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# Towards a stable and agreed nomenclature for North Sea Tertiary diatom floras – the ‘*Coscinodiscus*’ problem

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**Abstract:** Diatoms are one of the most useful microfossil groups to be found in Tertiary (particularly Palaeogene) sequences of the North Sea subsurface for their biostratigraphic utility, especially where other mineralized-walled microfossil groups (e.g. foraminifera, calcareous nannoplankton, etc.) are absent. An example from one offshore borehole (Shell UK; 29/25-1) is given. However, their further use in biostratigraphic and sequence correlation is hampered by the lack of any stable nomenclature applied to their taxonomy. The numbers of so-called ‘in-house’ taxa are legion with duplication of forms almost inevitable. Few of these many and varied taxa are directly comparable between these schemes, and this leads to almost inevitable confusion for exploration, production and development geoscientists trying to correlate between the various schemes.

One stratigraphically important and familiar diatom taxon (*Coscinodiscus* sp. 1) is formally described in this paper as *Fenestrella antiqua* (Grunow) Swatman. In the example shown here it is demonstrated that four forms, previously identified as four independent taxa in open nomenclature (with distinctive stratigraphic ranges), are in fact separate manifestations of the life habitat of this one single species. It is hoped that through an awareness of the biological complexity of these forms, and their relationships to morphology, a stable taxonomy will eventually arise. It is furthermore hoped that this will lead to a stimulus in the study of the biostratigraphic and palaeoenvironmental applications of this important microfossil group to exploration, production and development geoscience.

There can be few stratigraphers working on the commercial applications of micropalaeontology in the North Sea who are unfamiliar with the ‘benchmark’ diatom known as *Coscinodiscus* sp. 1 (in the sense of Bettenstaedt *et al.* 1962). It occurs widely in and around the North Sea basin, in both onshore and offshore sections (see Mitlehner 1996 for a diatom-based correlation of these strata). The highest stratigraphic occurrence (extinction) of a pyritized morphotype of this form (non-pyritized forms range higher) has been used as a reliable guide fossil for the down-hole penetration of the Balder Formation (Moray Group) – a strong seismic reflector in close stratigraphic proximity to both exploration targets and hydrocarbon accumulations. Fluctuations in its abundance can be used to mark various levels within the Balder and Sele formations throughout most of the North Sea basin.

In addition to this form, there have been perhaps several hundred additional diatom taxa recorded from various formations, which have potentially more or less stratigraphic utility. A detailed understanding of diatom stratigraphy has impacted subsurface issues on many producing reservoirs of the UK North Sea including Harding (Quadrant 9 Block 23), Gryphon (9/18), Sedgwick (16/6) and West Brae (16/7) fields (see also Payne *et al.* 1999).

Most of these forms have, for convenience, been placed within the genus *Coscinodiscus* Ehrenberg. However, it is readily apparent that ‘*Coscinodiscus*’ has been used in this sense as a convenient ‘bucket term’ for almost any circular diatom-like form, and an entire pantheon of species numbering systems have been erected by the various oil companies, stratigraphic laboratories and consultants working on them. In fact,

there may be very few 'true' species of *Coscinodiscus* in the fossil record at all (Sims 1989). Yet it remains the fact that these important microfossils, which may number up to several hundred individual taxa, have *never been documented in one place* within the public domain. We consider this to be a serious omission, restricting the enormous potential value of this microfossil group in both large- and small-scale exploration, development and production biostratigraphy. This problem is also prevalent in the literature with, for just one example, *Coscinodiscus* sp. 3 (*sensu* Thomas & Gradstein 1981) synonymous with the aforementioned important morphotype *Coscinodiscus* sp. 1 (*sensu* Bettenstaedt *et al.* 1962).

Different aspects of this paper were undertaken by the various authors. The taxonomic foundation was constructed by A. Mitlehner, with M. Bidgood, G. Jones and D. Jutson providing information on the stratigraphic and palaeoenvironmental applications of the flora to North Sea stratigraphy. Overall coordination of the various contributions was undertaken by M. Bidgood. Stratigraphic queries should be addressed to M. Bidgood, G. Jones or D. Jutson. Taxonomic queries should be addressed to A. Mitlehner.

#### *From a pragmatic to a more standardized approach*

The task of the micropalaeontologist is first to place all of the many morphotypes of diatoms recorded into a stable, scientific taxonomic framework, rather than into an arbitrary system of open nomenclature (normally based around a simple numbering scheme for vaguely similar forms). It can be justifiably argued that this latter 'pragmatic' approach to taxonomy can have advantages in the day-to-day analysis of samples from commercial boreholes – speed of analysis and interpretation, together with local (i.e. in-house) consistency results in an efficient service to the line customer. The authors themselves have experienced this system at first hand and, indeed, some of the diatom taxa illustrated in this paper remain in open nomenclature. However, we believe that the 'pragmatic' approach to diatom taxonomy has probably reached the limits of its usefulness in that true taxonomic (i.e. biological) relationships are becoming unclear which is potentially damaging to biostratigraphic, palaeoenvironmental and sequence stratigraphic interpretation. In addition, 'pragmatic' schemes differ between in-house and external contractors, and changing a biostratigraphic subcontractor can result in painful and time-consuming reconstructions of the in-house database.

