Cenozoic foraminiferal and dinoflagellate cyst biostratigraphy of the central North Sea

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ABSTRACT: We present a detailed Cenozoic biostratigraphy for Paleogene bathyal and Neogene neritic strata, north of 55° in the central North Sea, and offshore mid-Norway, using both foraminifera and dinoflagellate cysts. Construction of the zonations was assisted by the quantitative stratigraphic methods RASC and STRATCOR. Eight Paleogene and four Neogene interval zones of benthic and some planktonic foraminifera are defined. These zones involve the average last occurrence of 64 taxa present in a minimum of 7 of 33 wells studied. Eighteen geographically rare, but stratigraphically important foraminifers and dinoflagellate cysts were inserted as "unique events". Thirteen Paleogene dinoflagellate cyst interval and peak zones are defined that are interrelated with the foraminiferal zonation. The Paleocene-Eocene boundary is assigned at the top of dinoflagellate cyst zone T2c (*Apectodinium augustum* LO), immediately above the upper limit of the *Reticulophragmium paupera* Zone. The *Coscinodiscus* Zone and dinoflagellate cyst zone T3A (acme of *Deflandea oebisfeldensis*) are earliest Eocene in age. Uppermost Eocene strata may be largely missing in the central North Sea, as is part or all of the Upper Miocene.

INTRODUCTION

The central North Sea and Haltenbanken wells, north of 55° contain abundant dinoflagellate cysts and agglutinated benthic foraminiferal taxa in Upper Paleocene and Eocene shales. In the deeper, more central part of the basins the agglutinated foraminiferal assemblage also extends into Neogene strata. This so-called "flysch-type" agglutinated assemblage is part of a cosmopolitan benthic fauna that resides on fine-grained, siliciclastic continental slopes, typically in the bathyal bathymetric realm (Gradstein and Berggren 1981). Flysch-type assemblages also extend onto the oceanic basin floors in abyssal water depths. The fauna harbors many taxa that can be used for detailed correlations of strata in siliciclastic basins; the detailed correlations are only now beginning to be fully explored. An inherent problem in exploration-type micropaleontology is relatively poor sample quality, as most samples consist of cuttings rife with cavings. When the problem of cavings is compounded with stratigraphically inconsistent last occurrences of many of the benthic foraminiferal species, and with localized geological reworking, quantitative stratigraphic treatment of the microfossil distribution data is beneficial. Palynology, although more susceptible to reworking because of smaller specimen size, benefits from access to smaller samples of better quality, such as sidewall cores, and higher number of specimens per sampling level. In the Paleogene of the North Sea the dinoflagellate cyst zonation is more detailed than that using foraminifera, hence integration assists to calibrate the benthic foraminiferal zonation.

The combination of qualitative and quantitative stratigraphic techniques makes its easier to integrate zonations based on different microfossil groups in exploration well sites. For this reason we use in addition to subjective analysis Ranking and Scaling (program RASC; Agterberg et al. 1989), and a new method of zonation and correlation called STRATCOR (Gradstein 1990). The result is a detailed Cenozoic microfossil zonation for the Paleogene bathyal and Neogene neritic strata, north of 55°, in the central North Sea, and offshore mid-Norway.

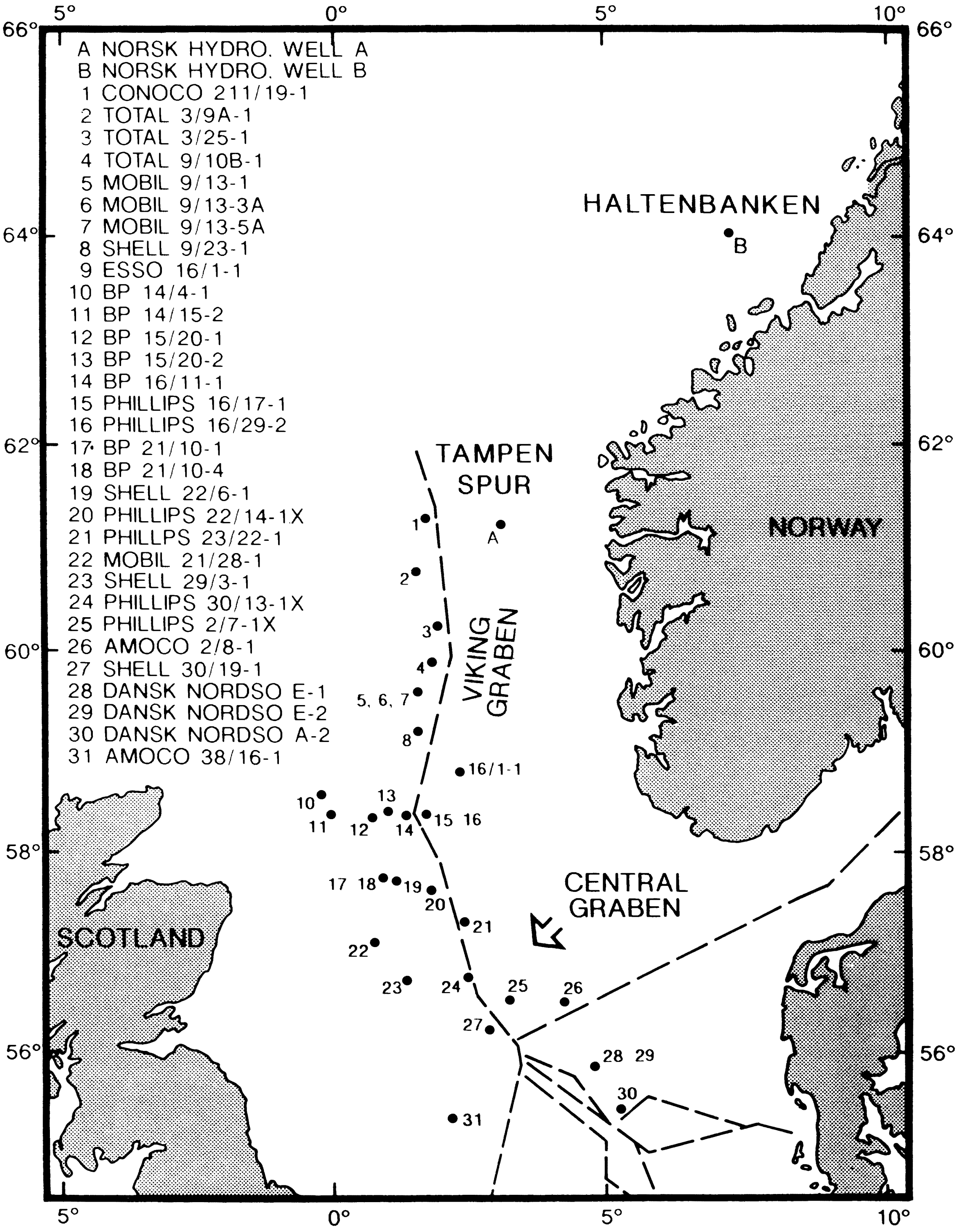
The foraminiferal information stems from our study of 33 hydrocarbon exploration wells (text-fig. 1; table 1). Detailed palynological data is available in three of the same well sites, listed in Appendix 1.

PREVIOUS LITERATURE

The Cenozoic microfossil record of the North Sea Basin has been the subject of several micropaleontologic and palynological studies, although no integrated biostratigraphic zonations were published.

Ioakim (1979) investigated the dinoflagellate cyst succession in the 14 cores from the Esso Norway 16/1-1 well, central North Sea. Nine preliminary assemblage zones were distinguished from Paleocene through Early Miocene, and correlated to Rockall Bank and Labrador Shelf. A more comprehensive dinocyst zonation for the circum-Central Tertiary of the North Sea is that of Costa and Manum (Vinken 1988). Twenty concurrent range zones were proposed, using both appearances and disappearances of taxa in Western Europe, North Sea and Norwegian Sea. The zonation proposed regional correlations of shallow marine Paleocene through Pliocene strata. No database for key wells or sections is provided, which makes comparison to the zonations proposed by us difficult.

A modified dinoflagellate cyst biozonation for latest Paleocene and earliest Eocene sediments form the central North Sea was published by Powell (1988). Four successive zones were proposed: *Paleoperidinium pyrophorum, Alisocysta margarita, Apectodinium augustum* and *Deflandrea oebisfeldensis* acme. The zones are based on 15 first and last occurrence events of 12 taxa. The first downhole appearance of *Apectodinium au-*



TEXT-FIGURE 1
Location of 33 exploration wells, central North Sea and offshore mid Norway, used to calculate the optimum foraminiferal interval zonation. Norwegian offshore wells A (= 34/8-1), B (= 6407/7-1) and 16/1-1 were studied both for foraminifers and dinoflagellates to arrive at first order integration among exploration zonations using these different microfossil groups.

gustum is selected to mark the top of the Paleocene, a close approximation to the base of calcareous nannoplankton Zone NP10 of Martini (1971) (see also Powell 1988).

Manum et al. (1989) studied the palynology of deep-water sediments cored during ODP Leg 104, Norwegian Sea, and compared the dinoflagellate cyst and pollen record to that of

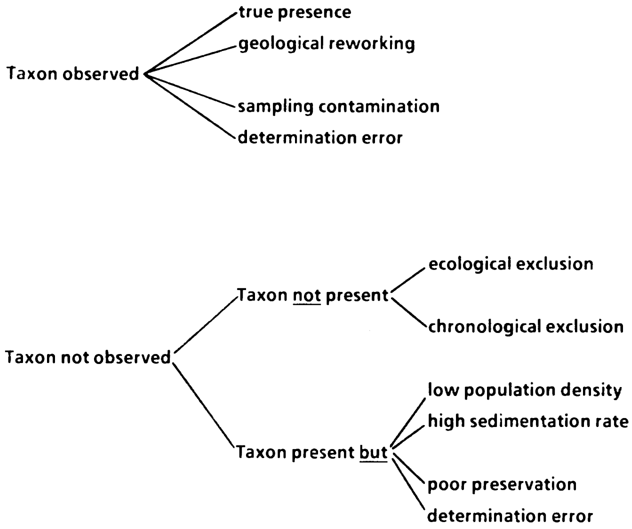
TABLE 1

Central North Sea wells and thickness in meters of Cenozoic interval studied (Pliocene to top Cretaceous). Wells are listed approximately from north to south as shown in Text-figure 1. Wells marked with an asterisk (*) employed coring techniques in addition to cuttings sampling. Cumulative thickness studied is approximately 51,000m, or over 5200 samples.

1	Norsk Hydro	6407/7-1	910-1975
2	Conoco	211/19-1	609-1806
3	Norsk Hydro	34/8-1	1034-2010
4	Total	3/9A-1	1355-2180
5	Total	3/25-1	554-2580
6	Total	9/10B-1	1682-2952
7	Mobil	9/13-1	548-2652
8	Mobil	9/13-3A	301-2694
9	Mobil	9/13-5A	487-2712
10	Shell	9/23-1*	274-2042
11	Esso Norway	16/1-1*	381-2751
12	BP1	4/4-1	280-989
13	BP	14/15-2	509-1931
14	BP	15/20-1	1240-1966
15	BP	15/20-2	870-2343
16	BP	16/11-1	793-2200
17	Phillips	16/17-1	1090-2895
18	Phillips	16/29-2	609-2726
19	BP	21/10-1	1514-2432
20	BP	21/10-4	1217-2808
21	Shell	22/6-1*	451-2494
22	Phillips	22/14-1X	1036-3010
23	Phillips	23/22-1	464-3086
24	Mobil	21/28-1	637-1402
25	Shell	29/3-1*	432-2865
26	Phillips	30/13-1X	160-3079
27	Phillips	2/7-1X	618-2956
28	Amoco	2/8-1	362-2502
29	Shell	30/19-1*	429-3200
30	Danish North Sea	E-1*	1341-2041
31	Danish North Sea	E-2*	1435-1972
32	Danish North Sea	A-2*	1417-1853
33	Amoco	38/16-1	451-1179

TABLE 2

Factors bearing on the quality of the paleontological record observed in well samples.



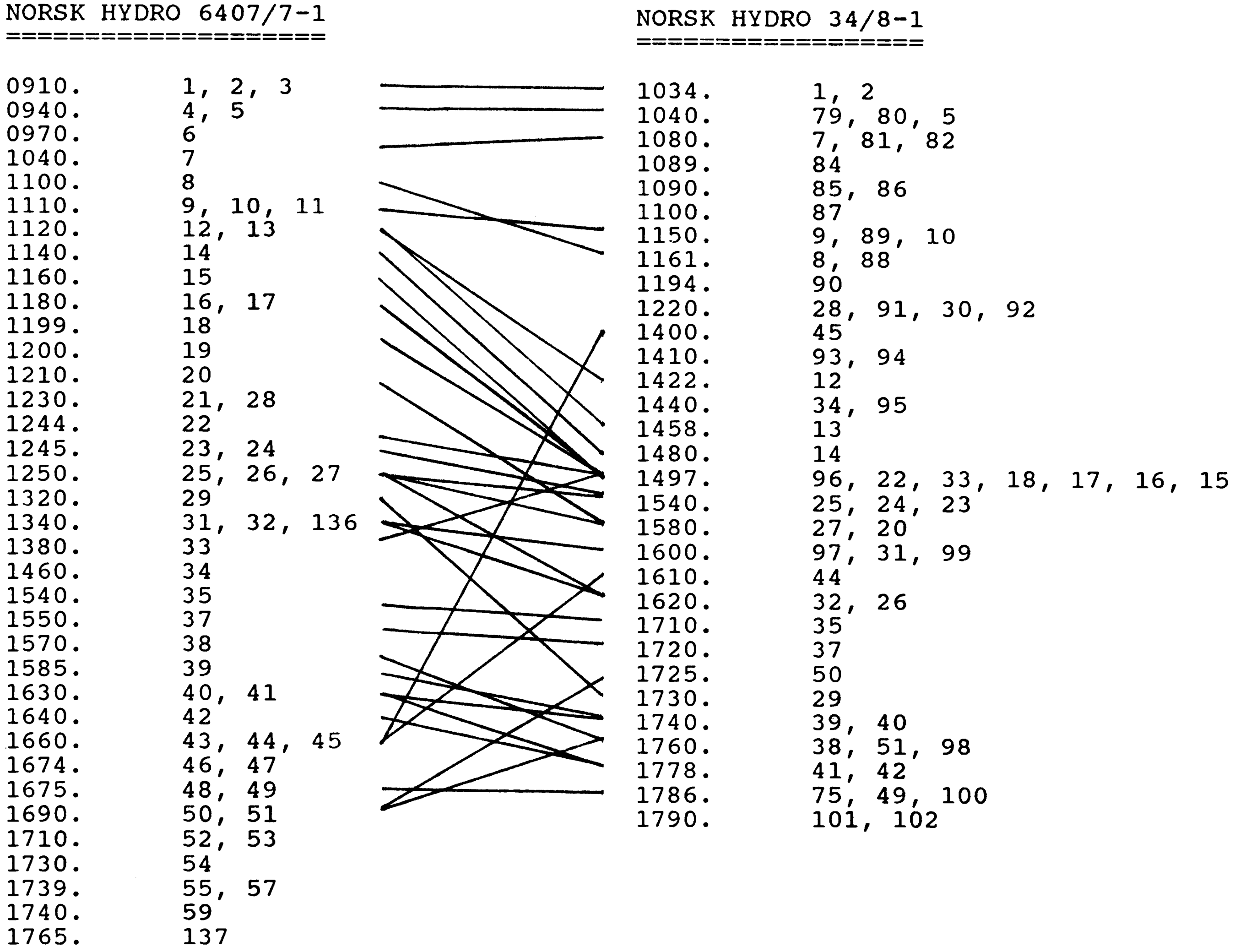
DSDP Leg 38 located in the same region, and the Labrador Shelf. Fifteen successive dinoflagellate cyst assemblage zones were recognized, ranging from early Eocene through late Miocene.

A taxonomic inventory of Cenozoic deep-water agglutinated foraminiferal assemblages from the North Sea and Labrador basins was compiled by Gradstein and Berggren (1981). This study provided a paleoecologic model for so-called "flysch-type" agglutinated foraminiferal assemblages of many petroleum basins. In this model the occurrence of "flysch-type" agglutinants in slope basins and rapidly subsiding siliciclastic troughs is related to somewhat restricted bottom water circulation, leading to oxygen-deficient substrates that may limit the occurrence of normal deeper marine, calcareous benthic taxa and favor instead the development and preservation of agglutinating forms. Subsequent actualistic and fossil-based studies by Schroeder (1986) and Kaminski (1987) led to the realization that diverse agglutinated assemblages are typical for normally oxygenated continental slopes and rises. Low-energy, siliciclastic substrate conditions are important, and the assemblages do tolerate oxygen deficiency. Although a strict paleobathymetric connotation for the flysch-type assemblages should be rejected, it is clear that bathyal or deeper conditions are a prerequisite. Minimum water depth for such assemblages is 200-500m, with many taxa only occurring below 1000m or more.

