monotypic genus, transferred to the genus *Trinacria* by Hustedt (1930). In a detailed LM and SEM study of this and other related genera, Ross & Sims (1987) showed that *Solium* has a number of unique features and decided to reinstate the original designation of Heiberg (1863). Very difficult to place within a suprageneric family, as it possesses features common to both the Biddulphiaceae (see discussion in Ross & Sims 1987) and the Hemiaulaceae. P.A. Sims (*pers. comm.* 1994) considers that the lack of a true ocellus makes *Solium* more characteristic of the Hemiaulaceae.

Solium exsculptum Heiberg

Pl. 9, figs. 7-8.

1863 *Solium exsculptum* HEIBERG: 52, pl. 4, fig. X (1-6).
1871 *Solium exsculptum* (Heiberg) KITTON: 102, pl. 3, fig. 10-15.
1884 *Solium exsculptum* Heiberg GRUNOW: 69, pl. 2 (B), fig. 61.
1896 *Hemiaulus exsculptus* (Heiberg) Schütt. SCHÜTT in ENGLER & PRANTL: Vol. 1 (1b), 97.
1927 *Solinum exsculptum* Heiberg SCHULZ: 118 (*sic.*).
1930 *Trinacria exsculpta* (Heiberg) Hustedt HUSTEDT: 889, illust. 533 a-c.
1972 *Trinacria exsculpta* (Heiberg) Hustedt. BENDA: pl. 3, fig. 18.
1976 *Trinacria exsculpta* (Heiberg) Hustedt. MUKHINA: 153, pl. 2, fig. 7.
1984 *Trinacria exsculpta* (Heiberg) Hustedt, 1930. GOMBOS (DSDP 73): 501, pl. 8, figs. 9, 10 (**non** fig. 11).
1985 *Trinacria Exculpta* (Heiberg) Hustedt. FENNER: 741, figs. 13.6-7 (*sic.*).
1987 *Solium exsculptum* Heiberg. ROSS & SIMS: 272-6, pl. 1, pl. 12, figs. 86-88.
1991 *Solium exsculptum* Heiberg. HOMANN: 105, pl. 37, figs. 1, 3, 5-7.

Number of specimens recovered: 4 (pyritised); 196 (non-pyritised, Fur Formation)

Revised description (abridged). "Valves with 4 or 5 projections separated from the central portion by deep sulci; central portion with straight sides between the projections, weakly domed; projections semi-circular to narrowly triangular with obtuse apices, slightly domed and rising towards the elevations. Elevations arising at the apices, not expanded above; height to their tops 18-38 µm. Areolae poroid, occluded by volae, irregularly scattered and 5-6 in 10µm on the central portion of the valve, 7-8 in 10 µm on the projections. Subocelli on the upper part of the distal face of the elevations, circular and circa 4 µm in diameter, surrounded by a narrow hyaline unthickened rim. 3-6 linking spines on the proximal sides of the tips of the elevations, usually expanded above and interlocking with those of the sibling valve, sometimes tapering upwards" (Ross & Sims 1987, p. 272-3).

Remarks. Two formas of *S. exsculptum* are known, *exsculptum* and *pentagonalis*. The latter was not found during the present study.

forma *exsculptum*

Synonymy: as for the species

Number of specimens recovered: as for the species

Description. As for the species, with quadripolar valves.
Dimensions. Length of side 30-110 µm, height at centre of valve 7.5-16 µm.

Remarks. Pyritised specimens normally have the ends of the projections broken, but otherwise even poorly-preserved specimens are easy to identify due to the diagnostic valve shape. Comparatively rare offshore, but common in the coeval Fur Formation, Denmark. Specimens from the Ølst Formation are completely replaced by pyrite and have a calcitic infilling, but the outlines of areolae are very clear. Known as "Diatom sp. 67" in the zonation of SPT.

Occurrence (this study). BP well 21/9-1, central North Sea, Horda Formation. Ølst, Ølst Formation. Knudeklint, Fur Formation.
North Sea range (unpublished). Upper Paleocene to Lower Eocene (SPT).
Range (literature). Upper Cretaceous (?Senonian): Baltic, Danzig Bay (Schulz 1935). Paleocene: Indian Ocean (Mukhina 1976); Cape Basin, South Atlantic (Gombos 1984, DSDP 73).
Upper Paleocene to Lower Eocene: Barents Sea (Grunow 1884); Fur Formation, Denmark (Heiberg 1863; Kitton 1871; Benda 1972; Fenner 1985; Ross & Sims 1987; Homann 1991).
Lower Eocene: England, London Clay (Shrubsole & Kitton 1881); Northern Germany, Unter Eozan (Schulz 1927); Russia, Middle Volga Basin (Glezer *et al.* 1974); Russia, eastern Urals (Ross & Sims 1987); Uzbekistan (Glezer *et al.* 1974).
Middle Eocene: Russia, eastern Urals (Paramonova 1964; Ross & Sims 1987).

Middle to Upper Eocene: Norwegian Sea (Dzinoridze *et al.* 1978, DSDP 38).
Upper Eocene: Norwegian Sea (Dzinoridze *et al.* 1978, DSDP 40); Russia, Sverdlovsk oblast (Ross & Sims 1987); Russia, eastern Urals (Ross & Sims 1987); Russia, Tomsk oblast (Ross & Sims 1987); Kazakhstan (Ross & Sims 1987).
Upper Eocene to Oligocene: Russia, eastern Urals (Ross & Sims 1987).
Lower Oligocene: Russia, northern and central Urals (Ross & Sims 1987).

INCERTAE SEDIS

General remarks. Included here are genera of doubtful affinity, unknown as vegetative cells and found only as resting spores.

Genus ODONTOTROPIS Grunow, 1884

Type species. Odontotropis cristata Grunow, 1884

Remarks. Odontotropis has long proved a problematic genus, and has been variously regarded as of no known affinity, or as a resting-spore (Homann 1991, p. 98). The latter is probable, as all species are heterovalvar, one valve being more highly arched than the other. Near each apex a long process projects outwards, which is enveloped by a high hyaline ridge. Two variants have been recovered in North Sea samples, both as pyritised infillings. Although the horns or hyaline areas are not preserved, the overall shape of these morphotypes is sufficient to allow species identification.

Species of *Odontotropis* have a wide distribution in lower Palaeogene strata from both open-ocean (i.e. DSDP) and more neritic (i.e. onshore) sections, and some species are useful stratigraphic markers.

Odontotropis carinata Grunow

Pl. 10, figs. 6-8.

1884 *Odontotropis? carinata*. GRUNOW: 59.

1884 *Odontotropis longispina*. GRUNOW: 58 **(nom. nud.)**

1905 *Odontotropis birostrata*. PANTOCSEK 1903-05: vol. 3: 85, pl. 14, fig. 214.

1927 *O. carinata* Grunow. SCHULZ: 118.

1930 *O. carinata* Grunow. HUSTEDT: 858, fig. 510c.

1949 *Odontotropis carinata* Grunow. PROSHKINA-LAVRENKO 1949-50: vol. 1, pl. 4a, fig. 10; vol. 2, 179, pl. 69, fig. 7.

1959 *Odontotropis carinata* Grunow. KROTOV & SHIBKOVA: 121, pl. 4, figs. 1, 2.

1972 *Odontotropis danicus* Debes ex Hustedt. BENDA: pl. 4, fig. 27.

1985 *O. danicus* Debes. FENNER: 734, pl. 14, fig. 11.

1991 *Odontotropis carinata* Grunow. HOMANN: 98-100, pl. 27, figs. 5, 7; pl. 28, figs. 1-8.

Number of specimens recovered: 14 (pyritised); 16 (non-pyritised, Fur Formation)

Revised description (abridged). "Valve lanceolate. Apical axis slightly curved towards apices. Upper part of cell ("epitheca") raised, becoming steeply concave towards poles. In girdle view, lower part of cell ("hypotheca") raised with steeply concave poles and a flat or slightly concave apical line. Keel along mid-length of the hypotheca, 20-40 µm high on the hypotheca, substantially higher on the epitheca. No areolae in the usual sense. Epitheca with an anastomosing, asymmetrical, longitudinal meshwork of spots; hypotheca generally completely structureless, rarely with scattered puncta. Valve mantle always free of ornament. Curving over each end of the hypovalve is a long spine, extending above the height of the valve. Epivalve with or without processes on the poles" (translated from Homann 1991, p. 99).

Dimensions. Length of valve 80-100µm.

Remarks. Only the internal robust, keeled hypovalve is preserved in pyritised specimens. A related form, *O. hyalina* (Debes ex Hustedt) is of stratigraphical importance, occurring around the NP4/NP5 boundary (Paleocene/Eocene) in a number of localities, including the Fur Formation of Denmark (Fenner 1985). *O. hyalina* is morphologically very similar to *O. carinata*, the only difference being a completely smooth hypovalve. It is likely that these "species" are conspecific.

Odontotropis carinata is known as "Diatom sp. 27" in the zonation of SPT.

Occurrence (this work). BP well 21/9-1, central North Sea, uppermost Balder Formation; Knokke borehole, Ieper Formation; Ølst, Ølst Formation; Knudeklint, upper Fur Formation.

Range (literature). Upper Cretaceous (?Senonian): Baltic, Danzig Bay (Schulz 1935); Upper Cretaceous (Campanian): Russia, western Siberia (Strel'nikova 1974).
Paleocene: Russia, locality uncertain (Proshkina-Lavrenko 1949-51).
Upper Paleocene to Lower Eocene: Denmark, Fur Formation (Kitton 1871; Grunow 1884; Stolley 1899; Tempere & Peragallo 1915; Schulz 1927; Hustedt 1930; Benda 1972; Homann 1991).
Lower Eocene: North Germany (Schulz 1927).
Upper Eocene: Russia, Sverdlovsk oblast (Pantocsek 1903-05).
Middle Eocene to Lower Oligocene: Russia, northeastern Urals (Strel'nikova 1960).

Odontotropis cristata Grunow

Pl. 10, figs. 1-5.

1882 *Odontella? cristata.* GRUNOW in VAN HEURCK 1880-85: pl. 102, fig. 4.
1884 *O. cristata.* GRUNOW: 59, pl. 2 (B), fig. 23; pl. 5 (E), fig. 58 a, b.
1930 *Odontotropis cristata* Grunow. HUSTEDT: 857, pl. 511.
1935 *O. cristata* Grunow. SCHULZ: 393, pl. 4.
1949 *Odontotropis cristata* Grunow. PROSHKINA-LAVRENKO 1949-51: vol. 2, 179, pl. 69, fig. 6.
1984 *Hemiaulus?* sp. 1. MALM *ET AL.*: 158, fig. 8h.
1988 *Odontotropis cristata* Grunow, 1884. HARWOOD: 85.
1991 *Odontotropis cristata* Grunow. HOMANN: 100, pl. 29, figs. 1-5.

Number of specimens recovered: 5 (pyritised); 18 (non-pyritised, Fur Formation)

Description. Frustule lanceolate in girdle view. Apical axis concave, sloping up towards apices. Valve margins steeply concave towards girdle, producing a hexagonal outline. A pronounced "girdle" extends across the centre of the frustule. Normally, a

hyaline area extends outwards between the apices, which is fimbriate and envelops both the valve and long, spinose processes which project from the apices. No areolae, but fine puncta extend in radial lines away from the "girdle".
Dimensions. Length 100-120µm.

Remarks. O. cristata is not strongly heterovalvar, but is nevertheless probably a resting spore as it has a marked hyaline ridge and long processes, and does not possess areolae in the usual sense. Several specimens have been recovered, in pyritised form, from in and around the North Sea. As is the case with *O. carinata*, only the internal hypovalve is preserved. Referred to as "Diatom sp. 16" and "Diatom sp. 63" in the informal zonation of SPT, and as "*Coscinodiscus?* sp. 24" in the zonation of Haliburton.

Occurrence (this work). BP well 21/9-1, central North Sea, upper Balder Formation; Knokke borehole, Ieper Formation; Ølst, Ølst Formation; Knudeklint, Fur Formation.
North Sea range (unpublished). Lower Eocene (SPT).
Range (literature). Upper Cretaceous (?Senonian): Baltic, Danzig Bay (Schulz 1927).
Upper Cretaceous (Campanian): Russia, western Siberia (Strel'nikova 1974)
Lower Paleocene (Danian): Seymour Island, Antarctica (Harwood 1988).
Paleocene: Russia, locality uncertain (Proshkina-Lavrenko 1949-51).
Upper Paleocene to Lower Eocene: Denmark, Fur Formation (Grunow 1884; Stolley 1899; Tempere & Peragallo 1915; Benda 1972; Homann 1991).
Lower Oligocene: Russia, north-central Urals (Proshkina-Lavrenko 1949-51).

Genus PSEUDOPODOSIRA Jousé, em. Vekschina, 1961

Type species: Pseudopodosira pileiformis Jousé, 1955

Description. Centric diatoms with a contoured valve face, heavily silicified and with a grooved valve margin which merges with the valve mantle. No discernible girdle. *Pseudopodosira* may be a resting-spore genus.
Remarks. A genus with no known affinities, listed in the "Index nominum

genericorum" of Round *et al.* 1990, but not placed within a family. Homann (1991) placed it in Incertae Sedis.

Pseudopodosira sp. 1 *sensu* Homann

Pl. 9, figs. 10-12.

1890 "fragmentary" A. SCHMIDT 1874-1959: pl. 178, fig. 41.
1991 *Pseudopodosira* sp. 1. HOMANN: 133, pl. 54, figs. 1-6.

Number of specimens recovered: 1 (pyritised)

Description. Valve circular, convex. Valve surface undulating, with elevations and depressions. Frustule biconvex in girdle view, with depressions near to valve margin. Girdle narrow, forming a discrete ridge between the valves. Areolae small, arranged in puncta, 20 in 10 µm, which form distinct grooves over the valve surface. These appear curved due to the surface undulations. Centre of valve indistinct.
Dimensions. Valve diameter 100 µm.

Remarks. Only one specimen observed, which has characters in common with *Pseudopodosira* sp. 1 of Homann (1991, Plate 54, fig. 5), in particular the girdle view and the description of areolae arranged in lines (puncta).

Occurrence (this work). BP well 21/9-1, central North Sea, top Balder Formation.
Range (literature). Paleocene: Russia, Ulyanovsk oblast (A. Schmidt 1874-1959, pl. 178/41).
Upper Paleocene to Lower Eocene: Denmark, Fur Formation (Homann 1991).

Genus STEPHANOGONIA Ehrenberg, 1844

General remarks. One of a number of genera known only as resting spores. All "species" are highly silicified and markedly heterovalvar, with no recogniseable areolae or girdle area. Its affinities are not known; Homann (1991) placed it in Incertae Sedis.

Stephanogonia sp.

Pl. 10, fig. 12.

Number of specimens recovered: 1 (pyritised)

Description. Cell robust, cylindrical. The "epivalve" has a deep mantle surmounted by a pronounced cone, tapering to a central pore. Papillae (poorly preserved in specimen) cover the mantle surface, except for the area adjacent to the "hypovalve" which has striae, 7-8 in 10 um. The "hypovalve" is strongly concave and has a smooth surface.
Dimensions. Valve diameter 80 µm.

Remarks. One specimen recovered, preserved as a pyritic infilling. The distinctive central process and radiating hyaline lines found in specimens from the Fur Formation are not present, which precludes species identification.

Occurrence (this work). BP well 21/9-1, top Balder Formation.

Genus et Species indet.

Pl. 10, fig. 13.

Number of specimens recovered: 1 (pyritised)

Description. Valve surface raised from the valve margin towards the centre. A nodulus is positioned at the valve centre, infilled with pyrite. A slightly curving pattern of strong ribs extends over the valve surface. No areolae are present.
Dimensions. Valve diameter 80 µm.

Remarks. A curious morphology, of unknown affinity. Its strong ribbing and lack of areolae are strongly suggestive of a resting spore.

Occurrence (this work). BP well 15/28a-3, central North Sea, Balder Formation.

Table 4.2 Taxonomic identity of selected diatom morphotypes from the Palaeogene of the North Sea basin.

Taxonomic status (this work)	Published reference (pyritised occurrences)	British Petroleum	S.P.T. (formerly Robertson)	Stratigraphic Range (**North Sea** and onshore)
Fenestrella antiqua (Grunow) Swatman Ref: Sims 1990, p. 279, pls. 1, 2	*Coscinodiscus* sp. 1. Bettenstaedt et al. 1962, pl. 52			**Balder & Sele**; Harwich Formation; Fur; Olst; Ieper; U.Eozan 1
F. antiqua (Gr.) Swat. resting spores Ref: Herein		"*Coscinodiscus* Sp. 6; N6"	"*Coscinodiscus* sp. 7"	**Balder & Sele** Fur
F. antiqua (Gr.) Swat. auxospores Ref: Herein		"*Coscinodiscus barreliformis*"	"*Coscinodiscus barreliformis*"	**Balder & Sele**
Coscinodiscus morsianus (Grunow) Sims Ref: Sims 1989, p. 354, figs. 8-15	**1.** *Coscinodiscus* sp. 2. Bettenstaedt et al. 1962, pl. 52 **2.** *Coscinodiscus* sp. 4. Thomas & Gradstein 1981, figs. 13-16			**Balder,Sele; Horda** London Clay (base); Fur; Olst; Ieper; U.Eozan 1
Aulacodiscus suspectus A. Schmidt Ref: Homann 1991, p. 36, pl. 5		"*Coscinodiscus* sp. 9"		**Lista; Balder, Sele; Horda; Lark** Fur; Ieper
Aulacodiscus allorgei Cheneviere Ref: Ross & Sims 1970, p. 54, pl. 4	*Coscinodiscus* sp. 1. Thomas & Gradstein 1981, figs. 1-4		"*Coscinodiscus* sp. 28"	**Lark**

Stellarima microtrias Hasle & Sims Ref: Hasle & Sims 1986, p. 111	**1.** *Coscinodiscus* sp. B. Hughes 1981, pl. 3; **2.** *Coscinodiscus* sp. 3. Thomas & Gradstein 1981, figs. 7-12	"*Coscinodiscus* cf sp.1"	"*Coscinodiscus* cf sp.1"	**Maureen; Lista; Balder; Sele; Horda; Lark** Fur; Olst; London Clay (base); Ieper
Trinacria regina (Heiberg) Homann Ref: Homann 1991, p. 124-5, pl. 50	*Triceratium* sp. 1 Ref: Bettenstaedt et al. 1962, pl. 52		"*Triceratium* sp. 30"	**Lista (top); Balder, Sele; Horda** Fur; Olst; London Clay (base)
Aulacodiscus insignis var. *quadrata* (King) Mitlehner Ref: Herein	"Diatom sp. 3" Ref: King 1983, pl. 1	"*Coscinodiscus* N2"		**Horda (upper); Lark**
Aulacodiscus insignis var. *aemulans* (Hustedt) Mitlehner Ref: Herein	"Diatom spp. 4 & 5" Ref: King 1983, pl. 1, figs. 5, 6			
Asterolampra insignis Schmidt Ref:Schrader & Fenner 1976, p. 988		"*Coscinodiscus* sp. 38"		**Horda (upper); Lark** **N.B. often caved**
Asterolampra marylandica Ehrenberg Ref: Schrader & Fenner 1976, p. 988		"*Coscinodiscus* sp. 37"	"*Cyclotella* sp. 87"	**Horda (upper); Lark** **N.B. often caved**

Table 4.2 (continued)

4.8.2 Diatom species encountered during analysis of samples from the Fur Formation

4.8.2.1 Introduction

In addition to offshore samples, material containing diatoms was analysed from the Fur Formation diatomite of northern Denmark (see chapter 3 for localities). All diatoms from Fur are preserved in original silica, and fall into two categories:-

1) specimens examined via SEM for comparative purposes, from samples sent to the Natural History Museum, London by Dr. M. Homann. Synonymies and diagnoses are given in Homann (1991); the "Remarks" refer to SEM observations made during the present study, some of which suggest that a taxonomic reassessment of these taxa, via SEM, is necessary. In addition to these taxa a completely new diatom genus, *Cylindrospira*, was discovered which is described here for the first time.

2) species observed in the LM for biostratigraphical and palaeoenvironmental analysis. Only the authors of these taxa are given here, for further information see Homann (1991). Many of these taxa are fragile forms, such as the pennate diatoms *Rhaphoneis* and *Sceptroneis*, and various species of the Biddulphioid genus *Hemiaulus* (e.g. *Hemiaulus kittonii*, pl. 8, fig. 12, this study), which have not been found in pyritised form during the present study. However, others are more robust and might be expected to be encountered therein; confidential data from exploration companies may reveal their otherwise undocumented occurrence there.

4.8.2.2 Diatom species from the Fur Formation, observed in the SEM

Stephanopyxis turris (Greville & Arnott) Ralfs

Pl. 1, fig. 1.

Synonymy: Homann (1991, p. 57)

Number of specimens recovered: 260

Remarks. A taxon displaying considerable morphological variation. Some varieties may be resting spores. *S. turris* is extremely long-ranging, and is known from deposits which range in age from Upper Cretaceous (Campanian) to Recent.

Trinacria heibergii Kitton, em. Homann

Pl. 9, fig. 2.

Synonymy: Homann (1991, p. 120)

Number of specimens recovered: 41

Remarks. A distinctive, robust species of *Trinacria* with markedly convex sides. In common with many diatoms in the Fur Formation, this taxon displays considerable morphological variation (See Homann 1991, pl. 48, figs. 1-6). Surprisingly, no specimens were recovered in pyritised form during the present study, but they are known from offshore samples, occurring in the Early and Mid Eocene in the zonation of SPT (known as "*Triceratium* sp. 40" -unornamented form; and "*Triceratium* sp. 47"- normal cells).

Sceptroneis gemmata (Grunow) Van Heurck

Pl. 9, fig. 9.

Synonymy: Homann (1991, p. 127)

Number of specimens recovered: 128

Remarks. One of several pennate diatom taxa in the Fur Formation, listed as *Opephora gemmata* in Homann (1991). The latter name is invalid, as true species of *Opephora* have a clavate to rhombic outline in valve view, and are not known from the fossil record.

Omphalotheca jutlandica Grunow, emend. Homann

Pl. 10, figs. 9-10.

Synonymy: Homann (1991, p. 131)

Number of specimens recovered: 22

Remarks. A resting-spore genus, of unknown affinity. It has a widespread geographical and stratigraphical distribution, occurring in open ocean samples and marine diatomites preserved onshore, from Late Cretaceous (Campanian) to Eocene age.

Cylindrospira Mitlehner, gen. nov. MS

Pl. 11, figs. 1-11.

Type species. Cylindrospira simsi sp. nov.

Diagnosis and description. Valves cylindrical, with dissimilar ends; one end of the valve terminates in a hyaline area, extending over the full width of the valve and punctuated by irregularly-spaced areolae with raised rims (cf. foramina) which are cribrate. Smaller, individual pores are distributed between the areolae. Two or more short spines project from the marginal ridge of the hyaline area, in addition to two distinctive raised, flattened elevated pads on opposite sides of the valve, the surfaces of these are punctuated with small, irregularly-spaced pores; a single, off-centre, labiate process may be present. The opposite end of the valve is hollow, and reveals an inward-extending hyaline rim. The aforementioned volate areolae with raised rims are regularly spaced over the valve surface, in a spiral pattern which extends from left to right towards the hyaline end of the valve. There are two species, each of which is formally described for the first time.

Remarks. A previously unrecorded genus, recovered from the Fur Formation during reconnaisance of a strewn stub for comparative study. Two species have been identified, *C. simsi* and *C. homanni.* It is possible that the larger of the two species, *C. simsi,* may have been overlooked in earlier studies (such as the monograph by Homann, 1991), as it is rare and has probably been mistaken for part of a radiolarian; some of the samples, including the one in which the specimens were found, contain a large amount of debris (consisting of broken diatom valves and silicoflagellates) which tends to partially obscure some of the diatoms. Also, the few SEM studies on this deposit have concentrated on particular species of genera which are known from additional localities (e.g. Sims 1989, 1990).

Derivation of name. From the cylindrical shape of the valve, and the spiralling array of areolae on the valve surface.

Holotype. Natural History Museum cat. no. BM 82284

Paratypes. Natural History Museum cat. nos. BM 82285, BM 82286

Type locality. Knudeklint, Island of Fur, Denmark. Sample level "D 292" (Homann 1991).

Type level. Uppermost Paleocene, close to ash-layer -20 (see Pedersen & Surlyk 1983).

Occurrence. At present only recorded from the type material.

Cylindrospira simsi sp. nov. MS

Pl. 11, figs. 1-8; Fig. 4.1, p. 148.

?1974 *Melosira goretzkii* Tscherem. GLEZER *ET AL.*: Pl. 34, fig. 8.

Number of specimens recovered: 7

Diagnosis & description. Hyaline end of valve has four marginal, short spines, 2 µm in height, in addition to two raised, flattened processes 3 µm in diameter; and a single, prominent labiate process 2 µm in diameter. The opposite, hollow end of the valve has a hyaline, girdle-like structure extending from it which has a single row of pores, above which is an internal rim. The inside of the valve has internally linked ribbing, with hyaline lines extending lengthwise through the valve, and bisecting similar rows at 90°.

LM description. The external spiralling array of pores, the internal ribbing, and the basal hyaline girdle-like structure, are all clearly visible in the LM. However, the linking processes are not easily discernible.

Dimensions. Valve 125 µm in length, width 18 µm; areolae 7-8 in 10 µm.

Remarks. The overall valve shape of *Cylindrospira simsi* is reminiscent of *Melosira goretzkii*, an Upper Eocene to Oligocene species figured by Glezer *et al.* (1974, see synonymy above) from the Volga Basin, and subsequently by Schrader & Fenner (1976, p. 989; Pl. 41, fig. 10; Pl. 44, fig. 1) from the Norwegian Sea. However, in both cases the external ornament is randomly distributed, and neither portray any indication of linking processes. However, it is possible that *M. goretzkii* is a resting spore of *C. simsi.*

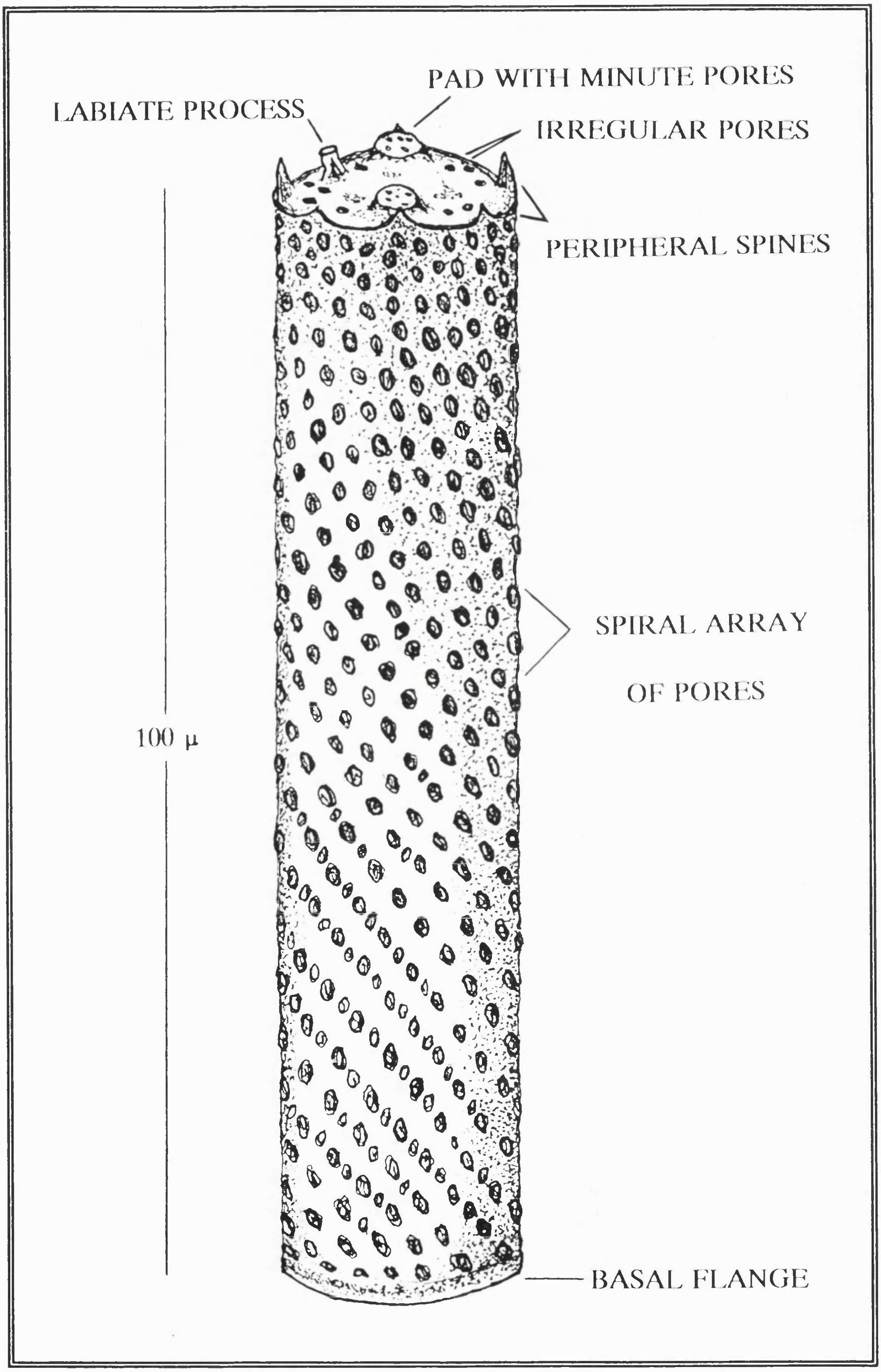


Fig. 4.1 Line drawing of *Cylindrospira simsi* Mitlehner, sp. nov.

A total of seven specimens have been found. None of these are linked together, which is unfortunate as it is difficult to precisely determine the positions of the various linking structures on the hyaline valve face, which are strongly suggestive of the hemiauloid-type processes found in genera such as *Hemiaulus* and *Trinacria*. Nevertheless, it is clear that this was a chain-forming diatom as the shape and arrangement of the raised pads on the valve face and at its margin are strongly suggestive of rigid linking processes. This feature is common to many other diatom taxa from both the Fur Formation and similar fossil diatom deposits such as the Oamaru Diatomite (Desikachary & Sreelatha 1989), and Sims + Ross (1988) consider this to have been a feature of many short-lived genera in the fossil record. More flexible, marginal structures appear to have been more successful, as shown by the long-ranging genera *Trochosira* and *Stephanopyxis*.

Derivation of name. Named for P.A. Sims.

Holotype. Natural History Museum cat. no. BM 82284

Type locality. Knudeklint, Island of Fur, Denmark. Sample level "D 292" (Homann 1991).

Type level. Uppermost Paleocene, close to ash-layer -20 (see Pedersen & Surlyk 1983).

Occurrence. At present only recorded from the type material.

Cylindrospira homanni sp. nov.

Pl. 11, figs. 9-11.

Number of specimens recovered: 2

Diagnosis. Hyaline end of valve has two marginal, short spines, 1 µm in height, in addition to two raised, flattened processes, 1.5 µm in diameter. Opposite end of valve indistinct, possibly broken but exhibiting an internal hyaline rim.

Dimensions. Length of valve 20 µm, width 4 µm. Areolae 7-8 in 10 µm.

Remarks. A smaller species of *Cylindrospira*, found in the same sample as *C. simsi*, from which it is distinguishable by its proportionally larger areolae and smaller number of linking spines. Only identifiable in the SEM, due to its small size.

Derivation of name. Named for M. Homann, who collected and prepared the sample containing the specimens.

Holotype. Natural History Museum cat. no. BM 82286 (on SEM stub).

Type locality. Knudeklint, Island of Fur, Denmark. Sample level "D 292" (Homann 1991).

Type level. Uppermost Paleocene, close to ash layer -20 (see Pedersen & Surlyk 1983).

Occurrence. At present only recorded from the type material.

Table 4.3 Other diatom species encountered during analysis of samples from the Fur Formation

Note: Species of diatoms encountered during biostratigraphic and palaeoenvironmental analysis of samples from the Fur Formation, but not recorded in pyritised form in offshore samples. These were identified with reference to Homann (1991). SEM electron micrographs were not taken, as identification was possible in the LM.

Arachnoidiscus indicus Ehrenberg
Aulacodiscus hirtus Barker & Meakin
Coscinodiscus ex gr. *argus* Ehrenberg *sensu* Homann
Coscinodiscus moelleri A. Schmidt
Coscinodiscus radiatus Ehrenberg
Goniothecium odontella var. *danica* Grunow
Hemiaulus cf. *C. curvatulus* Strel'nikova
Hemiaulus danicus Grunow
Hemiaulus elegans (Heiberg) Grunow, emend. Homann
Hemiaulus februatus Heiberg
Hemiaulus hostilis Heiberg

Hemiaulus kittonii Grunow
Hemiaulus mitra Grunow, emend. Homann
Hemiaulus muticus Strel'nikova
Hemiaulus polymorphus Grunow
Hemiaulus polymorphus var. *morsiana* Grunow
Hemiaulus proteus Heiberg
Hemiaulus pungens Grunow, emend. Homann
Hyalodiscus ex gr. *laevis/subtilis* sensu Grunow
Odontotropis hyalina Witt, emend. Homann
Omphalotheca jutlandica Grunow, emend. Homann
"*Paralia ornata*" Grunow
Paralia siberica var. *laevis* Crawford
Psudostictodiscus angulatus (Grunow) Grunow
Pterotheca aculeifera (Grunow) Grunow, emend. Homann
Rhaphoneis lancettula var. *juetlandica* Grunow, emend. Homann
Rhizosolenia dubia (Grunow) Homann
Rutilaria sp.
Stephanogonia danica Grunow
Stephanopyxis sp. 4 sensu Homann
Thalassiosiropsis wittiana (Pantocsek) Hasle
Triceratium flos Ehrenberg
Trinacria pileolus (Ehrenberg) Grunow var. *juetlandica* Grunow
Trochosira mirabilis Kitton
Xanthiopyxis oblonga Ehrenberg

Table 4.3 (continued)

4.9 Other siliceous microfossils encountered in samples from offshore wells and the Fur Formation

4.9.1 Introduction

In addition to diatoms other siliceous fossils, including radiolaria, silicoflagellates, and ebridians, were found whilst investigating samples from both offshore wells and the Fur Formation. In samples from the North Sea, the most abundant of these groups were radiolaria; in the mid Eocene these often dominated assemblages. However, in the Fur Formation the dominant siliceous group (other than diatoms) were silicoflagellates; these proved to be of great use for zonation of the samples from the Fur Formation within the scheme of Perch-Nielsen (1976, see Chapter 5).

4.9.2 Radiolaria: North Sea and onshore

4.9.2.1 North Sea morphologies

A number of radiolarian species were encountered in samples from BP wells 15/28a-3 and 21/9-1. These were normally too poorly-preserved for accurate taxonomic identification, but two of the more commonly-occurring forms are given here.

Cenosphaera sp. *sensu* King
Pl. 12, fig. 5.

1983 "*Cenosphaera* sp." KING: 20, pl. 1, fig. 8.

Number of specimens recovered: 77 (pyritised/calcified)

Description. Shape spherical, with reticulate pore-frames.
Dimensions. Diameter 140-300 µm.
Remarks. A generic name given to most poorly-preserved spumellarian (i.e. spherical) radiolaria in the North Sea Palaeogene (e.g. King 1983). These morphologies were found in a number of intervals through the Palaeogene section in wells 15/28a-3 and 21/9-1. Mid Eocene forms were generally better preserved than Paleocene forms.