#### *Preservation problems*

The fact that most fossil forms recovered from North Sea offshore boreholes are preserved as pyritized infilled moulds ('*steinkerns*'), rather than the opal-A silica which forms the original diatom frustule, provides a major challenge to classical taxonomic interpretation. Consequently few authors (e.g. Mitlehner 1994, 1996) have made attempts to understand the relationship between original internal structures and the external appearance of the pyritized fossil; extensive use of the scanning electron microscope (SEM) is essential in this respect as many taxonomically defining features cannot be seen with the light microscope (LM). There is a pressing need to publish and illustrate these pyritized morphologies, as it is appreciated that industrial micropalaeontologists may not have ready access to SEMs or do not have time or resources to devote to extensive SEM studies on which some of the diagnostic taxonomic features are based. However, in this publication we have attempted to include features that can also be seen with the LM, for example the ridges on either side of valves of *Fenestrella antiqua* which mark the positions of the rows of labiate processes (see below) which are of taxonomic importance.

#### **Diatom biostratigraphy: an example**

Although the use of diatoms in North Sea Palaeogene biostratigraphy is well known amongst workers, there are few published references (e.g. Jacqué & Thouvenin 1975; King 1983; Mudge & Copestake 1992; Mitlehner 1996; Jones 1999), as the majority of datasets are based on offshore commercial boreholes generated by commercial companies; their presentation in the public domain is therefore not encouraged. Added to this problem is the lack of a stable nomenclature, which is detrimental to an effective appreciation of the group's biostratigraphic potential.

As a basic example of diatom stratigraphic utility, North Sea well 29/25-1 is located some 25 km southwest of the Auk and Fulmar (Shell) oil fields, and lies near the northeastern margin of the Western Platform and Mid North Sea High structural elements of the UK sector of the North Sea (Fig. 1). It was drilled in 1970 by the Shell UK–Esso partnership at position 56°20'N; 01°50'E. The well provides important data with respect to diatom biostratigraphy in that extensive parts of the Lower Palaeogene succession in the well were sampled by sidewall

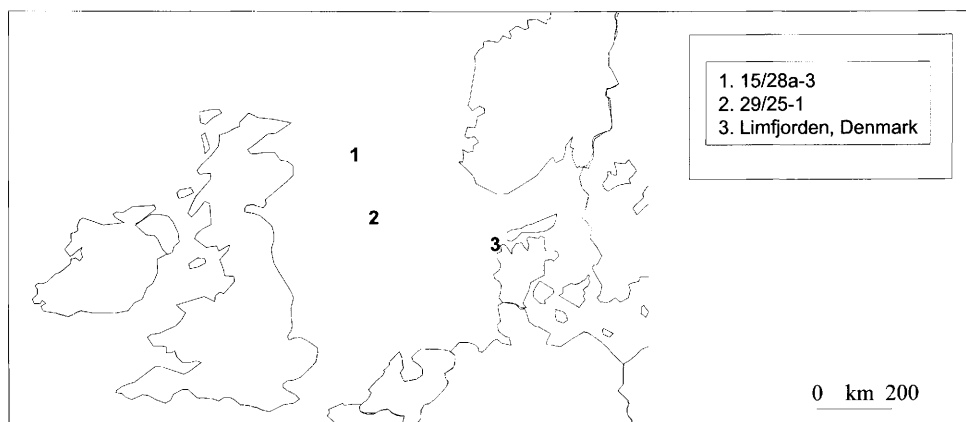


Fig. 1. Offshore wells and localities mentioned in text.

cores as well as drilled ditch cuttings, and therefore caving effects (the contamination of *in situ* assemblages by stratigraphically younger material as a by-product of the drilling process) are minimized.

In broad terms, the micropalaeontological assemblages comprise an apparently normal sequence of Lower Palaeogene pyritized diatoms, interspersed with three, perhaps four, distinctive horizons of reworking as indicated by very small though abundant mid-Early Cretaceous planktonic foraminifera. As is typical for this interval across much of the North Sea basin, *in situ* microfossils (e.g. foraminifera, ostracods, radiolaria, etc.) were extremely rare, thus illustrating the usefulness of the diatoms. The data distribution chart for the Lower Palaeogene section of the well is shown in Fig. 2 (after Bidgood 1995).

The precise dating of the reworked horizons may have important implications to sequence stratigraphic analysis which can impact on the understanding of play fairways and the prediction of lowstand fan deposition. The highest two reworked horizons occur between the highest stratigraphic occurrences of the diatom species *Fenestrella antiqua* and *Coscinodiscus morsianus moelleri*. The third reworked horizon lies between the latter event and the lowest recorded occurrence (in sidewall cores) of *F. antiqua*. A possible fourth reworked horizon lies near the lowest recorded occurrences of common and consistent *F. antiqua* and *C. morsianus moelleri*.

The position of well 29/25-1 lies on the Western Platform–Mid North Sea High, rather than within the boundaries of the Central Graben itself. Therefore it may be that sequences resulting from sea-level fluctuations (which globally during Late Palaeocene–Early Eocene times

were considerable; Haq *et al.* 1988) were better expressed in this well, rather than many of those from deeper parts of the basin (see also Neal *et al.* 1994; Bidgood 1995). A refined diatom biostratigraphy should therefore provide better calibration of such sequence events.

Throughout this paper the authors have used the chronostratigraphic and lithostratigraphic nomenclature of Knox & Holloway (1992) – the UKOOA standard – as the primary *convenient* framework on which to base their taxonomic conclusions. In this case, the Palaeocene–Eocene boundary is placed within the lower part of the Sele Formation. Biostratigraphically in that publication, this boundary is placed at the acme horizon of the palynomorph *Apectodinium* spp. The present authors, however, recognize that there is still no clear agreement as to the position of the Palaeocene–Eocene boundary within offshore subsurface Balder, Sele or adjacent sections (see Knox *et al.* 1996).