In the nine years following the publication of the Gradstein and Berggren (1981) study, knowledge of agglutinated foraminiferal taxonomy and geographic and stratigraphic distribution has steadily expanded. Miller et al. (1982) extended the Labrador margin taxonomic database into the abyssal Labrador Sea in their study of samples from DSDP Site 112. The taxonomy and biostratigraphy of the deep Labrador Sea was considerably refined by Kaminski et al. (1989) using continuously-cored samples from Labrador Sea ODP Site 647. Ranges of agglutinating taxa were calibrated to magnetostratigraphy and standard nannofossil zones, thereby providing age constraints to foraminiferal assemblages on the Labrador margin.

Concurrent studies by other workers have provided much needed comparative taxonomic and biostratigraphic data. Verdenius and van Hinte (1983) independently developed a workable taxonomy and paleoecologic model for the Paleogene bathyal to abyssal agglutinated benthic fauna from Leg 38 DSDP sites in the Norwegian-Greenland Sea. The taxonomy of agglutinating foraminifera from ODP Site 643 of Leg 104 in the same region was revised by Kaminski et al. (1989) and Kaminski et al. (in press). In the Alpine-Carpathian region, Morgiel and Olszewska (1981) illustrated and reported the biostratigraphic ranges of many agglutinated taxa, and the study by Geroch and Novak (1984) provided the basis for the first formal Tithonian to Eocene zonation based on agglutinated foraminifera in the Carpathian deep marine basins.

King (1983; see also Gramann and von Daniels in Vinken 1988), in his well-illustrated North Sea biostratigraphy study, concentrated on last occurrences of almost 100 benthic and over 25 planktonic central North Sea foraminifera, including taxa of diatoms and some Miocene *Bolboforma*. Seventeen interval zones use benthic foraminifera and 16 use planktonic taxa. The zonation is largely based on species occurring in the neritic (shelf) to upper bathyal realm. The zonation appears most useful for the circum Central Graben, rather than the deep marine graben itself. It is unfortunate that the author did not provide



NORSK HYDRO 6407/7-1

0910.	1, 2, 3
0940.	4, 5
0970.	6
1040.	7
1100.	8
1110.	9, 10, 11
1120.	12, 13
1140.	14
1160.	15
1180.	16, 17
1199.	18
1200.	19
1210.	20
1230.	21, 28
1244.	22
1245.	23, 24
1250.	25, 26, 27
1320.	29
1340.	31, 32, 136
1380.	33
1460.	34
1540.	35
1550.	37
1570.	38
1585.	39
1630.	40, 41
1640.	42
1660.	43, 44, 45
1674.	46, 47
1675.	48, 49
1690.	50, 51
1710.	52, 53
1730.	54
1739.	55, 57
1740.	59
1765.	137

NORSK HYDRO 34/8-1

1034.	1, 2
1040.	79, 80, 5
1080.	7, 81, 82
1089.	84
1090.	85, 86
1100.	87
1150.	9, 89, 10
1161.	8, 88
1194.	90
1220.	28, 91, 30, 92
1400.	45
1410.	93, 94
1422.	12
1440.	34, 95
1458.	13
1480.	14
1497.	96, 22, 33, 18, 17, 16, 15
1540.	25, 24, 23
1580.	27, 20
1600.	97, 31, 99
1610.	44
1620.	32, 26
1710.	35
1720.	37
1725.	50
1730.	29
1740.	39, 40
1760.	38, 51, 98
1778.	41, 42
1786.	75, 49, 100
1790.	101, 102

TEXT-FIGURE 2
Correlation of stratigraphic events (first, acme or last occurrence events using dinoflagellates and foraminifers), as observed in the upper part of wells 34/8-1 and 6407/7-1. The event correlation shows some mismatch (cross-over) of relative order. This stratigraphic cross-over is common when the range end points and acmes of many taxa in several wells are involved. Quantitative methods are effective in calculating the most likely biostratigraphic zonations and correlations using such "noisy" paleontological data. The left column per well shows sampling depth, the right column shows taxa observed recorded per sample with their unique dictionary number (see Appendix).

access to the original database on which his interpretation was based. Such would make it much easier to relate his zonation to the observed record in the wells studied by us, and facilitate first-order integration with other regional zonations. King (1983) provided the reader with a detailed summary of the interrelation of his zonation with that developed by Doppert (1980) and Doppert and Neele (1983) for The Netherlands, and by a number of different authors for shorter stratigraphic intervals in Denmark, Germany and England. The eleven-fold assemblage zonation developed by Doppert and co-workers for the Cenozoic of The Netherlands uses over 90 species (mostly calcareous benthic taxa) typical of shallow- to deep-neritic environments.

Recently, the second edition appeared of "Stratigraphical Atlas of Fossil Foraminifera" (Jenkins and Murray 1989), in which C. King updates his 1983 zonation for the North Sea. The detailed study offers minor modifications and taxonomic revisions to his 1983 zonation, and adds a zonal scheme based on agglutinated benthic foraminifera. A detailed discussion of the relation to our zonation is in Gradstein et al. (in preparation).

A forerunner of the present study, using RASC on the micropaleontological record in 29 central North Sea wells, was published in 1988 by Gradstein et al. Ten interval zones were proposed, which are being succeeded by the present, more detailed zonation. The taxonomy of six new taxa, and their detailed stratigraphic ranges are presented by Gradstein and Kaminski (1989).

METHODS OF STUDY

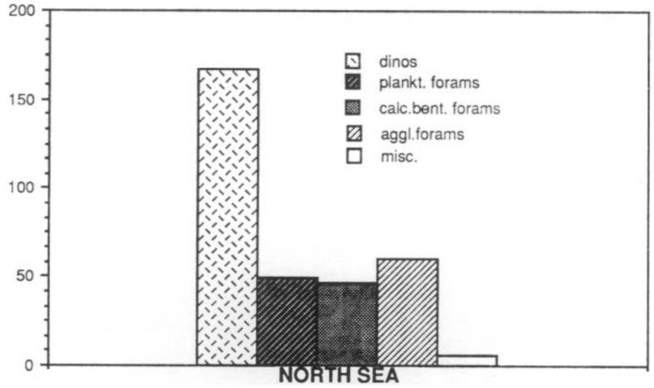
Biostratigraphy involves organizing information on fossil distributions along the "arrow of time" for the purpose of zoning, correlating and dating sedimentary strata. The discipline makes use of continual changes in fossil content through time by detailing the presence and absence of fossils in a number of stratigraphically long sedimentary sections. Often, taxa that can be identified are rare and occur at relatively few sites in a given region. Consequently, threshold values for minimum frequency of occurrence have to be set in most quantitative approaches. The majority of highest and lowest occurrences of species events generally appear to be mutually somewhat inconsistent when several sections in a basin are considered simultaneously (text-fig. 2). This means that events may cross-over from site to site; this cross-over frequency can be easily tabulated for all pairs of events present in a data set. Such inconsistencies are largely due to the great variety in the processes (often unknown), that controlled stratigraphic persistence and preservation of species, sediment mixing after burial of tests, and observer bias (e.g. misidentification) (table 2). Differences in local stratigraphic ranges also play an important role, particularly with agglutinated benthic foraminifera (Gradstein and Agterberg 1982).

Several quantitative techniques have been developed during the past two decades, to eliminate inconsistencies from a regional paleontological data base and provide superior interpretations. For exploration micropaleontology and palynology, among the most useful methods are a highly modified type of "graphic correlation" (STRATCOR) and ranking and scaling (RASC). STRATCOR is a crossplot method that composites successive wells two at a time. It allows calculation of a zonation with data from few wells only, making it suitable for the combined dinocysts and foraminifer record in the three Norwegian wells dealt with in this report. Recent overviews and details on these quantitative biostratigraphic methods may be found in Gradstein et al. (1985), Gradstein (1990), and D'Iorio (1986).

The quantitative biostratigraphic methods are either probabilistic or deterministic. In probabilistic models, as automatically generated with RASC and optional with program STRATCOR, the local inconsistencies in relative position of the end points of ranges (first and last occurrence events) are "explained" as local, random deviations from estimated average event locations. The average first or last occurrences may have an error bar to indicate standard deviations. In deterministic models, as generated with conventional graphic correlation (Edwards 1989) and optional with STRATCOR, the inconsistencies are assumed to be due to missing data and eliminated by filling in data gaps, until a consistent data base is obtained. On the other hand it is quite possible to proceed with this graphic correlation method in a more probabilistic manner.

In a stratigraphic sense, deterministic means that the highest of the last occurrences and the lowest of the first occurrences are sought. This maximizes stratigraphic ranges, rather than averaging them, as advocated in probabilistic techniques. In actual practice there may be little stratigraphic difference between the two approaches, depending on the scatter in the data and the type of fossil group. It is probably true that calcareous planktonics, when present in abundance, show smaller deviations between average and total stratigraphic range in any given area than benthic organisms (see Doeven et al. 1982). Probabilistic techniques are better suited to such noisy data as the stratigraphic distribution of benthic foraminifers in ditch cuttings samples from exploration wells.

During the course of this study, considerable insight was gained in the stratigraphic properties of the Cenozoic microfossil data from the central North Sea. Although it would be quite possible to erect a subjective, qualitative biostratigraphic framework, as advanced, for example by King (1983) for Cenozoic shallower water deposits of the North Sea, we consider it advantageous to utilize quantitative stratigraphic methods as well. In this study we employ RASC to define Cenozoic foraminiferal zones, and use both RASC and STRATCOR to better integrate the detailed Paleogene dinoflagellate cyst and the foraminiferal zonations offshore Norway.



TEXT-FIGURE 3
Bargraphs indicating the number of dinoflagellate taxa, and agglutinated, calcareous benthic and planktonic foraminiferal taxa recorded in the North Sea wells studied. Miscellaneous "taxa" refers to silicious fossil species and physical log markers.

MATERIAL

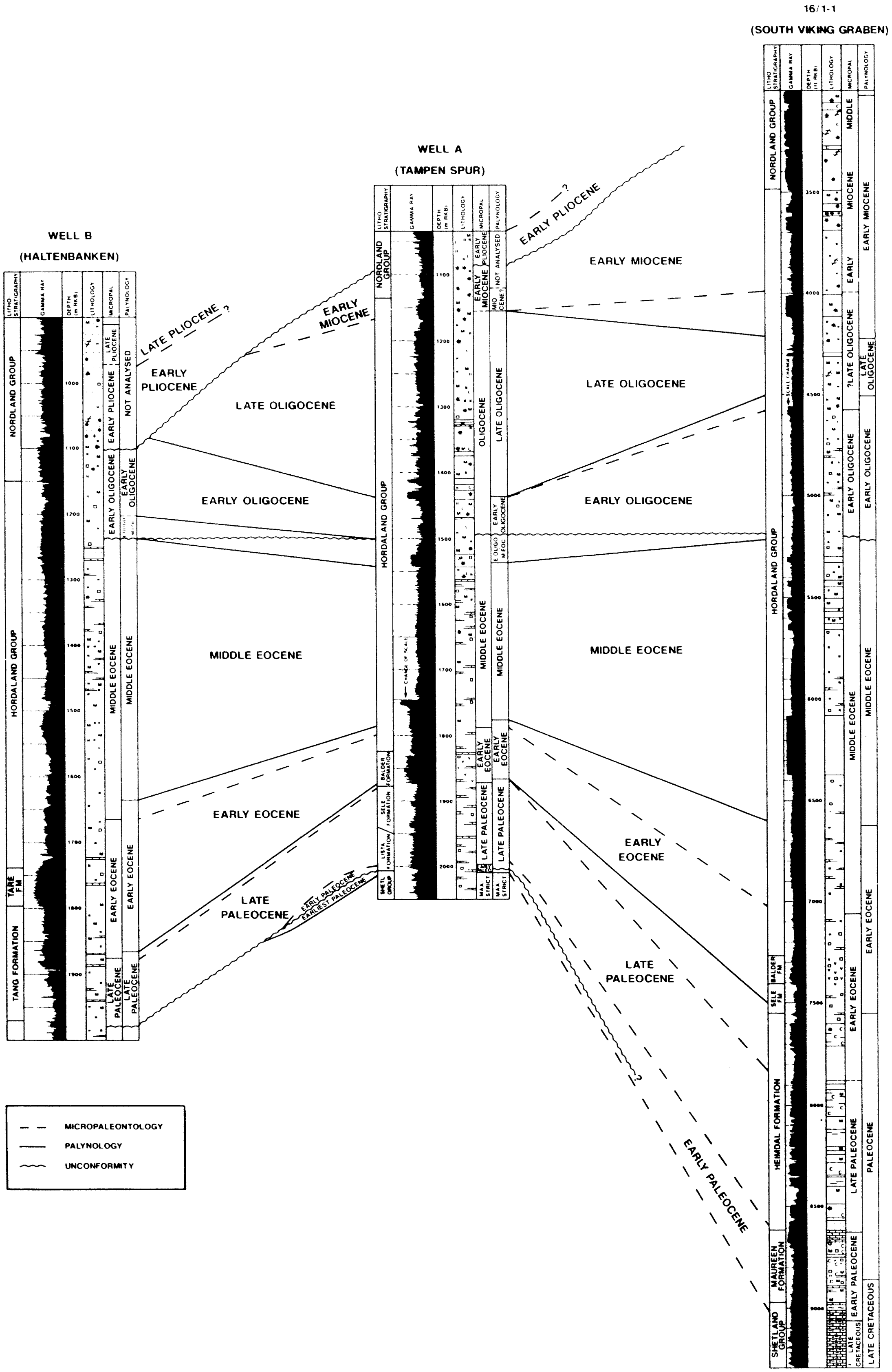
The database for this biostratigraphic study consists of the last occurrences (LO) of over 160 benthonic and planktonic foraminiferal taxa in over 5200 ditch cuttings and several conventional core and sidewall core samples from 33 wells, located in the central North Sea and offshore mid-Norway (text-fig. 1). In addition we studied the first (FO), last common (LCO) and last occurrence (LO) of over 160 dinocyst taxa and spores in sidewall cores and ditch cuttings in two of the same Norwegian offshore wells, 34/8-1 and 6407/7-1, and combined it with the reevaluated, published palynology record in the Esso Norway 16/1-1 well (Ioakim 1979), which has 14 Eocene and Paleocene cores (text-figs. 3-7). A listing of microfossil events used in these three wells is found in Appendix 1. All wells were selected on the basis of representative microfossil coverage of the basins, and the availability of sidewall cores.

The North Sea wells are situated between 55° and 62° North in the Central and Viking Grabens, except for one well on Haltenbanken at 64° North. Thus the region spans mid to high latitudes. Table 1 shows which interval in each well was studied, from the base of surface casing to the base of Cenozoic (except in the Danish North Sea wells, where only the Paleogene record was obtained). Depths are listed in meters in table 1.