Occurrence (this work). Sporadically through the Palaeogene in BP wells 15/28a-3 and 21/9-1. Especially abundant in the mid Eocene, where they are often the only microfossils encountered.

Range (literature). Paleocene, Eocene and Oligocene: southern, central and northern North Sea (King 1983, 1989; Gradstein *et al.* 1992).

Calocyclas ?extensa talwanii (Bjorklund & Kellogg)
Pl. 12, fig. 6.

Reference to good illustrations. Dzinoridze *et al.* 1978, DSDP 38 (Supplement), pl. 34, figs. 8-10.

Number of specimens recovered: 7 (pyritised)

Description. A nassellarian form with a prominent cephalis and large, hexagonal pore frames.

Dimensions. Length 120 µm.

Remarks. Relatively well-preserved, but often broken, nassellarian radiolarians were encountered in samples from the top of the Balder Formation in BP well 21/9-1. These may be caved, as they are only otherwise known from the mid to late Eocene in both the North Sea (Entwisle 1993) and Norwegian Sea (Dzinoridze *et al.* 1978).

4.8.1.2 Fur Formation

Two radiolarian species were positively identified in samples from the Fur Formation. Although the presence of radiolaria within the Fur Formation has been noted by a number of authors (e.g. Perch-Nielsen 1976; Homann 1991), none had been formally identified before the present study. Specimens of both taxa recovered are remarkably well-preserved, allowing identifications to be made, with reference to Bjorklund (1976, DSDP 38).

Ceratocyrtis hystricosus (Jørgensen)
Pl. 12, figs. 1-2.

Reference to good illustrations. Bjørklund (1976), Plate 8, figs. 19-24; Plate 11, figs. 4, 5.

Dimensions. Height of test 90 µm.

Remarks. A large, well-preserved radiolarian possessing a large pore-frame, with a cephalis bearing small spines, becoming longer at the apex. Rare in the samples studied, with only four specimens positively identified.

Occurrence (this study). Fur Formation: Silstrup, Island of Mors (near to ash layer -10, see Pedersen & Surlyk 1983).
Range (literature). Mid to Upper Eocene: Norwegian Sea (Bjorklund 1976, DSDP 38).

Peridium longispinum Jørgensen
Pl. 12, figs. 3-4.

Reference to good illustrations. Bjørklund (1976), Pl. 7, figs. 9-15.
Dimensions. Height of test 80 μm. Length of spines up to 50 μm.

Remarks. A radiolarian possessing large, thickened spines, which extend from the interior of the test and project outwards from the cephalis and thorax. Fairly abundant in some of the samples studied from the Fur Formation, often broken.

Occurrence (this study). Fur Formation: Skarrehage, Island of Mors (ash layer -6); Knudeklint, Island of Fur (ash layer -8); Silstrup, Island of Mors (ash layer -10); Hanklit, Island of Mors (ash layer -11). See Pedersen & Surlyk (1983); Chapter 3 (this study) for position of ash layers.
Range (literature). Mid to Upper Eocene: Norwegian Sea (Bjorklund 1976, DSDP 38).

4.8.2 Silicoflagellates and ebridians

Silicoflagellate taxa were identified with reference to Perch-Nielsen (1976 & 1985); SEM electron micrographs were taken of some species (Table 4.4), but most were easily identifiable in the LM. The species found, with authors, are given in Table 4.4 One ebridian species was also identified, with reference to Loeblich *et al.* (1968). Its description is as follows.

Falsebria ambigua Deflandre
Pl. 12, fig. 10.

1968 *Falsebria ambigua* Deflandre. LOEBLICH ET AL.: pl. 37, figs. 19-24.

Reference to good illustrations. Loeblich *et al.* (1968, pl. 37, figs. 19-24.

Dimensions. Width of specimens 15-20 µm.

Remarks. Loeblich *et al.* (1968) gave detailed line drawings which illustrate the morphological variation occurring within *F. ambigua* in samples from the Fur Formation; this variation was held to reflect different growth stages. In the present study two of these variants were found, both of which occurred most commonly in the basal sample ("D 292") in the samples examined from the Fur Formation.

Occurrence (this study). Knudeklint, Island of Fur, "D 292", "D294" (see Homann 1991; chapter 3).

Range (literature). Paleocene: Mors Island, Jutland, Denmark (Loeblich *et al.* 1968).

Corbisema naviculoidea (Frenguelli 1940) Perch-Nielsen 1976 (=*Corbisema disymmetrica* in Perch-Nielsen 1985)	
**Corbisema hastata globulata* Bukry (1976)	Pl. 12, fig. 8
Corbisema hastata hastata (Lemmermann, 1901) Bukry (1976)	
Corbisema glezerae Bukry (1976)	
Corbisema inermis crenulata Bukry (1976)	
Corbisema inermis inermis (Lemmermann, 1901) Bukry (1976)	
Corbisema inermis minor (Glezer, 1966) Bukry (1976)	
**Dictyocha elongata* Glezer 1960	Pl. 12, fig. 8
Dictyocha sp. aff. *D. fibula* Ehrenberg 1839	
Dictyocha precanteris Bukry (1976)	
Naviculopsis constricta (Schulz, 1928) Frenguelli (1940)	
**Naviculopsis danica* Perch-Nielsen (1976)	Pl. 12, fig. 9

Table 4.4 Silicoflagellate taxa, identified from the Fur Formation during the present study (* indicates stratigraphically important).

5. BIOSTRATIGRAPHY; CORRELATIONS

5.1 Introduction

This chapter includes a summary of the micropalaeontological and lithostratigraphic characteristics of samples obtained from offshore wells and coeval onshore exposures (see Chapter 3 for localities). Where possible, diatom data have been calibrated with other, stratigraphically well-defined fossil groups such as foraminifera and silicoflagellates, recovered and identified from the same samples as the diatoms. This has enabled the accurate placement of diatom assemblages within existing biostratigraphical schemes for the North Sea Palaeogene, which can be tied in with other key microfossil events extending beyond the North Sea.

5.2 Offshore wells: 15/28a-3 and 21/9-1

The distribution of diatoms, foraminifera and other fossils recovered from the above wells is represented in Charts 1 and 2 (Appendix A). The lithologies and microfossil assemblages present in each sample analysed are described below, together with age determinations where possible. The lithostratigraphy follows that of Knox & Holloway (1992); biostratigraphical zonation is based on the microfaunal NSB (benthic) and NSP (planktonic) zones of King (1983, 1989); additional data is derived from Charnock & Jones (1990), Gradstein *et al.* (1992), and Mudge & Copestake (1992a & b).

All of the samples described are from ditch-cuttings (DC, see Chapter 3) and are therefore subject to caving; consequently, the first downhole occurrences (FDO) of taxa are given (see charts 1 and 2, Appendix A). In addition, much of the Lower Miocene and Oligocene section in the Central North Sea has undergone moderate to extensive reworking (Gradstein *et al.* 1992, p. 120); age-diagnostic taxa are often missing from here and assemblages are commonly characterised by long-ranging species of agglutinated foraminifera (the "*Rhabdammina* biofacies" of King 1983, 1989; see Chapter 2). In such cases, it has sometimes been possible to date samples via stratigraphically-restricted species of diatoms (e.g. *Aulacodiscus insignis*, vars.

aemulans and *quadrata*). Thus, it has been possible to accurately date many of the samples obtained from well 15/28a-3. Unfortunately, large sections of the post-Early Eocene in well 21/9-1 have extremely poor microfossil recovery (with very few age-diagnostic taxa present), and are contaminated by cavings in a number of cases; only the lowermost samples contain diatoms, and detailed descriptions have only been attempted for these samples. The reader is referred to Chart 2 (Appendix A) for the complete distribution of fossils in well 21/9-1.

In the sample descriptions which follow, the proportions of microfossils (recovered from a maximum of four picking trays of each sample residue) are quantified according to the following scheme:-

Rare	1-4 specimens
Few	5-9 specimens
Common	10-24 specimens
Abundant	25+ specimens

5.2.1. BP well 15/28a-3

The important microfaunal taxa, including diatoms, recovered from this well (and the relative positions of key samples) are shown in Fig. 5.1 (p. 160), together with lithostratigraphy and age determinations, through the Palaeogene sequence (see 5.5 for further discussion).

Note: Depths in feet. Sampling interval (to 6310' depth) = 30 feet.

3520'

Lithostratigraphy: Lark Formation.

Lithology: Pale greyish brown, soft, sticky, micaceous, non-calcareous claystone; with traces of sand, framboidal pyrite, glauconite, and shell debris.

Diatoms: Rare *Stellarima microtrias, Paralia* sp., *Asterolampra?* sp.

Other microfauna: Abundant calcareous benthic foraminifera. Rare planktonic foraminifera. Rare agglutinated foraminifera (reworked). Rare radiolaria (reworked).

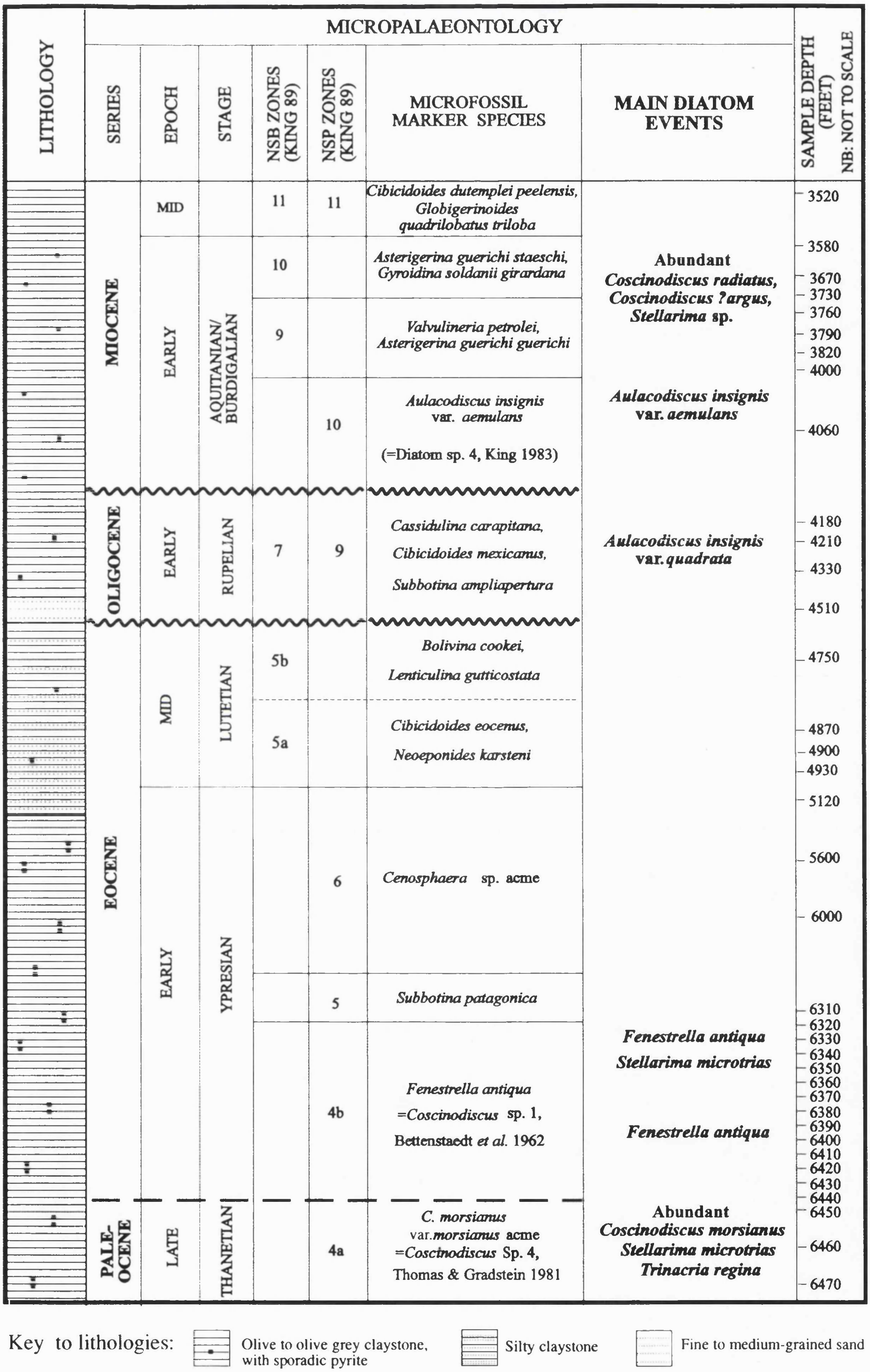


Fig. 5.1 BP well 15/28a-3: lithology, lithostratigraphy and micropalaeontology of the Palaeogene section, with significant diatom events.

Zone: Base NSB 11 (Age-diagnostic taxon: *Cibicidoides dutemplei peelensis*);[1]
NSP 11 (Age-diagnostic taxon: *Globigerinoides quadrilobatus triloba*).
Age: early mid-Miocene.

3580'

Lithostratigraphy: Lark Formation.
Lithology: Olive-grey, soft, micaceous, claystone; with framboidal pyrite.
Diatoms: Rare *Asterolampra?* sp., *Coscinodiscus ?radiatus, Paralia* sp., *Stellarima microtrias, Brightwellia?* sp.
Other microfauna: Common calcareous benthic foraminifera, some caved/reworked.
Zone: Top NSB 10 (Age-diagnostic taxa: *Asterigerina guerichi staeschi, Cibicidoides dutemplei peelensis, Melonis pompiloides*).
Age: mid-Miocene.

3670'

Lithostratigraphy: Lark Formation.
Lithology: Olive-grey, soft, micaceous, claystone; with framboidal pyrite, glauconite.
Diatoms: Rare *Aulacodiscus insignis* var. *aemulans* (reworked) *Asterolampra?* sp., *Coscinodiscus ?radiatus, Paralia* sp., *Stellarima* sp.
Other microfauna: Abundant calcareous benthic foraminifera, some caved/reworked. Rare planktonic foraminifera (caved). Rare agglutinated foraminifera (reworked).
Zone: NSB 10 (Age-diagnostic taxa: *Gyroidina soldanii girardana, Melonis pompiloides, Sigmomorphina regularis*).
Age: late early Miocene.

3730'

Lithostratigraphy: Lark Formation.
Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with shell debris.

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[1] This and subsequent calcareous benthic foraminiferal taxa were identified by the present author, with reference to King (1989); see Appendix A for full list of species found.

Diatoms: Common *Coscinodiscus ?radiatus*; few *Paralia* sp.. Rare *Coscinodiscus ?argus, Stellarima microtrias* resting spores, *Stellarima* sp.

Other microfauna: Abundant calcareous benthic foraminifera, some reworked. Rare radiolaria with large pore frames (reworked).

Zone: NSB 10 (Age-diagnostic taxa: *Cibicidoides dutemplei peelensis, Gyroidina soldanii girardana, Massilina secans, Sigmomorphina regularis*).

Age: late early Miocene.

3760'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with shell debris.

Diatoms: Common *Coscinodiscus ?radiatus*; few *Coscinodiscus ?argus, Stellarima microtrias* resting spores, rare *Asterolampra?* sp.

Other microfauna: Common calcareous benthic foraminifera, some reworked. Rare radiolaria with large pore frames (reworked).

Zone: Base NSB 10 (Age-diagnostic taxa: *Cibicidoides dutemplei peelensis, Melonis pompiloides, Uvigerina acuminata*).

Age: late early Miocene.

3790'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with framboidal pyrite.

Diatoms: Common *Coscinodiscus ?radiatus, Stellarima microtrias*. Rare *Paralia* sp.

Other microfauna: Common calcareous benthic foraminifera, some caved.

Zone: Top NSB 9 (Age-diagnostic taxa: *Asterigerina guerichi guerichi, Nodosaria* sp. A *sensu* King, *Valvulineria petrolei*).

Age: mid early Miocene.

3820'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with framboidal pyrite, glauconite.

Diatoms: Common *Coscinodiscus ?radiatus*; few *Stellarima microtrias*. Rare *Paralia* sp., initial cell of *Stellarima microtrias*.

Other microfauna: Common calcareous benthic foraminifera, some caved. Few radiolaria (*Cenosphaera* sp.).

Zone: NSB 9 (Age-diagnostic taxa: *Asterigerina guerichi guerichi, Nodosaria* sp. A *sensu* King, *Valvulineria petrolei*).

Age: mid early Miocene.

4000'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with crystalline pyrite, glauconite.

Diatoms: Common *Coscinodiscus ?radiatus*; few *Stellarima microtrias*. Rare *Asterolampra insignis* (reworked), *Aulacodiscus* sp. 1.

Other microfauna: Few calcareous benthic foraminifera, some caved.

Zone: NSB 9 (Age-diagnostic taxon: *Asterigerina guerichi guerichi*).

Age: mid early Miocene.

4060'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with crystalline pyrite.

Diatoms: Common *Coscinodiscus ?radiatus*, *Stellarima microtrias*. Rare *Aulacodiscus insignis* var. *aemulans*, *Stellarima microtrias* initial cells, *Paralia* sp., *Trinacria?* sp.

Other microfauna: Rare calcareous benthic foraminifera, caved.

Zone: ?NSB 9 (No age-diagnostic taxa); NSP 10 (Age-diagnostic taxon: *Aulacodiscus insignis* var. *aemulans* [= "Diatom sp. 4" of King 1983]).

Age: mid early Miocene.

4180'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone; with framboidal pyrite, glauconite.

Diatoms: Common *Stellarima microtrias*. Rare *Coscinodiscus ?radiatus*. Rare *Aulacodiscus insignis* var. *quadrata*, *Odontella heibergii*.

Other microfauna: Common calcareous benthic foraminifera. Few agglutinated foraminifera, radiolaria (*Cenosphaera* sp.), sponge spicules. Rare planktonic foraminifera.

Zone: NSB 7 (Age-diagnostic taxa: *Cibicidoides mexicanus, Cassidulina carapitana*); NSP 9 (Age-diagnostic taxa: *Aulacodiscus insignis* var. *quadrata* [= "Diatom sp. 3" of King 1983], *Subbotina ampliapertura*).

Age: latest early Oligocene.

4210'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone.

Diatoms: Rare *Stellarima microtrias*, *Coscinodiscus ?radiatus*, *Brightwellia?* sp.

Other microfauna: Few calcareous benthic foraminifera, some caved. Few agglutinated foraminifera. One radiolarian (*Cenosphaera* sp.).

Zone: NSB 7 (Age-diagnostic taxa: *Melonis pompiloides, Valvulineria petrolei*).

Age: early Oligocene.

4330'

Lithostratigraphy: Lark Formation.

Lithology: Medium light grey to olive-grey, soft, sticky, non-calcareous claystone.

Diatoms: Few *Aulacodiscus insignis* var. *aemulans* (caved). Rare *Aulacodiscus insignis* var. *quadrata*, *Cerataulus ?weisflogii*, *Coscinodiscus ?radiatus*, *Coscinodiscus ?argus*, *Stellarima microtrias*.

Other microfauna: Few calcareous benthic foraminifera, some caved. Rare agglutinated foraminifera, planktonic foraminifera, radiolaria (*Cenosphaera* sp.).

Zone: NSB 7 (Age-diagnostic taxa: *Cassidulina carapitana, Cibicidoides mexicanus*);

NSP 9 (Age-diagnostic taxa: *Aulacodiscus insignis* var. *quadrata* [= "Diatom sp. 3" of King 1983], *Subbotina ampliapertura*).

Age: early Oligocene.

4510'

Lithostratigraphy: ?Skade Formation.

Lithology: Clear, colourless, loose, fine to medium grained, sub angular to sub rounded sandstone.

Diatoms: Rare *Paralia siberica.*

Other microfauna: Common calcareous benthic foraminifera. Rare agglutinated foraminifera. One radiolarian (*Cenosphaera* sp.).

Zone: NSB 7 (Age-diagnostic taxa: *Cassidulina carapitana, Cibicidoides mexicanus, Globobulimina socialis*).

Age: early Oligocene.

4750'

Lithostratigraphy: Horda Formation.

Lithology: Medium to light grey, silty, non-calcareous claystone.

Diatoms: None.

Other microfauna: Rare agglutinated and calcareous benthic foraminifera.

Zone: NSB 5b (Age-diagnostic taxa: *Bolivina cookei, Lenticulina gutticostata*).

Age: mid Eocene.

4870'

Lithostratigraphy: Horda Formation.

Lithology: Medium to light grey, silty, non-calcareous claystone.

Diatoms: Rare *Stellarima* sp., *Paralia* sp.

Other microfauna: Few agglutinated foraminifera; one calcareous benthic foraminifer, caved.

Zone: ?NSB 5b (No age-diagnostic taxa).

Age: mid Eocene.

4900'

Lithostratigraphy: Horda Formation.

Lithology: Medium to light grey, silty, non-calcareous claystone.

Diatoms: None.

Other microfauna: Few agglutinated foraminifera. Rare sponge spicules.

Zone: ?NSB 5b (No age-diagnostic taxa).

Age: mid Eocene.

4930'

Lithostratigraphy: Horda Formation.

Lithology: Medium to light grey, silty, non-calcareous claystone; with pyrite, glauconite.

Diatoms: None.

Other microfauna: Common agglutinated foraminifera. Rare calcareous benthic foraminifera.

Zone: NSB 5a (Age-diagnostic taxa: *Cibicidoides eocenus, Neoeponides karsteni*).

Age: mid Eocene.

5120'

Lithostratigraphy: Horda Formation.

Lithology: Medium to light grey, silty, non-calcareous claystone.

Diatoms: None.

Other microfauna: Few radiolaria (*Cenosphaera* sp.).

Zone: NSP 6 (Age-diagnostic taxon: *Cenosphaera* sp., acme zone).

Age: late early Eocene.

5600'

Lithostratigraphy: Horda Formation.

Lithology: Greyish olive grey, firm, non-calcareous claystone.

Diatoms: None.

Other microfauna: Few radiolaria (*Cenosphaera* sp.).

Zone: NSP 6 (Age-diagnostic taxon: *Cenosphaera* sp.).

Age: late early Eocene.

6000'

Lithostratigraphy: Horda Formation.

Lithology: Greyish olive grey, firm, non-calcareous claystone; with pyrite.

Diatoms: None.

Other microfauna: Few radiolaria (*Cenosphaera* sp.).

Zone: NSP 6 (Age-diagnostic taxon: *Cenosphaera* sp.).

Age: late early Eocene.

Note: Sampling interval now = 10 feet.

6310'

Lithostratigraphy: Horda Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: None.

Other microfauna: Few radiolaria (*Cenosphaera* sp.); planktonic foraminifera; rare agglutinated foraminifera.

Zone: NSP 5 (Age-diagnostic taxa: *Cenosphaera* sp., *Subbotina patagonica* [= *Subbotina* gr. *linaperta* of King 1989]).

Age: early Eocene.

6320'

Lithostratigraphy: Balder Formation (top).

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Common *Stellarima microtrias.* Rare *Fenestrella antiqua* (vegetative cell), *Hemiaulus?* sp., *Paralia* sp.

Other microfauna: Few agglutinated foraminifera. Rare planktonic foraminifera (caved). Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6330'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells, *F. antiqua* auxospores, *F. antiqua* initial cells, *F. antiqua* resting spores.

Other microfauna: None.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6340'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells.

Other microfauna: One radiolarian (*Cenosphaera* sp.).

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6350'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells.

Other microfauna: One agglutinated foraminifer.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6360'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells.

Other microfauna: None.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6370'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Few *Fenestrella antiqua* vegetative cells. Rare *F. antiqua* auxospores, *F. antiqua* resting spores, *Stellarima microtrias*.

Other microfauna: None.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6380'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells, *F. antiqua* auxospores, *F. antiqua* resting spores, *Stellarima microtrias*.

Other microfauna: One agglutinated foraminifer.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6390'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Common *Fenestrella antiqua* vegetative cells. Rare *F. antiqua* auxospores.

Other microfauna: None.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6400'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells.

Other microfauna: One agglutinated foraminifer.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6410'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells, *F. antiqua* auxospores.

Other microfauna: Rare agglutinated foraminifera.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6420'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Aulacodiscus suspectus*, *Hemiaulus* sp., *Trinacria regina* (=*Triceratium* sp. 1 of Bettenstaedt *et al.* 1962), *Fenestrella antiqua* vegetative cells, *F. antiqua* auxospores.

Other microfauna: Rare agglutinated foraminifera.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6430'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells, *F. antiqua* auxospores.

Other microfauna: Few agglutinated foraminifera.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6440'

Lithostratigraphy: Balder Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Rare *Fenestrella antiqua* vegetative cells, *F. antiqua* auxospores, *F. antiqua* resting spores.

Other microfauna: Common agglutinated foraminifera.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: earliest Eocene.

6450'

Lithostratigraphy: Sele Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Common *Stellarima microtrias*; few *Hemiaulus*? sp., *Fenestrella antiqua* vegetative cells, *Trinacria regina*. Rare *Coscinodiscus morsianus* var. *morsianus* (= *Coscinodiscus* sp. 2 of Bettenstaedt *et al.* 1962), *Coscinodiscus morsianus* var. *moelleri*, *F. antiqua* auxospores.

Other microfauna: Few agglutinated foraminifera.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: latest Paleocene. *Note:* identified by acme of *Stellarima microtrias* (= *Coscinodiscus* sp. 4 of Thomas & Gradstein 1981), see Mudge & Copestake 1992a & b; Knox & Holloway 1992.

6460'

Lithostratigraphy: Sele Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Abundant *Stellarima microtrias*; common *Hemiaulus*? sp., *Trinacria regina*. Rare *Coscinodiscus morsianus* var. *morsianus* (= *Coscinodiscus* sp. 2 of Bettenstaedt *et al.* 1962), *Coscinodiscus morsianus* var. *moelleri*, *F. antiqua* vegetative cells.

Other microfauna: Rare agglutinated foraminifera.

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: latest Paleocene.

6470'

Lithostratigraphy: Sele Formation.

Lithology: Olive black, soft to firm, silty, micaceous claystone.

Diatoms: Common *Fenestrella antiqua* vegetative cells; rare *Stellarima microtrias*, *F. antiqua* auxospores, *F. antiqua* initial cells, *F. antiqua* resting spores.

Other microfauna: Common agglutinated foraminifera.

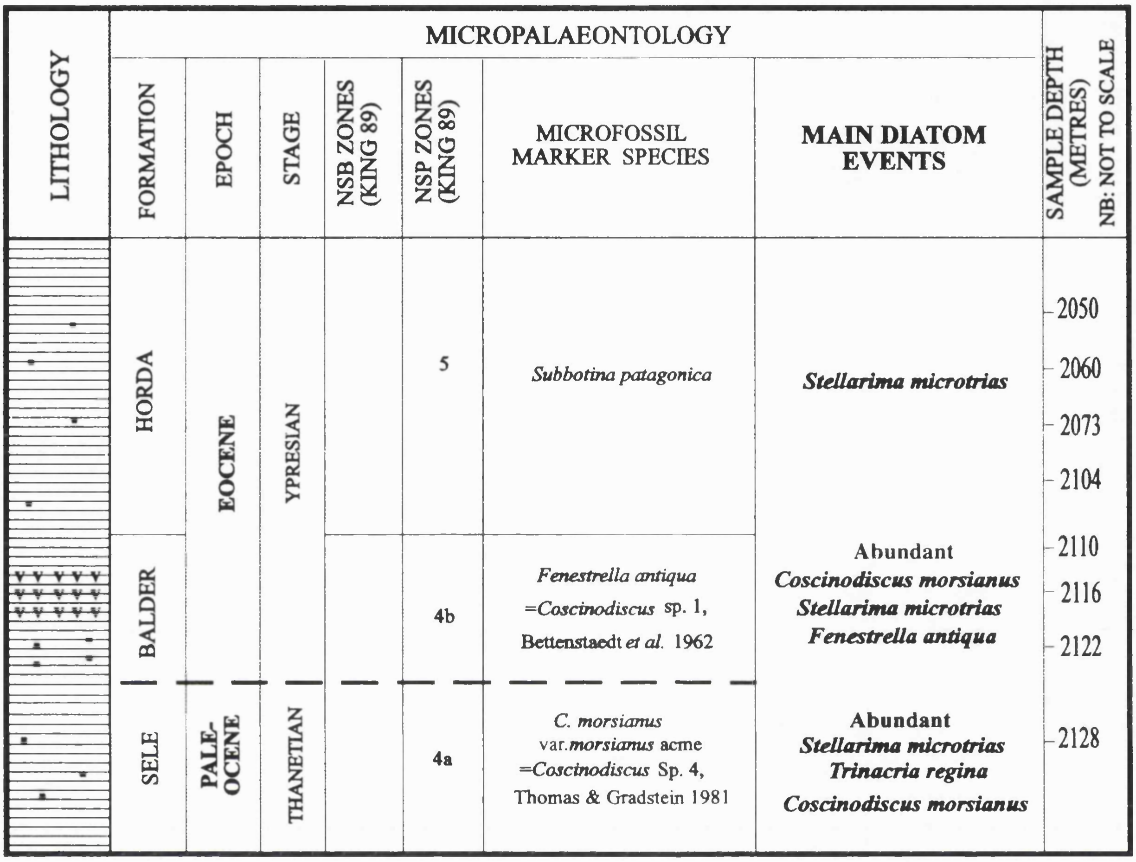
Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962]).

Age: late Paleocene.

5.2.2 BP well 21/9-1

Recovery of microfossils above 2060 metres depth in this well was extremely poor. Therefore, an integrated bio- and lithostratigraphical sequence was not possible for the post-early Eocene. However, rich assemblages of diatoms and agglutinated foraminifera were recovered from the uppermost Paleocene to Lower Eocene interval, which included stratigraphically-important diatom taxa; Fig. 5.2 (p. 173) gives the combined lithostratigraphy and micropalaeontology for this section.

Note: Sample depths in metres. Sampling interval variable.



LITHOLOGY	MICROPALAEONTOLOGY							SAMPLE DEPTH (METRES) NB: NOT TO SCALE
	FORMATION	EPOCH	STAGE	NSB ZONES (KING 89)	NSP ZONES (KING 89)	MICROFOSSIL MARKER SPECIES	**MAIN DIATOM EVENTS**	
	HORDA	**EOCENE**	YPRESIAN		5	*Subbotina patagonica*	***Stellarima microtrias***	2050 2060 2073 2104
	BALDER				4b	*Fenestrella antiqua* =*Coscinodiscus* sp. 1, Bettenstaedt *et al.* 1962	**Abundant** ***Coscinodiscus morsianus*** ***Stellarima microtrias*** ***Fenestrella antiqua***	2110 2116 2122
	SELE	**PALE-OCENE**	THANETIAN		4a	*C. morsianus* var.*morsianus* acme =*Coscinodiscus* Sp. 4, Thomas & Gradstein 1981	**Abundant** ***Stellarima microtrias*** ***Trinacria regina*** ***Coscinodiscus morsianus***	2128

Key to lithologies: ▤ Olive to olive grey claystone, with sporadic pyrite ▤ Variegated, sub-fissile mudstone, with volcanic glass shards

Fig. 5.2 BP well 21/9-1: lithology, lithostratigraphy and micropalaeontology of the upper Paleocene to lower Eocene section, with significant diatom events.

2060 m

Lithostratigraphy: Horda Formation.

Lithology: Olive black, firm, non-calcareous, slightly pyritic mudstone.

Diatoms: Few *Stellarima microtrias*, *Asterolampra insignis* (caved); rare *Actinoptychus senarius*, *Coscinodiscus radiatus*, *Trinacria excavata*, *T. regina* (reworked), *Solium exsculptum*, *Triceratium* sp.

Other microfauna: Common agglutinated foraminifera ("*Rhabdammina* biofacies").

Zone: NSB 3b (Age-diagnostic taxon: *Gaudryina hiltermanni*).

Age: early Eocene.

2073 m

Lithostratigraphy: Horda Formation.

Lithology: Olive black, firm, non-calcareous, slightly pyritic mudstone.

Diatoms: Few *Stellarima microtrias*; one *S. microtrias* resting spore.

Other microfauna: Common agglutinated foraminifera ("*Rhabdammina* biofacies").

Zone: ?NSB 3b (No age-diagnostic taxa).

Age: early Eocene.

2104 m

Lithostratigraphy: Horda Formation.

Lithology: Olive black, firm, non-calcareous, slightly pyritic mudstone.

Diatoms: Rare *Coscinodiscus morsianus* var. *moelleri*.

Other microfauna: Abundant agglutinated foraminifera ("*Rhabdammina* biofacies"). Rare planktonic foraminifera, radiolaria (*Cenosphaera* sp.).

Zone: NSP 5 (Age-diagnostic taxa: *Subbotina patagonica* [= *Subbotina* gr. *linaperta* of King 1989]; *Cenosphaera* sp.).

Age: early Eocene.

2110 m

Lithostratigraphy: Balder Formation (top).

Lithology: Variegated, light and moderate brown, greenish grey & minor greyish purple and pale yellowish green, firm, sub fissile, non-calcareous mudstone.

Diatoms: Abundant *Coscinodiscus morsianus* var. *morsianus*, *Trinacria regina*; common *Stellarima microtrias*; few *Fenestrella antiqua* vegetative cells; rare *Odontella heibergii*, *Odontotropis carinata*, *Paralia siberica.*

Other microfauna: Abundant agglutinated foraminifera ("*Rhabdammina* biofacies"). Few radiolaria (*Cenosphaera* sp.). Rare planktonic foraminifera (caved).

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962).

Age: earliest Eocene.

2116 m

Lithostratigraphy: Balder Formation.

Lithology: Variegated, light and moderate brown, greenish grey & minor greyish purple and pale yellowish green, firm, sub fissile, non-calcareous mudstone; with large pyrite aggregations, volcanic ash, and glass shards.

Diatoms: Common *Coscinodiscus morsianus* var. *morsianus*, *Fenestrella antiqua* vegetative cells, *Stellarima microtrias*, *Trinacria regina*; few *Paralia siberica*; rare *Asterolampra marylandica* (caved), *Asterolampra insignis* (caved), *Aulacodiscus suspectus*, *Hemiaulus ?elegans*, *Trinacria excavata.*

Other microfauna: Abundant agglutinated foraminifera ("*Rhabdammina* biofacies"). Few radiolaria with large pore frames (caved).

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962).

Age: earliest Eocene.

2122 m

Lithostratigraphy: Balder Formation.

Lithology: Olive green, firm, slightly calcareous mudstone.

Diatoms: Common *Coscinodiscus radiatus*, *Fenestrella antiqua*, *Stellarima microtrias*; few *Coscinodiscus morsianus* var. *morsianus*, *Trinacria regina*; rare *Fenestrella antiqua* initial cells, *Paralia siberica.*

Other microfauna: Common agglutinated foraminifera ("*Rhabdammina* biofacies"). Rare radiolaria with large pore frames (caved).

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962).

Age: earliest Eocene.

2128 m

Lithostratigraphy: Sele Formation.

Lithology: Olive green, firm, slightly calcareous mudstone.

Diatoms: Abundant *Stellarima microtrias*; common *Coscinodiscus morsianus* var. *morsianus*, *Fenestrella antiqua*; few *Asterolampra insignis* (caved), *Trinacria regina.* Rare *Stellarima microtrias* resting spores, *Paralia siberica.*

Other microfauna: Common agglutinated foraminifera ("*Rhabdammina* biofacies"); one radiolarian with large pore frames (caved).