There is a good alternative case, for example, to include the whole of the Sele Formation within the uppermost part of the Late Palaeocene. It is thought that the influx of *Fenestrella antiqua* (the ‘normal’/vegetative cells herein) at the top of the Sele Formation (a discrete influx which occurs stratigraphically below the first main downhole influx of this taxon normally associated with the upper Balder Formation) may represent the beginnings of a change in water-circulation pattern prior to the main Early Eocene transgressive phase in northwest Europe. In such a case, this event – the downhole disappearance of abundant *F. antiqua* – may be regarded as a useful proxy for the Palaeocene–Eocene chronostratigraphic boundary (Mitlehner 1996). This event is approximately coincident with the first downhole appearances

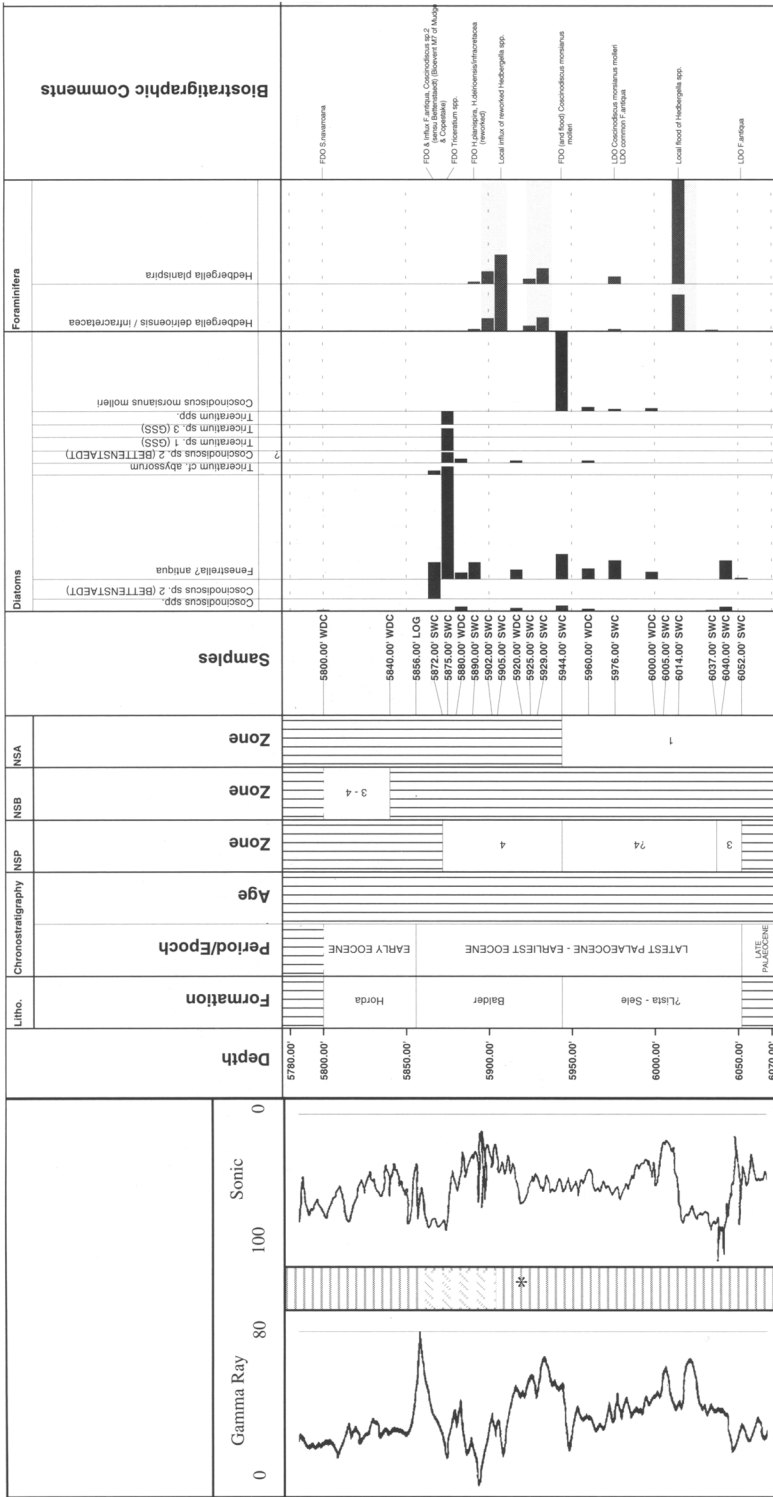


Fig. 2. Biostratigraphy of Shell UK well 29/25-1 (scale 1 : 750).