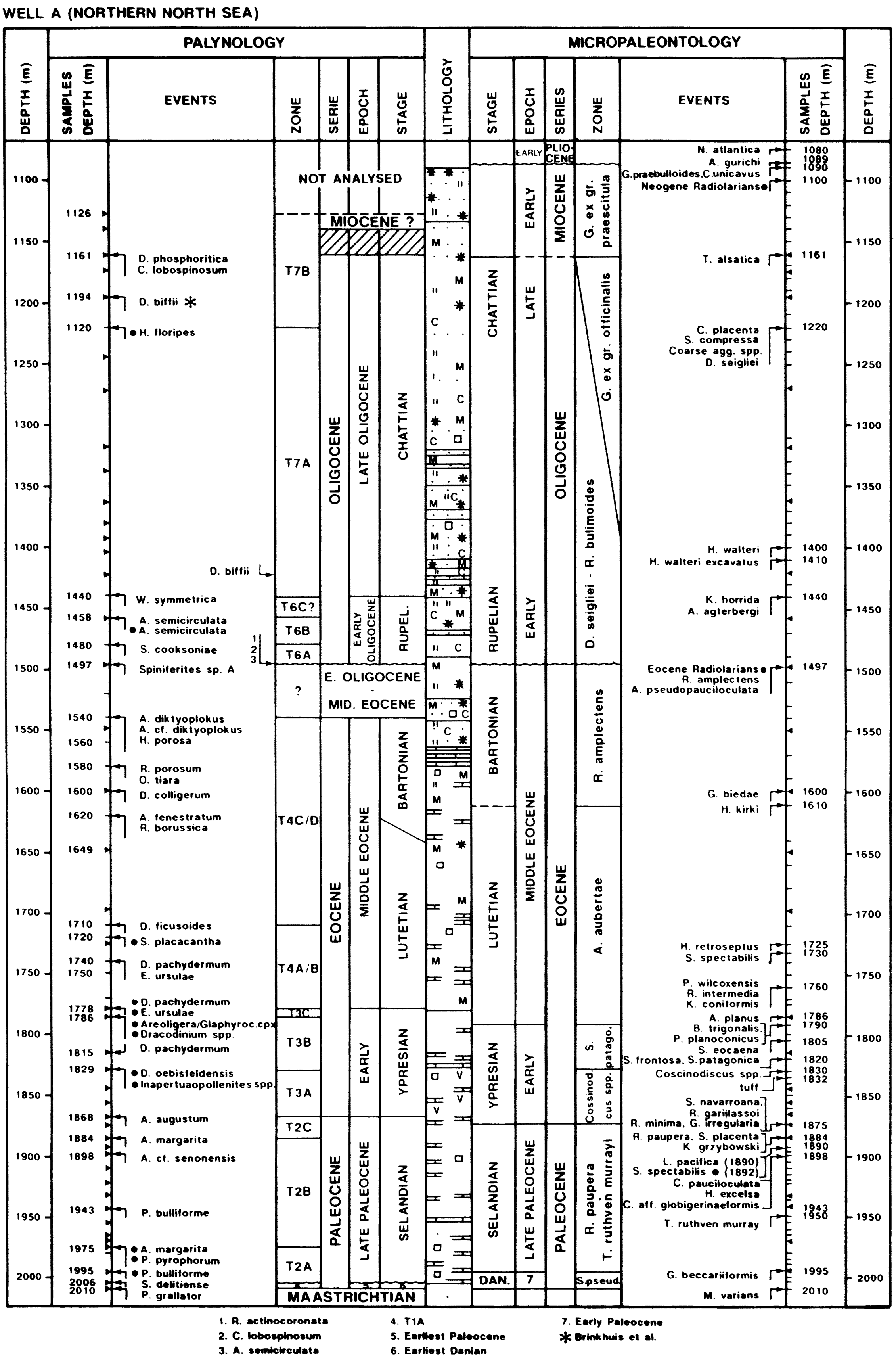
We used dictionary numbers for the stratigraphic events and three simple rules to prepare the census data. The rules are:

1) a local identification with the qualifier aff. (affinis) is the same as the nominate taxon;

2) a local identification with the qualifier cf. (confer) for a regular dictionary taxon has not been taken into account, or is a different taxon, e.g. *Areoligera* cf. *senoniensis;*



TEXT-FIGURE 4
Chronostratigraphic correlation of Central Graben well 16/1-1, Viking Graben well A (=34/8-1) and Haltenbanken well B (= 6407/7-1), offshore Norway using the dinoflagellate and foraminiferal zonations proposed in this study. There is good agreement between fossil disciplines for the relative age intervals assigned in the wells; minor deviations in the Eocene are shown as the offset between solid and dashed correlation lines. The Neogene record is highly incomplete on Haltenbanken, with Miocene strata missing. The gamma log patterns are shown in reverse contrast, and although the 6407/7-1 well has no visible (Eocene) volcanic tuff, its interval corresponding to tuffs in the other wells also displays the characteristic gamma pattern. For legend see text-figure 5a.



TEXT-FIGURE 5
Stratigraphic column with distribution of dinoflagellates and foraminifers in Norsk Hydro well A (= 34/8-1), northern Viking Graben, northern North Sea. For legend see text-figure 5a.

3) obviously reworked, or for other reasons (e.g. cavings) badly misplaced highest occurrences of taxa have gradually been eliminated, either from initial observation or through normality testing (Gradstein et al. 1985). Such outliers may be apparent from anomalous, poor preservation of tests relative to the rest of an assemblage at that particular depth, and from erratic stratigraphic positions, easily detected in the RASC results.

THE CENOZOIC MICROPALEONTOLOGICAL ZONATION

In this section we propose a detailed micropaleontological zonation for the Viking and Central Grabens, North Sea, extending to the Haltenbanken area, offshore mid-Norway. Using both the RASC and STRATCOR method we analyzed the Cenozoic foraminiferal record in 33 wells to derive the optimum zonation. This record includes 60 agglutinating, 46 calcareous benthic, and 49 planktonic foraminiferal taxa; in addition there also are 6 *Bolboforma* and diatom/radiolarian events, and 6 physical events that represent regional log markers. In all there are 167 dictionary entries (text-fig. 3), with over 1200 mostly last occurrences in the well sites. The majority of taxa occur in few wells only; in fact, the cumulative frequency distribution of the events indicates that over half of the taxa occur in fewer than 5 wells, and 30% in less than 9 wells. Last occurrence events of the following taxa were observed in more than 20 wells:

Reticulophragmium amplectens
R. paupera
Coarse agglutinated foraminifera assemblage
Spiroplectammina spectabilis
Subbotina pseudobulloides
Haplophragmoides walteri
Karreriella conversa

The RASC computer program used to calculate the optimum (average) interval zonation(s) and test stratigraphic normality of the individual well record relative to the calculated standard, performed with thresholds kc = 5 through 10, mc1 = 1 and mc2 = 4 through 8. Kc represents the minimum number of wells in which each event must occur to be ranked, mc1 the number of wells in which each pair of events in the ranked optimum sequence must occur, and mc2 the minimum number of wells in which each pair of events in the scaled optimum sequence occurs. RASC runs are designated by their kc/mc1/mc2 thresholds, e.g. a 7/1/5 run means that kc = 7 , mc1 = 1 and mc2 = 5 (Gradstein et al. 1985). In all, over 100 RASC runs were executed, with a varying number of wells to also evaluate sub-zonations in part of the regions. The dendrograms that display the interfossil distances between the stratigraphically ranked taxa are quite stable when RASC runs with different threshold parameters and different numbers of wells were used. In all cases approximately the same zones were recognized. The final scaled optimum sequence selected to represent the probabilistic interval zonation for the North Sea has optimum separation of stratigraphically successive dendrogram clusters, and is shown in text-figure 8.

Normality testing of the individual sequences in the 33 wells, relative to various scaled optimum sequences led to re-examination of scores of tops that turned out to have been placed too low or too high. It is beyond the scope of this paper to provide a listing of emendations that systematically "cleaned" the large file of more obvious outliers (Gradstein et al., in preparation). It should be stressed that this normality testing of individual well sections, during which numerous taxonomic and stratigraphic changes and additions were executed, is a highly valuable feature of the RASC program. As a result, wells were examined more than once to ascertain consistent assignments of as many taxa as possible.

Based on our analysis it appears reasonable to represent both the Viking and Central Grabens with one Cenozoic interval zonation. This central North Sea zonation, which is shown in text-figure 8 (left side) is a 7/1/5 run, retaining 64 events, that represent 544 occurrences in 33 wells. The zonation includes the relative stratigraphic position of physical North Sea (NS) log markers B through G, which will be discussed in more detail later.

Eighteen other microfossil taxa, including 9 dinoflagellate cysts, in the zonation occur in fewer than 7 wells. Their stratigraphic last occurrences were inserted as so-called unique events (Gradstein et al. 1985) in the probabilistic interval zonation. In this manner their occurrence contributes to chronostratigraphic calibration of the interval zones. Unique events occur in less than the threshold number of wells. Following scaling, the program evaluates the stratigraphic position of events marked as unique ones in the few wells where they occur relative to those neighboring taxa that occur in the scaled optimum sequence. It then prints the unique taxa between these locally neighboring taxa in the final scaled optimum sequence. The unique or special events for the present North Sea interval zonation are from youngest to oldest:

Bolboforma metzmacheri (2 wells)
Uvigerina semiornata kusteri (4 wells)
Chiropteridium lobospinosum (3 wells)
Globigerina ex gr. *officinalis* (5 wells)
Deflandrea phosphoritica (2 wells)
Aschemonella grandis (4 wells)
Areoligera semicirculata (2 wells)
Adercotryma agterbergi (5 wells)
Heteraulacysta porosa (2 wells)
Globigerapsis index (5 wells)
Areosphaeridium diktyoplokus (3 wells)
Eatonicysta ursulae LCO (3 wells)
Acarinina pentacamerata (4 wells)
Turrilina robertsi (4 wells)
Acarinina pseudotopilensis (4 wells)
Deflandrea oebisfeldensis LCO (2 wells)
Apectodinium augustum (2 wells)
Alisocysta margarita LCO (2 wells)

Unique events are used in part to highlight the approximate stratigraphic position of rare taxa of potential value for regional correlation, and also to calibrate the scale in relative time with well known events, like the *Apectodinium, Deflandrea, Acarinina, Globigerapsis,* and *Globigerina* taxa listed. We will return to the calibrations when discussing the North Sea interval zonation.

The combined foraminiferal and palynological record in the Norwegian wells 16/1-1 (Central Graben), 34/8-1 (Viking Graben), and 6407/7-1 (Haltenbanken) (tezt-figs. 4-7) was also studied by means of the STRATCOR method. The total data file in these 3 wells includes 189 events, based on 137 taxa. Only taxa that occurred in 2 or more of the 3 wells were included in the STRATCOR zonation, with the following exceptions:

Areoligera semicirculata
Distatodinium biffii
Catapsydrax unicavus
Homotryblium floripes LCO
Haplophragmoides walteri excavatus

Planorotalites planoconicus
P. compressus
Rzehakina minima
Globoconusa daubjergensis

The stratigraphically low occurrences in well 34/8-1 of *Haplophragmoides walteri* and *Spiroplectammina navarroana* were assigned low weight in the calculation of the zonation. Two cycles of compositing were executed in STRATCOR, with little difference between the composite standard in rounds 1 and 2. The final composite standard calculated by STRATCOR includes 87 taxa and is printed on the right side of text-figure 8. It ties directly to the RASC sequence, with good concordance of order of events.

Below we propose twelve central North Sea interval zones, based on the average last occurrence of over 60 foraminiferal taxa, 9 physical log markers (B-G), diatoms and *Bolboforma* events, and first, last common and last occurrence of over 38 stratigraphically important dinoflagellate cysts and pollen. The interval zones are defined on the average last occurrence of the stratigraphically successive taxa in the relatively tight dendrogram clusters in text-figure 8 (left). Some last occurrence events were inserted in the zones from direct ties to the STRATCOR based composite standard (text-fig. 8, right). Because this is a probabilistic interval zonation, and not a deterministic one, no rigid definitions for the zonal upper and lower limits are provided. These limits are graphically visualized in the dendrogram of text-figure 8. We could have formulated the zonal definitions in RASC inter-event distances (cf. D'Iorio 1986), with standard deviations attached, but we have opted for a less formal approach, using instead the fossil events in the RASC groupings that form the body of the zones. It is our opinion that the content of a zone is more important than its upper and lower limits. The interval zones are listed from oldest to youngest, with average last occurrence of taxa within each zone also listed in that order. The zonation, as explained earlier, is relatively robust; it does not aim at maximum stratigraphic resolution, but at regionally widespread and ease of zonal recognition in North Sea wells. In text-figure 9 is a conventional stratigraphic range chart of principal foraminiferal and dinoflagellate cyst marker taxa, using the average (solid lines) and total (dashed lines) ranges based on the combined quantitative and qualitative observations. The North Sea dinoflagellate cyst T zonation, to which the foraminiferal zonation is directly correlated (table 3), is explained in more detail in the next section.

Subbotina pseudobulloides Zone

Age: Danian (Zones P1-P2), Early Paleocene

Corresponding Dinoflagellate Zones: T1A and B

Taxa: The following taxa or log events have their last occurrence in this zone: *Gavelinella beccariiformis, Planorotalites compressus, Subbotina triloculinoides, Matanzia varians, Subbotina pseudobulloides,* North Sea Log marker B, *Hormosina ovulum* (rare). *Globoconusa daubjergensis* and *Spongodinium delitiense* were observed in the lower part of the zone, and *Alisocysta reticulata* ranges upward in it.

Discussion: The *S. pseudobulloides* Zone probably largely coincides with the regional distribution of the carbonate bearing Ekofisk Formation. In a few wells, like Esso Norway 16/1-1 at 2740m, the basal part of the zone contains abundant small globigerinids, including *Globoconusa daubjergensis,* which indicates Zone P1. *Dorothia oxycona, Arenobulimina* sp., including *A. dorbignyi, Clavulinoides globulifera* and *Bolivinoides spectabilis* also disappear in this zone. Frequent reworking of Ekofisk sediment in the overlying terrigenous clastics obscures precise delineation of the top of the *S. pseudobulloides* Zone, and in one or two cases we included isolated specimens of *Morozovella* aff. *angulata* of Zone P3 in the *S. pseudobulloides* Zone. The Maestrichtian strata underlying the *S. pseudobulloides* Zone in most wells are readily identifiable from the highest occurrence of globotruncaniids, incl. *G. contusa,* and *Abathomphalus mayaroensis, Globotruncanella havanensis, Pseudotextularia, Globigerinelloides, Heterohelix* and *Rugoglobigerina.* The palynological top for the Maestrichtian is based on the highest occurrence of *Palynodinium grallator.*

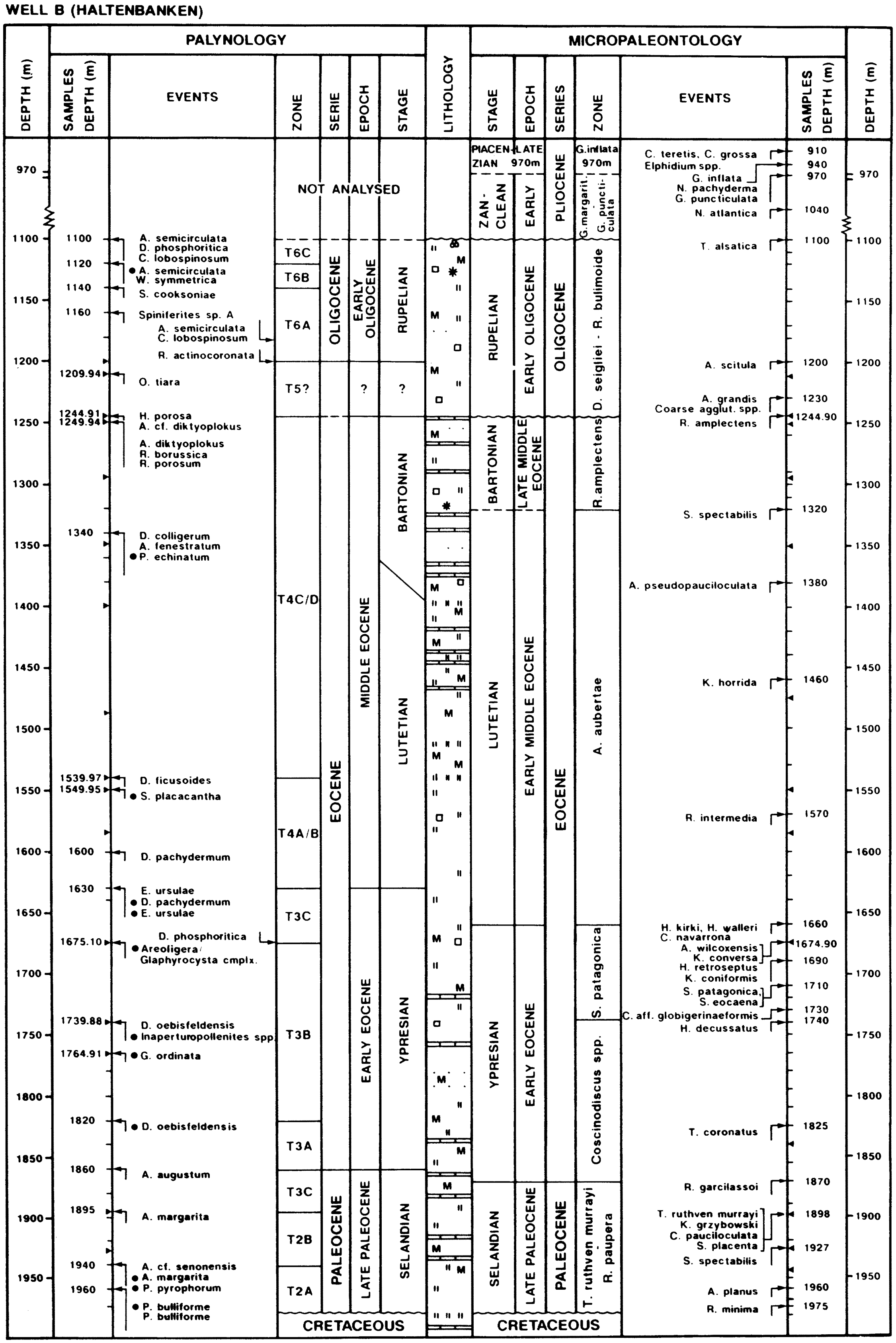
The Danian *S. pseudobulloides* Zone corresponds to King's (1983) zone of the same name and age. *Gavelinella beccariiformis* has been reported from sediments as young as Zone P5 (Tjalsma and Lohmann 1983). The report agrees with its disappearance along the Canadian Atlantic margin together with *Aragonia velascoensis,* just below the appearance of the genus *Pseudohastigerina* (post P5) (Gradstein et al. 1985, p. 346). In the central North Sea the average disappearance of *G. beccariiformis* is approximately 5 m.y. earlier than in the Atlantic Ocean, and may relate to the change near the end of Danian time from predominantly carbonates of the Ekofisk Formation into overlying terrigenous clastic sediments of the Maureen, Andrew and Forties Formations.