Zone: NSP 4 (Age-diagnostic taxon: *Fenestrella antiqua* [= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962).

Age: uppermost Paleocene. *Note:* identified by acme of *Stellarima microtrias* (= *Coscinodiscus* sp. 4 of Thomas & Gradstein 1981), see Mudge & Copestake 1992a & b; Knox & Holloway 1992.

5.2.3 Core sections: BP wells 16/13a-4, 16/13a-5

Samples were analysed from cores taken through the Sele and basal Balder formations in the South Viking Graben (see Fig. 3.1, Chapter 3 for locations), in order to produce a refined diatom biostratigraphy for this interval, and to recover any non-pyritised diatoms which may be present within calcareous concretions. However, despite intensive and extensive processing (including both mechanical and chemical treatments), only a few, poorly preserved specimens of *Fenestrella antiqua* were recovered[2], which confirm that these sections are uppermost Paleocene to lowermost Eocene in age. The lithologies in both cores consist of a sequence of laminated,

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[2] The small quantities of specimens found did not warrant the construction of range charts for these wells.

highly-indurated claystones with ash-layers and some horizons with hydrocarbon shows, a lithological sequence characteristic of the Balder Formation. In some parts of the central and northern North Sea, the Balder Formation is an important hydrocarbon reservoir; it is possible that the source of this petroleum may have been diatoms in part, which are thought to have contributed to hydrocarbon formation in the Miocene Monterey Formation of California (Isaacs & Petersen 1987). Kerogen analysis, which may shed light on this matter, was outside the scope of the present study.

5.3 Comparative onshore sections

In addition to the offshore well samples, a number of onshore sections were analysed for diatoms. These onshore samples were taken from strata coeval with the Sele and Balder formations of the North Sea, this being the main diatomaceous interval in the Palaeogene sequence which coincides with the Paleocene/Eocene boundary, a poorly-defined interval in northwest Europe (see Chapter 2).

5.3.1 Harwich and Wrabness, eastern England

Samples taken from the Harwich Formation (see Fig. 5.8), exposed on the foreshore at the above localities (see Fig. 3.1, Chapter 3), were donated to the present author by M.A. Charnock. Of a total of eight samples processed, only one was found to contain diatoms. Taken from Wrabness, this sample was recovered from a reddish, silty clay. A total of 15 specimens of *Coscinodiscus morsianus* var. *morsianus* were found, all highly oxidised.

5.3.2 Knokke well no. 1, Belgium

Samples from Knokke well no.1 were analysed for diatoms from 278-298 metres depth (see King 1990 for detailed lithostratigraphy), at around the base of the Ieper Formation (correlatable with the uppermost Balder Formation in the North Sea). Although only one sample was found to contain diatoms, these were abundant and diverse, and SEM analysis showed that these specimens, although almost completely pyritised (see Chapter 6), had many original features preserved which permitted their taxonomic identity to be deduced (see Chapter 4). The assemblage composition is as follows:-

283 m
Lithostratigraphy: Ieper Clay (base).
Lithology: Fine, reddish clay.
Diatoms: Abundant *Coscinodiscus morsianus*, vars. *morsianus* and *moelleri* (and possible transitional forms; *Coscinodiscus ?argus*; *Trinacria regina*; few *Fenestrella antiqua* vegetative cells (poorly preserved), *Paralia siberica*, *Stellarima microtrias*; rare *Odontotropis cristata.*
Other microfauna: none.
Age: Paleocene/Eocene boundary.

5.3.3 Samples from Ølst, Denmark

A number of samples were collected from the clay pit at Ølst, eastern Jutland, by the present author (see Chapter 3 for locality). These samples were taken from stratigraphically well-defined intervals in the sequence of muds with cementstone and volcanic ash-layers which together form the Ølst Formation, the lateral equivalent of the Fur Formation (Heilmann-Clausen 1985a, 1994), and of the Sele and Balder formations in the North Sea (e.g. Knox 1984, 1994). Relatively rich assemblages of diatoms were recovered from three samples within the mud layers, but although all specimens were pyritised enough detail was preserved to make comparisons with non-pyritised specimens from the Fur Formation (see Plates 1-10). The style of pyritisation, which has often preserved delicate structures such as spines (features not normally encountered in specimens from the central North Sea) suggests that replacement occurred at an early stage after death (see Chapter 6, this study).

The diatoms recovered from each sample from Ølst are described below; the lithostratigraphy follows that of Heilmann-Clausen (1987).

NB: the Paleocene/Eocene boundary lies within the section, but its precise level has yet to be determined; it is likely that either ash-layer +19 or -17 (which have been identified elsewhere) will form the boundary marker (Berggren 1993; Knox 1994). Therefore, only tentative age assignments are given here.

"Ølst B"

Lithostratigraphy: Ølst Formation, Vaerum Member.

Lithology: Organic-rich, stiff, carbonaceous clay.

Diatoms: Abundant *Trinacria regina*; common *Fenestrella antiqua*; few *Coscinodiscus morsianus* var. *morsianus*, *Paralia siberica*, *Stellarima microtrias*; few *Hemiaulus ?elegans*; one specimem each of *Odontotropis carinata*, *Solium exsculptum.*

Other microfauna: Abundant sponge spicules, pyritised. One well-preserved sharks tooth.

Stratigraphic horizon: Beneath ash-layer +19 (Bøggild 1918; see Fig. 3.3, Chapter 3). Equivalent to Zone NSP 4 (King 1989).

Age: ?early Eocene.

"Ølst C"

Lithostratigraphy: Ølst Formation, Vaerum Member (base).

Lithology: Laminated, fissile, indurated mudstone; with fish debris.

Diatoms: Abundant *Coscinodiscus morsianus* var. *morsianus*; rare *Trinacria regina*, *Fenestrella antiqua* auxospores.

Other microfauna: None.

Stratigraphic horizon: Beneath ash-layer +1 (Bøggild 1918; see Fig. 3.3, Chapter 3). Equivalent to Zone NSP 4 (King 1989).

Age: latest Paleocene to earliest Eocene.

"Ølst D"

Lithostratigraphy: Ølst Formation, Haslund Member (top).

Lithology: Soft, friable, silty, partially silicified mudstone.

Diatoms: Abundant *Trinacria regina*; common *Coscinodiscus morsianus* var. *morsianus*; few *Fenestrella antiqua*, *Odontotropis carinata*; rare *Paralia siberica*, *Solium exsculptum*, *Stellarima microtrias*, *Stephanogonia danica*, *Trinacria excavata*.
Other microfauna: None.
Stratigraphic horizon: Beneath ash-layer -1 (Bøggild 1918; see Fig. 3.3, Chapter 3). Equivalent to Zone NSP 4 (King 1989).
Age: latest Paleocene to earliest Eocene.

5.3.4 Fur Formation: results and interpretation

Results of quantitative analysis of strewn slides, obtained from calcareous concretions within the Fur Formation (see Chapter 3) are given in Table 5.1 (p. 181). This shows that there are noticeable assemblage changes[3], shown by all of the siliceous fossil groups examined; these correlate well with the silicoflagellate zones of Perch-Nielsen (1976). The chief characteristics of each assemblage are given below. Sample numbers refer to those given in Fig. 3.3 (Chapter 3).

Sample number 292

Naviculopsis danica assemblage [Ash Layer -20].

The dominant diatom taxa in sample -20 are benthic forms such as the pennate species *Sceptroneis gemmata* and *Rhaphoneis lancettula*, and the neritic species *Actinoptychus senarius*; there is an absence of the larger planktonic centric and chain-forming species found in the succeeding samples. This sample is also characterised by large numbers of silicoflagellates (mainly *Naviculopsis danica*), and fairly abundant ebridians; radiolaria are absent. This probably indicates a shallow, neritic environment with depths of less than 50 metres (R. Ross, *pers. comm.* 1994). The presence of ebridians is suggested by some authors to indicate relatively cool or temperate waters (Loeblich *et al.* 1968).

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[3] Multivariate statistical analyses were not attempted on these assemblages, as assemblage changes are readily distinguishable by eye (see Table 5.1)

LITHOSTRATIGRAPHY (PEDERSEN & SURLYK 1983)	ASH LAYERS (BOGGILD 1918)	LOCALITY (LIMFJORDEN REGION)	SAMPLE NUMBER (HOMANN 1991)	Stephanopyxis turris	Stephanopyxis sp. 4	Sceptroneis gemmata	Solium exsculptum	Stellarima microtetris	Hemiaulus polymorphus	Coscinodiscus radiatus	**"Pterotheca aculeifera"**	Hemiaulus pungens	Trochosira mirabilis	Coscinodiscus moelleri	Aulacodiscus suspectus	Hemiaulus elegans	**Goniothecium odontella**	Trinacria regina	Trinacria excavata	Hemiaulus danicus	**Omphalotheca jutlandica**	Pseudostictodiscus angulatus	Fenestrella antiqua	**Odontotropis carinata**	**"Pyxilla carinifera"**	**Stephanogonia danica**	Hemiaulus mitra	Rhizosolenia dubia	Stictodiscus morsianus	Stephanopyxis sp. 1	Paralia ornata	Triceratium flos	Hemiaulus kittoni
SILSTRUP MBR	.+29	KNUDEKLINT	298	150	21	19	18	9	4	2	10	6	4	6	4	37	32	22	14	5	2	3	5	7	15	2	8	9	11	3	2	2	1
KNUDE-KLINT MEMBER	-6	SKARREHAGE	335	25	30	5	23	12	1	2	3			2		53	9	200	46	3	8	7	12	1	4		4	1					
	-8	KNUDEKLINT	294	21	31	24	56	18	11	1	1	4	4	6		39	16	132	16	24	9	26	21	4	4	4	12	7					
	-10	SILSTRUP	330	37	21	17	25	25	9	2		3	1			10	2	200	32	4	1	2	37			1							
	-11	HANKLIT	293	13	19	12	70	18	4	4	1	1	2			14	4	180	65	12	2	1	31	4	3		3						
	-20	KNUDEKLINT	292	14	44	53	4	5	20	5	4	9	29	14	2																		

LOCALITY (LIMFJORDEN REGION)	SAMPLE NUMBER (HOMANN 1991)	Coscinodiscus morsianus	Trinacria heibergii	**F. antiqua resting spores**	**S. microtetris resting spores**	**Odontotropis cristata**	**Odontella heibergii**	Rhizosolenia clavigera	Hemiaulus hostilis	Coscinodiscus morsianus v. argus	Paralia sulcata	"Rhaphoneis morsiana"	Trinacria pileolus	**"Xanthiopyxis oblonga"**	Actinoptychus senarius	Aulacodiscus suspectus	Coscinodiscus morsianus v. moelleri
KNUDEKLINT	298																
SKARREHAGE	335	11	7	7	3	2	1	1									
KNUDEKLINT	294	6	5	8	5	3	1	1	6	4	2		9	4			
SILSTRUP	330	24	13	14	9	10	2		5			4					
HANKLIT	293	11	16	9	8	3	2	3				2					
KNUDEKLINT	292												3	15	21	2	18

											SILICOFLAGELLATES															SILICOFLAGELLATE ZONES (PERCH-NIELSEN 1976, 1985)	
Hemiaulus curvatulus	Hemiaulus februatus	Hyalodiscus "laevis/subtilis"	Rhaphoneis lancettula	Rutilaria sp.	"Thalassiosiropsis wittiana"	Triceratium heibergii	Genus et species indet.	**Indet. resting spores**	TOTAL NUMBER OF SPECIMENS COUNTED		Corbisema hastata globulata	C. hastata hastata	C. glezerae	C. inermis inermis	C. inermis minor	Naviculopsis constricta	Dictyocha precanteris	Corbisema naviculoidea	Dictyocha elongata	Dictyocha sp. aff. D. fibula	Corbisema inermis crenulata	Naviculopsis danica	Radiolarian sp. 1	Indet. Radiolaria	Ebridians	SUBZONE	ZONE
									433		13	2	13		2	10	2									*N. aspera*	*Naviculopsis constricta*
									483		1					10	1						9			*Corbisema naviculoidea*	
									545		6			4		7	12						21		2		
									510		5					4	15	1	2				27				
									517		8			8		20	8	7	3				8	6			
20	3	4	95	3	3	2	7	23	422							13	8			6	7	41			13	*N. danica*	

Table 5.1 Quantitative distribution of diatom species, silicoflagellates, radiolaria and ebridians in samples analysed from the Fur Formation, incorporated within the silicoflagellate zonation of Perch-Nielsen (1976). Diatom resting spores in bold.

Sample numbers 293, 294, 330, 335

Corbisema naviculoidea assemblage [Ash Layers: -11, -10, -8, & -6].

The four samples following -20 are characterised by a dominance of planktonic centric (*Coscinodiscus morsianus, Fenestrella antiqua*, and *Stellarima microtrias*) and chain-forming (*Trinacria regina, T. excavata*, *Solium exsculptum* and *Hemiaulus elegans*) diatom taxa, with declining benthic pennate diatoms and the appearance of two radiolarian taxa (*Ceratocyrtis hystricosus* and *Peridium longispinum*), previously unrecorded from the Fur Formation. The silicoflagellate assemblage also changes markedly, and becomes dominated by *Corbisema hastata globulata*. Ebridians are absent in all of these samples. It was decided not to further subdivide this assemblage into diatom subzones, as fluctuations in dominant taxa are probably explained by localised blooms, caused by seasonal variations in nutrient levels (J. Fenner, *pers. comm.* 1993). The abundance of diatom resting spores (Round *et al.* 1990, p. 52) indicates environmentally-stressed conditions related to seasonal nutrient depletion, and possibly the periodic suppression of photosynthesis by large loadings of volcanic dust (Kitchell *et al.* 1986).

Sample number 298

Naviculopsis aspera assemblage [Ash layer +29].

The uppermost sample analysed shows broad similarities with the preceding assemblage, but is distinguished by an absence of many of the diatom resting-spores found therein. The silicoflagellates are dominated by *Corbisema glezerae*, a characteristic marker for the *N. aspera* subzone of Perch-Nielsen (1976; Table 5.2, p. 186).

5.4 Discussion: comparison with previous work

5.4.1 Offshore wells

The offshore wells analysed in this study generally exhibit poor recovery of diatoms, in comparison both with coeval onshore assemblages from around the North Sea, and with other diatom assemblages elsewhere. However, one of the wells studied, 15/28a-3, has been biostratigraphically zoned using both diatoms and other microfossils, and this demonstrates the value of utilising an integrated biostratigraphy in dating the sections present, which are otherwise difficult to precisely correlate using lithostratigraphic and geophysical data alone. Other wells studied (e.g. 21/9-1) exhibit an extremely patchy microfossil recovery, and only parts of the sequence can be correlated with confidence. Nevertheless, there are certain intervals within these wells which are extremely rich in diatoms, and these have proved invaluable for both taxonomic purposes (see Chapter 4) and for stratigraphy (Fig. 5.2, p. 173).

5.4.1.1 BP well 15/28a-3

The lithostratigraphy and key micropalaeontological markers for the Palaeogene section in well 15/28a-3 (Fig. 5.1, p. 160) demonstrate the following features.

1) The relative proportion of different microfossil groups changes markedly from the uppermost Paleocene to the mid-Miocene (Figs. 5.3, 5.4). In particular, diatoms show several abundance peaks, the most prominent being in the basal samples (6450-6470' depth), which correspond to the Sele Formation (Fig. 5.1, p. 160). These tend to coincide with peaks of radiolaria (Fig. 5.3), except for the upper part of the Lower Eocene (NSP 6, King 1989). This accords well with published information, which documents a radiolarian abundance peak during this interval, attributed to water deepening, with increased oceanic contact, during a transgressive phase. The apparent absence of diatoms during this interval is difficult to explain, but may be due to dissolution (see Chapter 6) as the radiolaria present are poorly-preserved.

   Foraminifera also display marked compositional changes (Fig. 5.5, p. 185), with a gradual change in dominance from agglutinated taxa in the Lower Eocene towards calcareous benthic forms in the Miocene. This documents a changeover from relatively deep, oxygen-poor conditions in the central parts of the basin during the early Palaeogene (the "*Rhabdammina* biofacies" of King 1983; see Chapter 2) towards a regime with improved bottom-water circulation during the later Paleogene to early Neogene (King 1989; Gradstein *et al.* 1992).

2) The presence of two major unconformities, with the entire Upper Eocene and Upper Oligocene sections missing, and the Lower Oligocene section much condensed (Fig. 5.1, p. 158).

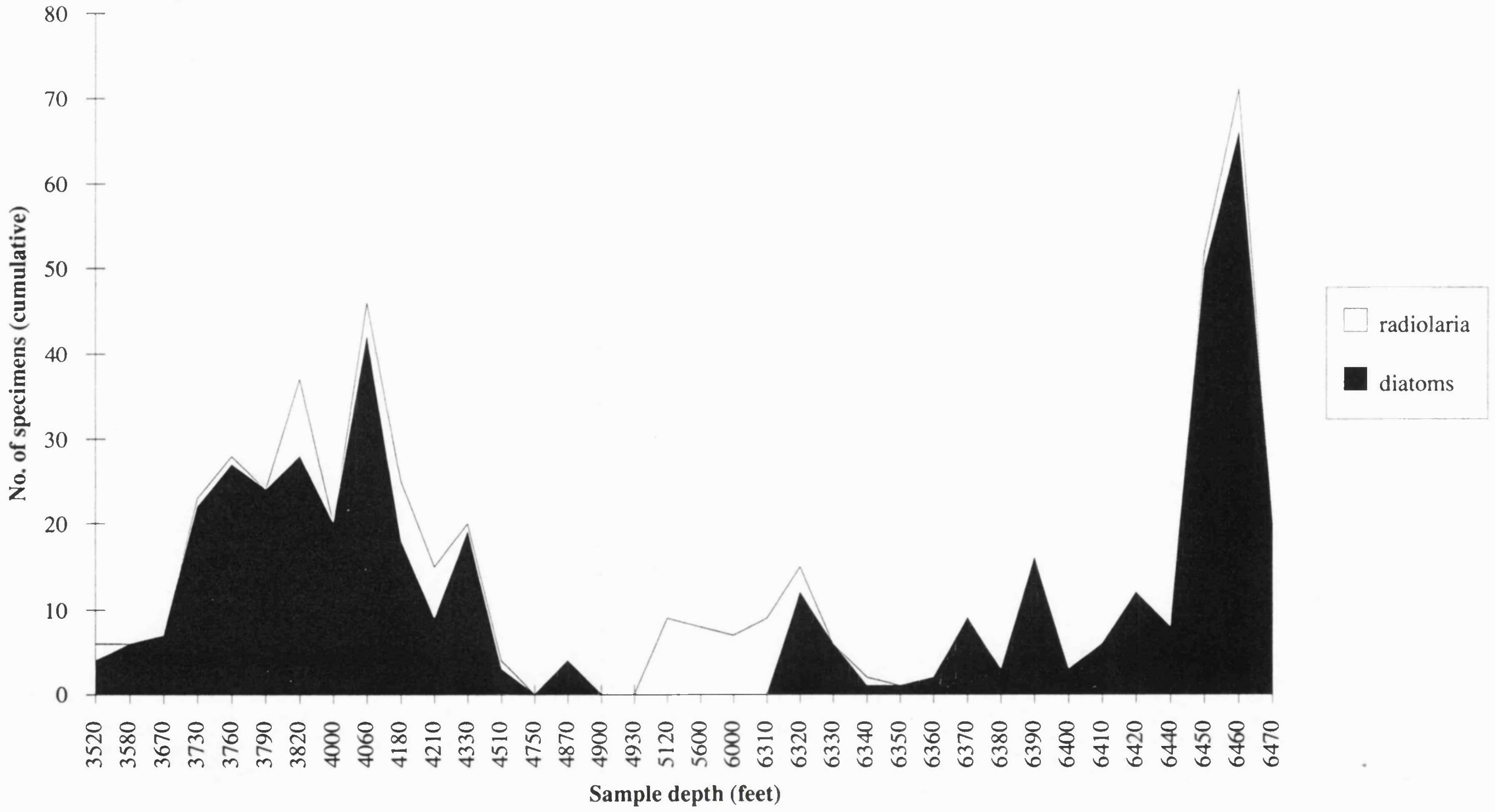


Fig. 5.3 Distribution of diatoms and radiolaria in BP well 15/28a-3. Note that abundance peaks of both fossil groups appear to coincide, except for the mid-Lower Eocene (samples 4930-6310) where radiolaria dominate. NB this well has been much affected by caving. Radiolaria and diatoms are normally mutually exclusive in the central North Sea (M.A. Charnock, *pers. comm.*)

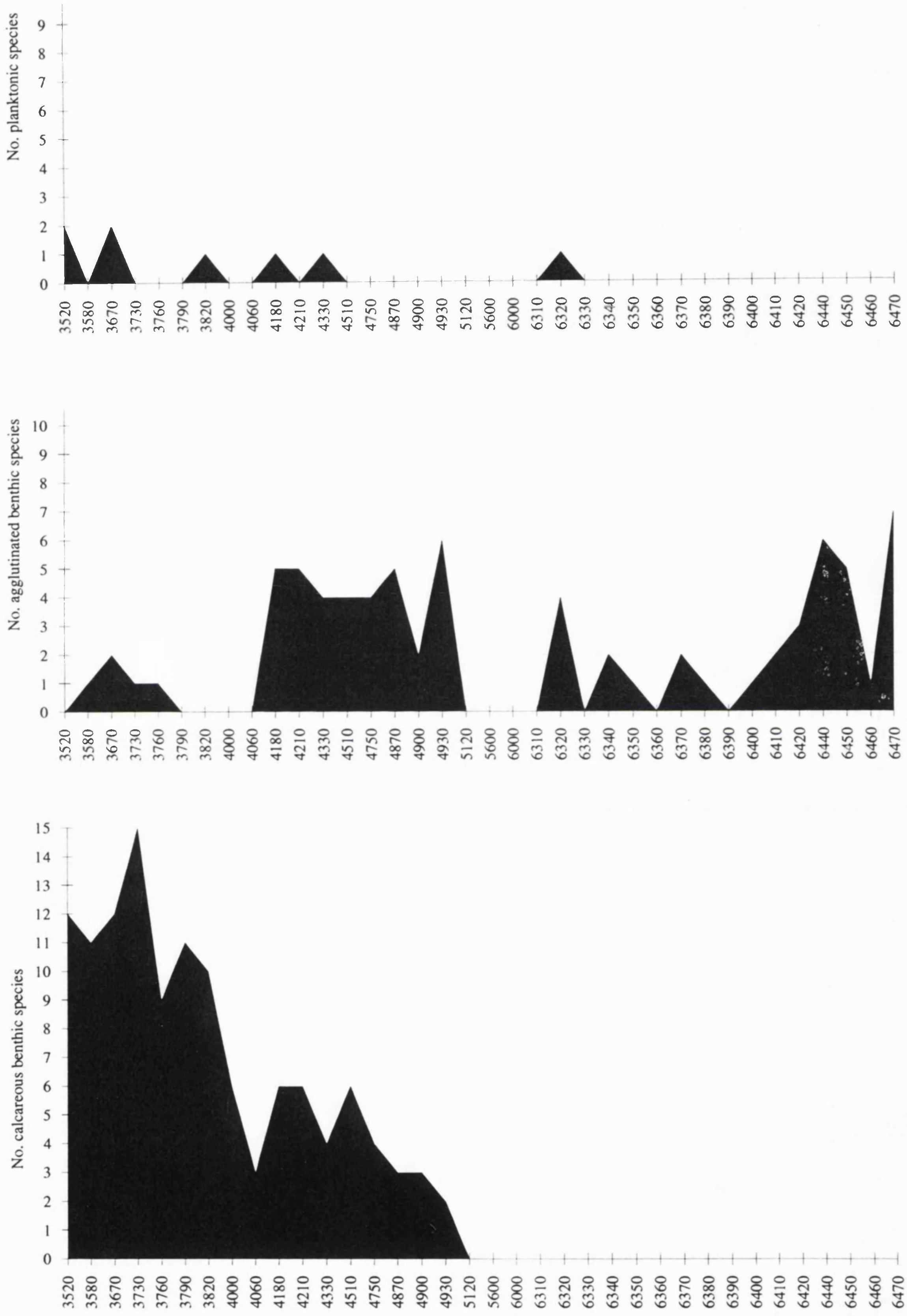


Fig. 5.4 A comparison of different types of foraminifera (agglutinated benthic, calcareous benthic, and planktonic) in BP well 15/28a-3. Note the increasing dominance of calcareous benthic taxa, and the corresponding decline in agglutinated benthic taxa, towards the top of the samples (3520').

This sequence compares closely with published well data for the central North Sea (e.g. Gradstein *et al.* 1992; Mudge & Bujak 1994), and has been attributed to periods of eustatic sea-level fall, coupled with regional tectonism; Galloway et al. (1993) have ascribed the top mid Eocene unconformity partly to the tectonic inversion and plate reorganisation that accompanied the terminal Eocene separation of Greenland and Norway, and partly to eustatic sea-level fall at a time of Antarctic ice-cap growth.

5.4.1.2 BP well 21/9-1

As was earlier stated, this well was extremely poor in microfossils above the Lower Eocene. This is probably because the samples had already been picked by industrial micropalaeontologists previous to this study; the reason that such abundant assemblages were recovered from the lowermost samples is that original abundances were far greater in those intervals than in successive levels. Fortunately, useful information was gleaned from the lowest samples, which span the Paleocene/Eocene boundary and are rich in diatoms (Fig. 5.2, p. 173).

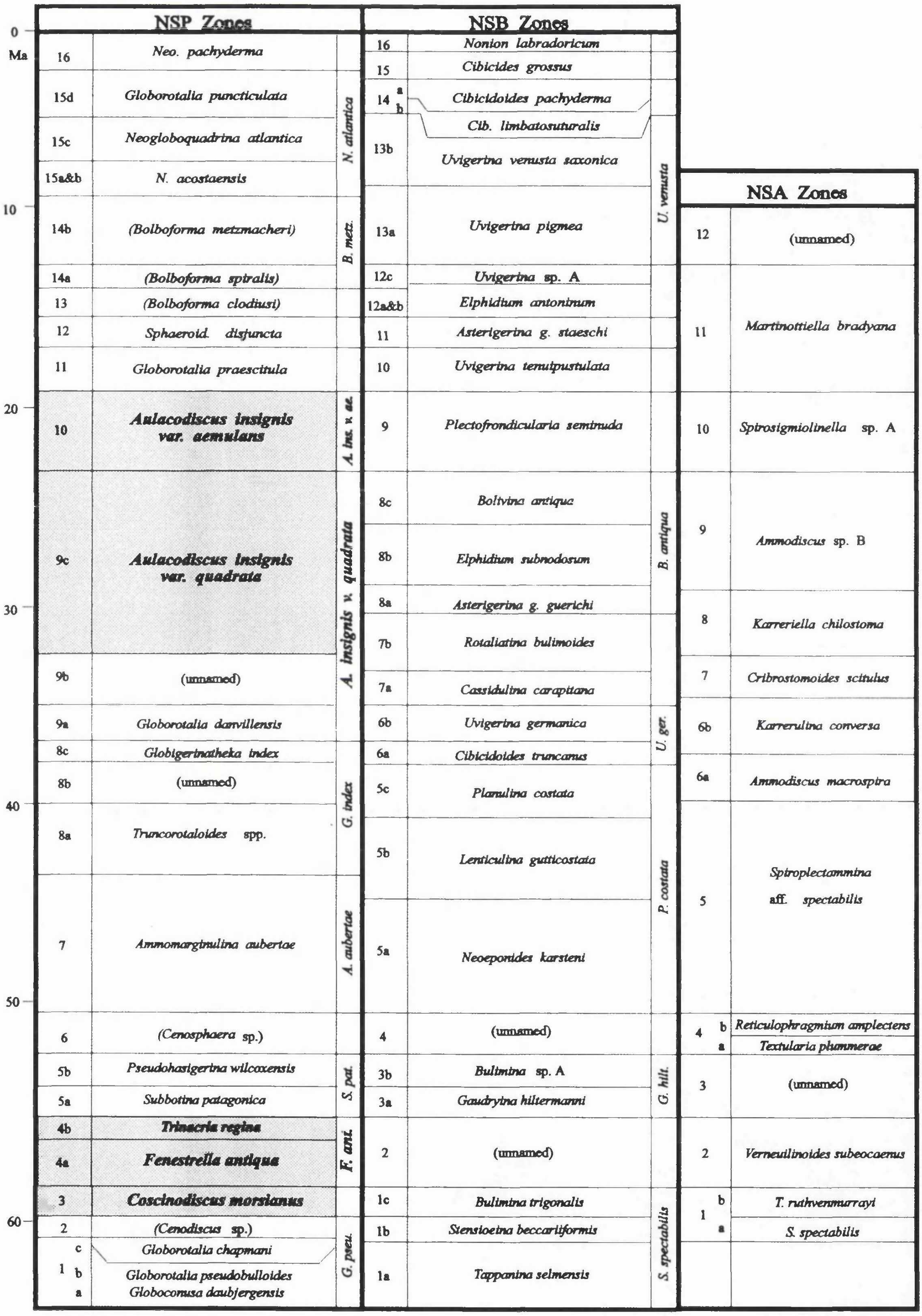
5.4.2. Comparison of diatom data with previous studies

5.4.2.1. North Sea

Fig. 5.1 (p. 160) shows that a number of stratigraphically important horizons were identified using diatoms. King (1983, 1989) recognised this, and included diatoms within a combined microfaunal scheme with applicability over the North Sea Basin. This scheme has been modified here (Table 5.1, p. 187) to include more diatom information. The key diatom events have also been incorporated with the combined microfossil events depicted by Knox & Holloway (1992), to form an improved biostratigraphic scheme for the North Sea Basin (Table 5.2, p. 190).

5.4.2.2. Comparison with onshore assemblages

The main abundance peak of diatoms in the North Sea Basin, which spans the Paleocene/ Eocene boundary, correlates with a number of coeval onshore assemblages, analysed during the present study. These have enabled a more refined correlation to be made for this interval over the North Sea Basin (shown in Fig. 5.8, p. 189).



NSP Zones		
16	*Neo. pachyderma*	
15d	*Globorotalia puncticulata*	*N. atlantica*
15c	*Neogloboquadrina atlantica*	
15a&b	*N. acostaensis*	
14b	*(Bolboforma metzmacheri)*	*B. metz.*
14a	*(Bolboforma spiralis)*	
13	*(Bolboforma clodiusi)*	
12	*Sphaeroid. disjuncta*	
11	*Globorotalia praescitula*	
10	***Aulacodiscus insignis var. aemulans***	*A. ins. v. ae.*
9c	***Aulacodiscus insignis var. quadrata***	*A. insignis v. quadrata*
9b	(unnamed)	
9a	*Globorotalia danvillensis*	
8c	*Globigerinatheka index*	*G. index*
8b	(unnamed)	
8a	*Truncorotaloides* spp.	
7	*Ammomarginulina aubertae*	*A. aubertae*
6	*(Cenosphaera* sp.)	
5b	*Pseudohasigerina wilcoxensis*	*S. pat.*
5a	*Subbotina patagonica*	
4b	***Trinacria regina***	*F. ant.*
4a	***Fenestrella antiqua***	
3	***Coscinodiscus morsianus***	
2	*(Cenodiscus* sp.)	
1 c	*Globorotalia chapmani*	*G. pseu.*
1 b	*Globorotalia pseudobulloides*	
1 a	*Globoconusa daubjergensis*	

NSB Zones		
16	*Nonion labradoricum*	
15	*Cibicides grossus*	
14 a	*Cibicidoides pachyderma*	
14 b	*Cib. limbatosuturalis*	*U. venusta*
13b	*Uvigerina venusta saxonica*	
13a	*Uvigerina pigmea*	
12c	*Uvigerina* sp. A	
12a&b	*Elphidium antoninum*	
11	*Asterigerina g. staeschi*	
10	*Uvigerina tenuipustulata*	
9	*Plectofrondicularia seminuda*	
8c	*Bolivina antiqua*	*B. antiqua*
8b	*Elphidium subnodosum*	
8a	*Asterigerina g. guerichi*	
7b	*Rotaliatina bulimoides*	
7a	*Cassidulina carapitana*	
6b	*Uvigerina germanica*	*U. ger.*
6a	*Cibicidoides truncanus*	
5c	*Planulina costata*	*P. costata*
5b	*Lenticulina gutticostata*	
5a	*Neoeponides karsteni*	
4	(unnamed)	
3b	*Bulimina* sp. A	*G. hilt.*
3a	*Gaudryina hiltermanni*	
2	(unnamed)	
1c	*Bulimina trigonalis*	*S. spectabilis*
1b	*Stensioeina beccariiformis*	
1a	*Tappanina selmensis*	

NSA Zones	
12	(unnamed)
11	*Martinottiella bradyana*
10	*Spirosigmiolinella* sp. A
9	*Ammodiscus* sp. B
8	*Karreriella chilostoma*
7	*Cribrostomoides scitulus*
6b	*Karrerulina conversa*
6a	*Ammodiscus macrospira*
5	*Spiroplectammina* aff. *spectabilis*
4 b	*Reticulophragmium amplectens*
4 a	*Textularia plummerae*
3	(unnamed)
2	*Verneuilinoides subeocaenus*
1 b	*T. ruthvenmurrayi*
1 a	*S. spectabilis*

Table 5.2 Integration of key marker diatom species (**bold**) with the North Sea microfossil NSA (North Sea Agglutinated), NSB (North Sea Benthic), and NSP (North Sea Planktonic) zones of King (1989).