Table 1. Cartoons of some North Sea Palaeogene diatom morphotypes, with Limnean taxonomic identity where established

Actinocyclus senarius (resting spores)		Stellarina microtrias		Hemiaulus elegans		Paralia ornata		Trinacria regina (chain var.)	
Arachnodiscus indicus		Thalassioiropsis wittiana		Fenestrella antiqua		Pseudostictodiscus angulatus		Trinacria regina (chain var.)	
Arachnodiscus indicus (variable no. of rays)		Cellataulus westflogii		Fenestrella antiqua (autospore)		Pterotheca sp.		Trinacria regina (chain var.)	
Aulacodiscus allorgei		Diatom 'ovalis bituberculatum'		Fenestrella antiqua (resting spore)		Stephanogonia danica		Trinacria regina (chain var.)	
Aulacodiscus insignis var. quadrata		Diatom 'ovalis'		Fenestrella cf. antiqua		Triceratium sp.		Trinacria regina (chain var.)	
Aulacodiscus singilewskyanus		Aulacodiscus aemulans		Hemiaulus 'elegans		Trinacria regina (chain var.)		Trinacria? regina tetragona	
Aulacodiscus subexcavata		Triceratium gibbosum		Hemiaulus elegans		Trinacria regina (chain var.)		Trochospira spinosa	
Coccinodiscus morsianus moelleri		Aulacodiscus hirtus		Odontella heidelbergi		Trinacria regina (chain var.)			
Coccinodiscus morsianus var. morsianus		Solium exsculptum		Odontotropsis cf. cristata		Trinacria regina (chain var.)			
Coccinodiscus morsianus var. morsianus (small)		Solium exsculptum		Odontotropsis cristata		Trinacria regina (chain var.)			

(which may be better suited for industrial application) of *Coscinodiscus morsianus molleri* and *Odontotropis cristata* (see Table 1). Whatever the chronostratigraphic interpretation placed on these approximately coincident events, the fact remains that they are correlatable horizons which lie close to or at the Sele–Balder Formation boundary.

## Formal diatom taxonomy

### Background

Until recently, diatom classification has been based almost entirely on the siliceous cell wall, mainly because early workers who devised the classification system in the 19th century studied dead specimens and/or fossil material preserved without alteration (see Mitlehner 1996 for references to early studies). This situation has been extremely fortuitous for palaeontologists, stratigraphers and Quaternary palaeoecologists, but it must be emphasized that although the outline of the valve has been an important feature historically, this is not invariably reliable and the totality of the valve structure must be considered (Round *et al.* 1990, p. 29). In this study we illustrate an important example where the intricacies of pore structure, and the arrangement of wall organelles, are important criteria for identification. However, it is also demonstrated that SEM features need to be illustrated together with low-resolution photographs of the same specimens, in order to obviate the need for painstaking studies by industrial workers who may have limited or no access to the SEM. By this method workers need only examine the size and shape of a specimen, as well as looking for any other readily apparent features, in order to be confident of a species designation.

### Diatom taxonomy: a state of flux

A number of authors have commented on the relatively chaotic present state of diatom taxonomy (Nikolaev 1990; Round *et al.* 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 subspecies 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 and thus may potentially further confuse commercial workers. 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* which occur in the North Sea Palaeogene – see Table 1) 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).

### Scope for further studies

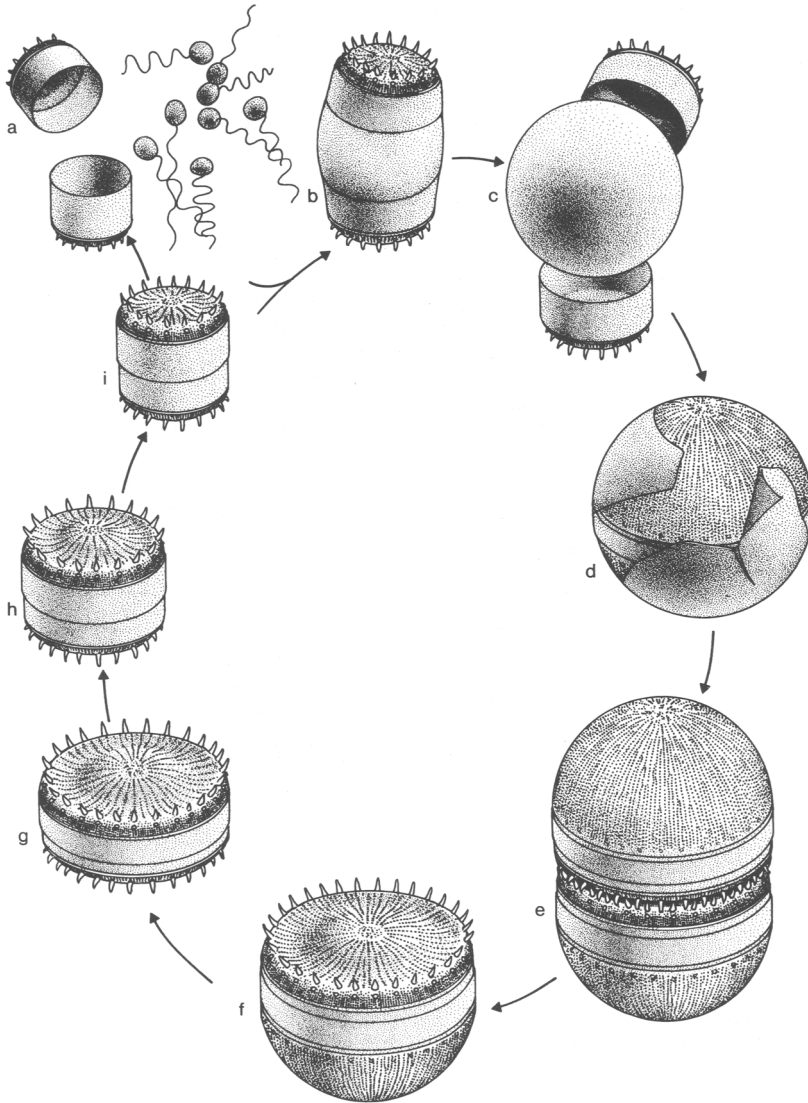
A complete taxonomic treatment of northwest European Tertiary diatom microfloras is monographic in extent and therefore lies outside the scope of this paper; it will be subject to a separate approach by the authors elsewhere. However, one well-known North Sea diatom taxon (and its associated morphotypes) is formally described here; in addition, a table of ‘cartoon’ drawings of some recorded taxa, together with Linnean nomenclature where appropriate, is also presented (Table 1). Table 1 is not intended to be a definitive taxonomic treatment as such, rather as a statement of what the authors believe to represent the present status of European Palaeogene diatoms *where some degree of formal taxonomy has already been assigned*. The authors recognize that there are potentially many more diatom taxa which remain to be adequately taxonomically treated.