In the northern Viking Graben well 211/19-1, a diversified Maestrichtian planktonic fauna below 1782m (5880') is followed by a few meters of probably Danian clayey and limestone sediment with *Subbotina pseudobulloides,* abruptly overlain by shales locally rich in agglutinated foraminifera. In most wells studied, Danian strata are chalky, with rare sand or shale interbeds, which may contain agglutinated foraminiferal assemblages.

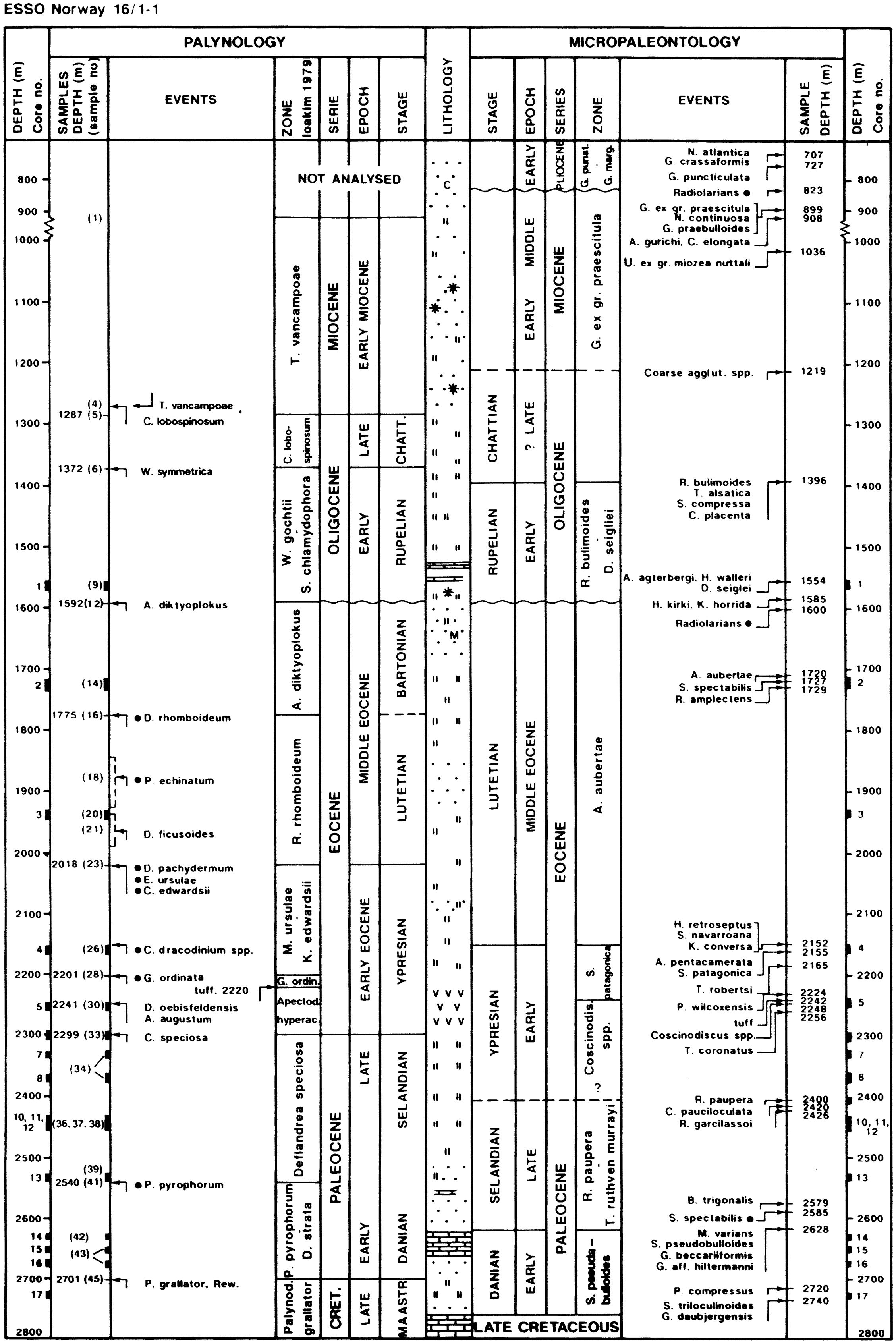
In Esso Norway 16/1-1 (text-fig. 7), the interval of about 2760-2600m, including cores 17 through 14, is Danian in age; here the basal Paleocene beds with *Globoconusa daubjergensis* (P1) at 2760-2677m contain reworked Maestrichtian, Jurassic and Triassic dinoflagellate cysts, assigned by Ioakim (1979) to the Maastrichtian zone of *Palynodinium grallator.* The overlying Danian-lower Selandian dinoflagellate cyst zone of *Cerodinium striatum-Palaeoperidinium pyrophorum* at 2658-2496m corresponds to our Danian zone of *S. pseudobulloides* (P1-P2) and the lowermost part of our overlying Selandian, Late Paleocene zone. The Danian microfossil slides contain reworked Upper Cretaceous carbonate fragments with Maestrichtian *Inoceramus* and globotruncaniids (found as high as core 14).

In Viking Graben well 34/8-1 (text-fig. 5) and Haltenbanken well 6407/7-1 (text-fig. 6), *Palynodinium grallator,* the last occurrence (LO) of which defines the base of North Sea dinoflagellate cyst zone T1A (table 3), occurs at the base of the *S. pseudobulloides* Zone of Danian age. The last occurrence of *Spongodinium delitiense,* which defines the top of North Sea zone T1A, is within the lower part of the *S. pseudobulloides* Zone.

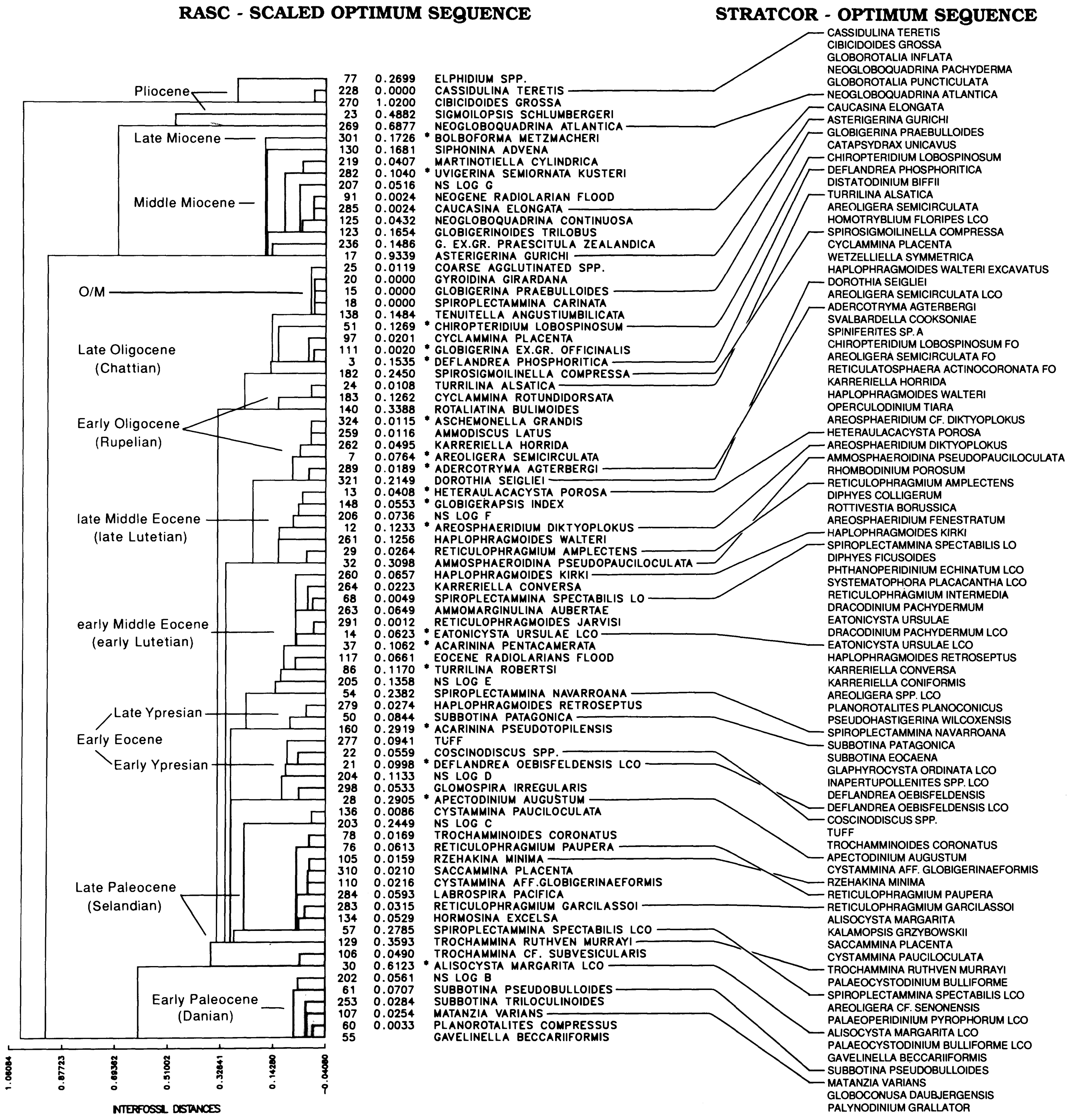
In southern Central Graben well 30/19-1 the lower Paleocene (Danian and slightly younger strata ?) is recovered in cores 2 through 8 at 3050-3128m, which contain a melange of chalks of Maestrichtian and Danian age, and sands and dark shales, referred to the Maureen Formation. The shales contain rather



TEXT-FIGURE 6
Stratigraphic column with distribution of dinoflagellates and foraminifers in Norsk Hydro well B (= 6407/7-1), Haltenbanken, offshore mid Norway. For legend see text-figure 5a.



TEXT-FIGURE 7
Stratigraphic column with distribution of foraminifers and dinoflagellates in the Esso Norway 16/1-1 well, Central Graben, southern North Sea. For legend see text-figure 5a.