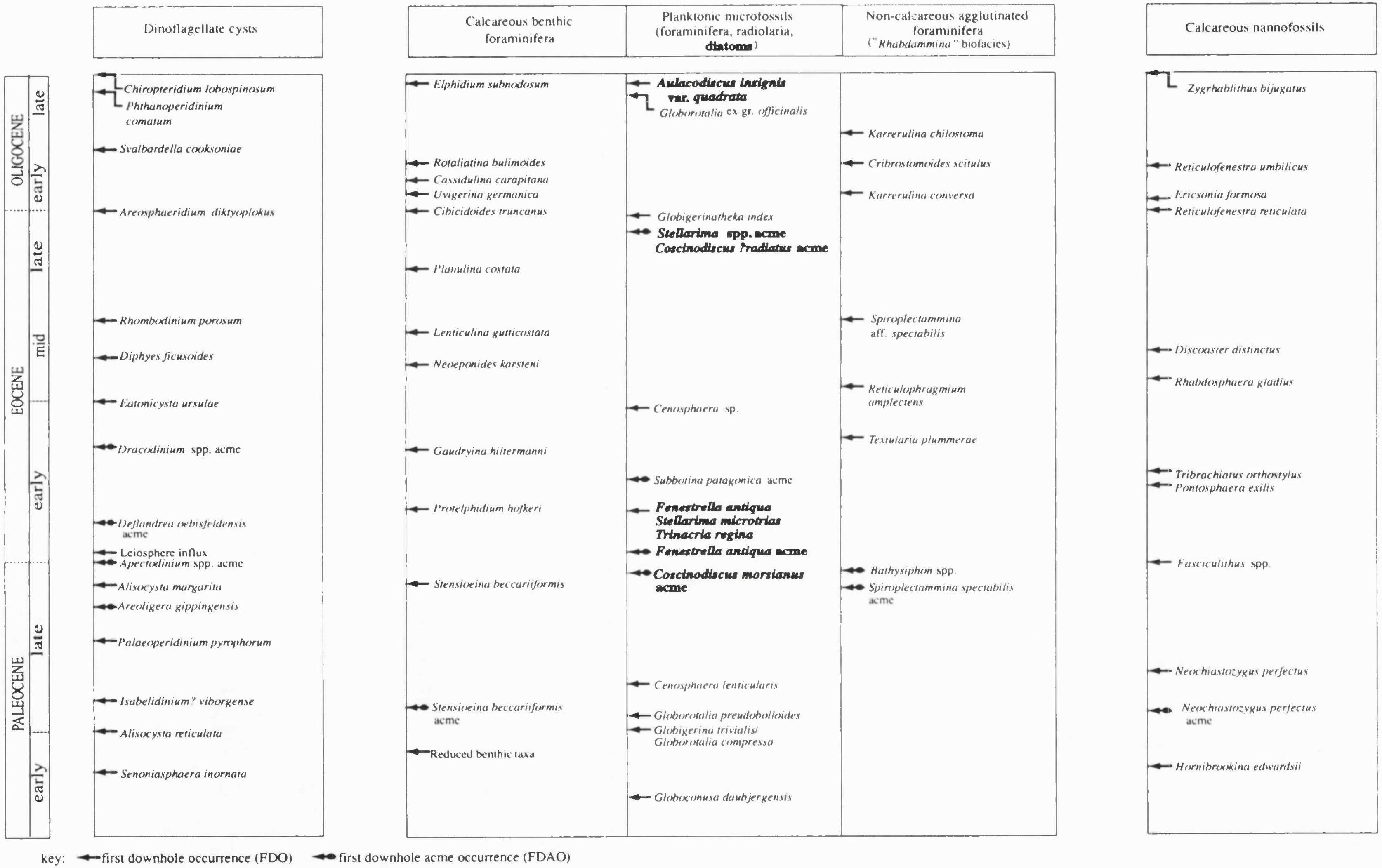


Table 5.3 Important diatom events in the Paleogene of the North Sea, compared with those of other microfossil groups. After Knox & Holloway 1992, with the addition of diatom species identified during this study (in bold).

5.4.2.2.1 Fur Formation

There is a close correlation of the diatom assemblages present in the Sele and Balder formations of the central North Sea, with the flora present in the Fur Formation. The North Sea assemblages appear to represent a residual part of a flora which was originally more abundant and diverse (see Chapter 6 for a discussion on the various palaeoenvironmental and diagenetic factors influencing diatom preservation in the North Sea Palaeogene).

In a thorough taxonomic survey of diatoms from the Fur Formation (with transmitted light micrographs only), Homann (1991) considered that it was not possible to erect diatom zones for the deposit as various taxa appear, vanish and reappear through the samples (possibly due to localised blooms and sediment reworking). J. Fenner (*unpublished data*) conducted a preliminary quantitative study on diatoms from the Harre Borehole (20 km south of the Limfjorden localities, Figure 3.1, Chapter 3), and found fluctuations in taxonomic abundances up through the section which are in broad agreement with those recognised in the present study. However, silicoflagellates, ebridians and radiolaria were not included in her counts.

5.4.2.2.2 Other localities in northwest Europe

The diatom assemblages from Fur have broad similarities with pyritised assemblages recovered from onshore localities in northwest Europe. Although poor preservation generally precludes accurate taxonomic identification, there are enough morphological features preserved to permit their confident correlation. The most diverse and best-preserved of these assemblages is from the Lower Eocene of northern Germany (Benda 1965) which has a very similar floristic content to the Fur Formation. A remarkable feature of the German assemblage is that, although almost entirely pyritised or phosphatised, the diatoms have not suffered secondary pyrite overgrowth (in contrast to offshore diatom material), and are translucent to a degree which allows accurate identification. Pyritised diatoms found in a distinct zone at the base of the London Clay (now Harwich Formation) were the first to be identified as such (Shrubsole & Kitton 1881), and these again show close similarities to assemblages recovered during this work, in particular the predominance of *Coscinodiscus morsianus* var. *morsianus* and *Trinacria regina*. Other pyritised assemblages, again bearing similarities to Fur, have been recorded from The Netherlands (Ten Dam 1944); Belgium (King 1990) and the Paris Basin (Bignot 1983).

AGE	**BIOZONATION (Diatoms & *Foraminifera*)**	**LITHOSTRATIGRAPHY**			
		CENTRAL NORTH SEA	SOUTHERN ENGLAND	BELGIUM	DENMARK
EARLY EOCENE	*Globigerina linaperta*	HORDA FORMATION	LONDON CLAY FORMATION	**IEPER FORMATION**	ROSNAES CLAY FORMATION
	④	**BALDER FORMATION**	**HARWICH FORMATION**	**"UNIT X"**	①
	Fenestrella antiqua		WOOLWICH/ READING FORMATIONS	(Absent)	**OLST FORMATION** ② **FUR FORMATION**
LATE PALEOCENE	***F. antiqua*** ***Trinacria regina*** ***Coscinodiscus morsianus***	**SELE FORMATION**		LANDEN FORMATION	③
	Impoverished agglutinated foraminifera assemblage	LISTA FORMATION	THANET FORMATION		HOLMEHUS FORMATION
	Bolivinopsis spectabilis	MAUREEN FORMATION	(Absent)	(Absent)	KERTEMINDE FORMATION
EARLY PALEOCENE	*Globigerina simplicissima* *G. trivialis*	EKOFISK FORMATION		"MONTIAN"	DANSKE-KALKE FORMATION

① KNUDSHOVED MBR.
② SILSTRUP MBR.
③ KNUDEKLINT MBR.
④ DIVERSE DIATOM ASSEMBLAGE

Table 5.4 Proposed (this work) diatom zones around the Paleocene/Eocene boundary interval, North Sea Basin, with comparative lithostratigraphy. Diatoms and diatomaceous units in bold.

5.4.3 Comparison with diatom assemblages in other areas

5.4.3.1 Localities in the former Soviet Union

Diatom assemblages from Russia (The "Diatom Complexes" of the Volga Basin and Urals, Glezer et al. 1974; see Fig. 2.5, p. 51 for localities) show strong affinities with those from the North Sea Basin (including the Fur Formation). Homann (1991) found a total of 71 taxa common to the Fur Formation and the Russian deposits. This floral similarity suggests at least some connection across the Russian Platform during the Palaeogene period, probably in the form of a shallow, epicontinental sea (Barron 1987). Benda (1972) proposed a "eurasiatic diatom-province" for the Palaeogene of this region.

5.4.3.2 Arctic Ocean

Biogenic silica accumulation occurred during at least three main phases during the late Cretaceous and Palaeogene in the Arctic Ocean (Kitchell & Clark 1982; Barron 1985). Recent data (Dell'Agnese & Clark 1994) suggests the close correlation of a richly siliceous interval (containing diatoms, silicoflagellates, archaeomonads and ebridians) from the Lower Eocene in the central Arctic Ocean, with that from the Fur Formation, with a total of 18 taxa common to both areas. This suggests at least an intermittent connection of the restricted North Sea Basin-Barents Sea with the Arctic Ocean during the early Eocene.

5.5.3.3 Deep Sea Drilling Project/ Ocean Drilling Program sites

Few continuous diatomaceous sections have been recovered from oceanic Palaeogene sediments (Fenner 1985), a marked contrast with the relatively complete Neogene record (Barron 1985). Diatom species used in the zonation schemes of the Deep Sea Drilling Project (DSDP) and its successor the Ocean Drilling Program (ODP) have mainly been recovered from sequences in the open oceans, from the low and southern high latitudes, e.g. the Indian Ocean zonation of Fourtanier (1991) and the Southern Ocean schemes of Mukhina 1976; Gombos 1977, 1983, 1984; Fenner 1991. Only a few species from these areas correlate with those from the North Sea area, for example *Trinacria regina* and several resting-spore taxa.

Those from northern high latitudes tend to have a discontinuous distribution, being restricted to certain parts of the Palaeogene sequence, as in the Norwegian Sea

(Schrader & Fenner 1976; Dzinoridze et al. 1978). Here, diatomaceous sediment was recovered from the middle Eocene, and at various intervals in the upper Oligocene to Pliocene which were separated by lengthy hiatuses. As a result there is only a limited correlation of these sediments with those in the North Sea Basin, with only 10 species common to both areas.

Some workers (e.g. Haq 1981; Kitchell & Clark 1982; Rea *et al.* 1990) have suggested that the lack of inter-regional correlation for the Northern Hemisphere during the Palaeogene is a reflection of the tectonically-related isolation of northern high-latitude basins from the low-latitude Tethyan seaway.

5.5.3.4. Other pyritised diatom assemblages: Eastern Canadian shelf; Beaufort-Mackenzie Basin.

Pyritised diatoms have also been recovered from hydrocarbon exploration wells offshore Eastern Canada (Thomas & Gradstein 1981) and in the Beaufort-Mackenzie Basin, Arctic Canada (McNeill 1990). The former is closest to the North Sea Basin assemblage in terms of age and composition, with four of the morphotypes figured being present in the North Sea (see Table 4.2, p. 143, Chapter 4). The Beaufort Sea assemblage is mid-Eocene in age; although it is dominated by the genera *Coscinodiscus*, *Stellarima* and *Trinacria* (as in the North Sea) none of the species were found to correlate. Both these and unpublished reports of relatively rich pyritised diatom assemblages from the Upper Paleocene-Lower Eocene in the Barents Sea (M.A. Kaminski, *pers. comm.* 1993) suggest that similar conditions prevailed, in partially or fully restricted basinal settings in high northern latitudes, during the early Palaeogene.

5.6 Ranges of diatoms in the North Sea Palaeogene; implications for changes in circulation regime

A complete diatom-based zonation for the North Sea has not been possible to define during the present study. This is due to the patchy occurrence of diatoms through the Palaeogene (see Fig. 5.4, p. 183) which, coupled with the effects of caving (as ditch-cuttings are normally only available through this section, especially above the Lower Eocene) limits the usefulness of a normal biostratigraphic zonation.

However, it has been possible to construct a range-chart of the more important diatom taxa (Fig. 5.9, p. 193), compiled from this study and from informal range charts from exploration companies; the taxonomic identity of a number of these taxa is given in Table 4.2 (p. 143). The range chart shows that periods of floral turnover have occurred through the Palaeogene, with a Paleocene/Eocene "Fur" assemblage, dominated by *Fenestrella antiqua*, being replaced by a mid-late Eocene assemblage dominated by cosmopolitan species, e.g. *Asterolampra marylandica*, an important world-wide marker for the mid-late Eocene (Fenner 1984); this event has been identified in the Norwegian Sea (Schrader & Fenner 1976) and signifies improved connections with the Atlantic Ocean during this period. In the Atlantic proper, biosiliceous sedimentation reached a peak, and diatoms have been recovered from ODP sections during this interval (Barron 1987; Baldauf 1992). Above this Eocene assemblage, a distinctive Oligocene to Miocene flora occurs, dominated by species of *Aulacodiscus*. Many of the latter are important stratigraphical markers and can be tentatively correlated with similar assemblages occurring in the Volga Basin and Urals (the "Diatom Complexes" of Glezer *et al.* 1974), showing that connections across the Polish seaway were firmly established by this time (see Palaeogeography, Fig. 2.5, Chapter 2). However, other later Palaeogene diatom assemblages recovered from onshore localities from northern Europe (which are few in number) show few similarities with those in the North Sea; lower Oligocene assemblages from the Carpathian flysch (Kaczmarska 1982) have some floral elements in common, e.g. the long ranging taxa *Stephanopyxix turris*, *Trinacria excavata*, and *T. heibergii*, an apparent absence of the *Aulacodiscus* species referred to above. However, a complete floral list was not given by Kaczmarska (ibid.), and further study may reveal the presence of other stratigraphically important species, which would allow a closer correlation with coeval assemblages from the North Sea.

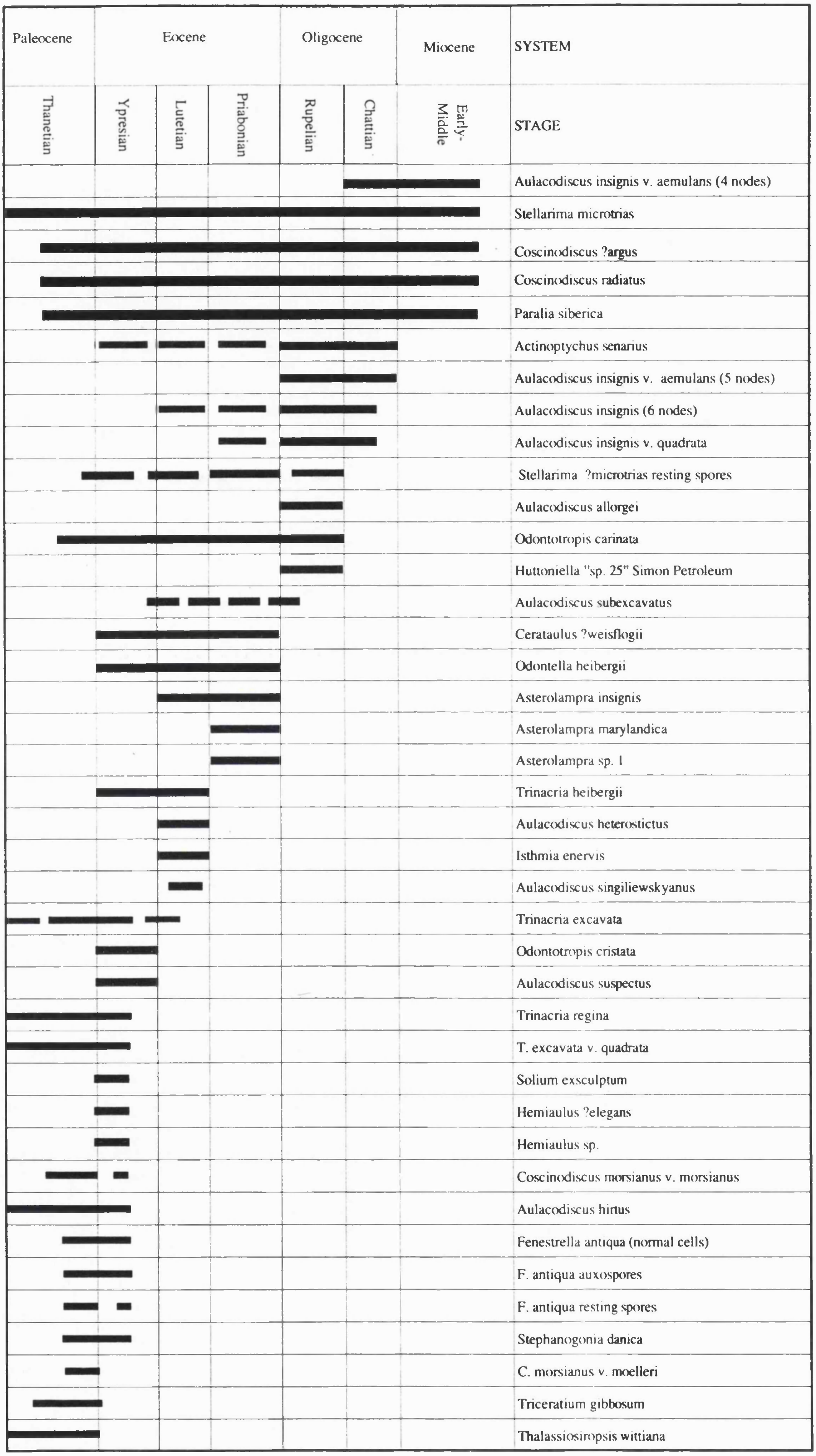


Fig. 5.5 Range chart of important diatom species in the Palaeogene of the North Sea. NB only taxa identified during this study are shown; some of the ranges, especially in the Upper Eocene (Priabonian) are inferred from various informal zonations of exploration companies.

6: PRESERVATION OF DIATOMS IN NORTH SEA PALAEOGENE SEDIMENTS

6.1. Introduction

Diatom frustules, in common with skeletons of other siliceous microfossils, are especially susceptible to the effects of post-mortem dissolution and diagenesis (e.g. Calvert 1966, 1974; Kakuwa 1984; Barron 1987). This often leads to considerable preservational bias in fossil assemblages (e.g. Mikkelsen 1977), which can lead to misinterpretation of the palaeoecological signal which these assemblages might be expected to represent (Calvert 1974; Sancetta 1982), as well as hindering species identification (see chapter 4, this study). In addition to differential dissolution of less robust taxa, the silica which comprises the skeletons is itself prone to phase changes (e.g. Hein *et al.* 1978; Riech & von Rad 1979); whilst the skeletons may also become infilled and/or replaced by authigenic minerals (e.g. Bohrmann & Theide 1989; Kaczmarska & Ehrmann 1990; McNeill 1990). The factors which lead to this situation will be considered, and their application to North Sea Basin diatom assemblages assessed, in the light of both electron microprobe analysis and observed differences in the preservation style of diatoms recovered during the present study.

6.2 Silica dissolution: palaeoecological interpretation

Seawater is a medium which is not conducive to the preservation of biogenic silica. This is because marine water in today's oceans is everywhere undersaturated with respect to silica (Berner 1968, 1970; Kastner 1981). Microscopic siliceous skeletons, including diatoms and radiolaria, are therefore prone to dissolution on exposure to seawater, a situation which leads to considerable preservational bias in assemblages, which only represent a percentage (or thanatocoenosis) of the original population in the water column (or biocoenosis). In the oceans, only 1% to 10% of the diatom frustules produced in the photic zone reach the bottom sediment (Calvert 1974), a situation compounded by morphological adaptations of diatom skeletons (such as large cell diameters, the production of spines and webs composed of chitinous fibres, and by the formation of chains) which help to sustain buoyancy in the water column during life. Preservation of delicate diatom frustules in diatomites is apparently due to the incorporation of diatom frustules into the faecal pellets of copepods and other zooplankton, which speeds their transport to the seafloor and provides some protection from dissolution in the water column (Schrader 1971).

In both marine and lacustrine environments, a number of studies have addressed the problem of under-representation when interpreting diatom assemblages from surface sediments (e.g. Sancetta 1982; Shemesh *et al.* 1989; Burckle *et al.* 1992); all have concluded that sediment trap studies provide the only reliable means of comparison with the biocoenosis in the water column, so that a transfer function can be derived and inferences made about the palaeoecological parameters of a preserved assemblage (Battarbee 1986; Shemesh *et al.* 1989; Juggins 1992). However, transfer functions can only be conducted on an assemblage where the ecological parameters of its constituent species are known, a particularly uncertain method of reconstruction for pre-Quaternary diatom assemblages. Although a number of taxa have remained morphologically unchanged for millions of years (*Actinoptychus senarius*, an extant species, is recorded from the Upper Cretaceous in the Volga Basin, see Andrews 1979) there is no guarantee that, for example, temperature tolerances have remained at similar levels for such a prolonged period. For example, *Stellarima microtrias*, a species encountered throughout the Palaeogene section of the North Sea during the present study (a climatically more equable period than at present, with low temperature gradients, Roberts *et al.* 1984; Rea *et al.* 1990) is today restricted to pack-ice offshore Antarctica (Hasle & Sims 1986a). It is therefore extremely difficult to attempt meaningful reconstructions of palaeoceanographic conditions using diatoms alone for pre-Quaternary conditions (and practically impossible where these have been pyritised, see below); such studies should only be attempted in conjunction with evidence from other fossil groups, ideally combined with sedimentology and geochemistry.

Over-representation of particular diatom species is a similar problem besetting palaeoceanographic studies. Burckle *et al.* (1992) conducted a laboratory time-based study on Quaternary opaline silica-rich sediments from the Sea of Japan and the North Pacific, largely consisting of the remains of the species *Coscinodiscus marginatus*; they concluded that the apparent dominance of that species was largely an artefact of preservation. It is probable that the widespread occurrence of oozes consisting almost entirely of broken valves of *Ethmodiscus rex* in Plio-Pleistocene sediments in the North Pacific (Mikkelsen 1977; Villareal 1993) may be due to the same phenomenon. Similarly, a mid-Pleistocene neritic diatom assemblage from the Nar Valley, eastern England analysed by the present author (Mitlehner 1992), was found to be dominated by the highly robust, resistant valves of the species *Lyrella lyra* and *Nitzschia punctata*, which together accounted for over 50% of the assemblage at some levels.

A study which is particularly pertinent to the present work was carried out by Pedersen (1981), who observed wide variations in the relative abundance of different diatom taxa within the Fur Formation diatomite of northern Denmark (see Chapters 2, 3 and 5, this study). Three types of laminae were recognised (Fig. 6.1, p. 198):-

Type 1: laminae almost exclusively composed of diatom frustules dominated by a single diatom species, either *Coscinodiscus* spp. or *Stephanopyxis turris.*

Type 2: laminae containing both diatoms and clay minerals, with variable thicknesses. The diatoms are evenly distributed within the laminae, but with variable density; several species are present.

Type 3: clay-rich laminae with few diatom frustules.

It was suggested that type 1 laminae may have been produced either by large blooms of particular species of diatoms or through selective dissolution of the frustules, with type 2 laminae representing long periods of "background" sedimentation and type 3 laminae produced by extraordinary supplies of clay minerals from rivers. No regular alternation of lamination types was observed, thus refuting the suggestion of Bonde (1974, 1979) that the Fur Formation is a varved (i.e. annually deposited) diatomite, and further illustrating the potential difficulties in interpretation of pre-Quaternary diatomaceous sequences.

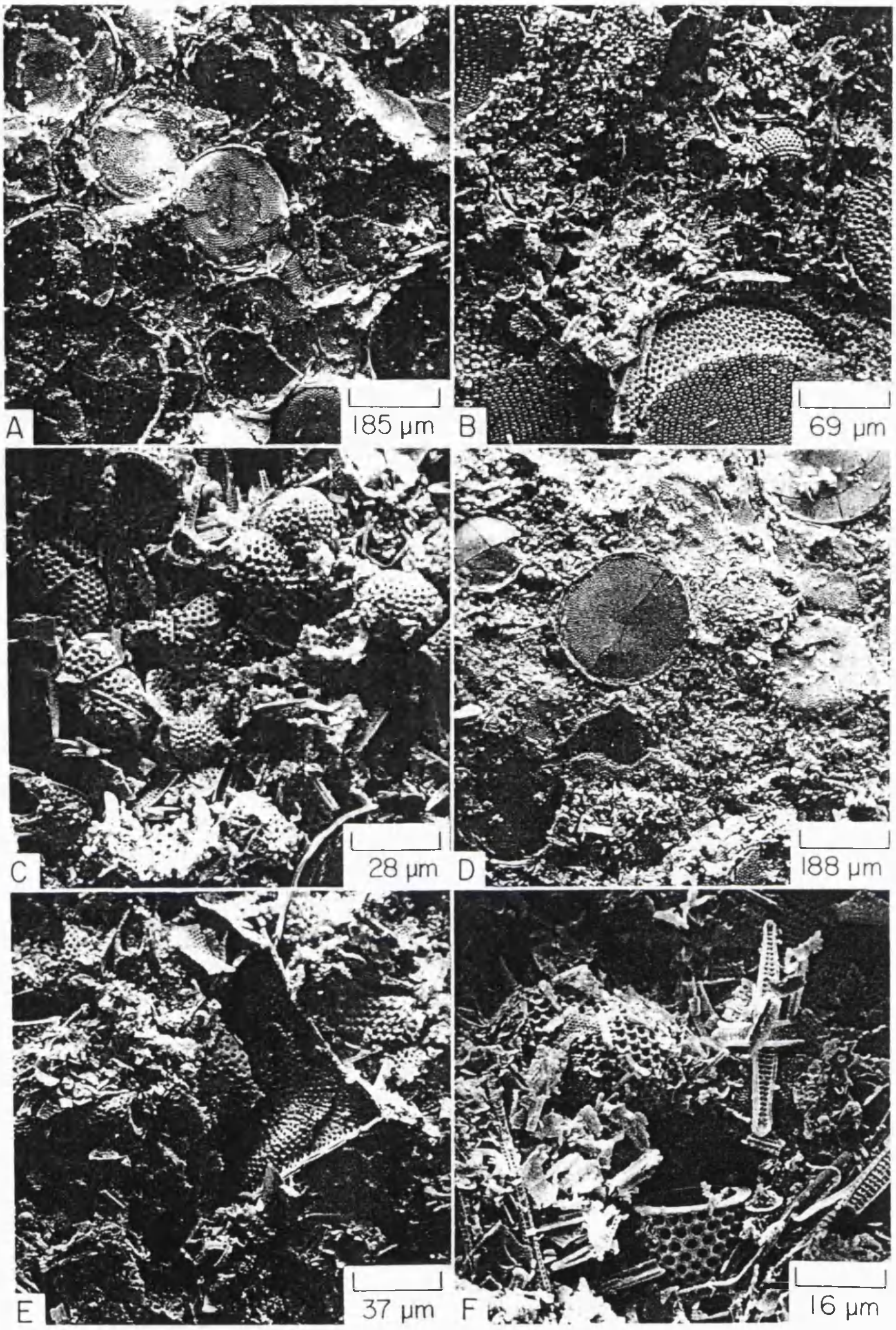


Fig. 6.1. Lamina types in laminated diatomite, Fur Formation (from Pedersen 1981). NB: Diatom species dominant in types 1 and 2 were found to be prevalent in the *Corbisema naviculoidea* silicoflagellate zone (Fig. 5.5) during the present study; the pennate-dominated assemblage in type 3 was more characteristic of the underlying *Naviculopsis danica* zone.

(A) Lamina type 1 with abundant large diatom valves (*Coscinodiscus morsianus*).

(B) Lamina type 1, detail, showing a matrix of small or fragmented diatom frustules and clay between the large valves of *Coscinodiscus morsianus*.

(C) Lamina type 1 with abundant small frustules of *Stephanopyxis turris*.

(D) Lamina type 2. *Coscinodiscus morsianus* scattered in a matrix of clay, diatom fragments and small diatom species.

(E) Lamina type 2. *Trinacria regina* in a matrix of diatom fragments. The density of *Coscinodiscus* valves is much lower than in the type 1 lamina.

(F) Possible type 3 lamina with fragments of diatoms, clay and complete specimens of small diatoms, *Sceptroneis gemmata* and *Stephanopyxis turris*.

6.3 Silica diagenesis: phase changes

In conjunction with dissolution is the related phenomenon of diagenesis. It is known from a number of DSDP sites (e.g. Hein *et al.* 1978) that biogenic silica, or opal-A, undergoes crystallographic changes after deposition in a known sequence, as follows (nomenclature after Jones & Segnit 1971):-

opal-A -> opal-CT -> authigenic quartz

(where opal-A = amorphous-opaline silica; opal-CT = disordered cristobalite-tridymite)

This transformation from unstable to stable mineral phases is influenced by time, burial depth, temperature, and host-rock facies (Reich & von Rad 1979). It is known that carbonate-rich sediments accelerate the opal-A to opal-CT transformation, whilst clays retard this process (Thein & von Rad 1987).

Kakuwa (1984) suggested that diatomite undergoes the following three-fold process of lithification:-

1) Delicate diatom frustules dissolve in the opal-A zone near to the contact with the opal-CT zone.

2) In the transitional zone between opal-A and opal-CT, severe dissolution of remaining diatom frustules occurs, combined with intensive precipitation of opal-CT on surviving larger diatoms.

3) In the opal-CT zone, most diatoms are converted to moulds and cementation increases.

4) In the transitional zone between opal-CT and quartz, and in the quartz zone, moulds composed of opal-CT lepispheres are converted to granular quartz.

Consequently, an estimate of the degree of lithification can be made for sediments containing a predominance of opal-A, opal-CT, moulds (containing or composed of a variety of authigenic minerals), or quartz. Bohrmann & Stein (1989) considered that an estimate of palaeoproductivity can be made from the percentage of biogenic opal remaining in a sediment, and concluded that production of biogenic silica reached a maximum during the (late) early and (early) middle Eocene in the North Atlantic; implications of this for the present study are discussed in Chapter 7.

6.3.1 Preservation of biogenic silica in concretions

Concretions, normally of carbonate but sometimes of phosphate (Benda 1965), may facilitate enhanced preservation of opal-A itself, by early precipitation of carbonate minerals which protect the siliceous skeletons from the effects of compaction and destructive pore-fluids percolating through the host sediment (Berner 1968, Blome 1984). Microfossil assemblages recovered from these concretions are more diverse than those from the surrounding rock, and are often remarkable for the preservation of delicate structures not normally observed in diatoms and radiolaria which are older than Neogene in age (Blome 1984).

In the North Sea Basin area, carbonate concretions have been well documented from the Fur Formation of northern Denmark (Bonde 1979; Pedersen 1981; Pedersen & Surlyk 1983; Pedersen & Buchardt 1994). Here they are known as "cementstones", and are renowned for the remarkable preservation of macrofossils (including fish, insects, leaves and even birds) contained within them (Bonde 1979, 1987; Hoch 1994). These concretions usually consist of highly-indurated, finely-laminated layers of mudstone and diatomite, with distinctive dark ash layers in some horizons (see chapters 2 and 6). Siliceous microfossils (including diatoms, silicoflagellates, ebridians, archaeomonads, sponges and rare radiolaria) preserved within the diatomite layers are exceptionally well-preserved (see Chapter 4). Recent data by Pedersen & Buchardt (1994) show that the cementstone concretions are an early diagenetic phase, formed when porosity was high and porewater was the same temperature as the bottom water. The concretions were formed mostly from bacterially-produced CO_2; if any calcareous shells were originally present they were dissolved quickly and reprecipitated in the concretions.

Calcareous concretions have also been described and analysed from the Balder Formation in the North Sea itself, equivalent in age to the upper part of the Fur Formation (C. Heilmann-Clausen, *pers. comm.*, 1993). Malm *et al.* (1984) recovered a well-preserved siliceous microfossil assemblage from some of these concretions, containing diatoms and silicoflagellates. Again, the exceptional preservation indicates precipitation of carbonate during an early stage of diagenesis. During the present study a core from the underlying Sele Formation was analysed for concretions, but although calcareous layers were observed, none contained any fossils and it is probable that these layers represent diagenetic calcite, formed at some considerable time after deposition.

6.4 Authigenic mineral infilling and replacement

"Mineralisation is the most frequent means of halting the information loss associated with the decay of organisms" (Allison 1990).

Organisms that are permineralised early in their host sediments' diagenetic history frequently exhibit higher levels of preservation than those that form later (Allison 1988). Authigenic mineralisation is thus an important process, preserving details of organisms which would otherwise have been lost from the fossil record through dissolution; often a fossil's original dimensions, and occasionally even soft parts, may be preserved by this process (Brett & Speyer 1990).

Siliceous microfossils are often preserved as mineralised infillings and/or replacements. Several studies have investigated this phenomenon in relation to Quaternary diatom assemblages from lacustrine settings (J. Reed, *pers. comm.* 1993; D. Ryves, *pers. comm.* 1993); often, the biogenic silica of the diatom frustule is replaced by clay minerals (e.g. Barker *et al.* 1990).

In Kakuwa's (1984) silica transformation process (see 6.3, above), stage 3 refers to the formation of moulds of diatom frustules. During this stage, infilling of these moulds and/or complete replacement of the original silica may occur by authigenic minerals to form pseudomorphs. In deep-sea sediments, these are normally carbonates (of manganese, siderite, rhodochrosite, and calcite) and/or smectites (Bohrmann & Theide 1989), which can preserve the original structural details of diatoms and radiolarians with remarkable clarity (see Bohrmann & Theide 1989, pl. 4, fig. 3). Carbonates, which form in concretionary zones, preserve the finest detail and this indicates that precipitation occurred when the siliceous skeletons were still preserved as biogenic opal-A.

6.4.1 Pyritisation

In continental shelf and neritic settings with predominantly clastic, fine-grained sediments, authigenic mineral replacement often takes the form of pyrite and/or marcasite. The general process by which this transformation takes place is well-known, and has been shown to be directly related to the activity of sulphate-reducing bacteria. This process may be represented by the following reaction:-

$$2CH_2O + SO_4^{=} \text{ -> } H_2S + 2HCO_3^{-}$$

where sedimentary organic matter is represented by the idealised formula CH_2O (see Berner, 1984, p. 606 for further discussion); H_2S then reacts with iron to form iron sulphide, which later converts to pyrite.

There is however considerable debate regarding the mechanisms and duration of iron sulphide formation, with a number of authors commenting on the variation which occurs in its style and intensity (Berner 1970, 1984; Baird & Brett 1986). Early studies suggested that this process only occurs in stagnant, fully anaerobic, euxinic conditions, with no water circulation (e.g. Berner 1970). However, more recent work has shown that this phenomenon can occur in more dysaerobic conditions and is enhanced in sulphidic microenvironments, within nonsulphidic sediments, and with moderate sediment accumulation rates (Baird & Brett 1986; Allison 1990 in Fig. 6.2 herein, p. 203). Berner (1984) gave four requirements for the formation of pyrite:-

a) a large amount of metabolisable organic matter;
b) the presence of dissolved sulphate (derived from seawater);
c) a source of reactive iron;
d) the presence of elemental sulphur (derived from seawater sulphate).

The above conditions have occurred at various times since the late Precambrian (Love & Amstutz 1966); they were especially common during deposition of the widespread Mesozoic "black shale" facies (Tyson & Pearson 1991), including the upper Jurassic Kimmeridge Clay, the main hydrocarbon source-rock in the North Sea (Glennie 1990). Fossils found within these facies are commonly pyritised and include ammonites, crinoids and other marine organisms, including radiolaria (Dyer & Copestake 1989; Kavouras 1994).