### Diatom biology and ecology – importance for taxonomy

Lack of understanding of diatom biology and ecology in living forms can have undesirable consequences for the interpretation of fossil specimens. In this example four forms, previously regarded as separate (and stratigraphically important) open taxonomic entities, are shown to be the results of adaptations of a single species (i.e. *Fenestrella antiqua*) to life-cycle strategies and responses to environmental stress. It is therefore necessary to appreciate these biological principles when considering the revised taxonomic descriptions which follow.

### The diatom life-cycle: ‘Russian dolls’

Diatom reproduction involves alternating sexual (meiotic) and asexual (mitotic) stages (Fig. 3). The asexual stage results in progressive reduction in mean *normal* cell size, in the manner of ‘Russian dolls’, so that eventually a generation



**Fig. 3.** The diatom life-cycle (reproduced from Round *et al.* 1990, with the permission of the authors and Cambridge University Press). (a) Formation of motile gametes, (b) and (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)–(i) vegetative size reduction.

results which must find some means of size restitution if it is to continue to sustain itself. This is achieved by the process of sporulation, resulting from the production and fusion of gametes from parent cells. An *auxospore* is formed 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 and must be borne in mind when a taxonomic identification is attempted. The following descriptions illustrate this phenomenon.

*Normal (vegetative) cells.* Usually equivalvar, with two equally sized valves separated by one or more *girdle bands*. Typical representatives of *F. antiqua* (= *Coscinodiscus* sp. 1) are recognized by all North Sea Palaeogene workers, although



smaller examples (which probably represent successive stages in the normal growth period) may be referred to as *Coscinodiscus* cf. sp. 1 in some schemes.

*Initial cells.* The first stage in the diatom vegetative cell division cycle, formed after the fusion of gametes during sexual reproduction, inside an *auxospore* (see Fig. 3c–e). The shape of these cells is invariably cylindrical or ‘barreliform’ due to a very wide girdle, often with distinct cingula. The valves are typically highly domed, and do not exhibit the pronounced angle with the girdle seen in vegetative cells. Initial cells of *Fenestrella antiqua* (*Coscinodiscus barreliformis*) of M. A. Charnock and others) often occur in conjunction with vegetative cells.

*Initial cells, after first cell division.* A stage in the vegetative life-cycle of diatoms, revealed after the auxospore breaks open. Two cells are thus formed, with an *initial cell valve* and a *normal cell valve*, the former being more markedly domed than the other (Fig. 3f). After several divisions, the cells take on the form of the normal, equally shaped, vegetative valves. Distinguishable 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.

*Resting spores: an environmental adaptation.* A further mechanism which helps to increase the likelihood of a population surviving is via the production of *resting spores*. These are mainly formed in modern oceans by planktonic centric species, and take the form of thickly silicified cells which may, or may not, bear spines. 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 (Hargraves & French 1983). Resting spores are of widespread occurrence in the Upper Palaeocene and Lower Eocene diatom assemblages in and around the North Sea basin (Mittlehner 1994, 1996), and reflect the stressed environment present at the

time, with widespread periods of anoxia, basin stratification, ‘greenhouse warming’ and volcanic ash falls.

### Systematic descriptions/micropalaeontology

This section, by its very nature, is highly technical in content but is necessary to establish the taxonomic basis by which palaeontologists work. It is provided as a formal requirement of the procedure to establish new or emended taxa (i.e. species) in publications. If biostratigraphy is taken as one of the key underpinning agents of stratigraphy/sequence stratigraphy, then taxonomy is the key underpinning agent of biostratigraphy. Without a descriptive, illustrated taxonomy there can be no uniformity in species concepts between different workers and it is for this reason that this exercise is undertaken here.

#### *Pyritized morphologies – rationale for description*

*Terminology.* In recent years, a number of diatom taxa have been revised to take into account SEM observations (see Round *et al.* 1990). These are referred to under ‘Revised diagnosis and description’. In addition, it has sometimes been necessary to further emend descriptions, as pyritized morphotypes usually preserve the original frustule shape with girdle bands intact, a feature not often observed in non-pyritized specimens which are usually preserved as isolated valves. Any further revision is referred to under ‘Emended diagnosis (herein)’. Synonymy listings in bold type refer to pyritized forms.

*Sample derivation.* Well 15/28a-3, Outer Moray Firth, North Sea (see Fig. 1); comparative material from the Fur Formation diatomite, Island of Fur, Denmark, on a strewn slide housed in the collections of the Natural History Museum, London (see Mittlehner 1995, 1996 for further information on the Fur Formation diatomite).