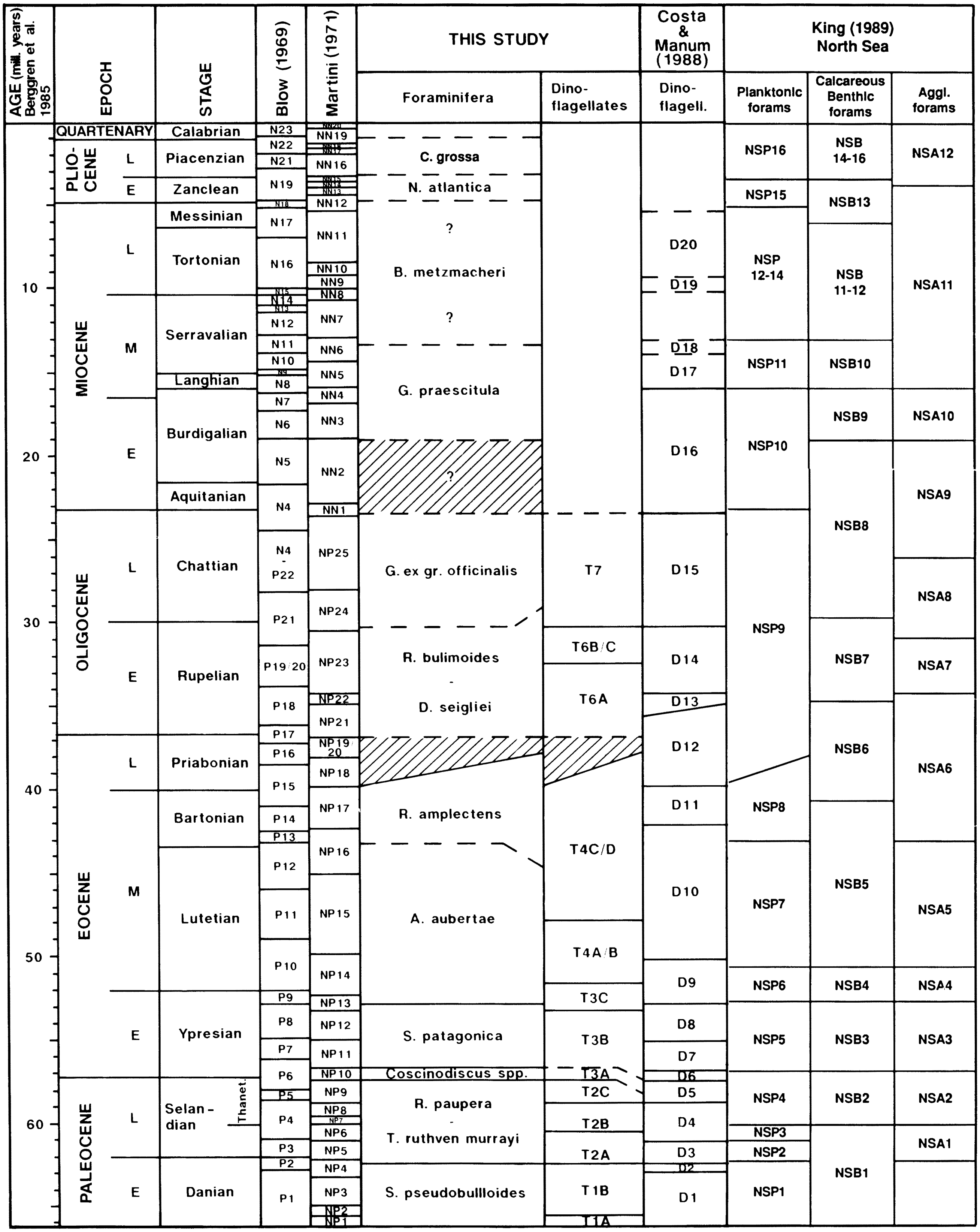


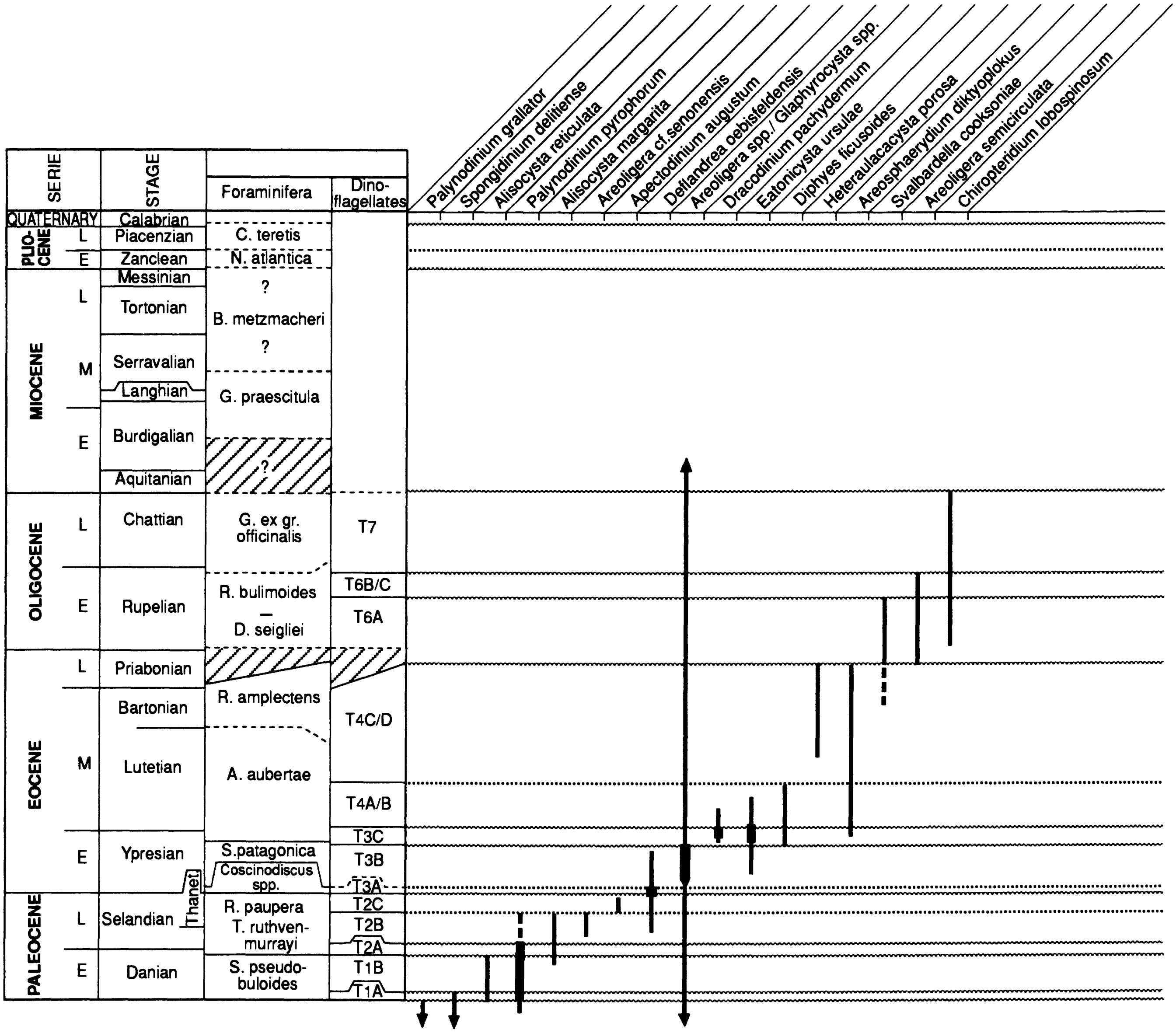
TEXT-FIGURE 8

(left) Cenozoic interval zonation for the North Sea, showing the average last occurrence of 82 foraminifers, selected dinoflagellates, miscellaneous microfossils and physical log markers B-G. Each zonal event occurs in a minimum of 7 out of 33 wells examined, except for 18 unique (rare) events shown with *. Dendrogram values along the y-axis are distances between events in relative time; scaling is stratigraphically downward, in line with the routine study of wells. The generalized 11 fold zonation, Danian through Pliocene in age, is representative for the regional Tertiary stratigraphy (see text); a shading pattern enhances the stratigraphically most useful part of the dendrograms, with zonal nominators shown in bold. Relatively large interfossil distances in the mid Paleocene, at the Paleocene/Eocene boundary and the Oligocene/Miocene correspond to major stratigraphic facies changes, with relatively large turnover of assemblages.

(right) Cenozoic composite standard based on stratigraphic ranking of the detailed dinoflagellate cyst and foraminiferal record in offshore Norwegian wells 34/8-1, 6407/7-1 and 16/1-1, using program STRATCOR. The STRATCOR and RASC zonations correlate well, and reshuffling of event positions is minor and within zones.

TABLE 3
Approximate interrelation among standard interregional zonations using planktonic foraminifers and nannofossils (after Berggren et al. 1985a, 1985b; Aubry et al. 1988), our RASC interval zonation using foraminifers and dinoflagellates for the central North Sea and Viking Graben, our interval (T) zonation in the North Sea wells using dinoflagellate cysts only, and the central North Sea zonation by King (1983), mainly using circum Central Graben foraminifers and the North Sea dinoflagellate cyst zonation of Costa and Manum (in Vinken 1988).





TEXT-FIGURE 9a
Stratigraphic range charts of selected Tertiary foraminifers and Paleogene dinoflagellate cysts for the central North Sea and Haltenbanken. Note: *C. teretis* Zone is noe *C.* (*Cibicidoides*) *grossa* Zone

monotypic and coarsely grained agglutinated assemblages, with *Trochamminoides coronatus*, *Rhabdammina/Bathysiphon*, *Ammodiscus cretaceus* and *Spiroplectammina spectabilis*. The monotypic nature of the assemblages and the unusually coarse-grained tests indicate resedimentation from upper slope settings. Some core samples with largely tubular or disk shaped taxa may have experienced hydrodynamic sorting during deposition of these olistostrome like Danian deposits. The melange testifies to tectonic collapse of the Upper Cretaceous-lower Danian chalk platform.

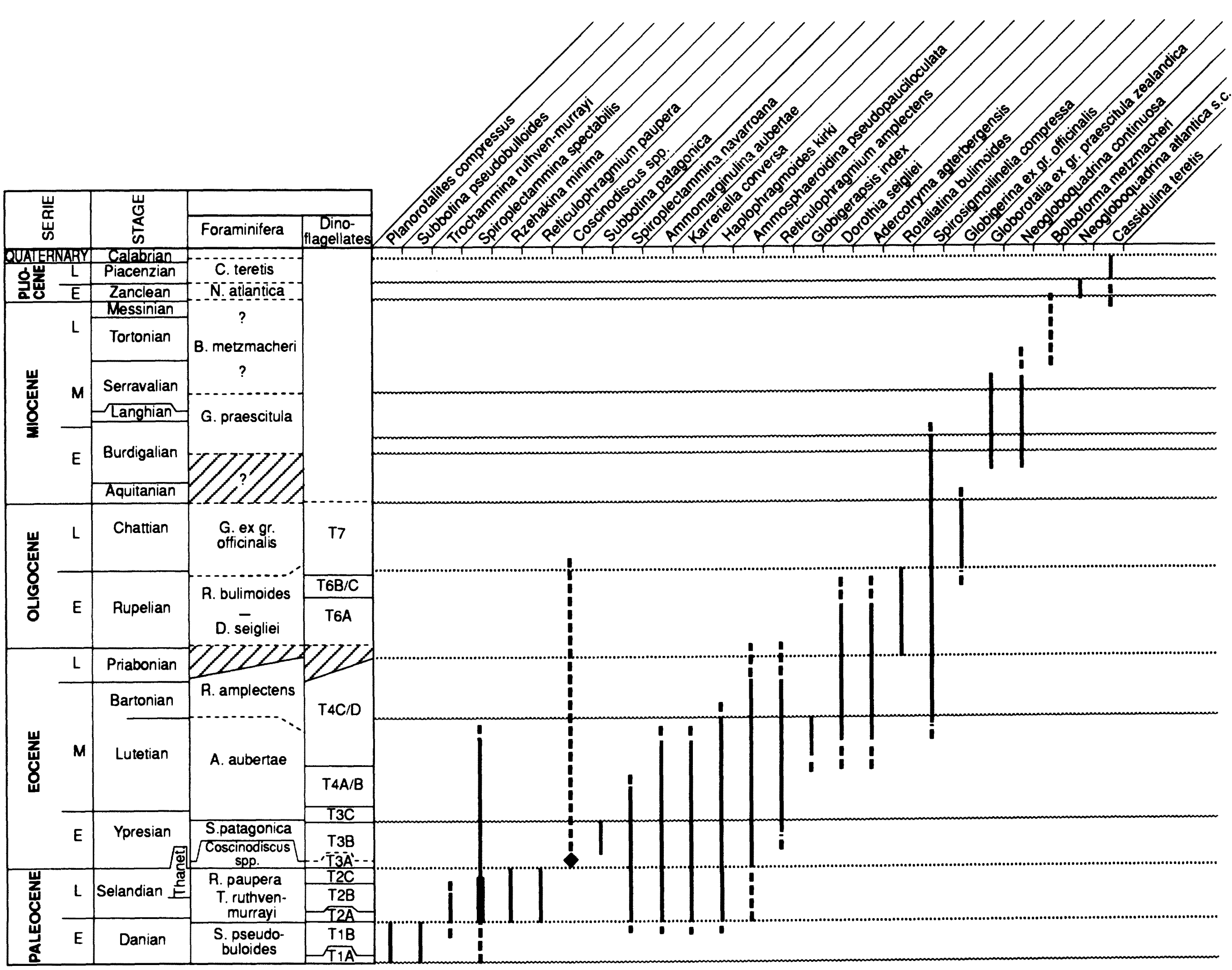
Trochammina ruthven murrayi-Reticulophragmium paupera Zone

Age: Selandian, Late Paleocene

Corresponding Dinoflagellate Zones: T2A, B and C.

Taxa: The following taxa or physical events have their last occurrence in this zone: *Palaeocystodinium bulliforme* LCO, *Alisocysta margarita* LCO, *Palaeoperidinium pyrophorum* LCO, *Areoligera* cf. *senonensis*, *Trochammina* cf. *subvesicularis*, *T. ruthven murrayi*, *Spiroplectammina spectabilis* LCO, *Palaeocystodinium bulliforme*, *Labrospira pacifica*, *Hormosina excelsa*, *Reticulophragmium garcilassoi*, *Cystammina* aff. *globigerinaeformis*, *Saccamina placenta*, *Kalamopsis grzybowskii*, *Alisocysta margarita*, *Reticulophragmium paupera*, *Rzehakina minima*, *Trochamminoides coronatus* (may also be found in the overlying zone), North Sea Log marker C (base Sele Formation) and *Cystammina pauciloculata*. *Apectodinium augustum* occurs immediately above this zone in the RASC sequence.

Discussion: This zone is easily recognized in the North Sea wells. It corresponds to the Maureen, Andrew and Forties



TEXT-FIGURE 9b
Stratigraphic range charts of selected Tertiary foraminifers and Paleogene dinoflagellate cysts for the central North Sea and Haltenbanken.

Formations in the Central Graben and the extremely fine grained Lista Formation in the Viking Graben. The zone is composed exclusively of agglutinated benthic foraminifera, which frequently occur in abundance, and particularly in the Lista Formation are greenish in color, relatively small (deep marine) and with a smooth test. Its taxa group tightly in the zonation, reflecting considerable scatter in their relative last occurrences in the wells. This is also apparent from minor reshuffling of relative stratigraphic positions of taxa in the upper and lower part of the zone, when comparing the RASC and STRATCOR zonations.

Some other, less common taxa that have their last occurrence in this zone include *Ammodiscus planus, Glomospira diffundens* and *Hyperammina rugosa, Hormosina excelsa, Kalamopsis grzybowskii* and *Cribrostomoides trinitatensis* range through this zone, but are only infrequently found higher in the (Eocene) well sections studied. *Spiroplectammina spectabilis* ranges into the Eocene of the wells studied, but its last common occurrence (labelled LCO) is confined to this zone. The overlap in occurrence of *Rzehakina minima, Labrospira pacifica* and primitive cyclamminids, is typical of the lower Lizard Springs Formation in Trinidad of P1 through P4 age (Kaminski et al. 1988). Primitive cyclamminids, at least two of which occur in the Paleocene of the North Sea, *R. paupera* and *R. garcilassoi,* and a third one, *R. intermedia* (a forerunner of *R. amplectens*) which extends in Eocene strata, are also known from upper Paleocene to lower Eocene of Australia (Ludbrook 1979) and Tunisia (F. M. Gradstein, unpublished). In Trinidad, the earliest cyclamminids are post P1c in age, which appears to agree with the central North Sea record.

Although the exact last occurrence of the zonal taxa shows considerable scatter in the North Sea Paleocene, the average last occurrence of *T.* cf. *subvesicularis, T. ruthven murrayi* and *R. garcilassoi* is slightly above the Danian zone with planktonic foraminifers. In several wells, e. g. 30/19-1, 16/11-1, 3/25-1 and 3/9A-1, the taxa disappear at or below the highest occurrence of Danian planktonics. In a few other wells, particularly 9/23-1, the taxa in this zone disappear closely below tuffs of the Balder Formation in the upper part of the *R. paupera* zone, which agrees with the fact that in the Lizards Spring Formation of Trinidad, both *T. ruthven murrayi* and *R. garcilassoi* range into Zones P5 and P6a, at the top of Paleocene (Kaminski et al. 1988).

The *T. ruthven murrayi-R. paupera* Zone probably equates with part or all of King's zone NSP2 (large radiolaria), NSP3 (unnamed), and subzone NSB1b (*Spiroplectammina spectabilis*). In the Esso Norway 16/1-1 well, Ioakim (1979) reported the Selandian *Deflandrea* (*Cerodinium*) *speciosum* Zone from approximately 2540 to 2300m, which overlaps with our zone that extends from approximately 2628-2409m (2307m using quantitative interpolations of zonal boundaries).

In Viking Graben well 34/8-1 and Haltenbanken well 6407/7-1, the dinoflagellate cysts *Palaeocystodinium bulliforme, Palaeoperidinium pyrophorum* LCO, *Areoligera* cf. *senonensis* and *Alisocysta margarita* disappear in the lower or middle part of our zone (text-fig. 8). According to Powell (1988) the taxa approximately disappear in nannofossil zones NP6-8, middle Selandian. Their last occurrence levels define North Sea zone T2 (table 3). The last occurrence of *Apectodinium augustum,* which defines North Sea (sub) zone T2C, is positioned at the base of the overlying *Coscinodiscus* Zone, immediately above the *T. ruthven murrayi-R. paupera* Zone. This is in good agreement with its use as marker event for the top of the Selandian or Thanetian stages, at the Paleocene-Eocene boundary (Powell 1988).

Coscinodiscus spp. *Zone*

Age: Earliest Eocene (early Ypresian)

Corresponding Dinoflagellate Zone: T3A

Taxa: The following taxa or physical events have their last occurrence in, or at the base of, this zone: *Apectodinium augustum, Glomospira irregularis, Trochamminoides coronatus,* North Sea log marker D (top Sele Formation), *Coscinodiscus* spp., *Deflandrea oebisfeldensis* LCO and LO, *Inapertupollenites* spp., "Tuff".

Discussion: The *Coscinodiscus* Zone is characterized by predominance in the well samples of large, pillbox-shaped pyritized diatoms and indications of volcanic ash ("tuff"). This volcanic ash manifests itself on the test of agglutinating benthic foraminifera, directly in the sediments, and on the physical well logs. Similar diatoms also occur in younger strata in the wells examined, but not so commonly and consistently and with such a relatively large size of tests. There are various indicators for the younger tuff series (pyroclastic phase 2) in the North Sea wells, assigned to the Sele and Balder formations (Knox and Morton 1983). From a microfossil point of view the predominance of the large, pyritized *Coscinodiscus* is often accompanied by a characteristic preservation of agglutinated foraminifera using vitric (volcaniclastic) sand to silt size particles for test building. The tests also show a characteristic flattening (collapse) of the chamber walls, particularly noted with species of *Trochamminoides.* This merits further study, using microprobe analysis. The preservation, including a typically light gray color of tests helps to distinguish in situ from caved taxa, which helps to determine that *Reticulophragmium amplectens* and *Cyclammina placenta* do not range down into this zone, but have their first appearance in the overlying zone of *Subbotina patagonica.*

A typical wireline log pattern, with a higher (Sele Formation) and lower (Balder Formation) gamma ray response, is mapped as North Sea log marker C (base Sele) and North Sea log marker D (top Sele, base Balder Formations). The RASC zonation on average positions North Sea log marker C at the top of the underlying Zone of *Trochammina ruthven murrayi-Reticulophragmium paupera,* and North Sea log marker D slightly above it in the *Coscinodiscus* Zone. The last occurrence of *Apectodinium augustum,* in both wells 34/8-1 and 6407/7-1 occurs immediately below the *Coscinodiscus* interval Zone, and the last common occurrence of *Deflandrea oebisfeldensis,* which defines North Sea zone T3A (table 3) is within it. Following Powell (1988) this correlation helps to equate the *Coscinodiscus* zone with uppermost NP9 and the NP10 nannofossil zones, of earliest Ypresian age.