Diatoms have similarly been extensively documented in "pyritised" form, predominantly from clays and muds in sediments ranging in age from mid-Cretaceous to Pliocene (Shrubsole & Kitton 1881; Wick 1943-50; Bettenstaedt *et al.* 1962; Benda 1965; Kato 1967; Jacqué & Thouvenin 1975; Geroch 1978; Hughes 1981; Thomas & Gradstein 1981; King 1981, 1983; Bignot 1983; Malm *et al.* 1984; Kaczmarska & Ehrmann 1990; McNeill 1990; Mudge & Copestake 1992a & b; Copestake 1993). The majority of these occurrences are in fact pyritic infillings of the frustule casts, sometimes with residual fragments demonstrating original

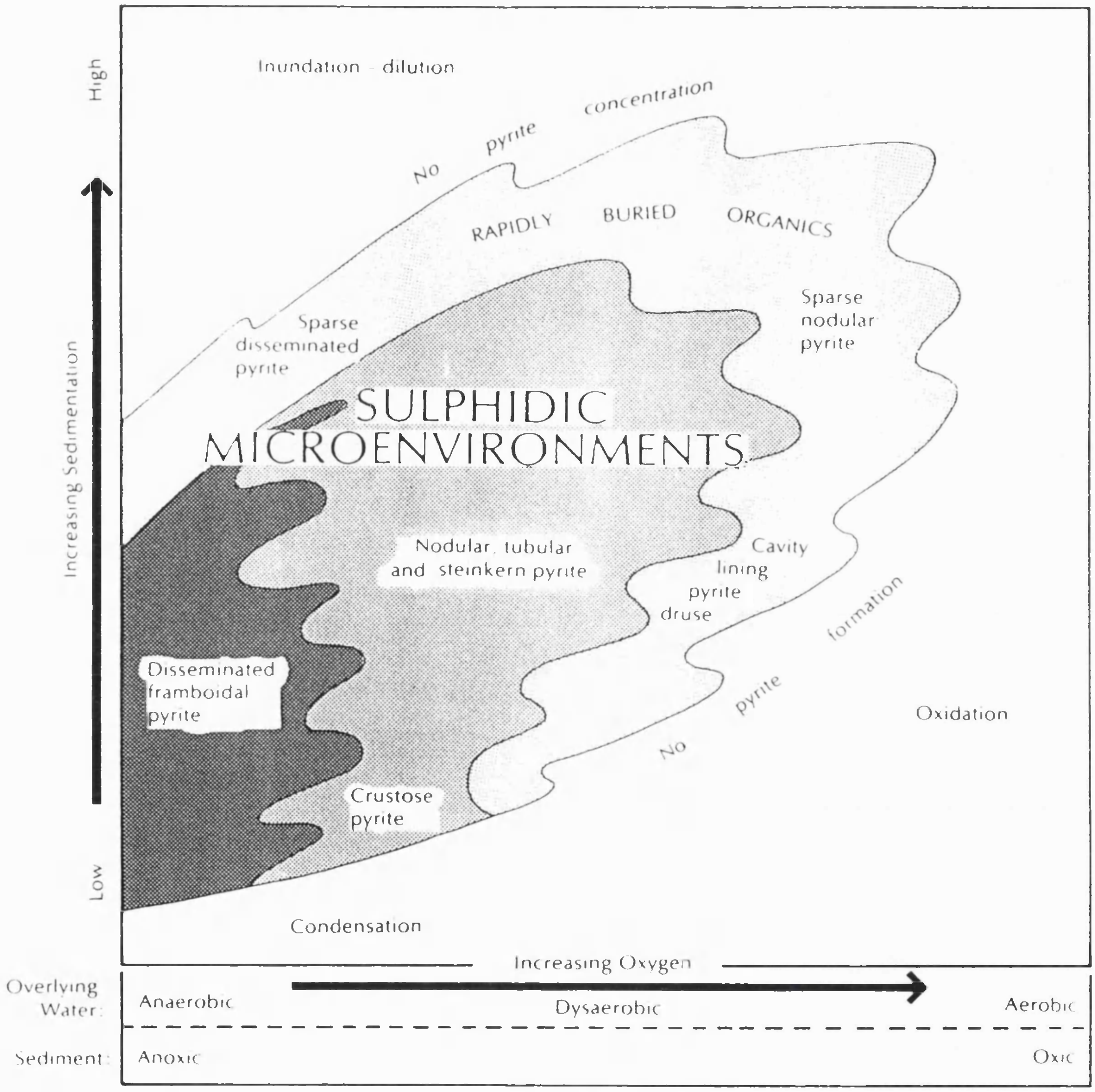


Fig. 6.2 Schematic diagram illustrating the range of conditions favouring the formation of various forms of early diagenetic pyrite (from Allison 1990).
Note that pyrite formation is enhanced in sulphidic microenvironments, within nonsulphidic sediments, and with moderate sedimentation rates. Little or no concentration gradient exists in anaerobic, organic-rich muds, while fully anaerobic conditions in the upper sediment militate against pyrite formation. Organic matter must be buried in sediment to initiate bacterial action; however, too high a rate of deposition will swamp early diagenetic reactions by diluting the necessary concentrations.

ornamentation; the surface of the cast generally consists of a layer of framboids.

Other reported diatom remnants associated with pyrite are biogenic opal-A frustules filled with framboidal pyrite (Vallentyne 1963; Schallreuter 1984). In both cases, pyritisation takes place in small chambers (created within buried skeletons or resulting from dissolution of the frustule) acting as a favourable microenvironment for crystallisation of the pyrite.

By contrast to the above forms of infilling is the actual replacement, molecule by molecule, of biogenic opal-A by sheetlike, microcrystalline pyrite. Such instances are rare in the literature, the most remarkable being a pyritised diatom assemblage recovered from Pliocene sediments at the distal end of the Bengal Fan by Kaczmarska & Ehrmann (1990: ODP Leg 116). SEM and microprobe analysis of their specimens revealed that, although residual silica was present, pyrite had completely replaced the original sieve membranes of the diatom frustules. This suggests that replacement must have occurred while the silica was still in the form of opal-A, although the lack of discernible crystallites of pyrite indicates that replacement was relatively gradual, the fine structure of the silica matrix restricting the ultimate size of pyrite microcrystals.

Other workers have found evidence for rapid pyrite formation. Howarth (1979) demonstrated that pyrite can form in salt-marsh conditions in a day or less, without any increase in pyrite concentration with depth; Clark & Lutz (1980) discovered partially pyritised shells of living molluscs from a salt-marsh; whilst living ostracods have also been found with half pyritised carapaces (A. R. Lord, *pers. comm.* 1994). These occurrences demonstrate that pyritisation is accelerated in environments which include a large amount of organic matter.

Marcasite is another authigenic iron sulphide mineral which is sometimes found replacing fossils, and as amorphous or crystalline masses. Whereas iron pyrites forms in alkaline, neutral or weakly acidic environments, marcasite only forms under acidic conditions (Kraus *et al.* 1959). It is best known in association with brown coal, suggesting that peat swamps are most suitable for marcasite crystallisation. However, Siesser (1978, DSDP 39) recorded sporadic concentrations of marcasite in deep water sediments from offshore Angola. It was suggested that this unique situation was caused by fluctuations in *p*H values, with marcasite forming in more alkaline conditions during the deposition of sapropelic shales.

6.5 Results from the present study: EDX microprobe analysis

The majority of diatom specimens recovered during this study were found to be replaced and/or infilled with pyrite. It was observed that the style and degree of pyritisation varied between assemblages recovered from the deeper, more central parts of the North Sea Basin and those from onshore localities around the basin periphery. In order to ascertain whether there was significant geochemical as well as observed variability in preservation of North Sea Palaeogene diatoms, it was decided to subject selected specimens to energy-dispersive X-ray electron microprobe analysis (EDX, see Chapter 3). Specimens of *Coscinodiscus morsianus* var. *morsianus* from three localities in and around the north Sea Basin were selected for analysis. The results are as follows:-

a) Fig. 6.3 (p. 206). Balder Formation, BP well 15/28a-3, central North Sea.

A highly-indurated, pyritised specimen, with crystalline pyrite on the surface and small plates of a white mineral. The EDX spectrum is dominated by a peak of S, with two smaller peaks of Fe and Ca. A smaller Ca peak is also present.

Interpretation: Pyritic infilling, probably in two phases, with some residual silica and diagenetic calcite on the surface.

b) Fig. 6.4 (p. 207) Ieper Formation, Knokke borehole, Belgium.

A fragile, brittle specimen. The EDX spectrum is completely dominated by two, equally-sized peaks, one of S and one of Fe. Smaller peaks of Ca and Fe and Si are also present.

Interpretation: Almost complete replacement of the siliceous frustule by reactive pyrite or marcasite. Unfortunately, the EDX analysis was insufficiently sensitive to differentiate between these atomically similar minerals.

c) Fig. 6.5 (p. 208) Fur Formation diatomite, Island of Fur, Denmark.

A non-pyritised specimen, included primarily as a control. The EDX spectrum displays a large, complex peak of Si, with a subsidiary peak of Al; and a smaller peak for S.

Interpretation: A frustule of almost pure silica. The sulphur peak is significant, and points to the presence of reducing, anoxic conditions.

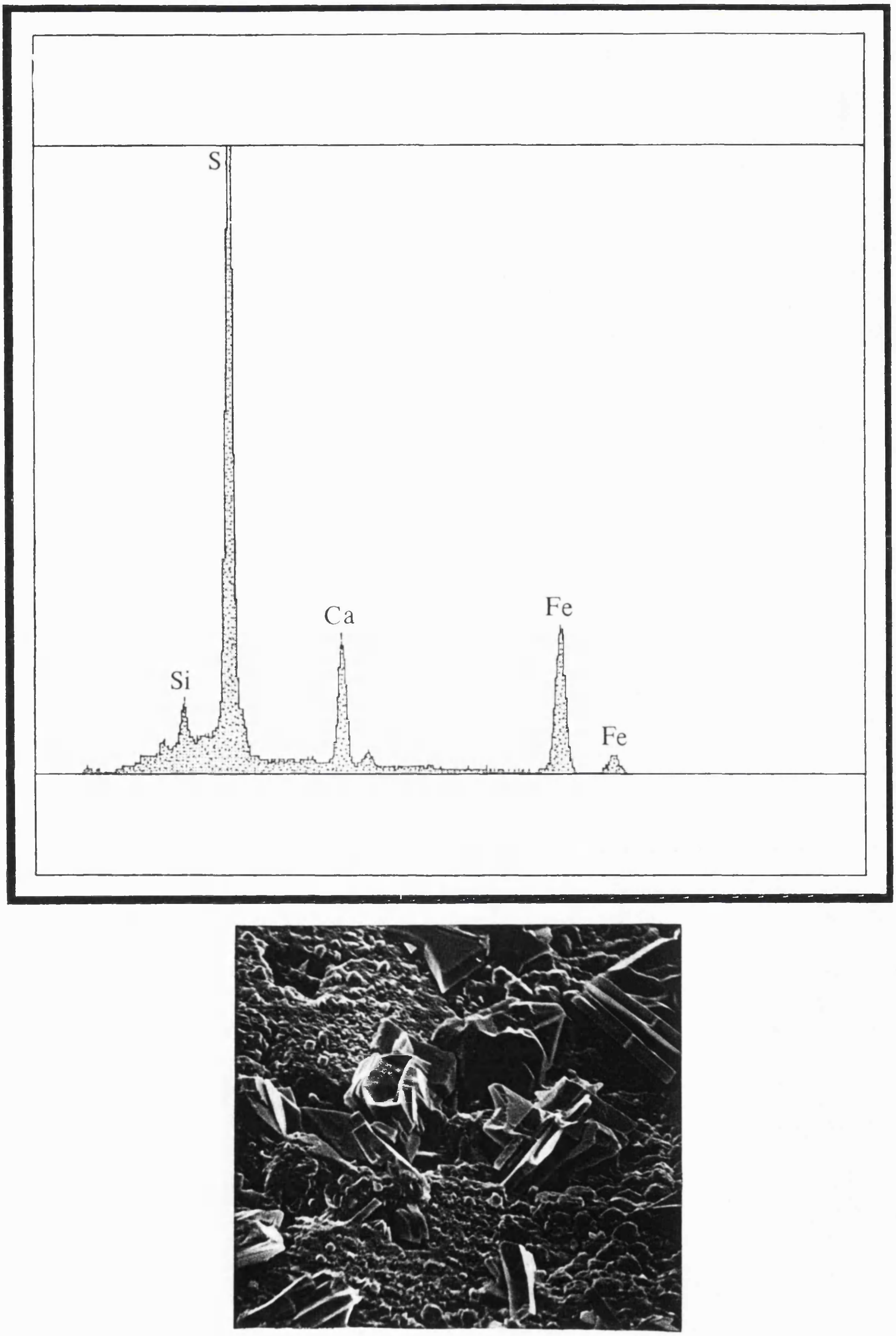


Fig. 6.3 Graph showing the results of EDX electron microprobe analysis of a pyrite-infilled specimen of *Coscinodiscus morsianus* from the Balder Formation in BP well 15/28a-3 (see text for explanation).

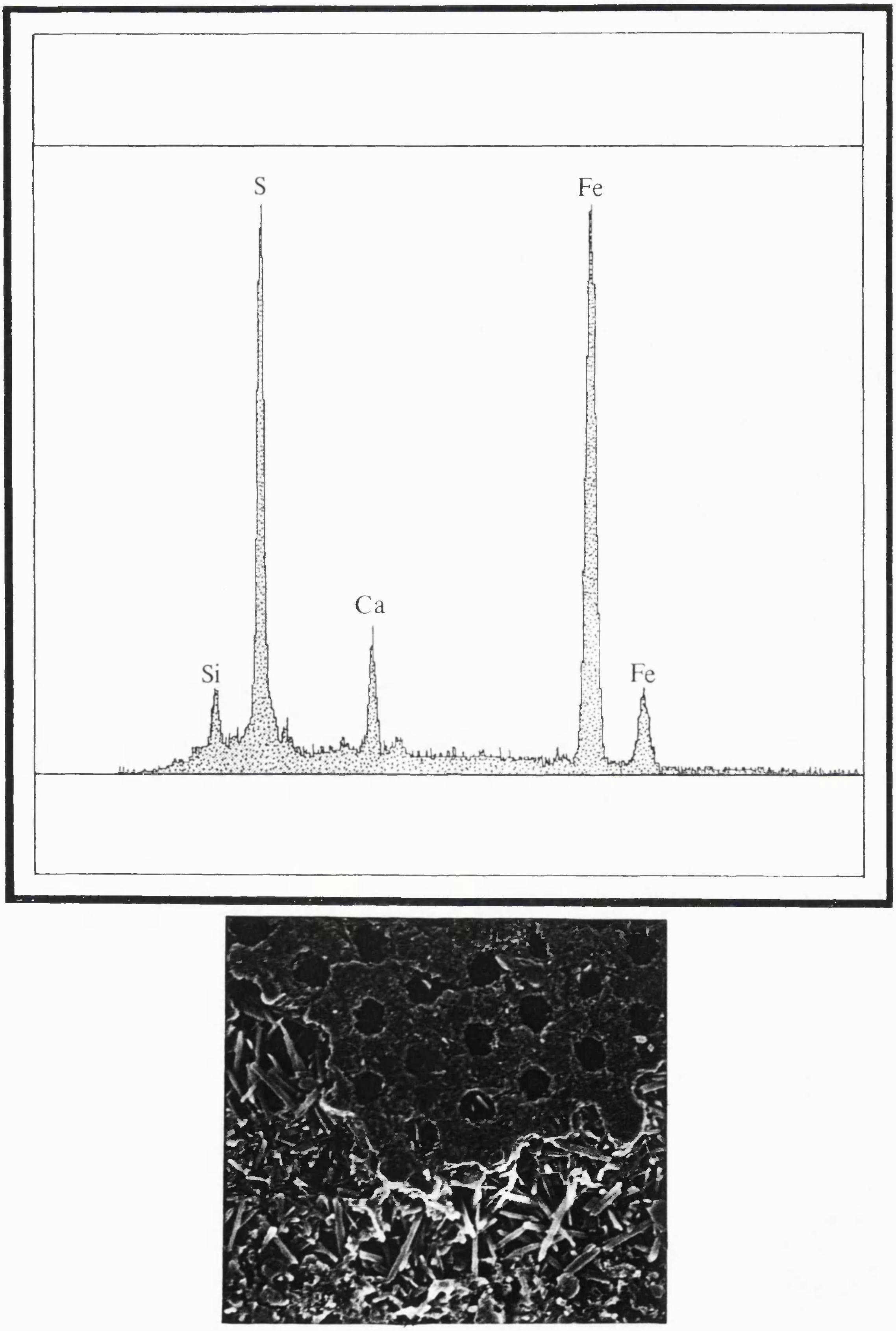
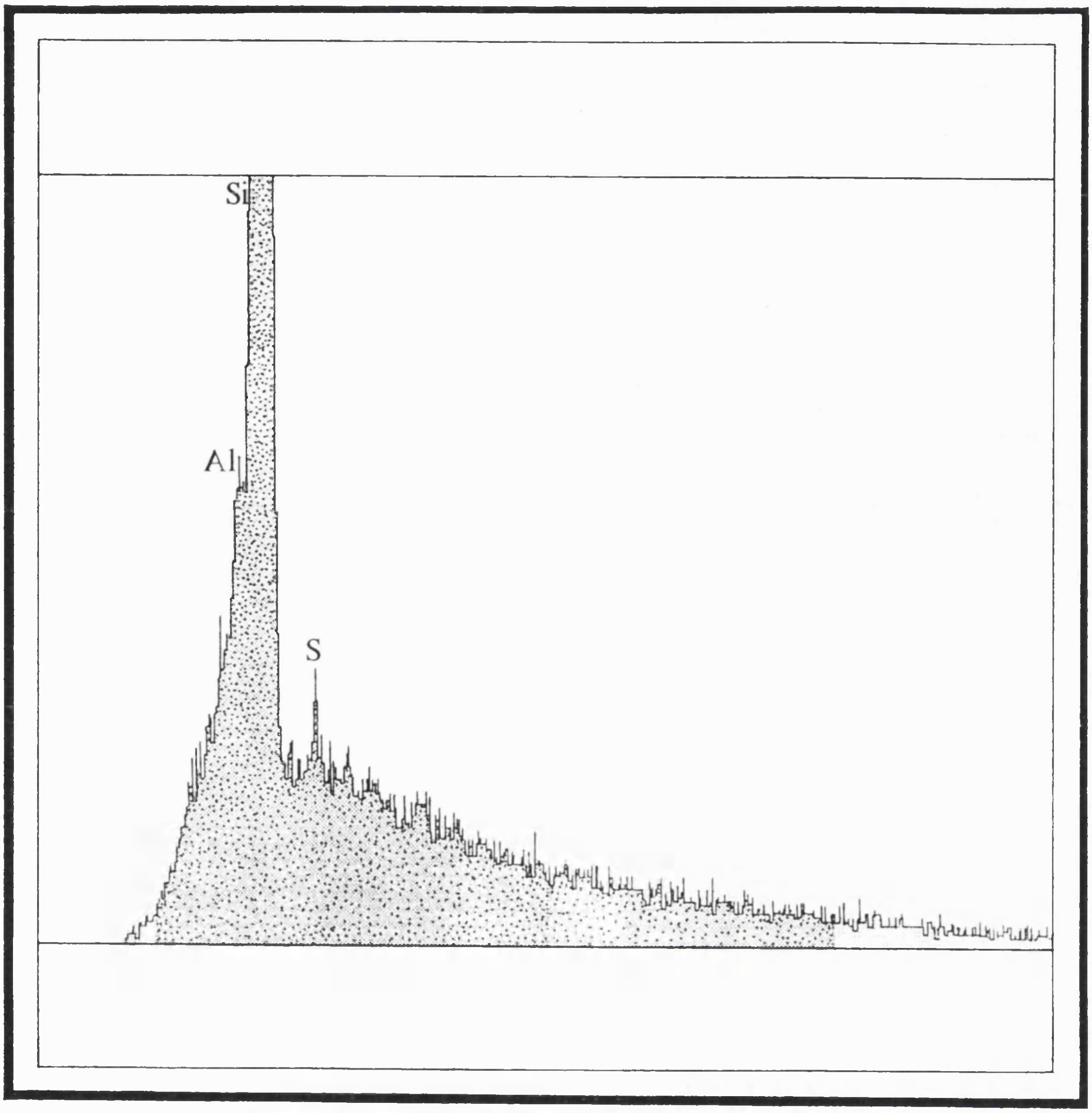


Fig. 6.4. Graph showing the results of EDX electron microprobe analysis of an almost completely pyrite-replaced specimen of *Coscinodiscus morsianus* from the Ieper Formation, Knokke no. 1 borehole, Belgium (see text for explanation).



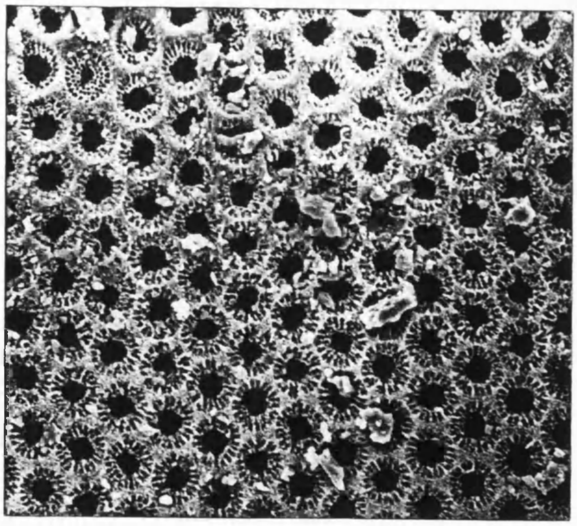


Fig. 6.5. Graph showing the results of EDX electron microprobe analysis of a non-pyritised specimen of *Coscinodiscus morsianus* from the Fur Formation, Island of Mors, Denmark.

6.6 Discussion

The microprobe analyses show that sulphur is present in both pyritised and unpyritised diatoms from three, widely separate, localities in the North Sea Basin. This suggests the presence of dysaerobic to anaerobic conditions throughout the basin during the latest Paleocene to earliest Eocene, an inference further borne out by the state of preservation of the pyritised diatoms which points to the relatively rapid infilling and/or replacement of diatom frustules from Knokke (towards the basin margin) and BP well 15/28a-3 (at the centre of the basin). Other pyritised diatom assemblages were recovered during the present study from the western margin of the basin in the Harwich Formation (=basal part of the London Clay) at Wrabness, England; as well as from the eastern periphery at Ølst, Denmark (see Fig. 3.1, Chapter 3 for locations). Although neither assemblage was subjected to microprobe analysis, SEM observations show a similar style of replacement to the specimens from Knokke. Together with published work on assemblages from northern Germany (Benda 1965), the Paris Basin (Bignot 1983) and The Netherlands (ten Damm 1944), these show that similar conditions prevailed throughout the North Sea area.

The style of pyritisation of specimens recovered appears to vary. Those from the more central, deeper part of the basin are characteristically infilled by pyrite to form *steinkerns* (see McNeill 1990) on which secondary, crystalline, pyrite has formed during a later stage in diagenesis; whereas those from more peripheral localities being almost completely replaced by pyrite, preserving details of the original siliceous frustule with remarkable clarity (Fig. 6.4). This suggests even more rapid mineralisation, and accords well with published studies, such as that of Clark & Lutz (1980, see above) which document extremely rapid rates of iron sulphide formation in coastal mudflats and swamps which include a large amount of organic matter. It is possible that the replacement in this case is in the form of marcasite, but more sophisticated geochemical methods would be necessary to determine this.

Calcium is also present on the two pyritised specimens analysed. In the case of the sample from well 15/28a-3, the calcium takes the form of a platy mineral, probably calcite, which encrusts the specimen (Fig. 6.3). Malm *et al.* (1984) found a similar occurrence in specimens from the Balder Formation in the Viking Graben, and attributed it to diagenetic replacement. The specimen from Knokke is also encrusted, but the mineral in this case forms needle-like laths (Fig. 6.4). This is probably gypsum, which occurs commonly in the coeval London Clay of southeastern England and has been attributed to the alteration of pyrite by calcium rich pore waters during weathering (Allison 1988).

It would appear that the only possible exception to the hypothesis of widespread dysaerobic conditions is the diatomite facies of the Fur Formation of Limfjorden, northern Denmark, where the vast majority of diatoms are preserved in biogenic opal-A (or possibly opal-CT; EDX microprobe analysis did not distinguish between these forms of silica). However, the microprobe analysis conducted during this study shows the presence of sulphur and this, together with occasional pyrite observed in calcareous concretions and the general lack of a benthic fauna (Pedersen 1981; Pedersen & Surlyk 1983) points to dysaerobic to anaerobic conditions present in this area also. The purity of diatomite, its exceptional preservation and the general lack of pyritisation of its contained fossils, may be attributable to a slower rate of deposition (evidenced by the extremely fine laminations present, and a lack of other sedimentary structures), facilitated by the general, but not complete, isolation of the area from the North Sea proper during the latest Paleocene to earliest Eocene interval (probably caused by rising salt diapirs and differential subsidence rates, Pedersen 1981); similar conditions facilitated the production of the Miocene Monterey Formation Diatomite of California, where certain coastal basins became isolated by tectonic activity from the influx of terrigenous material entering other, nearby, basins (Barron 1987). However, these conditions do not promote the widespread formation of iron sulphide, which occurs most readily in areas of high terrigenously-derived sedimentation, especially in nutrient-rich waters which bring about a high rate of organic matter production and sedimentation, with rapid burial enabling relatively reactive compounds and more organic matter in general to become available for bacterial sulphate reduction at depth (Berner 1984). Such conditions were certainly prevalent elsewhere in the North Sea area during the time in question, with the prograding Forties Fan extending into the Central Graben and enhanced terrigenous runoff contributing to increased organic matter being preserved throughout the NSB (Schröder 1992).

This chapter has demonstrated that preservation is of utmost importance in any palaeoenvironmental study involving diatoms. It is a factor which explains why indirect inferences about the palaeoenvironment of the North Sea Basin during the period of greatest diatom production had to be deduced from other sources, which included microprobe analysis and an evaluation of the coeval assemblage of siliceous microfossils preserved in the Fur Formation (see Chapter 5). A synthesis of this information, together with that from other sources, forms the subject of the next chapter.

7. DIATOMS AND PALAEOENVIRONMENTS DURING THE PALAEOGENE IN THE NORTH SEA BASIN

7.1 Introduction

This chapter is concerned with an evaluation of the known distribution, in both time and space, of diatomaceous strata in the North Sea Basin and possible reasons for its proliferation during some intervals. The greatest concentration of pre-Quaternary diatoms in the region occurs around the Paleocene/Eocene (P/E) boundary, at approximately 56 million years (ma) B.P. (Chapter 5), and although diatoms occur at other intervals in the Palaeogene sequence (and in the Upper Cretaceous in the West Shetland Basin, Copestake 1993), at no point do they occur in such proliferation. In the Central and Viking grabens they form a reliable stratigraphic marker, allowing the P/E boundary sequence to be recognised even in sand-rich, deltaic sections where the high gamma-ray peak, normally portrayed in more basinal mud-rich sections, is very indistinct (Mudge & Copestake 1992a & b). In most offshore sections, this diatom-rich interval is intercalated with bands of volcanic ash and tuff which together form the Sele and Balder formations (see Chapter 5, this study). Onshore, the coeval Fur Formation of the Limfjorden region, north Denmark has yielded large and diverse assemblages of diatoms and other microfossils (Chapter 5). In a detailed survey, Pedersen & Surlyk (1983) described this deposit as a diatomite with interbedded ash layers. Elsewhere in the North Sea Basin, diatomaceous sections from this interval are known from northern Germany (Bettenstaedt *et al.* 1962), Belgium (King 1990), the Paris Basin (Bignot 1983) and the London and Hampshire basins of southern England (King 1981), whilst reworked diatoms from this period have been found incorporated in Quaternary deposits in Sweden (Miller 1979). It is significant that, in each case, the diatoms are found interbedded with volcanic ash or its degraded equivalent.

7.2 The relationship of diatomaceous deposits to volcanism

The subject of the origin of silica in richly diatomaceous marine deposits has long been surrounded in controversy, with a number of authors commenting on the co-occurrence of diatomaceous sediments and volcanogenic strata (e.g. Taliaferro 1933; Jacqué & Thouvenin 1975; Barron 1987; Edwards 1991). Taliaferro (1933, pp. 2-6) gave an extensive review of some of the early investigators' theories on this subject, including those of C.G. Ehrenberg who studied diatoms preserved in volcanic material collected by Charles Darwin in Patagonia[1]; and Sir Charles Lyell, who considered that great masses of marine infusoria might be carried downward through the "leaky bottom" of the ocean by marine waters and accumulate in submarine caverns, "and they may then be cast up again to furnish the materials of volcanic tuff" (quoted in Taliaferro 1933, p. 4).

Taliaferro (ibid.) also surveyed known occurrences of diatomaceous sediments around the world. He recognised the stratigraphic association between diatomaceous and volcanic strata, both marine and non-marine, and concluded that volcanism provided the only adequate source for the large amounts of silica deposited as biogenic sediments. By contrast, Calvert (1966) contended that the diatom-rich nature of the sediments in the Gulf of California resulted from the upwelling of nutrient-rich waters unrelated to volcanism. It is now widely considered that marine diatomaceous sediments result from diatom production brought about by the upwelling of relatively cool, nutrient-rich, waters and that the association with volcanism most likely reflects the active earth movements needed both to promote that upwelling and to form a bottom topography that permits diatomaceous sediment to accumulate in basins largely starved of land-derived debris (Barron 1987).

It should be stressed that silica is not necessarily a limiting factor in diatom growth and productivity in marine water; it is probable that volcanic material generates high pore-water silica concentrations that favour diatom preservation, by oversaturating bottom waters at the sediment-water interface with respect to silica. This enhances the preservation potential of diatoms by buffering the silica dissolution reaction (Fenner 1991; J. Hinchey, *pers. comm.*); few studies have addressed this phenomenon in detail.

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[1] Ehrenberg 1845

7.2.1 Previous models: North Sea

Jacqué & Thouvenin (1975) extended the model of Taliaferro (1933, see above) to the North Sea, suggesting that the widespread volcanic input to the North Sea Basin during the late Paleocene to early Eocene (see Chapter 2) was responsible for an increased level of silica in the water, which was available for the production of biogenic silica by diatoms and silicoflagellates (and radiolaria in some intervals). Most of the subsequent work on the North Sea sediments of this period followed this model with only minor modifications (e.g. Malm *et al.* 1984). The notable exception was the series of papers by Bonde (1974, 1979) in which a case was made for invoking an upwelling period for the North Sea Basin, similar to that envisaged by Calvert (1966, see above) for the Gulf of California. Using oceanographic as well as palaeontological and lithostratigraphic evidence, Bonde (ibid.) suggested that the North Sea Basin was essentially a stratified, virtually land-locked basin in which nutrient-rich surface waters were driven by prevailing NW-SE winds towards the coast of Denmark (Fig. 2.3, Chapter 2). This produced an "anti-estuarine" circulation pattern, similar to the present-day Mediterranean. Bonde argued that a prolonged period of coastal upwelling would have resulted, running parallel to the coast of Norway along the continental shelf, in the upper 200 metres of the water column. Below this, the water was oxygen-poor and deficient in benthic faunas (this is true for the whole of the North Sea Basin during this time, with reducing conditions portrayed by an abundance of pyrite and laminated muds, see Charnock & Jones 1990).

7.2.1.1 Discussion

A number of workers have questioned Bonde's (1979) model, chiefly because he applied a circulation model based on today's oceans, where current movements are far more vigorous than data suggest was the case for the early Palaeogene (e.g. Rea *et al.* 1990; Robert & Chamley 1991).

In today's oceans, a prerequisite for a prolonged period of upwelling to occur is a large ocean basin, necessary in order to draw seasonally strong, prolonged water currents along the coast (as in California and Peru, see Barron 1986). The North Sea Basin at the time of the P/E boundary was not of this nature, being a virtually enclosed basin together with the Norwegian Sea, with connections to the opening

Atlantic being blocked by the Thulean land-bridge (Ziegler 1988), and at least temporary isolation from Tethys (due to a worldwide lowstand in sea-level, Haq *et al.* 1987).

However, it is possible that some other mechanism may have provided the necessary currents for upwelling. Certainly, prevailing winds would have to be present in order to explain the great thicknesses of volcanic ash in the Fur Formation, which is now known to have been some considerable distance from the nearest volcanic source, to the northwest of Shetland (Knox & Morton 1988). The climate during this period is known to have been subtropical, with areas of mangrove swamps over southeast England (Davis & Elliott 1957; Jolley & Spinner 1991), and widespread lateritic horizons attesting to deep weathering of the soil regolith (Isaac 1983); all of which are suggestive of warm, moist conditions. Bonde suggested that Coriolis force, affecting both water and wind, would cause water to "pile up" along the western basin margin, thereby causing sinking and recirculation. At the southern margin, wind stress is also thought to have piled up the water, with the lighter, river-derived water on top. Moving northward, this freshwater mixture would have affected the N-S surface current and stopped the upwelling system north of the Ringkobing-Fyn High (Fig. 2.1, Chapter 2). Recent work by Thomsen & Danielsen (1994) shows that diatomite occurs in offshore wells to the west of Denmark in the North Sea, which suggests that this peculiar facies is of greater extent than previously suggested by some authors (e.g. Pedersen 1981), and may have been induced by fairly extensive, seasonal upwelling.

However, diatomite *sensu stricto* may not have extended south and west of the Ringkøbing-Fyn High. Mudge & Copestake (1992a) suggested that the widespread occurrence of diatoms in the North Sea Basin south and west of this limit may be explained by the influx of terrigenous nutrients (including freshwater run-off) into the basin from the rapidly-uplifting Scottish landmass to the west (Fig. 2.2, Chapter 2), as well as from other rivers draining into the southern margins of the basin; Barron (1987) suggested that nutrients from an increased period of river run-off may have contributed to the extensive occurrences of diatomite in the Urals and Volga Basin of Russia which formed in a relatively shallow, epicontinental sea during the Palaeogene, with no related vulcanicity or upwelling.

7.2.2 Synthesis

Taken together, the models of Jacqué & Thouvenin (1975) and Bonde (1979) would seem to represent two widely differing hypotheses to explain the widespread occurrence of diatomaceous sediments at the P/E boundary in the North Sea Basin. Since these ideas were postulated, a greater refinement of the relationship between diatoms, vulcanicity and upwelling has occurred, largely through the work of Barron (1986, 1987). It is now known that there is indeed an intimate relationship between these factors, but that it is not necessary for volcanically-derived silica to be present for the production of diatomaceous sediment. It is now known that nitrogen and phosphorus play an equally important role in diatom growth (R.W. Battarbee, *pers. comm.*, 1994).

With regard to the abundance of diatoms in the North Sea Basin, the following factors should be considered at this point.

1) The greatest concentration of diatoms, in terms of both numbers and diversity, occurs in the Fur Formation; here, they form what may be termed a diatomite. Elsewhere, diversity is lower, although this may be explained by the effects of differential preservation, with only the more robust, heavily-silicified taxa being preserved. The occurrence of well-preserved diatoms, in concretions, in the east of the basin would seem to bear this out (Malm *et al.* 1984). No diatoms have been recovered from calcareous concretions in cores from the same interval in the central or southern parts of the basin, despite an intensive and extensive search during the present study.
2) Diatoms occur most abundantly in association with horizons of volcanic ash and tuff, in both the Fur Formation and in other clastic facies, in and around the NSB.
3) Stagnant, anaerobic to dysaerobic conditions (probably seasonal to allow for nutrient recycling from bottom waters for diatom proliferation) have been suggested for the bottom part of the water column over the North Sea Basin during the latest Paleocene to earliest Eocene in the North Sea Basin as a whole (associated with a period of lowered sea-level in the basin, Bonde 1974, 1979; Schroder 1992; Mudge & Copestake 1992a, b). The abundance of disarticulated fish skeletons, found in some horizons of both the Fur and Ølst formations by the present author (Fig. 3.5, Chapter 3), and in more fragmented form in cores and

or no benthic fauna (apart from occasional, poorly preserved agglutinated foraminifera, Charnock & Jones 1990). The widespread occurrence of pyrite (both as isolated clumps and as an infilling or replacement of diatom frustules; see Chapter 6), and of laminated sediment, also suggest relatively stagnant bottom waters. In the Fur Formation there is also an almost complete absence of benthic fauna (except for some horizons of ichnofacies, Pedersen & Surlyk 1983).

4) Diatom taxa which occur in the Balder Formation (the main horizon of volcanic ash in the central and northern North Sea) often occur as resting spores (i.e. stages of encystment, which enable survival during periods of lowered light-levels). In the Fur Formation also, many morphologies are found as resting spores (Fig. 7.1, p. 218). The main dinoflagellate taxon found at the same interval, *Wetzeliella astra* is also found in encysted form (Schröder 1992; see Fig. 5.5, chapter 5).