- Division **Bacillariophyta**  
 Class **Coscinodiscophyceae** Round & Crawford,  
 in Round *et al.* (1990)  
 Subclass **Coscinodiscophycidae** Round &  
 Crawford, in Round *et al.* (1990)  
 Order **Coscinodiscales** Round & Crawford, in  
 Round *et al.* (1990)  
 Family **Stellarimaceae** Nikolaev ex Sims &  
 Hasle 1990  
 Included genera: *Fenestrella*, *Stellarima*

*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. Both of the included genera feature prominently in North Sea Palaeogene assemblages and have been described in detail only recently (but not in pyritized form), and so are given a comprehensive description. *Fenestrella* is described here; *Stellarima* is covered in the unpublished PhD thesis of Mitlehner (1994), but will be further considered in a future work. 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. (Sims 1990, p. 287)

*Stratigraphic range.* Upper Cretaceous (Campanian)–Recent.

Genus *Fenestrella* Greville 1864  
Type species *Fenestrella barbadensis*  
Greville 1864

*Original diagnosis*

Frustules free, disciform: disc with a minute, radiant cellulation, interrupted in the middle by linear bands, composed of parallel lines of cellules, each band terminating in a flat ocellus. (Greville 1861–66, 1864, Vol. 9, 67 [80])

*Remarks.* Sims (1990, p. 278) considers that the main diagnostic features of *Fenestrella* 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. A hitherto rarely recorded fossil genus, ranging from Palaeocene 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 pyritized 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.

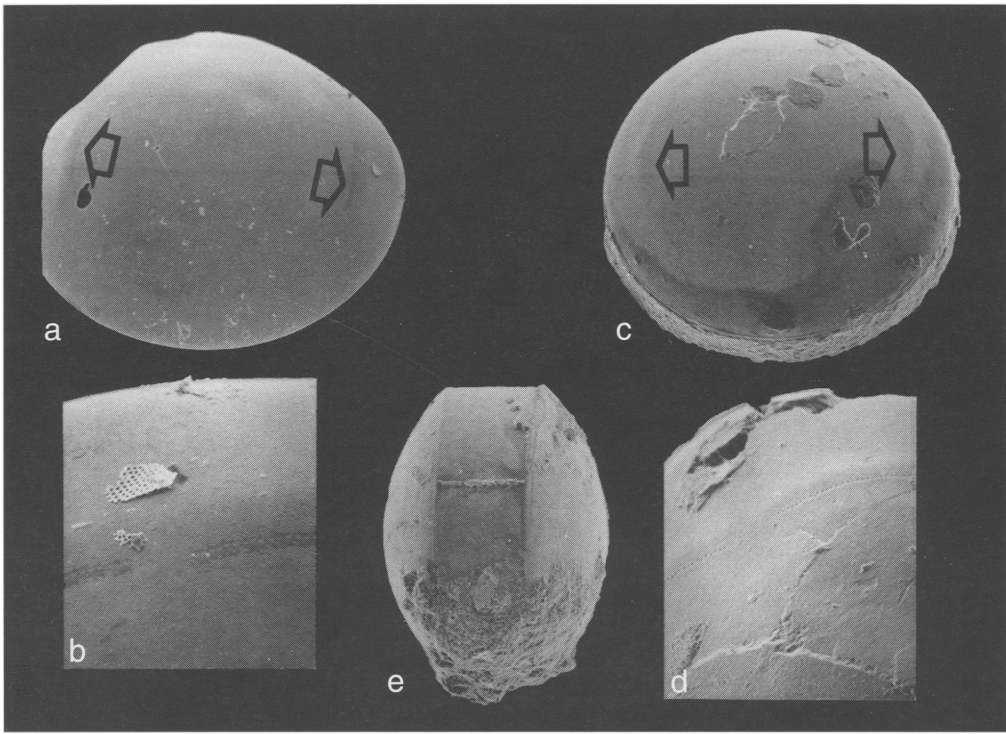
*Fenestrella antiqua* (Grunow) Swatman, emend  
(Figs 4a–6e)

- 1882 *Janischia antiqua* (Grunow in Van Heurck 1896, pl. XCV bis, figs 10 and 11).  
1889 *Coscinodiscus ludovicianus* Rattray (Rattray 1889, p. 596).  
1896 *Janischia antiqua* Grun. 1882 (Van Heurck 1880–85, p. 536, fig. 282).  
1940 *Coscinodiscus* sp. (bikonvex) (Staesche & Hiltermann 1940, p. 15, pl. 6, fig. 3).  
1943 *Coscinodiscus* sp. 1 (bikonvex) (Wick 1943–50, p. 5, pl. 1, figs 47–66).  
1948 *Fenestrella antiqua* (Grunow) Swatman comb. nov. (Swatman 1948, p. 53, pl. 2, figs. 10 and 11).  
1962 *Coscinodiscus* sp. 1 (Bettenstaedt *et al.* 1962, p. 357, pl. 2, figs 18 and 19).  
1972 *Janischia antiqua* Grun (Benda 1972, pl. 2, figs 10 and 11).  
1975 *Coscinodiscus* sp. 1 (Jacqué & Thouvenin 1975, p. 462, pl. 2, figs. A–E).  
1983 *Coscinodiscus* sp. 1 Bettenstaedt *et al.* (Bignot 1983, p. 17, pl. 1, figs 5, 6 and 8).  
1983 *Coscinodiscus* sp. 1 Bartenstein and others (King, 1983, p. 20, figs 1 and 2).  
1984 *Coscinodiscus* sp. 1. (Malm *et al.* 1984, p. 158, fig. 8a).  
1990 *Fenestrella antiqua* (Grunow) Swatman (Sims 1990, p. 179, figs. 1–14 and 22).  
1991 *Fenestrella antiqua* (Grunow) Swatman (Homann 1991, p. 48, pl. 18, figs 1, 2, 4 and 5).