The *Coscinodiscus* Zone correlates to Zone NSP4 (*Coscinodiscus* sp. 1 zone) of King (1983).

Subbotina patagonica Zone

Age: Ypresian, Early Eocene (Zones P6b-P8)

Corresponding Dinoflagellate Zone: T3B

PLATE 1

Scale bars = 50μm; swc = sidewall core samples; dc = ditch cutting samples.

1 *Chiropteridium lobospinosum* (Gocht in Weiler) Gocht 1960. Well 34/8-1, 1317m, swc.

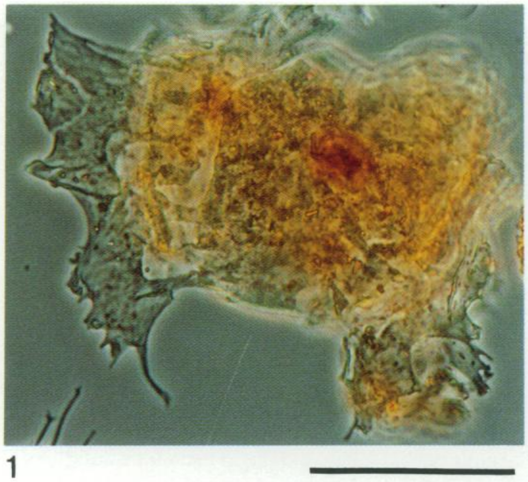
2 *Deflandrea phosphoritica* Eisenack 1938b. Well 6407/7-1, 1180m, dc.

3 *Distatodinium biffii* Brinkhuis et al., in press. Well 34/8-1, 1220m, dc.

4 *Reticulatosphaera actinocoronata* (Benedek) Bujak and Matsuoka 1986. Well 34/8-1, 1393.5m, swc.

5 *Spiniferites* sp. 2 Manum et al. 1989, pl. 17, fig. 2. Well 6407/7-1 1180m, dc.

6 *Areoligera semicirculata* (Morgenroth) Stover and Evitt 1978. Well 6407/7-1, 1140m, dc.



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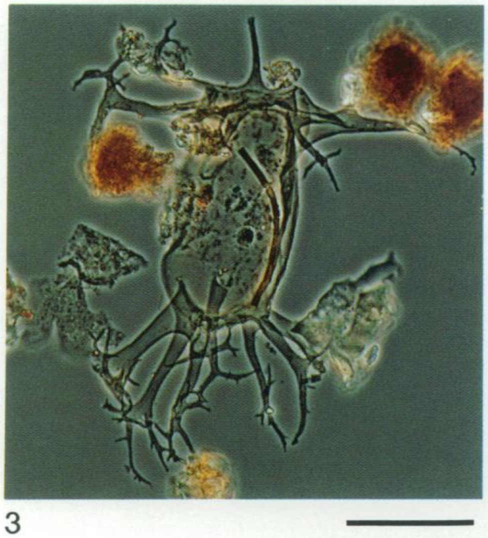

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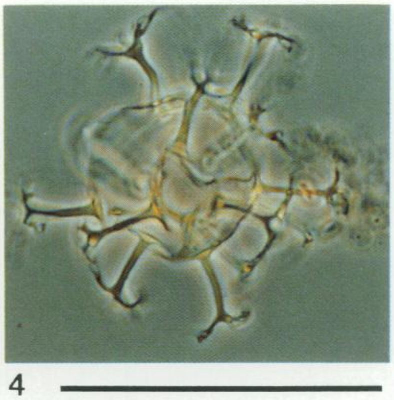

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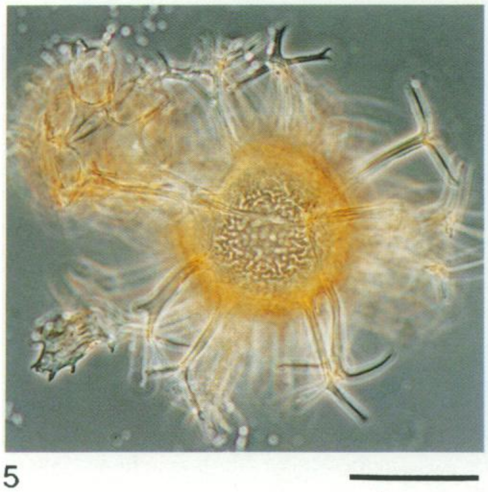

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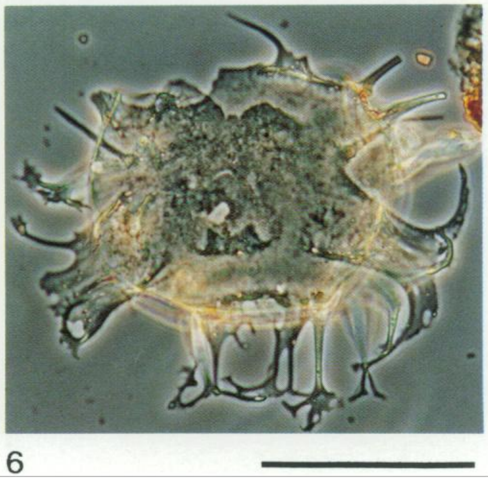

6

Taxa: The following taxa have their (average) last occurrence in this zone: *Glaphyrocysta ordinata* LCO, *Subbotina eocaena, Subbotina patagonica, Haplophragmoides retroseptus.* Rarely occurring are: *Acarinina pseudotopilensis, A. densa, A. soldadoensis, A. pentacamerata* (which also ranges in the overlying zone), *Planorotalites planoconicus, P. australiformis, Morozovella formosa gracilis, Pseudohastigerina wilcoxensis* and *Bulimina trigonalis.* Lowest occurrences of *Reticulophragmium amplectens* and *Cyclammina placenta* (rare).

Discussion: This zone is easily identified by the occurrence of its (sometimes reddish-colored), 3.5-4 chambered specimens of *Subbotina patagonica.* The species always has its highest occurrence in this zone and more or less forms an acme in it. Other planktonics listed above are rare and only occurr in a few Central Graben or Viking Graben wells, such as 15/20-1, Esso Norway 16/10-1, 22/14-1x, and 9/13-1. Rare calcareous benthics in this zone in some wells include *Turrilina robertsi* (with granular extinction pattern of the test wall under crossed nichols) and *Bulimina trigonalis.* The lowest stratigraphic range of *Reticulophragmium amplectens* is in the *S. patagonica* Zone, where this distinctive species is more compact, more disk shaped, and has a more angular periphery than in its younger stratigraphic range; such a morphotype is referred to as *R. intermedia.*

The *S. patagonica* Zone with its common to frequent occurrence of *S. patagonica,* identified in local well literature as *Globigerina* ex gr. *linaperta* or *G. eocaena* may also be recognized in the Rosnaes Clay (Ypresian) of Denmark and in the Ypresian of Belgium (Gradstein and Agterberg 1982). It is also known from DSDP Sites on the Vring Plateau and the Labrador Sea (Kaminski et al. 1989). The top of the *S. patagonica* peak occurs within NP12, which coincides with the standard planktonic zone of *Morozovella aragonensis,* at the time of polarity reversal 23, at approximately 55 Ma (Baldauf et al. 1989).

In the Esso Norway 16/1-1 well Ioakim (1979) assigns the interval from about 2000 to 2200m, including core 4, to the *Kisselovia edwardsii-Eatonicysta ursulae* Zone and the interval from about 2200 to 2220m to the *Glaphyrocysta ordinata* Zone, both Early Eocene. This correlates to our Lower Eocene *S. patagonica* Zone, which extends from 2152 to 2242m. In Viking Graben well 34/8-1, the *S. patagonica* Zone includes the first occurrence of *Dracodinium pachydermum;* in the 16/1-1 well *Glaphyrocysta ordinata* and *Deflandrea oebisfeldensis* disappear in this zone, rather than in the underlying *Coscinodiscus* spp. Zone as observed in Haltenbanken well 6407/7-1. The *S. patagonica* Zone correlates to the North Sea dinoflagellate cyst zone T3B (table 3), defined on the upper limit of the acme of *Areoligera/Glaphyrocysta* complex, together with the common occurrence of *Dracodinium varielongitudum* and *D. samlandicum.*

The *S. patagonica* Zone correlates with Zone NSP5 (*G.* ex gr. *linaperta*) and Zone NSB3 of King (1983). The latter author also refers to *Textularia plummerae* in this zone, which is our *Spiroplectammina navarroana* at the base of the overlying zone of *Ammomarginulina aubertae.*

Ammomarginulina aubertae Zone

Age: latest Early Eocene to early part of Middle Eocene

Corresponding Dinoflagellate Zones: T3C, T4A/B, T4C (pars)

Taxa: The following taxa have their (average) last occurrence in this Zone: *Spiroplectammina navarroana,* North Sea log marker E, *Turrilina robertsi* (rare), *Areoligera* spp. LCO, *Karreriella coniformis,* "Eocene" radiolarian flood, *Acarinina pentacamerata* (rare), *Eatonicysta ursula* LCO + LO, *Dracodinium pachydermum* LCO + LO, *Systematophora placacantha* LCO (last peak occurrence), *Diphyes ficusoides, Phthanoperidinium echinatum* LCO, *Reticulophragmoides jarvisi, Spiroplectammina spectabilis* LO, *Ammomarginulina aubertae, Karreriella conversa, Haplophragmoides kirki, Areosphaeridium fenestratum;* the first occurrence of *Spirosigmoilinella compressa* is in the younger part of this zone.

Discussion: This assemblage, which is almost exclusively composed of agglutinated benthic foraminifera is typical for the relatively thin Eocene mudstone intervals, largely devoid of calcareous benthic or planktonic foraminifera, overlying the Lower Eocene *S. patagonica* Zone.

Although both RASC (text-fig. 8) and particularly STRATCOR indicate a distinct break between this zone and the overlying zone of *R. amplectens,* it may not be possible in individual wells to draw a distinct boundary between the two zones. The reason is local scatter in the tops of the constituent taxa. This is why in a previous zonation using fewer wells, the *A. aubertae* and *R. amplectens* Zones were not separated (Gradstein et al. 1988). Stratigraphic inconsistencies of the last occurrence events in the wells may be caused equally by reworking, sampling uncertainty and local differences in the stratigraphic range of the agglutinated benthic taxa. Nevertheless, we have observed that the highest occurrence in the wells (albeit with isolated specimens) of *Spiroplectammina spectabilis* is a reliable indicator for the middle part or top of this zone, and *S. navarroana* indicates its base (= top of the underlying zone of *S. patagonica*).

The age of this zone is determined through superposition, the presence of rare planktonics and correlation to palynological events. Firstly, it occurs above the underlying Lower Eocene Zone of *S. patagonica* and below the overlying zone of *R. amplectens,* of (largely) late Middle Eocene age. This interpolated age of latest Early Eocene to early Middle Eocene agrees with the highest occurrence in this zone in a few wells (e.g. 9/13-1 at 1225 m) of *Acarinina pentacamerata.* The basal zone taxon *Spiroplectammina navarroana* in Labrador Sea ODP Site 647A was found in Lower and Middle Eocene strata; its lower stratigraphic range is in the Upper Cretaceous of the Gulf Coast and Carpathians (Gradstein and Kaminski 1989).

The average position of North Sea Log marker E near the base of the *A. aubertae* Zone, suggests an early Middle Eocene age for the lower part of the Zone. This log event is defined as a shift of the gamma ray log spectrum to lower values in core hole 81/46A off north-east Yorkshire (Lott et al. 1983); it was dated early Middle Eocene, close to the top of the Lower Eocene, based on its position slightly above the base of *Areosphaeridium diktyoplokus,* in the *Kisselovia coleothrypa* Zone, and slightly above the *G.* gr. *linaperta* zone (= our *Subbotina patagonica* Zone).

Spiroplectammina spectabilis does not range above the *A. aubertae* Zone in the central North Sea, in agreement with the observation that along the Canadian Atlantic margin *S. spectabilis* also ranges into Middle Eocene. Interestingly, in the abyssal environment of the central Labrador Sea, in ODP Site 647A, the taxon is found as high as core 647A-31X, coinciding with the assigned Eocene-Oligocene boundary. We conclude that the total stratigraphic range of *S. spectabilis* is Campanian through latest Eocene.

A. aubertae is apparently a higher-latitude species, restricted to the North Sea and Labrador Margin, where it ranges from Maestrichtian (*A. mayaroensis* Zone) through part or all of Middle to Late Eocene.

The *A. aubertae* Zone in the Esso Norway 16/1-1 well, at approximately 1584-2152m, overlaps with the upper half of the *Kisselovia edwardsii-Eatonicysta ursulae* Zone and all of the *Rhombodinium rhomboideum* and *Areosphaeridium diktyoplokus* Zones as assigned in this well by Ioakim (1979). The author interprets the age as Lutetian-Bartonian. A hiatus in 16/1-1, with the *R. amplectens* Zone missing, makes the Bartonian age less likely (text-fig. 7).

In Viking Graben well 34/8-1 and Haltenbanken well 6407/7-1, the following dinoflagellate cysts range into the *A. aubertae* Zone: *Eatonicysta ursulae* (LCO + LO) and *Dracodinium pachydermum* (LCO + LO), the LCO events of which define zone T3C, *Systematophora placacantha* LCO, *Diphyes ficusoides* (its LO defines Zone T4A/B), *Phthanoperidinium echinatum* LCO, and *Areosphaeridium fenestratum* (text-figs. 4, 5 and 8; table 3). *Eatonicysta ursulae* extends into NP14 (Vinken 1988) to NP16 (Head and Norris 1989). From its position in the basal *A. aubertae* Zone, immediately above the *S. patagonica* Zone, we conclude it more likely that in the North Sea, *E. ursulae* disappears in NP14. Accordingly, we assign an age to the *A. aubertae* Zone of NP14 through NP16 (pars), Lutetian.

The *A. aubertae* Zone probably extends into zones NSP7 (*Pseudohastigerina micra*) and NSB5 (*Planulina palmerae*) of King (1983), both of which can only be recognized in relatively shallow marine Eocene environments outside the Central and Viking Grabens.

Reticulophragmium amplectens Zone

Age: late Middle Eocene, possibly extending into Late Eocene

Corresponding Dinoflagellate Zone: T4C/D

Taxa: The following taxa and log events (on average) have their last occurrence in this zone: *Rottnestia borussica, Diphyes colligerum, Ammosphaeroidina pseudopauciloculata, Reticulophragmium amplectens, Rhombodinium porosum, Haplophragmoides walteri, Areosphaeridium diktyoplokus,* NS log marker F, *Globigerapsis index* (rare), *Heteraulacysta porosa, A.* cf. *diktyoplokus, Operculodinium tiara.*

Discussion: Marginulopsis decorata ranges through this zone, but it occurs in few wells only, as it is more common in a shallower environment of deposition.

As mentioned above, the *R. amplectens* Zone in some wells cannot be separated from the underlying *A. aubertae* Zone. This is the result of variation in local ranges of the zonal taxa. On average the last consistent occurrence of *R. amplectens* (with disk shaped test, sharp, circular periphery and umbilical depression) ranges above the *A. aubertae* Zone; typical specimens have not been observed in the overlying zone of *Dorothia seigliei-Rotaliatina bulimoides.* The zone is probably most easily distinguished on the highest occurrence in many wells of *Ammosphaeroidina pseudopauciloculata.* We have not been able to determine if rare occurrences in some wells of *A. pseudopauciloculata* and of atypical *R. amplectens,* with a more rounded periphery, in the overlying zones of *D. seigliei* are due to reworking or are in fact stratigraphic events. *Haplophragmoides walteri* locally extends up into the overlying (Oligocene) Zone, but its average last occurrence is in the *R. amplectens* Zone; its relatively rare subspecies *H. walteri excavatus,* with more pronounced keel, evolute coiling and more "caved-in" chambers ranges well into Oligocene strata.

Atypical *R. amplectens* was found in low numbers in the Upper Eocene-? Oligocene-Lower Miocene of cores 49-41 of ODP Site 643A, Vøring slope, but specimens are more lobate and have more incised chambers than known from regular Eocene occurrences. These particular forms may be morphologically close to *R. acutidorsata* (Hantken), originally described from the Oligocene of Hungary. The age of the mid-Tertiary cores in Site 643 is somewhat controversial and shows disagreement between palynomorph and foraminiferal biostratigraphy (Kaminski et al. in press).