The above factors appear to suggest a highly unfavourable environment for marine organisms (although the effects of preservational bias should be borne in mind). Only those species with an in-built adaptation to periods of environmental stress would have been able to survive. Marine diatoms and dinoflagellates exhibit such a mechanism, and this feature is observed especially in areas of present-day upwelling, and in higher latitudes with strong seasonality. Some authors (Kitchell *et al.* 1986; Harwood 1988) have postulated that this is the main reason why the majority of diatom taxa survived the Cretaceous/Tertiary (K/T) boundary extinction event, in contrast to other plankton groups which suffered mass extinctions at this time. It seems highly probable that a combination of these factors could, between them, contribute to the observed patterns of diatom occurrence in the North Sea Basin during the period of the Paleocene/ Eocene boundary interval.

Recent data from the IRONEX cruise (K. Kennington, *pers. comm.* 1994) suggest that iron is of fundamental importance in diatom production, being a major factor in metabolic processes. This would appear to explain the observed increase in marine diatom production in the Northern Hemisphere during glacial maxima (when sea-levels were lower and wind strengths greater, bringing more iron into the ocean basins). In the North Sea basin, there is abundant evidence for lowered sea-level during the late Paleocene, together with increased lateritic weathering of surrounding land areas; these factors may be of significance in explaining the proliferation of diatoms at this time.

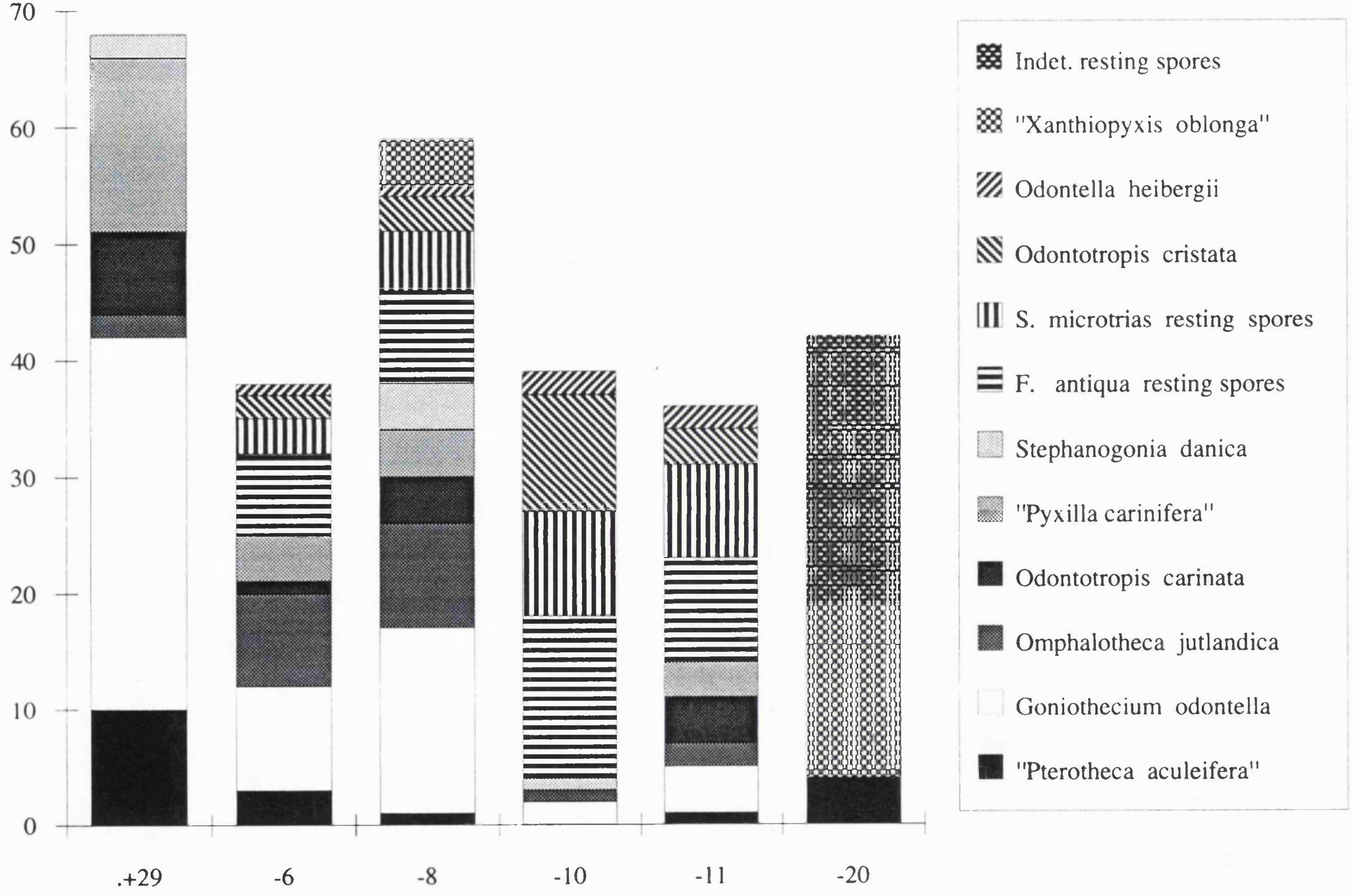


Fig. 7.1 Distribution of diatom resting spores within samples analysed from the Fur Formation.

7.3. The North Sea Basin during the latest Paleocene to earliest Eocene

7.3.1 Palaeogeography

As was stated in Chapter 2, the main abundance peak of diatoms and silicoflagellates in the North Sea coincides with a particularly active episode in the opening of the North Atlantic (Roberts *et al.* 1984; Ziegler 1988), with widespread vulcanicity occurring in northwest Britain, The Faeroe Islands and eastern Greenland (the Brito-Arctic Igneous Province of Boulter & Kvacek 1989), and the rapid uplift of the Scottish Highlands and Shetland Platform.

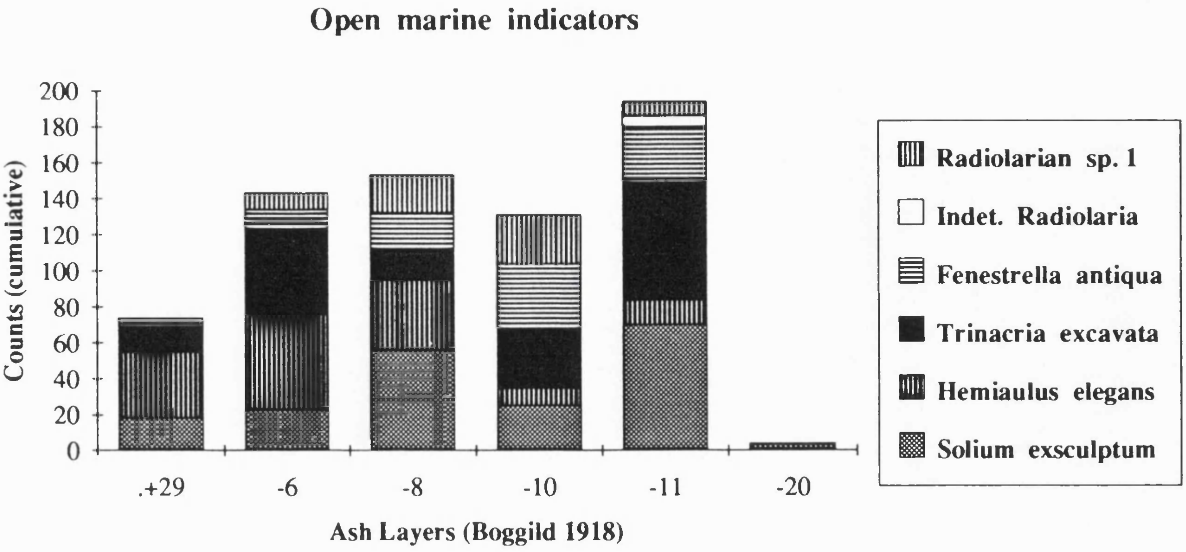
7.3.2 Palaeocirculation

Bonde's (1974) model was subsequently criticised by some authors, as it assumed that upwelling would occur in a seasonal pattern to form varves. Although certain parts of the Fur Formation are strongly laminated, it was shown by Pedersen (1981; see Chapter 6, this study) that these intervals are not seasonal and may be explained by periodic depletions of terrigenous material entering the basin (probably induced by tectonic activity). In addition, Bonde's original (1974) assertion that the diatomite was deposited in approximately 60,000 years was refuted by Perch-Nielsen (1976) who found that silicoflagellate assemblages present throughout the deposit showed distinct changes in species composition, and allow the Fur Formation to be divided into zones (Fig. 5.4); a period of 1-3 million years was suggested as the duration of its deposition.

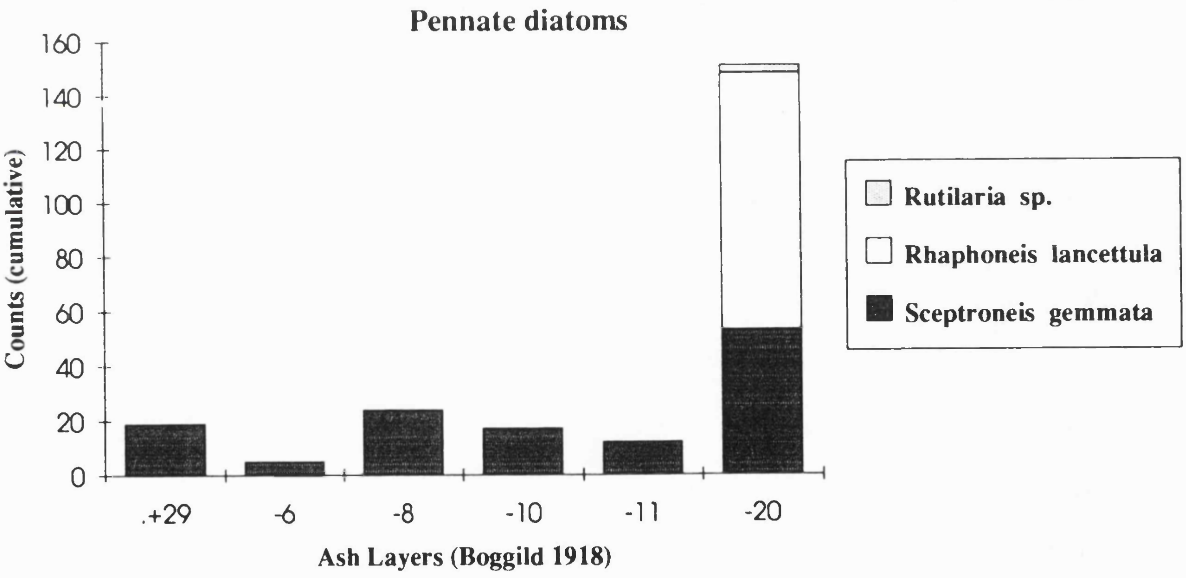
Evidence from the present study suggests that diatoms also undergo changes in assemblage composition through the Fur Formation. Although a diatom-based zonation is not possible (due to localised blooms of some taxa, see Chapter 5), nevertheless periods of sporadic, but probably localised, upwelling appear to be plausible, which became intensified during the earliest Eocene as the Ypresian transgression became established. The abundance of silicoflagellates in the Fur Formation would seem to support the upwelling hypothesis, as intervals of very strong upwelling in modern systems are often initially accompanied by a dominance of silicoflagellates (Loeblich *et al.* 1968; Harwood 1988), and quantitative analysis of samples for the present study accords with this pattern (Table 5.1, chapter 5). The increasing predominance of chain-forming diatoms (such as *Trinacria, Hemiaulus* and *Solium*) through the same sample sequence is also suggestive of a coastal neritic upwelling environment (Beers et al. 1971), whilst the absence of ebridians above the basal samples may indicate increased warming (Loeblich et al. 1968). Increased connections to the open ocean in the earliest Eocene are illustrated by the increasing dominance of open marine indicator species (deduced from a survey of DSDP and ODP reports for the same period, e.g. Schrader & Fenner 1976; Gombos 1984), shown in Fig. 7.2 (p. 221). Further evidence for open marine influence is provided by the upwards decline in benthic (mainly pennate) diatom taxa (Fig. 7.3, p. 221), by the presence of radiolaria in the upper samples from Fur (Plate 12), and by the presence of abundant, well-preserved sponge spicules, recovered from below ash-layer +19 at Ølst by the present author (see 5.3, above). It seems reasonable to assume that similar conditions were prevalent in the Limfjorden area during the same interval, as sponge spicules, and fragments of radiolaria, are common in the upper part of the Fur Formation.

7.3.3 Problems of interpretation: upwelling in a "Greenhouse World"

Possible mechanisms for strong wind stress and resultant upwelling in a warm, relatively isothermal setting dominated by low temperature gradients, and an equable climate (with high levels of CO_2 leading to greenhouse warming, Kitchell & Clark 1982; Roberts *et al.* 1984; Rea *et al.* 1990) need to be considered. Miller *et al.* (1987) gave evidence for decreased wind strengths at about Paleocene/Eocene boundary times, which would appear to discount the possibility of upwelling. However, their data were from the open ocean, essentially isolated from the North Sea area during this period (Mudge & Copestake 1992a,b). Kitchell & Clark (1982) examined palaeogeographic and palaeoclimatic factors promoting polar upwelling during the Late Cretaceous and Early Palaeogene, and considered that a circulation pattern dominated by cyclonic conditions was responsible for prolonged upwelling, with a semi-permanent atmospheric low being centred over the Alpha Ridge; tectonic events were held to have played a key role in the timing of transfers of global silica by the



a) Indicators of increasing open marine conditions, including radiolaria.



b) Benthic pennate diatom taxa, indicating deepening conditions up section.

Fig. 7.2 Graphic representation of selected diatom and radiolarian taxa through the Fur Formation. See Fig. 3.3 for position of ash layers (x-axis).

opening and closing of exchange routes for silica-rich deep waters. It is probable that similar, relatively stable though more markedly seasonal atmospheric conditions (Robert & Chamley 1991) may have occurred over the North Sea Basin during the early Palaeogene, with the necessary currents for upwelling being derived from seasonal monsoonal-type pressure systems which became more intensified as the early Eocene transgression became established (Jolley & Spinner 1991) and global climatic warming continued (Robert & Chamley 1991); the pronounced laminations present in certain intervals through the Fur Formation would seem to point to periods of seasonal variation in sediment input (Bonde 1979; but see Pedersen 1981).

Recent data by Thunell *et al.* (1994) from the modern Gulf of California suggest a close relationship between the seasonal pattern of biogenic silica flux and phytoplankton biomass levels, and is controlled by a monsoon-like climate system which leads to marked seasonal changes in weather and hydrographic conditions. The gulf is a major silica sink, playing an important role in the global silica cycle; the Fur Formation diatomite may have played a similar role in latest Paleocene to earliest Eocene times.

Palynological investigations from the uppermost Paleocene of Mull, Scotland (Boulter & Kvacek 1989) and the lower Eocene London Clay (now Harwich Formation, Ellison 1994; Table 5.2) by Jolley & Spinner (1991) point to the widespread occurrence of paratropical forests during this period with increased waterborne (rather than windborne) transport from a rapidly-eroding hinterland. This would account for the large amounts of terrestrially-derived organic matter found in sediments from the centre of the basin during latest Paleocene times (Schröder 1992), as well as at its eastern margin, in the Fur Formation (Larsson 1975); the presence of monsoonal conditions would further explain this situation.

7.4 Diatom ecology: modern analogues

7.4.1 *Ethmodiscus* abundance

Recent work by Villareal (1993) on the abundance of the giant diatom *Ethmodiscus* in the modern southwest Atlantic and central Pacific, indicates that an abundance of large, solitary diatoms does not in itself indicate strong upwelling. This contradicts the earlier suggestion of Gardner & Burckle (1975) that *Ethmodiscus* ooze was accumulated during intense upwelling associated with glacial periods; in which case the apparent dominance of the similarly-sized *Fenestrella antiqua* in the North Sea during the late Paleocene and early Eocene would appear to argue against the upwelling hypothesis. However, it must be stressed that this dominance is greatly distorted by the effects of differential preservation, as the pyritised assemblages common in the deeper parts of the basin are only a relict assemblage. The more delicate diatom species, which often possess spines, are not preserved here although they were present initially in at least the central part of the North Sea Basin, as is borne out by their occurrence in calcareous concretions in some areas (Malm *et al.* 1984).

7.4.1 Abundance peak of *Fenestrella antiqua*: a possible explanation

The great abundance of *Fenestrella antiqua* (= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.* 1962) in the Sele and Balder formations may in part be explained by reference to a recent study by Anderson (1994) in which a Holocene diatom stratigraphic record was constructed from a lake site in Iceland. This was correlated to four primary volcanic tephras preserved in North Atlantic deep-sea cores (Schrader *et al.* 1993). Significant changes in the diatom assemblages were seen to occur in association with these tephras, with a major shift to near total dominance by planktonic diatoms occurring with the main, Saksunarvatn tephra layer. Although this would appear to indicate that volcanism has a major influence on diatomaceous sedimentation, it should again be stressed that this apparent correlation may be due to enhanced preservation.

A second line of evidence for the proliferation of *F. antiqua* may be provided from a study by Villareal (1993, p. 175), who stated that "empirical studies from limnetic systems suggest that positive buoyancy or depth-keeping as an algal survival strategy is favoured in stratified, stable systems, but not in well-mixed systems"[2]. If this argument can be extended to restricted marine, stratified settings, there is no reason to assume that *Fenestrella antiqua* is an upwelling indicator *per se*. In the Fur Formation, the species is not a major assemblage constituent, although it forms blooms

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[2] although diatoms as a group, because of their Frustule abundance density, are favoured by seasonally well-mixed systems (R.W. Battarbee, *pers. comm.* 1994)

in some horizons. Rather, its proliferation throughout the basin during the Paleocene/Eocene boundary interval may be explained by its ability to encyst via the formation of resting spores (Round *et al.* 1990, p. 52) and thereby to survive the environmentally-stressed conditions of salinity and water-depth fluctuations (and periods of extensive ash falls, see Kitchell *et al.* 1986) which the North Sea area was undergoing at the time. Several workers have commented on the water column stratification which the North Sea area underwent during the late Paleocene to early Eocene (e.g. King 1983, 1989; Schroder 1992; Mudge & Copestake 1992a & b), with an upper layer of less saline water (resulting from increased run-off from the rapidly-uplifting Scottish landmass to the west, Mudge & Copestake 1992a & b) being separated from deeper, more saline and low-oxygen water by a pronounced halocline. Such an environment would favour plankton which was able to sink to deeper parts of the water column during pronounced periods of freshwater influx (such as monsoonal episodes) which would affect the upper water layers in the basin, and certain species of diatoms would have been able to achieve this by the formation of resting spores.

Significantly, *F. antiqua* declines in numbers towards the southern margins of the basin and would appear to have preferred deeper water; samples from the Ieper Formation of Belgium examined by the present author contained only a few, badly-preserved specimens, with no resting spores.

7.5 North Sea diatom occurrences in the later Palaeogene

Above the Paleocene/Eocene boundary interval there are sporadic, but often widespread, abundance peaks of small species of diatoms, such as *Stellarima microtrias* and *Coscinodiscus radiatus*. These low-diversity assemblages occur during several intervals from the middle Eocene to lower Miocene in the more central parts of the North Sea, normally in association with the Non-Calcareous Agglutinated (NCA) foraminiferal assemblage (King 1989). The persistence of only a few species in addition to other, more cosmopolitan taxa such as *Asterolampra marylandica*, and several species of the benthic genus *Aulacodiscus*, which sporadically appear in the basin at various times during the later Palaeogene (Fig. 5.9, Chapter 5), has been attributed to periods of increased eustatic and/or tectonically-related sea-level rise by some workers (King 1989; Mudge & Bujak 1994). The results of the present study do not support this assertion, as the majority of these abundance peaks do not coincide with peaks of radiolaria and planktonic foraminifera (see Table 5.2).

A further point is that the later occurrences of diatoms do not coincide with any significant volcanic activity. Although there was sporadic volcanism in the Faeroes and Iceland at various times through the later Cenozoic, the continued widening of the Atlantic meant that these areas were further away from the North Sea Basin (Ziegler 1988). Nevertheless, in the Oligocene in particular, there are sufficient numbers of the species *Aulacodiscus insignis* vars. *quadrata* and *aemulans* (= "Diatom spp. 3 & 4" of King 1983) to form zonal markers, whilst there are other sporadic low-diversity assemblages at various intervals during the later Eocene and Oligocene which probably indicate phytoplankton blooms (see Appendix A). It is significant that as in the case of the main P/E assemblage, these blooms coincide with a scarcity of calcareous foraminifera, and occur mainly in more clastic, sand-rich facies indicative of rapid deposition (there is a corresponding decline in numbers and diversity of diatoms in more muddy, glauconite-rich sections which contain rich assemblages of calcareous foraminifera). This pattern is also found in other basinal settings during the Palaeogene such as the Labrador Sea (Thomas & Gradstein 1981), The Mackenzie Basin offshore northern Canada (McNeill 1990), and the Costa of Ecuador (J. Hinchey, *pers. comm.*). It has been suggested that the controlling factor for this exclusivity of association may be increased tubidity, caused by periods of increased terrigenously derived sedimentation; the increased influx of nutrients would further contribute to diatom proliferation.

Oceanographic changes during the later Cenozoic also had an effect on the distribution of microfossil groups in the North Sea. In conjunction with the increased sedimentation referred to above, the causal mechanism for the turnover in the dominant plankton is likely to have been an influx of colder Arctic water into the basin, via the opening of the Fram Strait between Greenland and Spitzbergen (Zeigler 1988). In conjunction with the continued subsidence of the Greenland-Scotland Ridge (= Thulean land bridge) and the production of North Atlantic Deep Water, highly corrosive to silica (Barron & Baldauf 1989), this led to a greater integration of the North Sea Basin with the Atlantic Ocean, and a concurrent decline in the relative importance of diatoms compared to calcareous microfossils, in this area as a whole.

8: CONCLUSIONS

8.1 Achievements of the present study

1) The first formal taxonomic identification of 40 species of pyritised Palaeogene diatoms from offshore exploration wells in the North Sea, which were previously known informally in proprietary catalogues, or in open nomenclature. This was achieved by detailed SEM comparison of pyritised morphologies with well-preserved specimens.
2) The taxonomic revision of the following, stratigraphically important species, achieved via detailed SEM study and comparison with type species and original descriptions: *Aulacodiscus insignis* (two varieties erected, *aemulans* and *quadrata*); *Coscinodiscus morsianus* (two varieties erected, *morsianus* and *moelleri*); *Fenestrella antiqua* (recognition of vegetative cells, auxospores, initial cells and resting spores).
3) The discovery of a new diatom genus, *Cylindrospira* (from the Fur Formation of northern Denmark), consisting of two species, *C. simsi* and *C. homanni*. This genus has possible evolutionary significance, as it exhibits a combination of features, otherwise known only separately in post-Paleocene genera.
4) Biostratigraphical analysis of two wells in the central North Sea using both diatoms and foraminifera, identified during the present study. These have been integrated with the published biozonations of King (1983, 1989), Mudge & Copestake (1992a) and Knox & Holloway (1992) to give an improved combined micropalaeontological zonation for the North Sea Palaeogene.
5) Analysis of diatomaceous samples from the upper Paleocene to lower Eocene Fur Formation, to enable a detailed comparison with pyritised specimens from offshore wells; in addition to biostratigraphical and palaeoenvironmental analysis of assemblages from Fur by the identification of diatoms, silicoflagellates, radiolaria (including the identification of two species, *Ceratocyrtis hystricosus* and *Peridium longispinum*, not previously recorded in the Fur Formation) and ebridians. These assemblages have been placed within the published silicoflagellate zonation

of Perch-Nielsen (1976).

6) A consideration of the variation in preservation style of diatoms in North Sea Palaeogene sediments, with microprobe XRD analysis conducted on diatom specimens from different parts of the North Sea Basin. This shows that the style of preservation includes infilling of the diatom frustules in deeper parts of the basin; almost complete replacement in onshore mud-rich sections; and preservation as biogenic silica (or its phase-change equivalent) in the Fur Formation. These differences are attributed to variations in the amount of organic matter entering different parts of the basin, with the Fur Formation representing a possible lagoon, periodically isolated from the main North Sea Basin and major influxes of terrigenously-derived sedimentation.

7) A discussion of palaeoenvironments in the North Sea Basin during the Palaeogene, incorporating data from the present study and previously published information.

8.2 Suggestions for further research

Diatom analysis of the following would enable an improved correlation of the Palaeogene in NW Europe and further afield:-

1) Cored sections through the Mid-Eocene to Uppermost Oligocene in the northern, central and southern North Sea, and their correlation using diatoms. Most cores are available from the Paleocene and lower Eocene, as the majority of Palaeogene hydrocarbon reservoirs are concentrated through these sections.

2) Detailed diatom taxonomic, statistical and stratigraphical analysis of laminae within concretions in the Fur and Ølst formations, and from cores in the North Sea, and an investigation of the possible link between diatom blooms and anoxia in the Palaeogene. This would complement the work of Pedersen (1981).

2) Detailed taxonomic, stratigraphic and palaeoenvironmental analysis of other onshore and offshore diatom assemblages from the Carpathians and the Barents Sea, to enable closer correlation of these with North Sea assemblages.

3) Detailed sampling of sections in the former Soviet Union (Urals, Volga Basin) and their correlation with North Sea assemblages. Diatoms are well-documented from

several "Diatom-complexes" outcropping there (e.g. Glezer *et al.* 1974), and the assemblage composition strongly suggests a close correlation with North Sea Basin assemblages. However, no detailed stratigraphic sampling of the Russian sites has been carried out. An integrated study of diatoms and silicoflagellates from these localities would further improve their biostratigraphic resolution, helping to further understand the timescale and duration of Palaeogene diatomite distribution in the Northern Hemisphere.

3) The taxonomic identity of pyritised diatoms occurring in D.S.D.P. Holes 549 and 550, Bay of Biscay. Ashes present in the North Sea Basin are preserved at the above sites (W.A. Berggren, *pers. comm.* 1993); a detailed correlation of these using diatoms (which have been observed in these holes) would help to clarify the timing of the isolation and subsequent reestablishment of links with the North Atlantic, as well as determining whether certain diatom species (such as *Fenestrella antiqua*) can be used outside the North Sea Basin as a reliable marker for the Paleocene/ Eocene boundary.

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NB. Supplementary references are found on p. 252a.

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PLATES

NB. except where otherwise stated, plates are SEM photomicrographs of diatoms, recovered in ditch-cuttings from offshore wells in the North Sea. Figures in brackets refer to catalogue numbers; specimens without catalogue numbers are from the collections in The Natural History Museum, London. All measurements are approximate.

NB:-

1) Steinkern: internal cast, normally of pyrite, of inside of diatom frustule. SWC= side wall core.

2)?uppermost Paleocene/?lowermost Eocene: the precise position of the Paleocene/Eocene boundary was not determined at the time of writing (September 1994); a decision will be made by the I.G.C.P. working group 308 during 1995. Accordingly, only tentative age assignments are possible for this interval.

PLATE 1

Plate 1

STEPHANOPYXIDACEAE, PARALIACEAE AND COSCINODISCACEAE (part)

Fig. 1: *Stephanopyxis turris* (Greville & Arnott) Ralfs

1. Diameter 45µm. Non-pyritised specimen. Note spines, and prominent nodes between deeply-set areolae (arrow). Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

Figs. 2-3: *Stephanopyxis ?turris* (Greville & Arnott) Ralfs

2. (AGM 101) Diameter 50 µm. BP well 21/9-1, 2110m, ?uppermost Paleocene.

3. Detail of **2.** Width of view 10 µm. Note prominent nodes (arrow).

Figs. 4-6: *Paralia siberica* (A. Schmidt) Crawford & Sims

4. Diameter 40 µm. Non-pyritised specimen. Separation valve, showing characteristic ridges on valve face. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

5. (AGM 102) Diameter 55 µm. Chain composed of interlocking valves. Note raised central area on valve face (arrow). Ølst, Denmark ("Ølst D"), ?uppermost Paleocene.

6. Diameter 50 µm. Non-pyritised specimen. Linking valves, with interdigitating marginal spines (arrow). Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

Figs. 7-11: *Coscinodiscus morsianus* var. *morsianus* comb. nov.

7. Diameter 200 µm. Non-pyritised specimen. Valve view, showing central rosette (large arrow) and larger areolae at beginning of incomplete radial rows (smaller arrows). Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

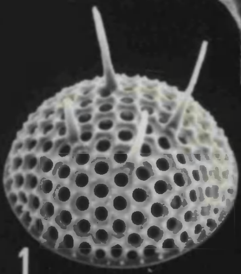
8. (AGM 103) Diameter 140 µm. Valve view of pyrite-replaced specimen. Arrows mark position of features shown on **7.** Knokke no. 1 well, Belgium, 283m, ?lowermost Eocene.

9. (AGM 104) Diameter 200 µm. Oblique view of complete frustule. Note high valve mantle (arrow) with smaller areolae near to girdle. Knokke no. 1 well, Belgium, 283m, ?lowermost Eocene.

10. (AGM 105) Diameter 150 µm. Oblique view of pyrite-infilled frustule. Note high, rounded mantle. BP well 21/9-1, 2110m, ?uppermost Paleocene.

11. Detail of **10.** Width of view 30 µm. Large areola (arrow) with incomplete radial rows of smaller areolae.

PLATE 1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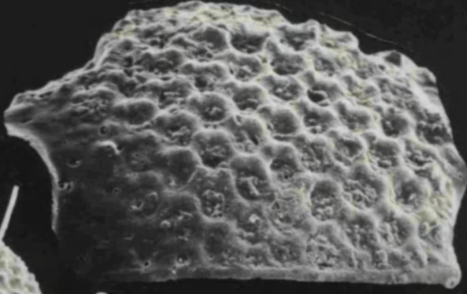
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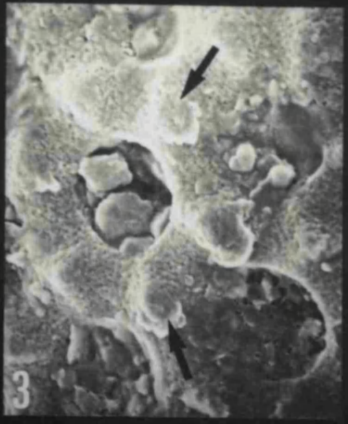
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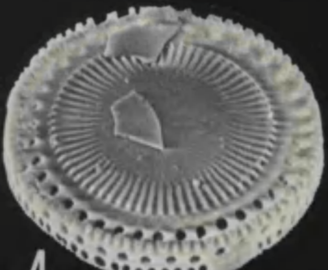
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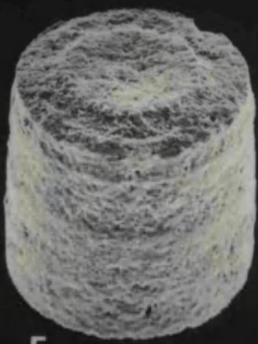
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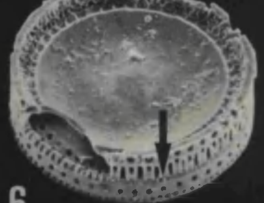
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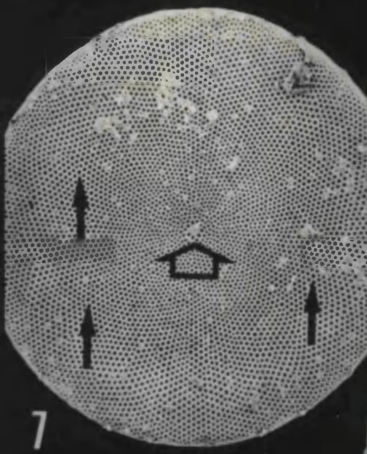
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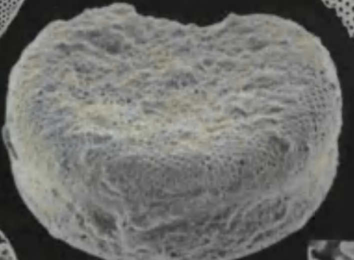
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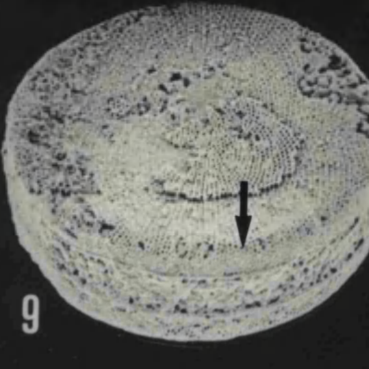
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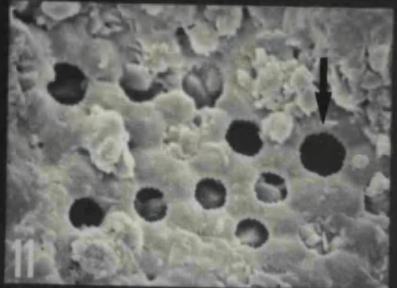
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PLATE 2

Plate 2

COSCINODISCACEAE (continued)

Figs. 1-5: *Coscinodiscus morsianus* var. *moelleri* Mitlehner MS

1. (AGM 106) Diameter 130 µm. Pyrite-replaced specimen. Note undulating surface, and central rosette (arrow). Knokke no. 1 well, Belgium, 283m, ?lowermost Eocene.

2. (AGM 107) Diameter 180 µm. Oblique view of frustule. Note raised rim. A possible transitional form between vars. *morsianus* and *moelleri*. BP well 21/9-1, 2116m, ?uppermost Paleocene.

3. Detail of **2**. Width of view 10 µm. Areolae near to valve margin. Note cribra attachments (arrow).

4. (AGM 108) Diameter 120 µm. Ølst, Denmark ("Ølst B"), ?uppermost Paleocene.

5. Diameter 80 µm. Non-pyritised specimen. Note heavily-silicified, hexagonal areolae. Central rosette indistinct. Natural History Museum, Homann Collection ("D 292"), ?uppermost Paleocene.

Fig. 6: *Coscinodiscus ?radiatus*

6. (AGM 109) Diameter 150 µm. Oblique view of valve. Note radial areolae. BP well 21/9-1, 2116m, ?uppermost Paleocene.

Figs. 7-8: *Coscinodiscus radiatus* Ehrenberg

7. Diameter 150 µm. Non-pyritised specimen. Oblique valve view. Natural History Museum ("Fur Nykøbing"), ?lowermost Eocene.

8. Valve view of **7**. Note hyaline area at centre of valve (arrow).

Fig. 9: *Brightwellia?* sp.

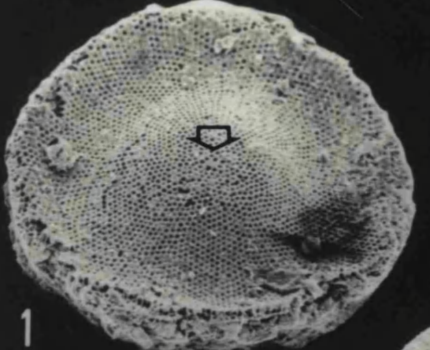
9. (AGM 110) Diameter 200 µm. Oblique valve view. Specimen infilled with euhedral pyrite. Note prominent groove in valve face, and highly domed centre of valve. BP well 15/28a-3, 3580', Mid Miocene.

Figs. 10-11: *Brightwellia spiralis* Glezer

10. (AGM 111) Diameter 110 µm. Valve view. Much of surface obscured by overpyrite, but note prominent groove (arrow). BP well 21/9-1, 2128m (caved from ?Mid Eocene).