*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 or plates, extend to the valve margin. (Sims 1990, p. 279)

*Emended diagnosis (herein).* Outline of frustule biconvex in girdle view, with prominent,



**Fig. 4.** Pyritized specimens (steinkerns) of *Fenestrella antiqua* (Grunow) Swatman, emend., with some non-pyritized specimens for comparison. (a)–(e) Vegetative cells. (a) and (b) Non-pyritized specimen. (a) Oblique valve view, showing lines of packed labiate processes on opposite sides of valve face (arrows). (b) Detail of (a). Note labiate processes, surrounded by fine areolae. Natural History Museum collections ('Fur Nykøbing'), ?lowermost Eocene. (c) and (d) Pyritized steinkern. (c) Oblique view of pyrite-infilled specimen, with a veneer of silica preserving areas of packed labiate processes (arrows). (d) Detail of (c). Note labiate processes (compare with b). BP well 15/28a-3, 6460 feet, ?uppermost Palaeocene. (e) Diameter 140  $\mu\text{m}$ . Girdle view. Note prominent break in girdle band. BP well 15/28a-3, 6420 feet, ?lowermost Eocene.

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-pyritized 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 pyritized specimens and take the form of indentations.

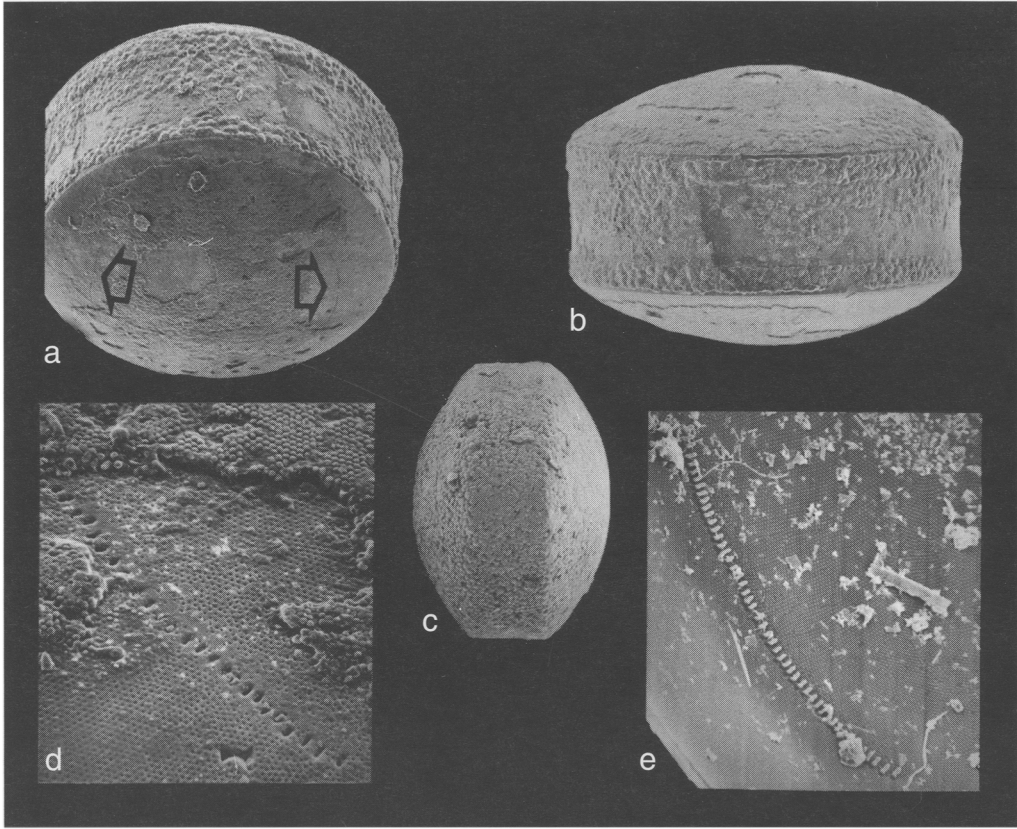
**Dimensions.** Valve diameter 150–360  $\mu\text{m}$ . Areolae 11–14 in 10  $\mu\text{m}$ .

**Remarks.** Sims (1990, p. 279, figs 1–14 and 22) gave plates, both LM and SEM, of this taxon. Her descriptions were of well-preserved, non-pyritized specimens. The largest diatom in Palaeogene sediments from the North Sea basin, the pyritized biconvex frustules of *F. antiqua*, has hitherto been identified as *Coscinodiscus*

sp. 1 (Bettenstaedt *et al.* 1962, see above). The distinctive labiate processes described above are preserved as indentations in pyritized specimens, thus forming an impression of the inside of the valve; these are normally only visible in the SEM in pyritized specimens, although they are clearly visible in the LM in non-pyritized 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.

**Occurrence (this work).** Wells 15/28a-3 and 29/25-1, North Sea, Sele and Balder formations; Island of Fur, Denmark, Fur Formation (Fig. 1).

**North Sea range.** Upper Palaeocene–lowermost Eocene (Bettenstaedt *et al.* 1962; Jacqué & Thouvenin 1975; King 1983; Malm *et al.* 1984; Mudge & Copestake 1992).