In the outer Carpathians the total range of *R. amplectens* is given as Lower to Upper Eocene (Morgiel and Olszewska 1981); in Poland the peak occurrence of *R. amplectens* is in Middle Eocene strata, where it defines the Middle Eocene *R. amplectens* Zone of Geroch and Nowak (1984). In Labrador Shelf-Grand Banks wells, the average disappearance of *R. amplectens* and other agglutinated taxa in this zone is well below the tops of *Turborotalia pomeroli* and *Globorotalia cerroazulensis* of Priabonian (Late Eocene) age. In the Labrador Sea Ocean Drilling Site 647, the acme of *R. amplectens* is in the Middle Eocene. For this reason, the *R. amplectens* Zone may be largely Middle Eocene in age, possibly extending into Late Eocene.

The last occurrence of *Globigerapsis index,* which on average occurs near the top of this zone, together with the NS Log marker F (text-fig. 8), was observed in 5 wells. Thin sediments at this stratigraphic level in the wells suggest a regionally condensed section. In 9/13-1 *G. index* occurs at 1188m, just above the top of *R. amplectens*; in 9/13-3A at 1103m below the top of *Ammosphaeroidina pseudopauciloculata* and above the top of *Spiroplectammina spectabilis* LO; in Danish North Sea well E-1 at 1911m below the top of *Reticulophragmium amplectens* at 1883m and above the Lower Eocene tuff at 1950 m; in well 23/22-1 *G. index* was found at 2468m between NS Log marker F and *Reticulophragmium amplectens,* and in well 38/16-1 it occurs at 859m below *Cibicidoides truncanus* and above *Reticulophragmium amplectens. C. truncanus* is known from zone P13 (Middle Eocene) to top Eocene (Van Morkhoven et al. 1986). According to King (1983), the *G. index* event falls within zone NSP8, equated with NP16 and P13, Middle Eocene. Such an interpretation agrees with information provided by P. Spaak (pers. comm. 1989) that the *G. index* influx in the southern North Sea consistently occurs in the upper part of NP16, and with the age of NP16-17 for this event in the Danish Sovind Formation. In the North Atlantic Ocean the taxon extends into P17, Late Eocene.

According to the stratigraphic information provided by A. C. Morton, North Sea log marker F marks a distinctive sonic log change, associated with "top Eocene". It provides an upper limit for the local top of the *R. amplectens* Zone, and may well be associated with a regional hiatus.

Based on the dinoflagellate cyst stratigraphy in Viking Graben well 34/8-1 and Haltenbanken well 6407/7-1, the *R. amplectens* Zone includes the highest occurrences of *Rottnestia borussica, Diphyes colligerum, Rhombodinium porosum, Areosphaeridium diktyoplokus, A.* cf. *diktyoplokus, Heteraulacacysta porosa* (the LO of which defines North Sea zone T4C/D; table 3) and *Operculodinium tiara* (text-fig. 8). Together we assign those taxa a late Middle Eocene age (Bartonian) to Late Eocene (pars). This age provides an upper limit for the *R. amplectens* Zone as defined.

Dorothia seigliei-Rotaliatina bulimoides Zone

Age: Early Oligocene (Rupelian)

Corresponding Dinoflagellate Zones: T6A and TB/C

Taxa: The following taxa have their (average) last occurrence in this zone: *Reticulatosphaera actinocoronata* FO, *Areoligera semicirculata* FO + LCO + LO, *Chiropteridium lobospinosum* FO, *Spiniferites* sp. 2 Manum et al. (1989), *Svalbardella cooksoniae, Dorothia seigliei, Aschemonella grandis* (rare), *Adercotryma agterbergi* (rare), *Haplophragmoides walteri excavatus* (rare), *Wetzeliella symmetrica, Ammodiscus latus, Karreriella horrida, Rotaliatina bulimoides, Cyclammina rotundidorsata, Turrilina alsatica, Homotryblium floripes* LCO.

Discussion: The taxa in the *D. seigliei-R. bulimoides* Zone are easily recognized, but individual "Oligocene" North Sea well records may be confusing, the result both of scatter in the tops of mid-Tertiary zonal agglutinated taxa and reworking of older species. For this reason we have combined what potentially looks like two superimposed zones, a *D. seigliei* Zone and a *R. bulimoides* Zone, in one larger interval zone.

In the 3/25-1 (860m) and 2/8-1 (1981m) wells, the zonal interval contains rare specimens of *Turborotalia* aff. *ampliapertura* (probably of P19 age); in several wells *Heterolepa mexicana* was also found. In well 9/23-1 at 844m, in well 9/13-3A at 1006m, and in well 15/20-2 at 1260m, the zonal interval is (also) represented by *Gyroidina soldanii mamilligera. Dorothia seigliei* in Norwegian Sea ODP Site 643A, Vøring slope appears to extend into early Miocene, if a palynomorph age is used, and may be older. We cannot exclude the possibility that its total stratigraphic range in the relatively restricted deep Norwegian Basin, behind the shallower Faroe Island sills, is greater than in the North Sea.

Turrilina alsatica (with radiate extinction pattern of test wall under crossed nichols, to distinguish it from granular patterned and Eocene *T. robertsi*) and *Rotaliatina bulimoides* belong in a foraminiferal assemblage that is typical for the Rupel Formation, including the Boom Clay, Lower Oligocene of Belgium and The Netherlands (Doppert 1980; Doppert and Neele 1983). *T. alsatica* is also known from the Viborg Formation of Denmark (Lower Oligocene). Along the Canadian Atlantic margin it is widespread in the *Turrilina alsatica* Zone, calibrated to the *Globigerina ampliapertura* Zone (P19) and *Paragloborotalia opima opima* Zone (P20-P21). In DSDP Sites 329, 363, 19 and 20 *T. alsatica* also occurs frequently in P19-P20, and as high as P21. In DSDP Site 357 there is a questionable occurrence as high as P22. We conclude that *T. alsatica* has been documented to extend into P21 and spans the Lower Oligocene, but it is not clear that it actually extends throughout the P21 zone. If so, the *D. seiglei-R. bulimoides* Zone may extend slightly above the Rupelian, Lower Oligocene and slightly into the Chattian, Upper Oligocene.

In the Esso Norway 16/1-1 well, the *D. seigliei-R. bulimoides* Zone, at about 1396-1585m, corresponds to the Lower Oligocene (Rupelian) dinoflagellate cyst zone of *Wetzeliella gochtii-Samlandia chlamydophora* at 1372-1592m. In Haltenbanken well 6407/7-1 we determined a diversified Rupelian dinoflagellate cysts assemblage between 1100 and 1200m (text-fig. 5). It incorporates the lowest occurrences of *Reticulatosphaera actinocoronata, Areoligera semicirculata* and *Chiropteridium lobospinosum,* and the highest occurrences of *Spiniferites* sp. A, *Svalbardella cooksoniae* (the latter of which defines North Sea zone T6A; table 3), *Areoligera semicirculata* LCO and LO (which defines North Sea zone T6B/C; table 3), and *Wetzeliella symmetrica.* The last occurrences of *Chiropteridium lobospinosum* and *Deflandrea phosphoritica* at 1100m are truncated below the Rupelian/Pliocene hiatus at 1100m.

In Viking Graben well 34/8-1 (text-fig. 4), the lower part of the *D. seigliei-R. bulimoides* Zone, between 1497 and 1400m corresponds to the interval with the disappearance of *Svalbardella cooksoniae, Areoligera semicirculata* LCO and LO, and *Wetzeliella symmetrica* of Rupelian age. In this well,

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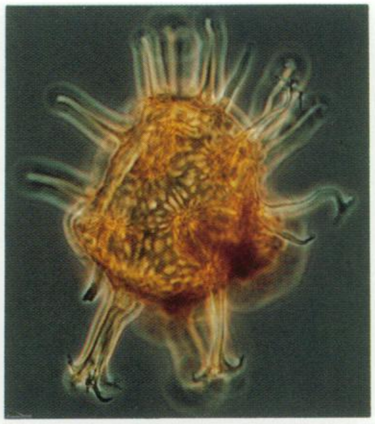
PLATE 2

Scale bars = 50µm; swc = sidewall core samples; dc = ditch cutting samples.

1	*Areosphaeridium diktyoplokus* (Klumpp) Eaton 1971. Well 34/8-1, 1697m, swc.
2, 6	*Cordosphaeridium funiculatum* Morgenroth 1966a. Well 6407/7-1, 1320m, dc.
3	*Svalbardella cooksoniae* Manum 1960. Well 6407/7-1, 1140m, dc.
4, 5	*Diphyes colligerum* (Deflandre and Cookson) Cookson 1965a; emend. Goodman and Witmer 1985. Well 6407/7-1, 1600m,dc. 4. Oblique apical view. 5. Oblique antapical view with short, broad antapical process.
7	*Heteraulacacysta porosa* Bujak in Bujak et al. 1980. Well 34/8-1, 1580m, dc.
8	*Diphyes ficusoides* Islam 1983b. Well 6407/7-1, 1600m, dc.
9	*Operculodinium tiara* (Klumpp) Stover and Evitt 1978. Well 34/8-1, 1724m, swc.


1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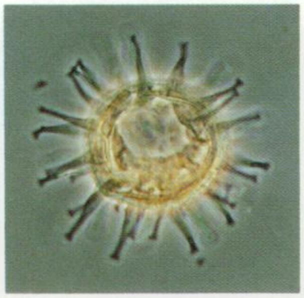
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5


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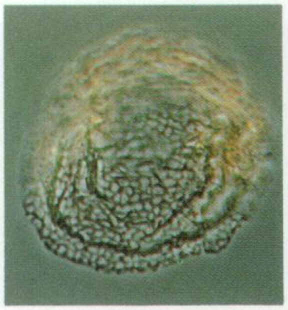
7


8


9

the zone might extend to 1161m using the top of *Dorothia seigliei* at 1220m, and of *Turrilina alsatica* at 1161m. On the other hand there is some evidence for the presence of the overlying zone of *G.* ex gr. *officinalis* between 1220m and 1161m, where *Spirosigmoilinella compressa* occurs. The latter would agree with the range of *Distatodinium biffii* between 1422 and 1194m, and the last occurrences of *Homotryblium floripes, Chiropteridium lobospinosum* and *Deflandrea phosphoritica* between 1220 and 1161m, indicate a Chattian age. The possibility exists that there is Rupelian reworking because *S. cooksoniae* occurs with few specimens in side wall core 1174m, just below *Turrilina alsatica* at 1161m. If so, the *D. seigliei-R. bulimoides* Zone may not range above 1220m. Because the *Dorothia seigliei-Rotaliatina bulimoides* Zone, as discussed, may extend slightly into Chattian strata, it is also possible that only the earliest Chattian is present in the 34/8-1 well.

The *D. seigliei-R. bulimoides* Zone correlates to upper NSB6 and NSB7 of King (1983), Early Oligocene.

Globigerina ex gr. *officinalis* Zone

Age: Late Oligocene (Chattian)

Corresponding Dinoflagellate Zone: T7

Taxa: The following taxa have their (average) last occurrence in this zone: *Spirosigmoilinella compressa, Cyclammina placenta, Globigerina* ex gr. *officinalis, Tenuitella angustiumbilicata,* coarse agglutinated foraminifera spp., *Distatodinium biffii* FO? and LO, *Deflandrea phosphoritica* and *Chiropteridium lobospinosum.*

Discussion: In Viking Graben well 3/25-1 there is a record of the typically late Oligocene *Almaena osnabrugensis* (Doppert 1980) at 650m, immediately above *Globigerina officinalis* at 720m.

In several wells this interval contains common to abundant small, and largely nondescript globigerinids. This includes the nominate zonal species together with *T. angustiumbilicata, P. opima nana, Catapsydrax unicavus* and rarely *G. ciperoensis,* of Late Oligocene age (P22). Sampling resolution is low in this interval and Miocene cavings hamper easy recognition of this interval zone. Floods of small radiolarians and sponge spicules are common, and attest to slow rates of terrigenous clastic deposition in a bathyal realm.

In the 16/1-1 well the *G. officinalis* zone may be present between 1219 and 1396 m; it overlaps with the *C. lobospinosum* Zone of Ioakim (1979) of late Oligocene age. In Viking Graben well 34/8-1 and Haltenbanken well 6407/7-1, a hiatus between Upper Oligocene and Pliocene strata truncates all microfossil ranges and makes integration of late Oligocene dinoflagellate cyst and foraminifer events difficult. From detailed analysis we consider it likely that the last occurrence of *Distatodinium biffii* is above the *R. bulimoides-D. seigliei* Zone, and in the overlying zone of *G.* ex gr. *officinalis,* but this is not certain for its first occurrence (text-fig. 5). We conclude that *Deflandrea phosphoritica, Chiropteridium lobospinosum* (the LO of which defines North Sea zone T7; table 3), *Distatodinium biffii* and *Homotryblium floripes* all extend into this zone of Chattian age. According to Head and Norris (1989) the upper range of *Chiropteridium lobospinosum* is in Upper Oligocene, in agreement with the correlation to the *G.* ex gr. *officinalis* Zone.

An important regional biofacies event in the central North Sea is the upper stratigraphic extent of the coarse agglutinated benthic foraminiferal assemblage. In Central Graben wells studied, e.g. from the 21, 29 and 30 blocks, there is an interval of several hundreds of meters of claystone above the *R. bulimoides-D. seigliei* Zone and below the *G. praescitula* Zone, in which almost exclusively agglutinated taxa occur with abundant radiolarians and sponge spicules. In a few cases the planktonic foraminifera discussed above also were found, e.g in the 22/6-1 well at approximately 1402m, which places the top of the agglutinated/radiolarian biofacies into the Oligocene. On no occasion did we observe *Spirosigmoilinella compressa* or *Ammodiscus latus* into the late Early to Middle Miocene *G. praescitula* Zone, which has a rather nondescript agglutinated benthic component in its assemblage, largely comprised of fragments of tubular taxa, *Cribrostomoides* and *Cyclammina* spp.

The average event succession in text-figure 8 shows that between the *G.* ex gr. *officinalis* Zone and the *G. praescitula* Zone there is a tight and small RASC cluster with *Gyroidina girardana, Globigerina praebulloides* and *Spiroplectammina carinata.* Interfossil distances are small values. It turns out that the pairs of taxa that make up this cluster occur less or only slightly more than five times in the wells examined, at or below the threshold of the selected RASC run for this zonation of 7/1/5. This includes indirect distances and means there is not enough data to accomplish reliable scaling. Certainly the standard deviations are many times larger than these small interfossil distances. Although this RASC cluster is poorly defined, the taxa occur in 7 or more wells. Ranking places these taxa at the positions shown in the RASC interval zonation, which means that on average their last occurrence level is above the *G.* ex gr. *officinalis* Zone and below the overlying Miocene zone.

The scaling of *S. carinata, G. girardana* and other taxa, separate from the underlying and overlying zones indicates a biofacies break (the abrupt transition from the predominantly agglutinated/radiolarian biofacies to a more mixed calcareous/siliceous biofacies), and possibly a hiatus near the Oligocene/Miocene boundary.

Globorotalia praescitula Zone

Age: Early-Middle Miocene (Zones ?N6 - N11)

Taxa: The following taxa or log events have their average last occurrence in this zone: *Asterigerina gurichi,* group of *G. praescitula-G. zealandica, Caucasina elongata, Globigerinoides trilobus, Neogloboquadrina continuosa,* NS Log marker G, *Siphonina advena,* Neogene radiolarian flood, *Uvigerina semiornata kusteri* (rare), *Martinotiella cylindrica.*

Discussion: Common to abundant planktonics in this zone in Central Graben wells also include: *Globigerinoides* spp., *G. trilobus, Globoquadrina dehiscens, G. baroemoensis, Globorotalia praemenardii,* the plexus of *G. praescitula* and *G. zealandica, Sphaeroidinella seminulina, Neogloboquadrina continuosa,* and *Globigerina praebulloides,* but no *Catapsydrax.* The upper part of the *G. praescitula* Zone yields *Orbulina universa,* but there is no record of *N. acostaensis.* The assemblage listed above correlates to the upper part of Lower Miocene and Middle Miocene strata (probably N6 or N7 to N11 or slightly younger), which agrees with the assignment by A. C. Morton of NS Log marker G as top of Middle Miocene (?Upper Miocene hiatus on logs). Although the total range of *G.*

praebulloides is from P22 to N18 (Kennett and Srinivasan 1983), this species does not range above the Lower to Middle Miocene of the North Sea and the Canadian margin.