11. Detail of **10**. Width of view 30 µm. Note spiralling areolae.

PLATE 2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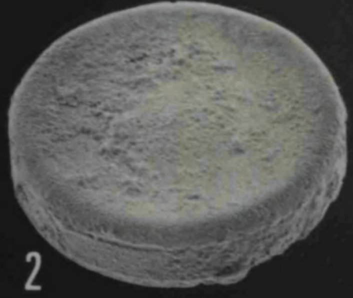
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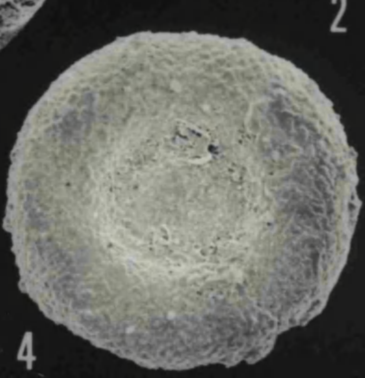
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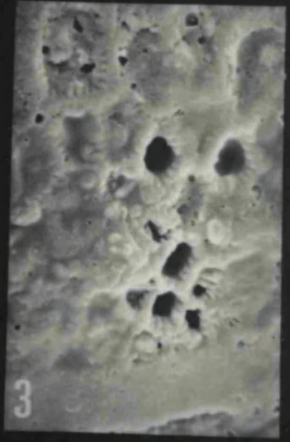
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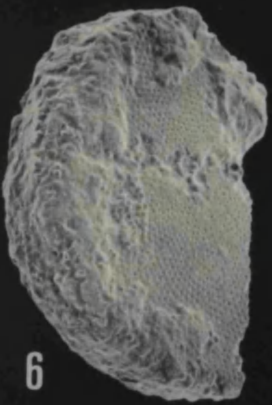
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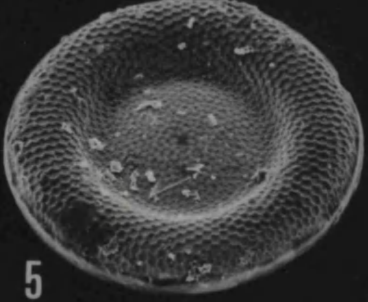
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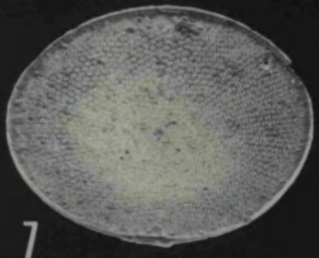
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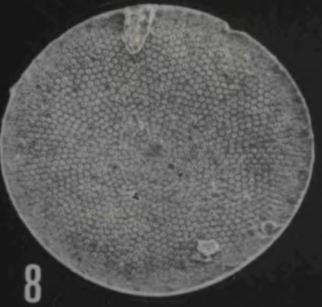
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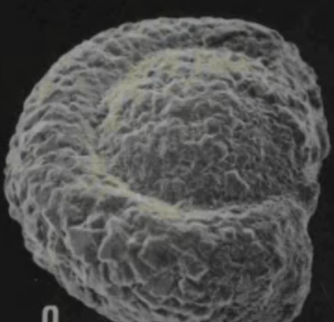
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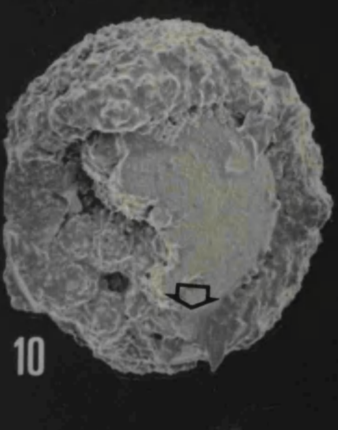
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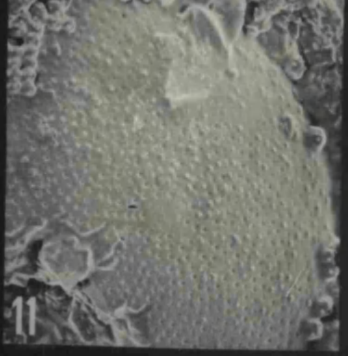
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PLATE 3

Plate 3

STELLARIMACEAE (part)

Figs. 1-10: *Fenestrella antiqua* (Grunow) Swatman, emend.

1-5, 8-10. Normal (i.e. vegetative) cells.

1. Diameter 270 μm. Non-pyritised specimen. Oblique valve view, showing lines of packed labiate processes on opposite sides of valve face (arrows). Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

2. (AGM 112). Diameter 250 μm. Oblique view of pyrite-infilled specimen, with a veneer of silica preserving areas of packed labiate processes (arrows). BP well 15/28a-3, 6460', ?uppermost Paleocene.

3. (AGM 113) Diameter 140 μm. Girdle view. Note prominent break in girdle band. BP well 15/28a-3, 6420', ?lowermost Eocene.

4. Detail of **1.** Width of view 40 μm. Note labiate processes, surrounded by fine areolae.

5. (AGM 114) Width of view 40 μm. Detail of pyrite-infilled specimen, with packed labiate processes. BP well 15/28a-3, 6450', ?uppermost Paleocene.

6-7. Initial cells.

6. (AGM 115) Diameter 220 μm. Oblique valve view. Note thickened girdle, and areas of packed labiate processes (arrows). BP well 15/28a-3, 6410', ?lowermost Eocene.

7. Girdle view of **6.** Note unequal convexity of valves, the uppermost (auxospore) valve being more highly domed than the lower (vegetative) valve.

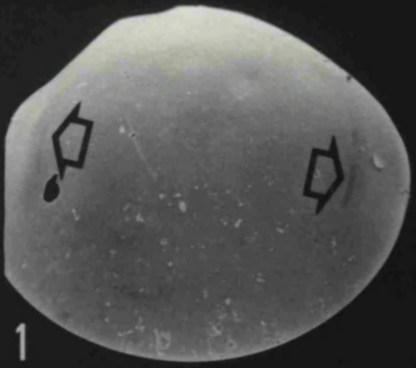
8-9. Detail of internal expression of packed labiate processes.

8. (AGM 116) Width of view 30 μm. Specimen infilled and replaced by pyrite. Labiate proceses form impressions in non-crystalline pyrite, while framboidal pyrite has infilled areolae (arrow). BP well 15/28a-3, 6410', ?lowermost Eocene.

9. Width of view 50 μm. Non-pyritised specimen. Note inwardly-projecting labiate processes. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

10. (AGM 117) Diameter 210 μm. Girdle view of normal cell. Ølst, Denmark ("Ølst D"), ?lowermost Eocene.

PLATE 3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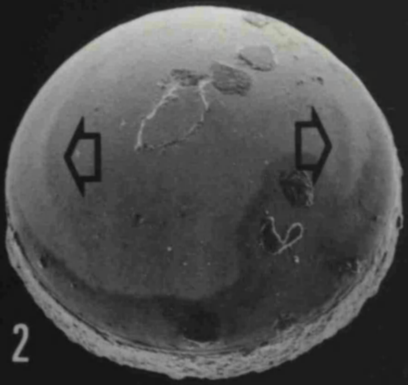
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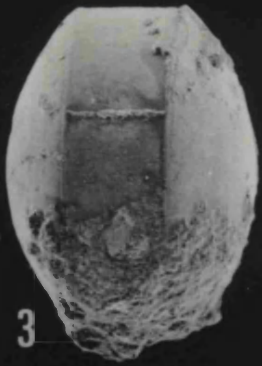
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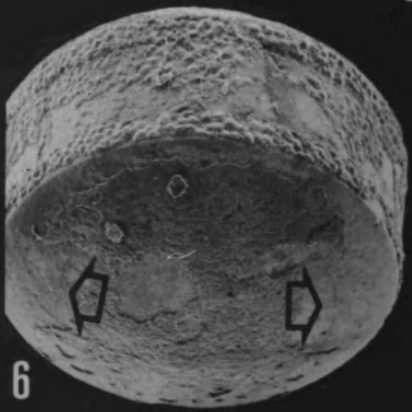
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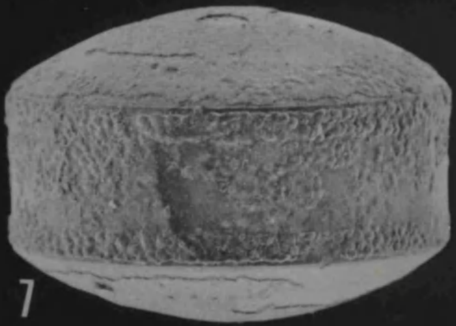
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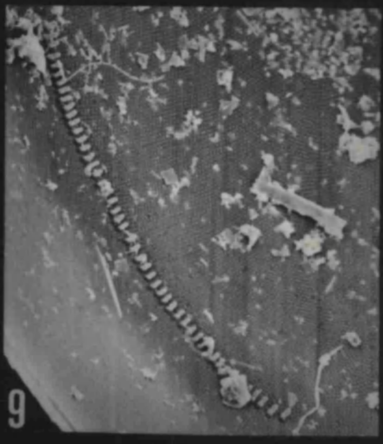
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PLATE 4

Plate 4

STELLARIMACEAE (continued)

Figs. 1-5: *Fenestrella antiqua* (Grunow) Swatman, emend.

1-2. Auxospores.

1. (AGM 118) Width of cell 260 µm. Girdle view. Note highly-rounded valves, merging with multiple girdle bands. Arrows mark valve/girdle junction. BP well 15/28a-3, 6360', ?lowermost Eocene.

2. (AGM 119) Diameter 190 µm. Oblique valve view. Specimen partially encrusted with overpyrite. BP well 15/28a-3, 6390', ?lowermost Eocene.

3-5. Resting spores.

3. (AGM 120) Diameter 220 µm. Girdle view. Note lack of girdle bands, and smooth surface. BP well FC 22, "Core 27", ?uppermost Paleocene.

4. (AGM 121) Diameter 250 µm. Valve view. Arrow marks position of packed labiate processes. BP well 15/28a-3, 6370', ?uppermost Paleocene.

5. (AGM 122) Diameter 240 µm. Girdle view, with cell opening to reveal girdle of vegetative cell beneath (base of specimen). Arrow marks position of packed labiate processes. BP well 15/28a-3, 6470', ?uppermost Paleocene.

Figs. 6-11: *Stellarima microtrias* (Ehrenberg) Hasle & Sims

6. Diameter 65 µm. Non-pyritised specimen. Internal view, showing three labiate processes projecting inwards from the valve centre. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

7. (AGM 123) Diameter 90 µm. Oblique valve view. Arrow marks impressions formed by central labiate processes. BP well 15/28a-3, 6320', ?lowermost Eocene.

8. (AGM 124) Diameter 90 µm. Oblique girdle view. Specimen with silica veneer. Note rim at valve/girdle junction. BP well 15/28a-3, 6460', ?uppermost Paleocene.

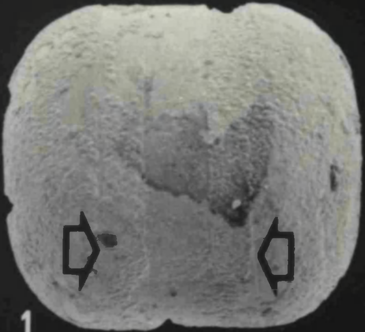
9. (AGM 125) Width of view 20 µm. Detail of valve centre, pyrite-infilled specimen. BP well 21/9-1, 2128m, ?uppermost Paleocene.

10. (AGM 126) Diameter 50 µm. Valve view. Compare with **8.** Ølst, Denmark ("Ølst D"), ?uppermost Paleocene.

11. (AGM 127) Diameter 60 µm. Oblique valve view. Specimen with four labiate processes. BP well 15/28a-3, 6460', ?uppermost Paleocene.

Fig. 12. *Stellarima* sp. (AGM 128) Diameter 50 µm. Note depression at valve centre. BP well 21/9-1, 2128m, ?uppermost Paleocene.

PLATE 4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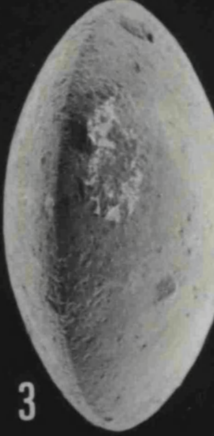
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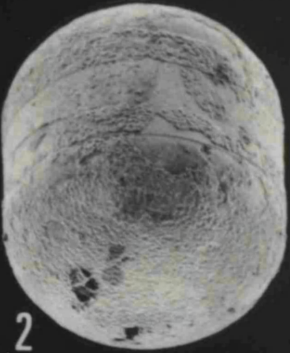
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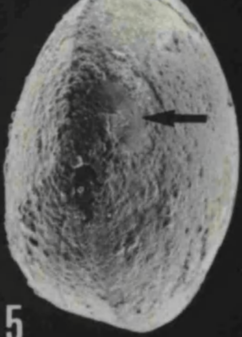
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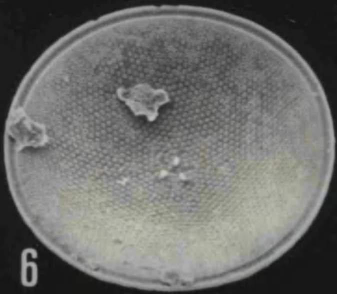
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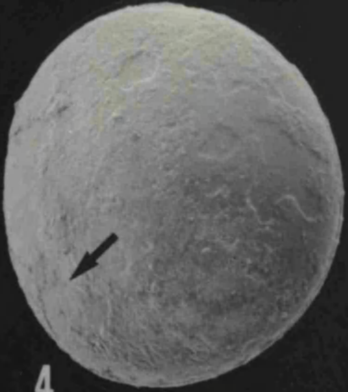
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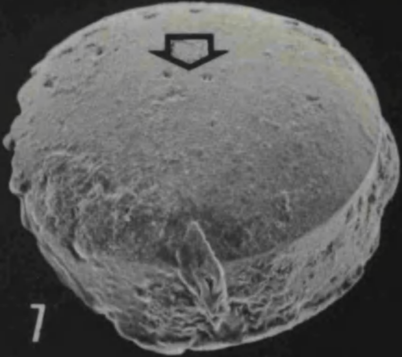
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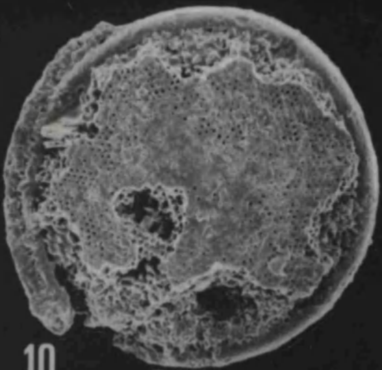
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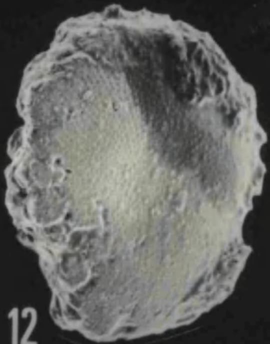
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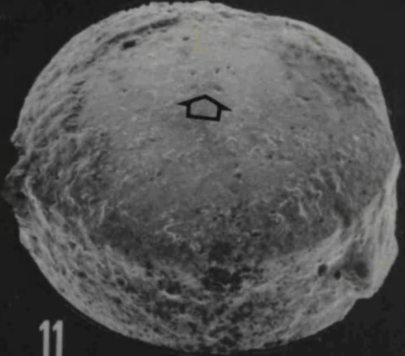
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PLATE 5

Plate 5

AULACODISCACEAE

Fig. 1: *Aulacodiscus subexcavatus* Hustedt

(AGM 129) Diameter 160 µm. Oblique valve view. BP well 208/15a-1, 1220m (core), lower Eocene.

Fig. 2: *Aulacodiscus heterostictus* Barker & Meakin

(AGM 130) Diameter 150 µm. Valve view. BP well 16/16a-3, 1322.7m (core), mid Eocene.

Figs. 3-4: *Aulacodiscus allorgei* Chenevière

3. (AGM 131) Diameter 180 µm. Valve view. BP well 3/25-1, 2162m (core), lower Oligocene.

4. Oblique valve view of **3**.

Figs 5-6, 10-12: *Aulacodiscus insignis* Hustedt, emend.

5-6. var. *aemulans* (Hustedt) Mitlehner, nom. nov. MS.

5. (AGM 132) Diameter 250 µm. Oblique valve view. BP well 16/16a-3, 1322.7m (core), upper Oligocene.

6. (AGM 133) Diameter 130 µm. Oblique valve view. BP well 15/28a-3, 3580', lower mid Miocene.

Fig. 7. *Aulacodiscus singiliewskyanus* Barker & Meakin

(AGM 134) Diameter 260 µm. Oblique valve view. BP well 208/15-1, 1315 m (SWC), mid Eocene.

Figs. 8-9: *Aulacodiscus suspectus* Schmidt

8. (AGM 135) Diameter 140 µm. Valve view. Note raised, pustular areolae on valve face. BP well 21/9-1, 2122m, ?uppermost Paleocene.

9. Detail of **8**. Width of view 40 µm. Note smaller areolae at valve margin (arrow).

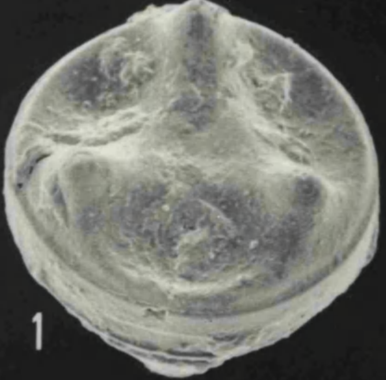
Figs. 10-12. *Aulacodiscus insignis* var. *quadrata* (King) Mitlehner MS.

10. (AGM 136) Diameter 180 µm. Oblique valve view. BP well 21/296-7, 5280', lower Oligocene.

11. Valve view of **10**.

12. (AGM 137) Diameter 225 µm. Valve view. Note hexagonal areolae (arrow). BP well 21/10-1, 5060', lower Oligocene.

PLATE 5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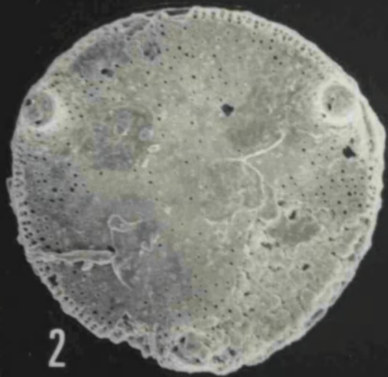
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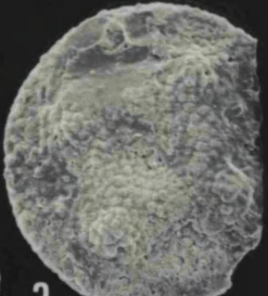
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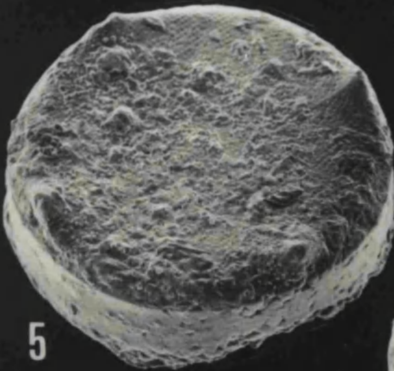
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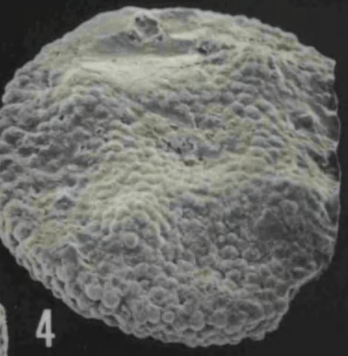
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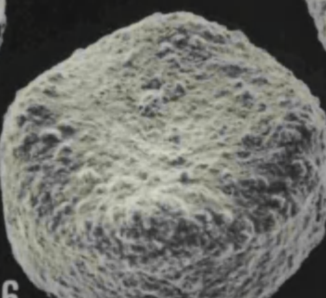
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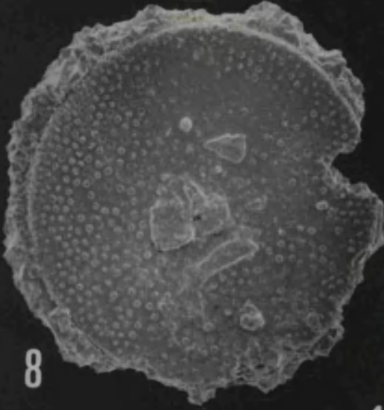
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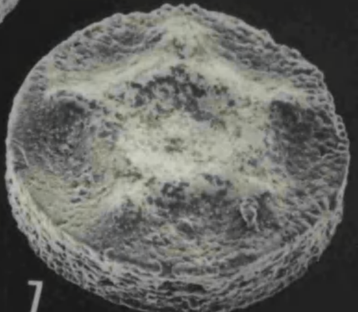
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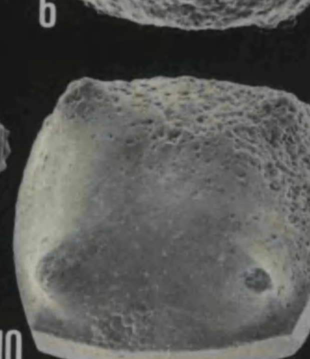
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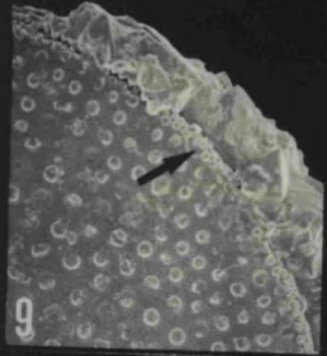
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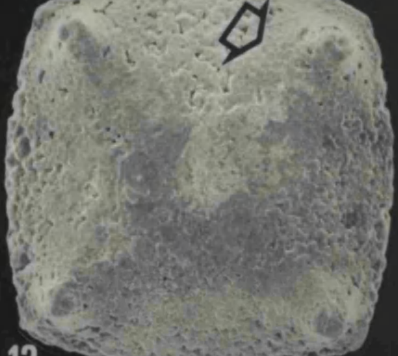
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PLATE 6

Plate 6

HELIOPELTACEAE AND ASTEROLAMPRACEAE

Figs. 1-4. *Actinoptychus senarius* (Ehrenberg) emend. Andrews & Abbott

1. (AGM 138) Diameter 90 µm. Valve view. BP well 21/9-1, 2060m, lower Eocene.

2. Oblique valve view of **1**.

3. Diameter 120 µm. Non-pyritised specimen. Internal view of valve (oblique). Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

4. Resting spore

(AGM 139) Valve diameter 120 µm. BP well 5406/30b-1, 6350' (SWC), lower Oligocene.

Figs. 5-6: *Asterolampra marylandica* Ehrenberg

5. (AGM 140) Diameter 140 µm. Valve view. BP well 21/9-1, 2116m, caved from mid-Eocene.

6. Oblique view of **5**. Note prominent hyaline rays, which meet at the valve centre.

Figs. 7, 10-11: *Asterolampra insignis* A. Schmidt

7. (AGM 141) Diameter 110 µm. Valve view. Note central areolation (specimen partially encrusted with overpyrite). BP well 21/9-1, 2116m, caved from mid/upper Eocene.

Figs. 8-9, 12: *Asterolampra* sp.

8. (AGM 142) Diameter 90 µm. Oblique valve view. Note small areolae at centre of valve (specimen encrusted with overpyrite). BP well 21/9-1, 2128m, caved from ?mid Eocene.

9. (AGM 143) Diameter 100 µm. Valve view. Specimen partially encrusted with euhedral pyrite, obscuring centre of valve. BP well 21/9-1, 2116m, caved from ?mid Eocene.

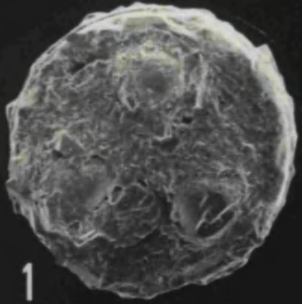
Figs. 10-11: Detail of **7**.

10. Width of view 30 µm. Edge of valve, showing elongate areolar compartments separated by hyaline ray.

11. Width of view 45 µm. Centre of valve. Note irregular mosaic of areolae in centre, and radiating hyaline rays.

Fig. 12: Detail of **9**. Edge of valve, showing rectangular areolar compartments.

PLATE 6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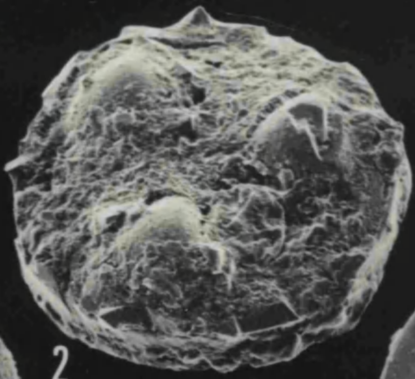
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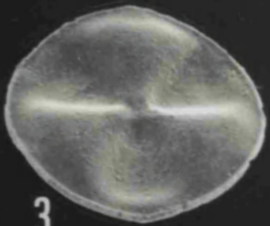
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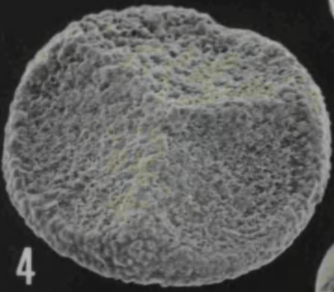
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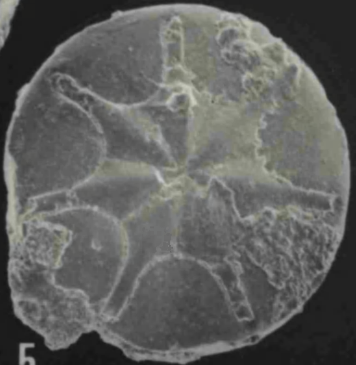
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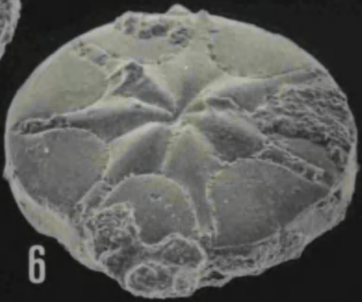
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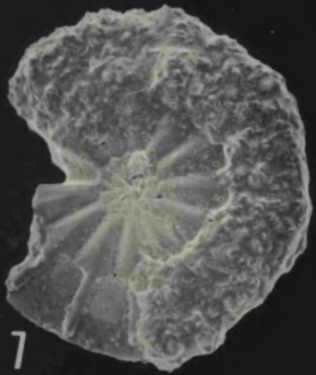
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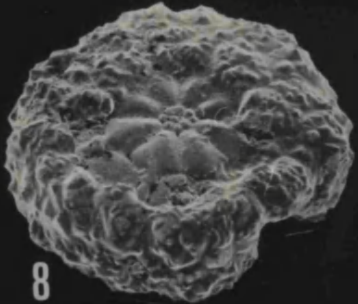
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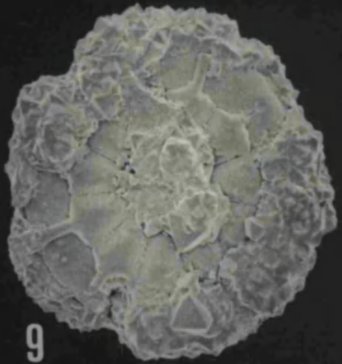
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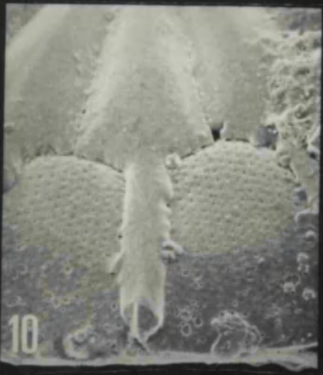
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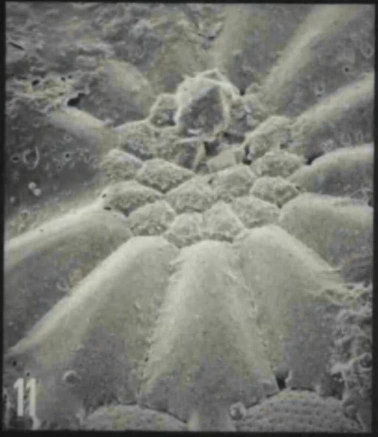
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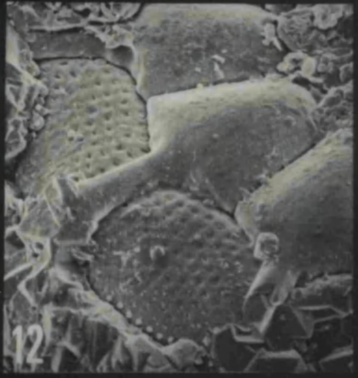
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PLATE 7

Plate 7

TRICERATIACEAE AND HEMIAULACEAE (part)

Figs. 1-5: *Odontella heibergii* Grunow

1. Diameter 120 µm. Non-pyritised specimen. Note prominent long, tubular ocelli projecting from ridges on valve face. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

2. Detail of **1**. Width of view 40 µm. Arrow marks thickened end of ocellus.

3. (AGM 144) Length of valve 85 µm. Oblique girdle view. Steinkern of frustule. BP well 21/9-1, 2110m, ?uppermost Paleocene.

4. Detail of **3**. Width of view 15 µm. Areolae on valve mantle, infilled by pyrite.

5. Valve view of **3**. Large arrow marks base of ocellus; smaller arrows mark ridges delimiting central area (compare with **1**).

Fig. 6: *Cerataulus ?weissflogii* Pantocsek

(AGM 145) Greatest width of valve 90 µm. Steinkern of frustule. Note two ocelli on upper valve, and ridge extending around valve face. BP well 15/28a-3, 4330', lower Oligocene.

Figs. 7-8: *Triceratium* sp.

7. (AGM 146). Width between apices 80 µm. Oblique valve view (specimen broken). Note central sulcus. Ocelli indistinct due to poor preservation. Knokke no. 1 well, Belgium, 283m, ?lowermost Eocene.

8. Detail of **7**. Apical region. Note prominent valve margin.

Fig. 9: *Hemiaulus ?elegans* (Heiberg) Grunow, emended Homann

(AGM 147) Width between spines 80 µm. Steinkern of frustule. Note small area of areolae, preserved at base of specimen (arrow). Ølst, Denmark ("Ølst B"), ?lowermost Eocene.

Fig. 10: *Hemiaulus elegans* (Heiberg) Grunow, emended Homann

Non-pyritised specimen. Length to ends of spines 50 µm. Complete frustule. Note similarity of general outline to **9**. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

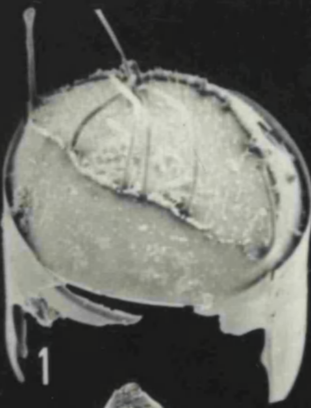
Fig. 11: *Hemiaulus?* sp.

(AGM 148) Width 80 µm. Steinkern of frustule. No original ornament preserved. BP well 15/28a-3, 6460', ?uppermost Paleocene.

Fig. 12: *Hemiaulus kittonii* Grunow

Length to ends of spines 80 µm. Non-pyritised specimen. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

PLATE 7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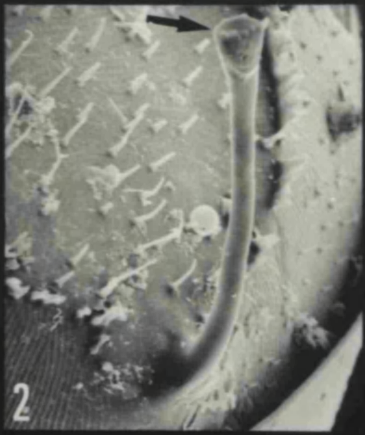
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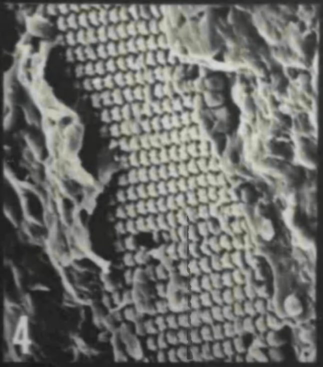
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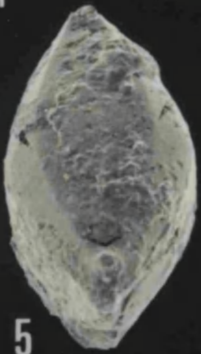
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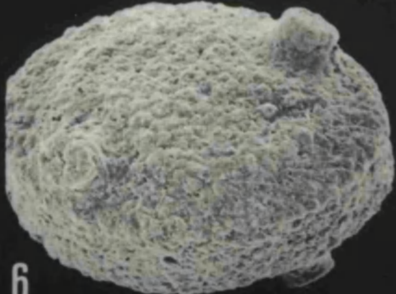
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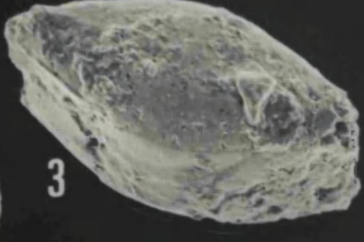
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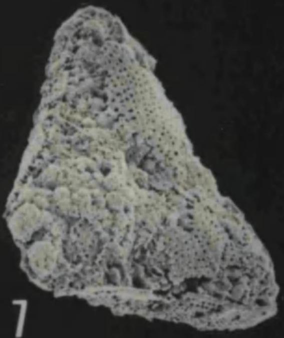
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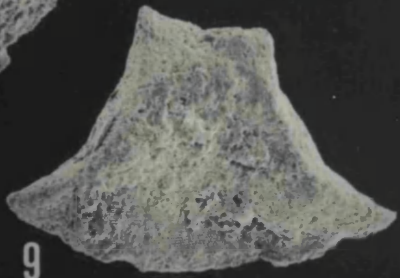
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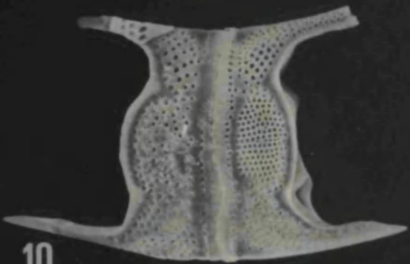
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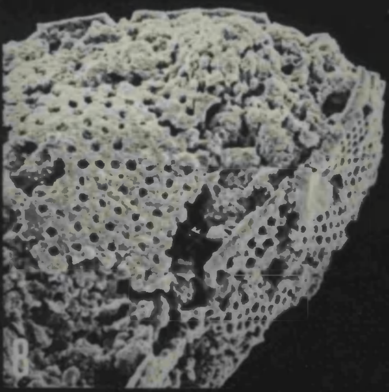
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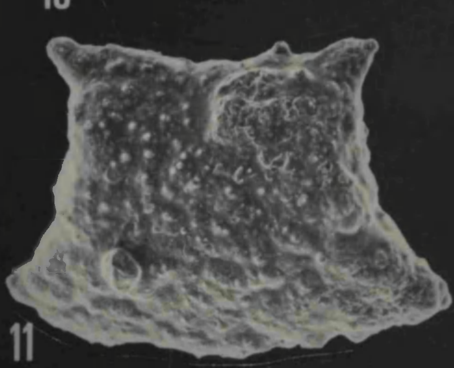
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PLATE 8

Plate 8

HEMIAULACEAE (continued)

Figs. 1-11: *Trinacria regina* (Heiberg) Homann

1. Length to apices 100 µm. Non-pyritised specimen. Oblique valve view, inside of separation valve. Note central node, and radiating areolae. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

2. (AGM 149) Width of specimen 80 µm. Note radiating areolae on bottom right of specimen, infilled by pyrite. Rest of specimen covered with overpyrite. BP well 15/28a-3, 6460', ?uppermost Paleocene.