**Fig. 5.** Pyritized specimens (steinkerns) of *Fenestrella antiqua* (Grunow) Swatman emend., with some non-pyritized specimens for comparison. **(a)** and **(b)** Initial cell, after first cell division; **(c)–(e)** Vegetative cells. **(a)** Pyritized specimen. Oblique valve view. Note thickened girdle, and areas of packed labiate processes (arrows). BP well 15/28a-3, 6410 feet, ?lowermost Eocene. **(b)** Girdle view of **(a)**. Note unequal convexity of valves, the uppermost (auxospore) valve being more highly domed than the lower (vegetative) valve (compare with Fig. 3f). **(c)** Pyritized specimen. Girdle view of normal cell. Ølst, Denmark ('Ølst D'), ?lowermost Eocene. **(d)** and **(e)** Detail of internal expression of packed labiate processes. **(d)** Specimen infilled and replaced by pyrite. Labiate processes form impressions in non-crystalline pyrite, while framboidal pyrite has infilled areolae (top of photograph). BP well 15/28a-3, 6410 feet, ?lowermost Eocene. **(e)** Non-pyritized specimen. Note inwardly-projecting labiate processes. Natural History Museum collections ('Fur Nykøbing'), ?lowermost Eocene.

*Range (literature).* Upper Palaeocene–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' (Chenevrière 1934; see also Ross & Sims 1985).

*Fenestrella antiqua* initial cells  
(Fig. 6a and b)

*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  $\mu\text{m}$  width of cell 300–500  $\mu\text{m}$ .

*Remarks.* A variant of *F. antiqua* commonly found in the volcanoclastic Sele Formation, central and northern North Sea. The unusually thickened girdle is strongly suggestive of an auxospore (see the section on 'Diatom biology and ecology' above), reflecting a period of vegetative reproduction with new, smaller diatom cells forming beneath the protective girdle band. Unpublished data from oil exploration and



**Fig. 6.** Pyritized specimens (steinkerns) of *Fenestrella antiqua* (Grunow) Swatman emend., with some non-pyritized specimens for comparison. (a) and (b) Initial cells (compare with Fig. 3e); (c)–(e) Resting spores (all pyritized). (a) Girdle view. Note highly-rounded valves, merging with multiple girdle bands. Arrows mark valve–girdle junction. BP well 15/28a-3, 6360 feet, ?lowermost Eocene. (b) Oblique valve view. Specimen partially encrusted with overpyrite. BP well 15/28a-3, 6390 feet, ?lowermost Eocene. (c) Note lack of girdle bands, and smooth surface. BP well FC 22, ‘Core 27’, ?uppermost Palaeocene. (d) Valve view. Arrow marks position of packed labiate processes. BP well 15/28a-3, 6370 feet, ?uppermost Palaeocene. (e) 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 feet, ?uppermost Palaeocene.

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 in proprietary zonation schemes. Known under various morphotype numbers in the informal diatom zonations of different companies, for example *Coscinodiscus* sp. 8 (RRI); *Coscinodiscus* N7 (British Petroleum). Informally named *Coscinodiscus barreliformis* by Charnock and others.

**Occurrence (this work).** Wells 15/28a-3 and 29/25-1, North Sea, Sele and Balder formations (Fig. 1).

**North Sea range (unpublished).** Upper Palaeocene (RRI), but Early Eocene based on presumed age of upper Sele Formation used herein (Knox & Holloway 1992).

**Range (literature).** The only published account of pyritized diatom auxospores is from the Middle Eocene of the Beaufort–Mackenzie basin, Canada (McNeil 1990). However, these clearly belong to the genus *Stellarima* as they exhibit labiate processes (‘endocorona’ of McNeil 1990) 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, after first cell division (Fig. 5a and b)

**Description.** A morphological variant of *F. antiqua* characterized 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 recrystallization.

*Dimensions.* Valve diameter 120–280  $\mu\text{m}$ .

*Remarks.* See the section on 'Diatom biology and ecology' above. This form often occurs in association with resting spores of *F. antiqua*.

*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

*Fenestrella antiqua* resting spores  
(Fig. 6c–e)

*Description.* Cells large (120–280  $\mu\text{m}$  in 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 (see the section on 'Diatom biology and ecology' above).

*Occurrence (this work).* BP wells 15/28a-3 and 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 and Balder formations. It is normally referred to as *Coscinodiscus* N6 (British Petroleum), *Coscinodiscus* sp. 7 (RRI), *Coscinodiscus* sp. 15 (GEUS) or *Coscinodiscus* sp. 9 (Halliburton).

*North Sea range.* Mudge & Copestake (1992) refer to the abundance of this morphotype at the top of the Sele Formation in the northern North Sea.

## Conclusions

Diatoms (in this case pyritized forms) are extremely useful biostratigraphic markers, particularly in northwest European Palaeogene sediments which lack calcareous microfossils, such as foraminifera and nannoplankton. However, their present degree of biostratigraphic utility has probably reached a limit due to the lack of understanding of diatom biology and the over-use of so-called 'pragmatic' or 'open' classification schemes. We have attempted to show that an understanding of the biological influences on diatom morphology requires the need for a comprehensive taxonomic revision of the group as it applies to northwest European Palaeogene biostratigraphy. For example, four diatom taxa (including the well-known *Coscinodiscus* sp. 1), previously thought to be distinct both taxonomically and biostratigraphically, are shown to be different life-cycle manifestations of one species, here identified as *Fenestrella antiqua*. The use of scanning electron microscopy is shown to be crucial in the discrimination of some important taxonomically significant features. Understanding of the organisms response to changes in environment, and the natural progression of its morphology through the 'normal' stages in its life-cycle, are shown to have an important bearing on palaeoenvironmental interpretations.

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