3. Length to apices 110 µm. Non-pyritised specimen. Oblique valve view, showing intact girdle band around edge of valve. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

4. Detail of **3**. Width of view 40 µm. Short apical spine, which interlocks with linking valve above (compare with **8**).

5. Width of view 25 µm. Non-pyritised specimen. Detail of separation valve, at base of complete frustule. Note cribra infilling pores. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

6. Width of view 30 µm. Non-pyritised specimen. Detail of apex. Linking valve, with long spine, attached to separation valve (partially obscured by girdle band). Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

7. (AGM 150) Length to apices 80 µm. Oblique view of two joined valves, replaced by pyrite. Note linking valve above separation valve. Ølst, Denmark ("Ølst B"), ?lowermost Eocene.

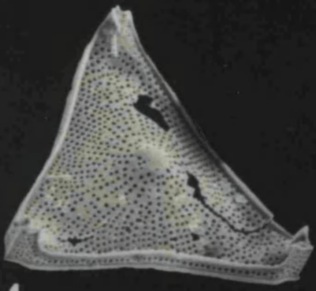
8. Length to apices 80 µm. Non-pyritised specimen. Compare with **7**. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

9. (AGM 151) Length to apices 70 µm. Base of deeply concave separation valve. Ølst, Denmark ("Ølst B"), ?lowermost Eocene.

10. Length to apices 80 µm. Non-pyritised specimen. Oblique view of top of frustule, with long spines which connect with a similar frustule to form a chain. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

11. Basal view of **10**.

PLATE 8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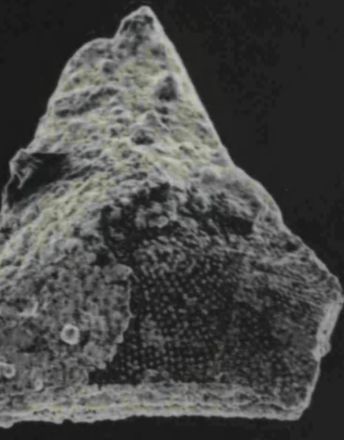
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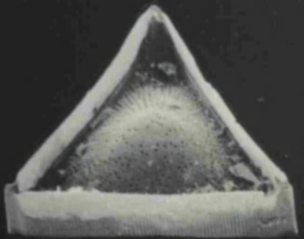
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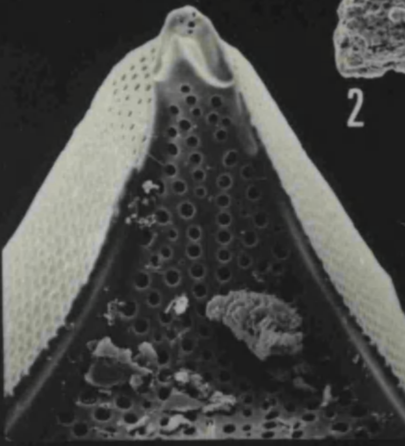
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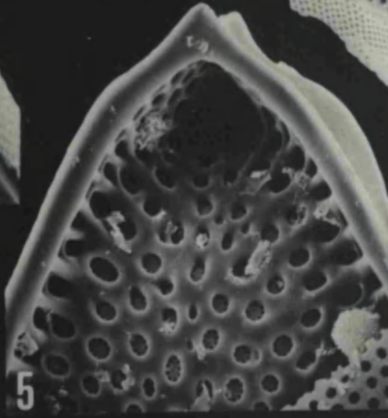
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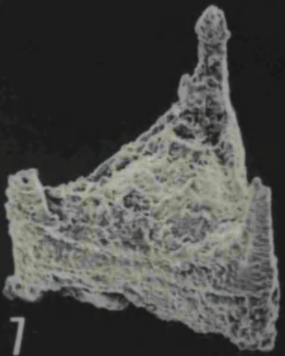
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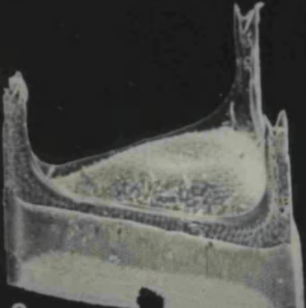
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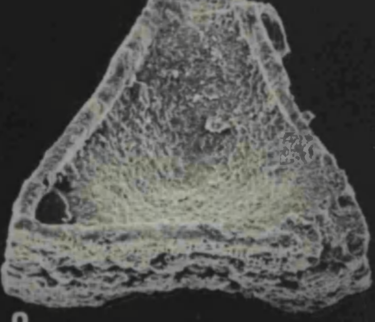
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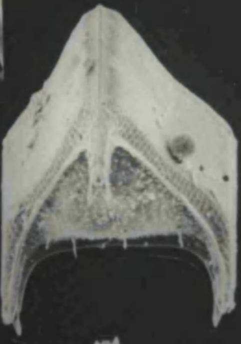
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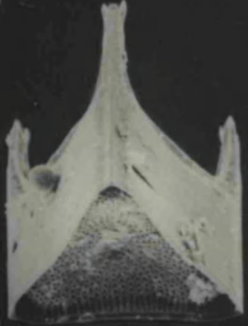
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PLATE 9

Plate 9

HEMIAULACEAE (continued), RHAPHONEIDACEAE, INCERTAE SEDIS (part)

Fig. 1: *Trinacria regina* var. *tetragona* Grunow

(AGM 152) Width 80 µm. Valve view. Specimen broken. Note recurved valve margins. BP well 22/6a-2, 2160m, lower Eocene.

Fig. 2: *Trinacria heibergii* Kitton, emend. Homann.

Length to apices 120 µm. Non-pyritised specimen. Complete frustule. Note rounded, convex periphery and long spines of linking valve. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

Figs. 3-6: *Trinacria excavata* Heiberg

3. Length to apices 80 µm. Non-pyritised specimen. Oblique view, base of separation valve. Note concave sides of valve. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

4. Length 100 µm. Non-pyritised specimen. Chain consisting of two interlocking frustules. The lower frustule is composed of a number of linking valves, surrounded by girdle bands. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

5. (AGM 153) Length to apices 80 µm. Oblique view of separation valve. Ølst, Denmark ("Ølst B"), ?lowermost Eocene.

6. Valve view of **5**.

Figs. 7-8: *Solium exsculptum* Heiberg, forma *exsculptum*

7. Width 50 µm. Non-pyritised specimen. Oblique valve view of linking valve. Note spines at valve corners. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

8. (AGM 154) Width 45 µm. Valve view. Frustule, replaced by pyrite. Ølst, Denmark ("Ølst B"), ?lowermost Eocene.

Fig. 9: *Sceptroneis gemmata* (Grunow) Van Heurck

Length 80 µm. Non-pyritised specimen. Araphid, pennate diatom, common in lower part of Fur Formation. Note constriction near top of valve. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

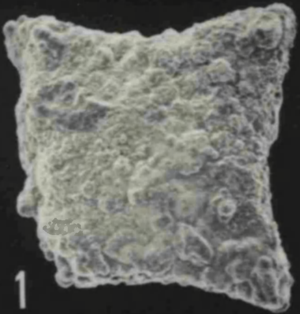
Figs 10-12: *Pseudopodosira* sp. 1 *sensu* Homann

10. (AGM 155) Diameter 100 µm. Oblique valve view. Note grooves on contoured valve face. BP well 21/9-1, 2104m, ?lowermost Eocene.

11. Girdle view of **10**. Note grooves around valve margins, and lack of girdle band.

12. Detail of **10**. Note undulating surface, and rows of areolae arranged in puncta.

PLATE 9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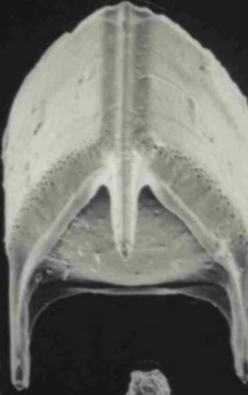
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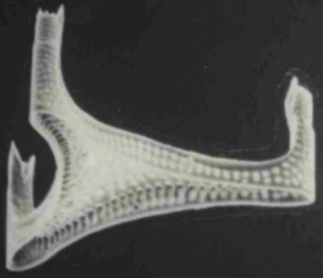
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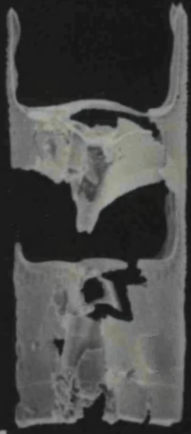
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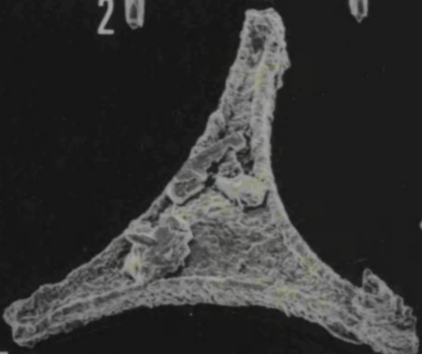
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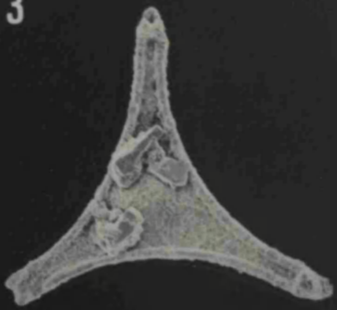
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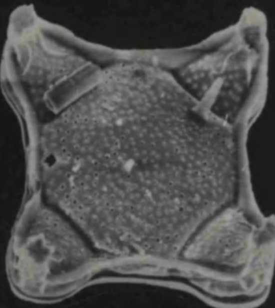
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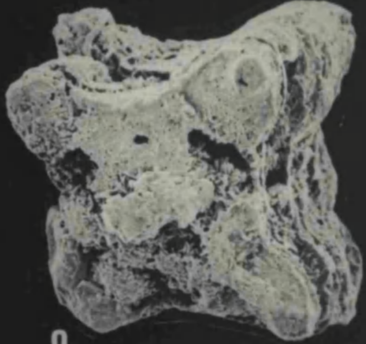
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12

PLATE 10

Plate 10

INSERTAE SEDIS (continued)

Figs. 1-5: *Odontotropis cristata* Grunow

1. Width of view 25 µm. Non-pyritised specimen. Detail of corner of valve. Note prominent spines (note: specimen partially enclosed by a hyaline envelope). Natural History Museum, Homann collection ("D 294"), ?lowermost Eocene.

2. Length of specimen 110 µm. Valve view of **1**.

3. Width of view 25 µm. Detail of **1**. Detail of spines.

4. (AGM 156) Length of specimen 110 µm. Girdle view. Steinkern of frustule ("warts" on surface are formed by pyrite). BP well 22/6a-2, 2170m, ?lowermost Eocene.

5. Oblique valve view of **4**.

Figs. 6-8: *Odontotropis carinata* Grunow

6. (AGM 157) Length of valve 140 µm. Oblique valve view. Steinkern of theca. Ølst, Denmark ("Ølst D"), ?uppermost Paleocene.

7. (AGM 158) Length of valve 110 µm. Steinkern of theca. Note less rounded outline than in **6**. Ølst, Denmark ("Ølst D"), ?uppermost Paleocene.

8. Length of valve 140 µm. Non-pyritised specimen. Valve view of theca. Note intact spines projecting from corners of theca. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

Figs. 9-10: *Omphalotheca jutlandica* Grunow, emended Homann

9. Length of specimen 30 µm. Valve view. Note small spines over surface, with a "crown" of larger spines. Valve diameter 80 µm. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

10. Basal view of **9**.

Fig. 11: *Stephanogonia danica* Grunow

Valve diameter 60 µm. Non-pyritised specimen. Oblique girdle view. Note smooth surface and prominent central process. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

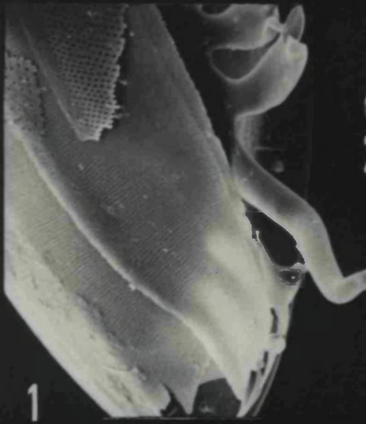
Fig. 12: *Stephanogonia* sp.

(AGM 159) Diameter 80 µm. Valve view. Note domed top of valve, and wide mantle (compare with **11**). BP well 21/9-1, 2110m, ?uppermost Paleocene.

Fig. 13: Genus et species indet.

(AGM 160) Diameter 95 µm. Oblique valve view. Note central node, and coarse ribbing on valve surface. BP well 15/28a-3, 6390', ?lowermost Eocene.

PLATE 10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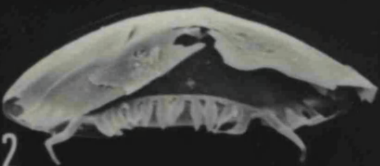
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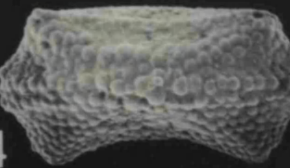
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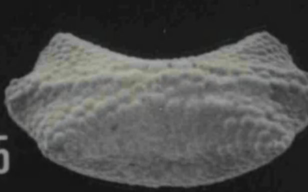
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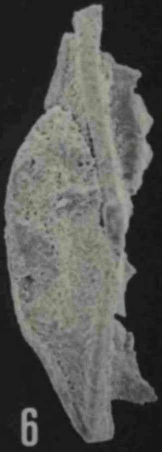
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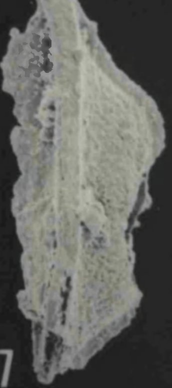
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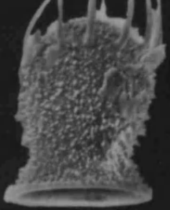
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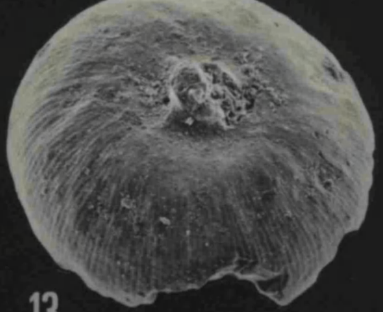
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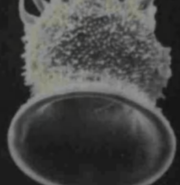
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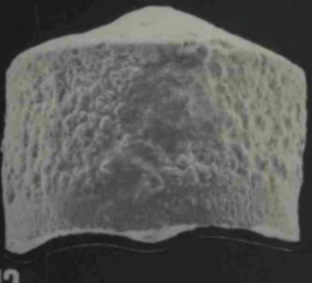
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PLATE 11

Plate 11

INCERTAE SEDIS (continued)

Cylindrospira Mitlehner, gen. nov. MS.

(All specimens non-pyritised)

Figs. 1-8: *Cylindrospira simsi* Mitlehner, sp. nov. MS.

1. Holotype (Cat. no. BM 82284). Width of valve 25 µm. LM of upper part of valve. Note relatively fine areolae on surface (arrow), with coarse ribbing beneath. Natural History Museum collections. Fur Formation (Knudeklint member, cementstone adjacent to ash-layer -20), Island of Fur, Denmark, upper Paleocene.

2. Paratype (Cat. no. BM 82285). Length of valve 120 µm. Side view of complete valve (partially obscured by siliceous debris). Note spiralling array of areolae. Natural History Museum, Homann collection ("D 292"), upper Paleocene.

3. Detail of upper part of **2**. Oblique view, showing upper surface of valve. Note marginal spines (small arrows) and raised pads on surface (large arrow).

4. Basal view of **2**. Note hollow base of valve, with basal flange.

5. Lower part of holotype (**1**). LM of valve. Note spiralling areolae, and thickened, transverse internal ribbing.

6. Different focal plane of **1**. Note well-defined internal ribbing.

7. Detail of base of **2**. Basal flange, with ribbing on inside. Note irregularly-sized areolae, raised above valve surface, between which are smaller, irregularly distributed, secondary areolae.

8. Different focal plane of **5**, showing apparently diffuse external ornament.

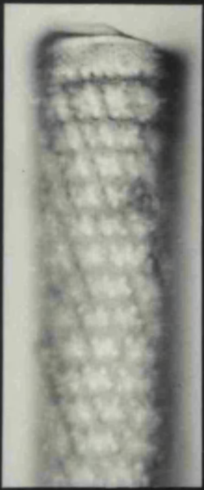
Figs. 9-11: *Cylindrospira homanni* sp. nov. MS.

9. Holotype (Cat. no. BM 82286). Width of valve 10 µm. Oblique view of top of valve. Note raised pads, and marginal spine (arrow). Natural History Museum, Homann collection ("D 292"), upper Paleocene.

10. Basal view of **9**. Length 30 µm. Complete specimen. Note spiralling areolae, larger in relation to valve size than in *C. simsi*.

11. Detail of **9**. Basal part of specimen (probably broken).

PLATE 11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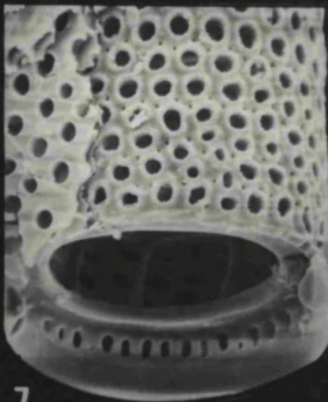
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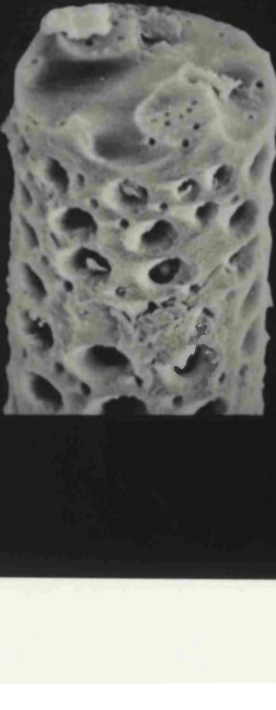
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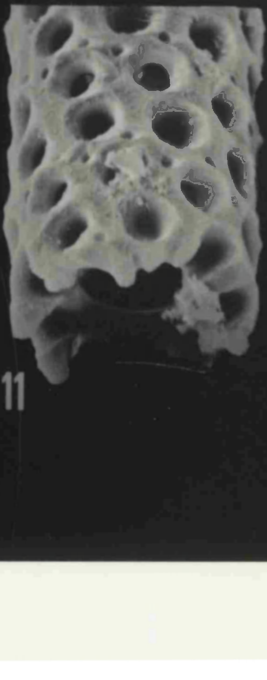
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PLATE 12

Plate 12

OTHER SILICEOUS MICROFOSSILS

Figs. 1-6: Radiolaria.

1-2: *Ceratocyrtis hystricosus* (Jørgensen)

1. Length 150 µm. Non-pyritised specimen. Side view of test. Note large, open pore frames, and small spines around cephalis. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

2. Internal view of **1.**

3-4. *Peridium longispinum* Jørgensen

3. Length of specimen (not including spines) 120 µm. Non-pyritised specimen. Side view of test. Note large, thickened spines. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

4. Internal view of **3**. Note spines extending from inside of valve.

5. *Cenosphaera* sp. *sensu* King

(AGM 161) Diameter 140 µm. Note large pore-frames infilled with pyrite. BP well 21/9-1, 2116m, caved from ?mid-upper Eocene.

6. *Calocyclas ?extensa talwanii* (Bjorklund & Kellogg)

(AGM 162) Length of specimen 120 µm. Note large pore frames, infilled with pyrite. BP well 21/9-1, 2116m, caved from ?mid-upper Eocene.

Figs. 7-10: Silicoflagellates (**7-9**) and ebridian (**10**). All non-pyritised.

7. *Dictyocha elongata* Glezer

Length between spines 60 µm. Natural History Museum, Homann collection ("D 330"), ?lowermost Eocene.

8. *Corbisema hastata globulata* Bukry

Width 50 µm. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

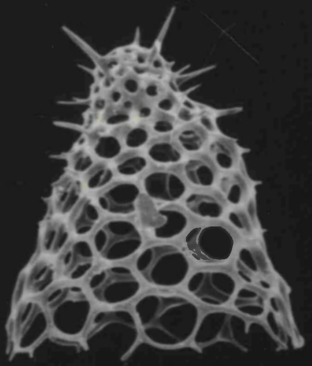
9. *Naviculopsis danica* Perch-Nielsen

Length 90 µm. Natural History Museum, Homann collection ("D 292"), ?uppermost Paleocene.

10. *Falsebria ambigua* Deflandre

Width 25 µm. Natural History Museum collections ("Fur Nykøbing"), ?lowermost Eocene.

PLATE 12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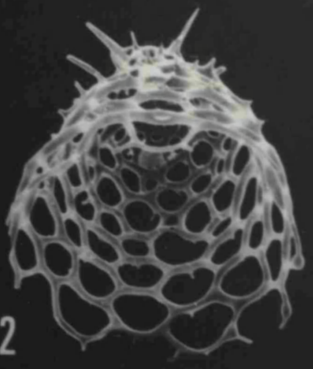
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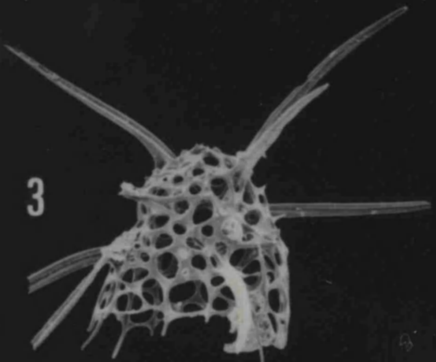
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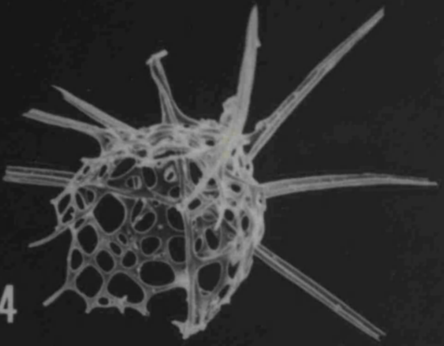
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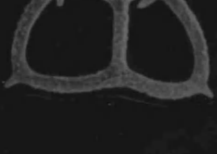
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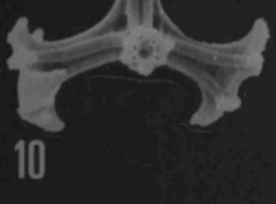
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APPENDIX

Charts showing abundances of microfossils (including diatoms, radiolaria, and foraminifera) in BP wells 15/28a-3 and 21/9-1.

PALEOCENE			EOCENE																				OLIGOCENE				MIOCENE									AGE
6479	6460	6450	6440	6420	6410	6400	6390	6380	6370	6360	6350	6340	6330	6320	6310	6000	5600	5120	4930	4900	4870	4750	4510	4330	4210	4190	4060	4000	3830	3790	3760	3730	3670	3580	3520	
																									1			4	3	5	1	2		5	1	Asterigerina guerichi staeschi
																											1		2	3	4	2			5	Alabamina tangentialis
																													6	1	1				1	Cancris auriculus
																											1			1	4	4	3	2	7	Cibicidoides dutempiei peelensis
																																3			2	Cibicidoides pachyderma
																																			1	Globobulimina sp.
																																	1		1	Globigerinoides quadrilobatus triloba
																													1				1		2	Globorotalia zealandica
																																			1	Gyroidina sp.
																																			1	Valvulineria mexicana grammensis
																																5	3	1		Lenticulina sp.
																									1	2			1		2			1		Melonis pompilioides
																							1					2	1	3	1	2	2	2		Nodosaria soluta
																																		1		Uvigerina pygmea langeri
																																		2		Uvigerina pygmea langeri/eiderensis
																								1	2	1								1		Recurvoides ex gr turbinatus
																									1					1				1		Valvulineria petrolei
																																	4			Cassidulina pliocarinata
																																1	2			Gyroidina soldanii girardana
																																	2			Sigmomorphina regularis
																																1	1			Spirosigmoilinella sp. A King
																																	2			Spiroplectammina carinata
																																	2			Vaginulinopsis sp. A King
																												1				1				Globobulimina ?auricula
																																1				Martinottiella bradyana
																																2				Martinottiella sp.
																																1				Massilina secans
																						1										1				Quinqueloculina ?juleana
																									1	1					2					Bathysiphon nodosariaeformis
																															1					Uvigerina acuminata
																												3	1	1						Asterigerina guerichi guerichi
																														1						Globulina ampulla
																														1						Nodosaria sp. A King
																													1							Triloculina enoplostoma
																												1								Uvigerina sp. A King
																										2										Subbotina sp.
																							1	2		1										Cibicidoides mexicanus
																										2										Globocassidulina sp.
																							11	3		3										Cassidulina carapitana
																										4										Uvigerina spp.
																										1										Bolivina sp.
										1				1					1	2	2	3	1		1	1										Cyclammina placenta
																					1				1	1										Cyclammina rotundidorsata
																										1										Psammosphaera sp.
																							1	1	1											Rhabdammina abyssorum
																								2												Nonion granosum
																								1												Globigerina ampliapertura
																								1												Spirosigmoilinella compressa
																						1		1												Usbekistania charoides
																							1													Cancris sp.
																							2													Globobulimina socialis
																							2													Melonis affinis
																							1													Cystammina pauciloculata
																							1													Verneuilinulla sp.1 Charnock & Jones
																			12	3		3														Rhabdammina discreta
																						1														Evolutinella ?rotalata
																						1														Turrilina brevispina
																						1														Bolivina ?cookei
																						1														Lenticulina gutticostata
																					4	1														Recurvoidella lamella
																			6	1	2															Labrospira scitula
									1										1		1															Bathysiphon sp.
																					1															Cassidulina sp.
																					1															Recurvoides sp. 1 Charnock & Jones
																			4																	Evolutinella rotulata
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												1		2	5																					Subbotina patagonica
				1		1			1					2	2																					Rhabdammina sp.
5		1		4	2									2																						Haplophragmoides "walteri"
5	3	4		1				1						3																						Psammosphaera fusca
2		1			1																															Recurvoides sp.
			2																																	Haplophragmoides excavatus
			3																																	Saccammina placenta
			1																																	Saccammina grzybowski
																																				Ammosphaeroidina sp.
			1																																	Paratrochammina sp.
		1	2																																	Lituotuba lituiformis
		1																																		Ammodiscus cretaceus
2																																				Haplophragmoides sp.
1																																				Rhabdammina (cylindrica) abyssorum
1																																				Bathysiphon capillaris
1																																				Karrerulina horrida
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	3	3	4	6	4	6	6	3	6	10	11	9	15	12	11	12	No. calcareous benthic species
7	1	5	6	3	2	1	0	1	2	0	1	2	0	4	0	0	0	0	6	2	5	4	4	4	5	5	0	0	0	0	1	1	2	1	0	No. agglutinated species
0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	2	0	2	No. planktonic species
6479	6460	6450	6440	6420	6410	6400	6390	6380	6370	6360	6350	6340	6330	6320	6310	6000	5600	5120	4930	4900	4870	4750	4510	4330	4210	4190	4060	4000	3830	3790	3760	3730	3670	3580	3520	SAMPLE DEPTH IN FEET

PALEOCENE			EOCENE																				OLIGOCENE				MIOCENE									AGE
6479	6460	6450	6440	6420	6410	6400	6390	6380	6370	6360	6350	6340	6330	6320	6310	6000	5600	5120	4930	4900	4870	4750	4510	4330	4210	4190	4060	4000	3830	3790	3760	3730	3670	3580	3520	SAMPLE DEPTH IN FEET
	27	19		1					1					2										4	4	12	11	6	6	10				3	1	Stellarima microtrias
														1																	6	3			1	S microtrias resting spores
																											2		1							S. microtrias initial cells
2		4												8							3											3	3	1		Stellarima sp.
																					1						4		2	2		5	1	2	1	Paralia sp.
																								3	4	2	22	12	16	12	12	14	8	3		Coscinodiscus radiatus
																										1					1		1	1	1	Asterolampra? sp.
																									1									1		Brightwellia sp.
																								7			1						1			Aulacodiscus insignis v. aemulans
																								2							6	3				Coscinodiscus ?argus
																										1	1	1								Asterolampra insignis
																												1								Aulacodiscus sp. 1
																											3									Trinacria sp.
																								1		1										Aulacodiscus insignis v. quadrata
																										1										Odontella heibergii
																								1												Cerataulus ?weissflogii
														1									3													Paralia siberica
				1																																Aulacodiscus suspectus
	17	6		1																																Trinacria regina
3	12	9		1										2																						?Hemiaulus sp.
12	4	7	4	6	4	3	12	3	4	2	1		1	1																						Fenestrella antiqua (normal cells)
1		2	1	1	2		4		2			1	2																							F. antiqua auxospores
1				1									2																							F. antiqua initial cells
1									2				1																							F. antiqua resting spores
	4	2		1																																Coscinodiscus morsianus v. morsianus
		1																																		C. morsianus var. moelleri
		1																																		Sollum exsculptum
	2																																			Odontotropis carinata
			3																					1					2		2	2				Genus et species indet.
20	64	50	8	12	6	3	16	3	6	2	1	1	6	12	0	0	0	0	0	0	4	0	3	19	9	18	42	20	28	24	27	22	7	6	4	Total number of diatoms
3	6	7	2	6	1	1	1	1	2	1	1	1	4	3	0	0	0	0	0	0	2	0	1	6	3	6	7	4	4	3	5	4	4	4	4	Species diversity
	5	2										1		3	9	7	8	9					1	1	6	7	4		9						1	Cenosphaera sp.
																																			1	Spinose radiolaria with small pores
																															1	1				Radiolaria with large pore frames
0	5	2	0	0	0	0	0	0	0	0	0	1	0	3	9	7	8	9	0	0	0	0	1	1	6	7	4	0	9	0	1	1	0	0	2	Total radiolaria
																			4							4	5									Sponge spicules
																			2					1		3	8	2	3	5			2	4	1	Framboidal /crystalline pyrite
																										2		3					2		2	Glauconite

Well no. 11/28b-3

2128	2122	2116	2110	2104	2073	2060	2050	1990	1960	1900	1810	1720	1660	1600	1540	1480	1420	1360	1300	1270	1240	Sample depth (metres)
											2		1	3	4	5	1	2			3	Elphidium excavatum (caved)
												2	4			2	5	5	2		2	Elphidium subarcticum (caved)
							1	12	7	6	9	15	3	15	20	4	12	10	13	9	11	Haynesina orbiculare (caved)
																		4		1		Elphidium sp. (caved)
								1					5	3		4		2		1		Alabamina tangentialis
																				1		Hyalina balthica
																				1		Nodosarid sp.
																				1		Uvigerina venusta deurnensis
																				1		Protelphidium orbiculare (caved)
																			1			Bucella frigida
																			2			Cibicidoides pachyderma
																4			9			Elphidium groenlandicum (caved)
																			1			Globigerina sp.
																			1			Islandiella helenae (caved)
													3					1				Bryozoa
											1		1	2	1	4	4					Ostracods
														1			1					Nonion granosum
																1	1					Quinqueloculina sp. 1
																	1					Miliolid sp.
							2					1		2		3						pyrite
													1	1		1						Pyrgo sp.
										1			1		2	1						Quinqueloculina ?julcana
															3	1						Quinqueloculina carinata
															1							Radiolarian (Cenosphaera sp.)
														5								Fish vertebrae
											1		1									Cibicidoides mexicanus
													2									Nodosaria soluta
							1	4	3	4	4	4										Algal cysts (?Bolboforma)
									1	1	1											Globorotalia ?increbescens
					1	2	2	3	1		1	1										Cyclammina placenta
							1				1	1										Cyclammina rotundidorsata
												1										Psammosphaera sp.
									1	1	1											Rhabdammina abyssorum
										2												Nonion granosum
										1												Globigerina ampliapertura
										1												Spirosigmoilinella compressa
								1		1												Usbekistania charoides
									1													Cystammina pauciloculata
									1													Verneuilinella sp.1 Charnock & Jones
					12	3		3														Rhabdammina discreta
								1														Evolutinella ?rotulata
							4	1														Recurvoidella lamella
					6	1	2															Labrospira scitula
					1		1															Bathysiphon sp.
							1															Cassidulina sp.
							1															Recurvoides sp. 1 Charnock & Jones
			1			2																Reticulophragmoides jarvisi
2	5				1	4																Subbotina patagonica
1		2				2																Cyclammina placenta
2	2	3	7	3	4	5																Rhabdammina sp.
2	3	4	2	3	5																	Haplophragmoides "walteri"
3		2			1																	Psammosphaera fusca
3		1		2	2																	Recurvoides sp.
2				1	1																	Haplophragmoides excavatus
1		1			3																	Saccamina placenta
5	3	4	1		2																	Saccamina grzybowski
				1																		Ammosphaeroidina sp.
	1		2	1																		Paratrochammina sp.
		2		1																		Lituotuba lituiformis
2	3	5	2	4																		Ammodiscus cretaceus
2	3	9	5	4																		Haplophragmoides sp.
6	8	9	3	7																		Rhabdammina (cylindrica) abyssorum
4	3	8	6	2																		Bathysiphon capillaris
1																						Karrerulina horrida
2128	2122	2116	2110	2104	2073	2060	2050	1990	1960	1900	1810	1720	1660	1600	1540	1480	1420	1360	1300	1270	1240	**SAMPLE DEPTH (METRES)**

																							AGE
	2128	2122	2116	2110	2104	2073	2060	2050	1990	1960	1900	1810	1720	1660	1600	1540	1480	1420	1360	1300	1270	1240	**Sample depth (metres)**
																		1					Aulacodiscus insignis v. quadrata
																1							Stellarima sp.
							1																Actinoptychus senarius
			2				7																Asterolampra insignis (caved)
	24	10	28	27			2																Coscinodiscus morsianus v. morsianus
							1																Solium exsculptum
	19	15	23	12		5	11																Stellarima microtrias
							1																Triceratium sp.
			1				2																Trinacria excavata
	8	8	17	41			2																Trinacria regina
	3					1																	S. microtrias resting spores
					1																		C. morsianus v. moelleri
	21	16	9	7																			Fenestrella antiqua (normal cells)
				1																			Odontella heibergii
				1																			Odontotropis carinata
				1																			Odontotropis cristata
				1																			Pseudopodosira sp.1 Homann
				1																			Stephanogonia sp.
			1																				Asterolampra marylandica (caved)
			1																				Aulacodiscus suspectus
		1	1																				F. antiqua initial cells
			1																				Hemiaulus ?elegans
	1		3																				Paralia siberica
	2																						F. antiqua resting spores
				3		1	1																Genus et species indet.
	78	**50**	**87**	**92**	**1**	**7**	**28**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**Total number of diatoms**
	7	**5**	**11**	**9**	**1**	**3**	**9**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**Species diversity**

BP well 21/9-1