Among the calcareous benthic foraminifers occur *Uvigerina* ex gr. *basicordata, U.* ex gr. *miozea nuttali* and *U. semiornata kusteri, Asterigerina gurichi, A. staeschi, Alabamina scitula,* and *Caucasina elongata.*

In Central Graben wells, particularly around the Ekofisk area, agglutinated foraminifera are common in this zone with taxa like *Cribrostomoides, Glomospira, Bathysiphon, Hyperammina, Martinotiella cylindrica, Trochammina, Reophax* and *Cyclammina,* including *C. cancellata, C. placenta* and rare *C. rotundidorsata. Martinotiella cylindrica* is a more slender form than its coeval *M. communis* in Norwegian Sea DSDP and ODP sites. In the southern North Sea wells, like 22/6-1, 29/3-1 and 30/19-1, the zone is associated with common to abundant planktonics, both foraminifers and radiolarians. These Miocene sediments were laid down in a bathyal (maximally 500m paleo waterdepth) depocenter and are thick and fossiliferous.

In northern North Sea wells studied, the Miocene interval is either missing, the result of uplift and erosion, or is relatively thin and shallower marine (mostly neritic), as in the 9/23-1 well and not particularly fossiliferous. Here we observed in this zone rare planktonics including *Globigerinoides obliquus* and *Globigerina praebulloides,* together with few specimens of the benthics *Uvigerina* ex gr. *miozea nuttali, Ceratobulimina contraria, Gyroidina girardana, Caucasina elongata, Martinotiella cylindrica, Spiroplectammina carinata, Ehrenbergina, Alabamina scitula, Asterigerina gurichi* and *A. staeschi.*

The *G. praescitula* Zone probably corresponds to NSP11 and 12 of King (1983), which lists fewer planktonics, but assigns a comparable age range for the Zone.

Bolboforma metzmacheri Zone

Age: Late Miocene

Taxa: The following planktonic algal cysts and planktonic foraminifera on average have their highest occurrence in this zone: *Bolboforma metzmacheri* (rare), *Bolboforma spiralis,* group of *Neogloboquadrina continuosa-acostaensis-humerosa, N. atlantica.*

Discussion: In 2 wells, 29/3-1 at 1378m and 22/6-1 at 1155-1186m, there is an interval with above listed taxa, below levels with *Globorotalia puncticulata* and above the highest occurrences of taxa in the *G. praescitula* Zone. The interval is relatively thin, probably less than 100m, and corresponds to an interval of time between Middle Miocene and Early Pliocene. Following Doppert (1980) and King (1983) this interval is Late Miocene in age and equates to NSP14 of the latter author.

In the 23/22-1 well at 1478m there is a record of dextrally coiled *Neogloboquadrina atlantica* and *N. humerosa,* together with reworked Middle Miocene planktonics, also of Late Miocene age.

Neogloboquadrina atlantica Zone

Age: Early Pliocene (N19 - N21)

Taxa: The following taxa have their last occurrence in this zone: *Neogloboquadrina atlantica* (sinistrally coiled), *Globorotalia puncticulata.*

Discussion: In several wells, notably 30/19-1 from about 762-1259m, 29/3-1 from about 1128-1311m, 22/6-1 near 1128m, and 16/1-1 from about 600-823m, occurs an assemblage rich in Pliocene planktonic foraminifera, assigned to the *N. atlantica* Zone. It contains the planktonics cited above plus *Globorotalia crassaformis, Neogloboquadrina pachyderma, N. humerosa, N. humerosa-acostaensis, Globigerina apertura, G. bulloides,* and *Orbulina universa.* Recently Jenkins et al. (1988) have described a similar assemblage from the Coralline Crag of Suffolk, eastern England. The authors cite ranges for these taxa throughout the Early Pliocene, which agrees with our observation, albeit in well samples, that the range of *Globorotalia inflata* probably does not overlap with these taxa, but is restricted to the overlying zone.

Among benthics in the *N. atlantica* Zone there are *Sigmoilopsis schlumbergeri* and rare *Monspeliensina pseudotepida;* the former and also *Cibicidoides grossa, Cassidulina teretis* and *Elphidium* spp. range throughout this interval and extend higher (see below).

The planktonics are relatively abundant in this part of the southern central North Sea, and testify to neritic to upper bathyal open marine conditions, which gradually changed in the overlying zone to a more restricted, colder and shallower emvironment that supported few benthics only.

The *N. atlantica* Zone correlates to the (oceanic) *G. puncticulata* Zone of Weaver and Clement (1986), and NSP15 of King (1983), of Early Pliocene age. The latter is defined similarly to our zone.

Cibicidoides grossa Zone

Age: Late Pliocene

Taxa: The following taxa have their average last occurrence in this zone, which generally forms the top of the sampled interval in the wells. *Sigmoilopsis schlumbergeri, Cibicidoides grossa, Cassidulina teretis, Elphidium* spp. The lower part of the zone has rare *Trifarina fluens, Globorotalia inflata* and *Neogloboquadrina pachyderma.*

Discussion: The *Cibicidoides grossa* Zone characterizes the highest interval sampled in the wells examined. The majority of the taxa in it are also known from the Recent, which means local disappearances there may be the result of water mass cooling and shallowing throughout the late Neogene. The zonal interval generally is rich in *Cassidulina* and *Elphidium* with uvigerinids, miliolids and nonionids being less common. Planktonics are rare and together with the benthics *Trifarina fluens* and *Sigmoilopsis schumbergeri* are confined to the lower part of this zone. The age for the zone is based on the presence of non-rugose and right-coiling *N. pachyderma* (Weaver and Clement 1986), and the assumption that we are dealing with the lower range of *G. inflata,* which appears in the Late Pliocene, as a descendant from *G. puncticulata. Cibicidoides grossa* is also thought to be restricted to the Pliocene and become extinct at about 2.7 Ma (Feyling Hansen 1980), although Sejrup et al. (1987) report it as possibly in situ in the Lower Pleistocene of the Fladen area, central North Sea. *Trifarina fluens, Sigmoilopsis schlumbergeri* and *Cassidulina teretis* are extant.

THE PALEOGENE DINOFLAGELLATE CYST RECORD AND ZONATION

In this section we report on the Paleogene palynostratigraphy of wells 34/8-1 in the Viking Graben and 6407/7-1 on

Haltenbanken (65° North; text-fig. 1 and table 1). This investigation was undertaken as part of a detailed biostratigraphic study at the Norsk Hydro Research Centre, Bergen, of the Paleogene of the Norwegian Shelf. From both wells a total of 50 sidewall cores (swc) and 40 ditch cuttings samples were processed for palynological analysis. Standard preparation techniques were used, with residue sieving at 15μm and oxidation in either diluted or concentrated nitric acid for 5 minutes. The palynological assemblages in general are dominated by well preserved dinoflagellate cysts (text-fig. 3). The dinoflagellate cyst zonation described below is based on the observed record in the 34/8-1 and 6407/7-1 wells, in combination with published dinoflagellate cyst zonations relevant to the North Sea region and our inhouse data. In addition we re-evaluated the published palynological record of the Esso Norway 16/1-1 well (Ioakim 1979). In all three wells analyzed palynologically, we also studied the foraminiferal record (see previous section). As a result, a first order integration was achieved of the dinoflagellate cyst and foraminiferal zonations, as illustrated in the optimum fossil sequences in text-figure 8 and the range charts in text-figure 9. For the purpose of the integrated, multiple zonation we selected last occurrences and some acme occurrences of dinoflagellate cyst and foraminiferal taxa from the 16/1-1, 34/8-1 and 6407/7-1 wells as input for calculation of the most likely zonation, using the quantitative zonation programs RASC and STRATCOR.

Many authors have published palynological zonal schemes for parts of the Cenozoic in Western Europe, relevant to the central North Sea, e.g. Hansen (1977), Ioakim (1979), Heilmann-Clausen (1985), Costa and Manum (in Vinken, 1988), Powell (1988), Biffi and Manum (1988), and Manum et al. (1989). None of these zonal frameworks are fully applicable for palynostratigraphy of samples extracted from industrial exploration wells in the North Sea. This is partly due to the fact that the zonation systems are restricted in age (e.g. Powell 1988), and partly because to a considerable extent the published zonations utilize both first and last occurrences (e.g. Costa and Manum 1988, Manum et al. 1989). For the biostratigraphic subdivision of exploration wells, where most of the available sediment is ditch cuttings, a zonation based on stratigraphic last occurrences is imperative. On the other hand, stratigraphic evaluation of first occurrences and of fossil assemblages is feasible when sidewall core (swc) or conventional core material is available. With swc and core material, acme occurrences are often easier to record than last occurrences. For this reason, we have developed an interval zonation scheme based on last (LO) and last common occurrences (LCO) of dinoflagellate cyst taxa which are commonly recorded in offshore sequences in the North Sea and offshore middle Norway. It is implicit that zonal bases, if not mentioned specifically, are defined by the top of the underlying zone. Details on the occurrence of the zones in specific wells are presented in the previous section dealing with the foraminiferal zonation.

The formal taxonomic nomenclature follows that cited in Lentin and Williams (1989). For more recently published species, the taxonomic authorship is given.

T1A Zone

Top defined on: last stratigraphic occurrence of *Spongodinium delitiense*

Base defined on: last stratigraphic occurrence of *Palynodinium grallator*

Age: Earliest Danian, Early Paleocene

Discussion: The palynological assemblage is characterized by the occurrence of *S. delitiense* and the common occurrence of *Senoniasphaera inornata.* The T1A zone corresponds to the lower part of the *Senoniasphaera inornata* Subzone of Hansen (see Vinken 1988, figure 172) of the same age, and to the lower part of our North Sea foraminiferal zone of *Subbotina pseudobulloides* (table 3).

T1B Zone

Top defined on: last stratigraphic occurrence of *Alisocysta reticulata*

Age: Danian, Early Paleocene

Discussion: The zone corresponds with the northwest European dinocyst zones D1(pars) - D2 of Costa and Manum (in Vinken 1988). These authors calibrate zones D1 and D2 to nannoplankton zones NP1 to NP4 (pars). This implies that the top of our zone T1B is in the uppermost Danian, close to the Danian/Selandian boundary. Zone T1B corresponds to the upper

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PLATE 3

Scale bars = 50μm; swc = sidewall core samples; dc = ditch cutting samples.

1, 2 *Systematophora placacantha* (Deflandre and Cookson) Davey et al. 1969. Well 6407/7-1, 1549, 95m, swc. 1. High focus showing an apical/lateral view. 2. Low focus showing an antapical/lateral view.

3 *Deflandrea oebisfeldensis* Alberti 1959b. Well 34/8-1, 1829m, swc.

4 *Eatonicysta ursulae* (Morgenroth) Stover and Evitt 1978. Well 34/8-1, 1778m, swc.

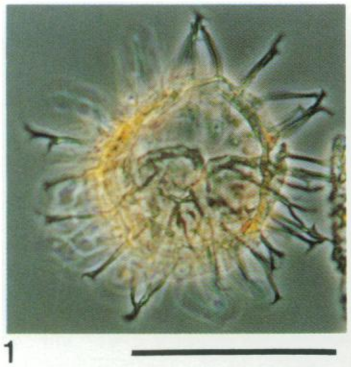
5 *Dracodinium pachydermum* (Caro) Costa and Downie 1979. Well 6407/7-1, 1600m, dc.

6 *Palaeocystodinium bulliforme* Ioannides 1986. Well 6407/7-1, 1975m, swc.

7 *Areoligera* cf. *senonensis* Lejeune-Carpentier 1938. Well 34/8-1, 1932m, swc.

8 *Alisocysta margarita* (Harland) Harland 1979a. Well 6407/7-1, 1940m, dc.

9 *Alisocysta reticulata* Damassa 1979b.



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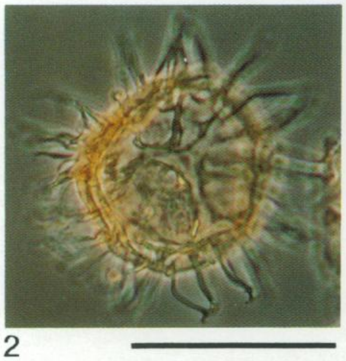

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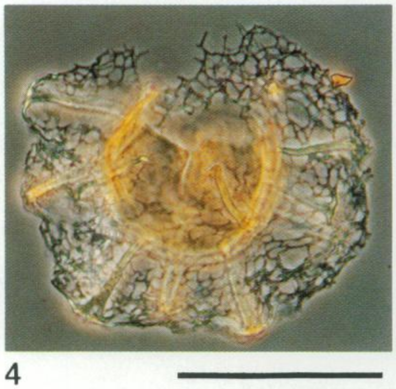

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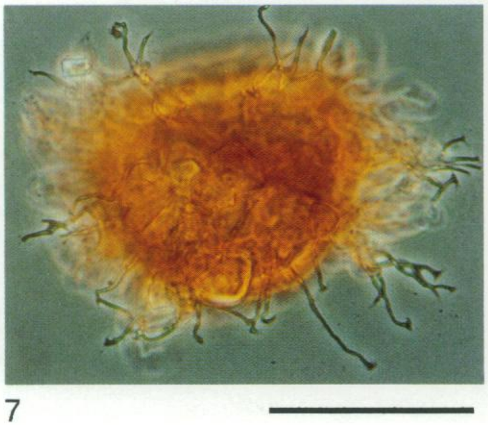

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part of the North Sea foraminiferal zone of *Subbotina pseudobulloides* (table 3).

T2A Zone

Top defined on: last occurrence of abundant *Paleoperidinium pyrophorum*

Age: Early Selandian (uppermost NP4 to NP6), early Late Paleocene.

Discussion: The top of zone T2A corresponds with the top of the dinoflagellate cyst zone 3 of Heilmann-Clausen (1985). The zone is characterized by the common occurrence of dinocysts of the *Areoligera* spp./*Glaphyrocysta* spp. complex and includes records of *Isabelidinium*? *viborgense*. Zone T2A includes the zone D3 and the lower part of zone D4 of Costa and Manum (in Vinken 1988). The lower part of zone D4, in offshore localities, is characterized by abundant *P. pyrophorum*. Zone T2A probably correlates to nannoplankton zones NP4 (pars) through NP6 (pars) [Costa and Manum (in Vinken 1988) and Powell (1988)]. Zone T2A corresponds to the lower part of the North Sea foraminiferal zone of *Reticulophragmium paupera-Trochammina ruthven murrayi* (table 3).

T2B Zone

Top defined on: last stratigraphic occurrence of *Alisocysta margarita* and/or *Areoligera* cf. *senonensis*

Age: Selandian, Late Paleocene

Discussion: The top of the T2B zone corresponds with the top of the *Alisocysta margarita* Interval Biozone of Powell (1988). The top of zone T2B probably also corresponds to the top of zone D4 of Costa and Manum (in Vinken 1988), although this zone top is defined using other criteria. The middle part of North Sea foraminiferal zone *Reticulophragmium paupera-Trochammina ruthven murrayi* also correlates to Zone T2B (see table 3).

T2C Zone

Top defined on: last stratigraphic occurrence of *Apectodinium augustum*

Age: Selandian, Late Paleocene

Discussion: Zone T2C is characterized by the presence of *Apectodinium* spp., including *A. augustum*. The zone corresponds with the *Apectodinium augustum* zone of Powell (1988). This author, by indirect correlation, proposed that the top of *A. augustum* is very close to the Paleocene/Eocene boundary. Our record (see also discussion of Paleocene and earliest Eocene foraminiferal zones in the previous chapter) also suggests that the highest occurrence of *A. augustum* is an excellent indicator for the upper limit of the Paleocene in the central North Sea. Zone T2C corresponds to the D5a zone of Costa and Manum (in Vinken 1988) and to the top of the foraminiferal zone of *Reticulophragmium paupera-Trochammina ruthven murrayi* (table 3).

T3A Zone

Top defined on: last common occurrence of *Deflandrea oebisfeldensis*

Age: earliest Ypresian (NP10), Early Eocene

Discussion: This zone is characterized by the acme of *D. oebisfeldensis,* and corresponds to the *Deflandrea oebisfeldensis* Acme Biozone of Powell (1988) and the D5b zone of Costa and Manum (op. cit.). In the North Sea, the *D. oebisfeldensis* acme is encountered within the Balder Formation, and corresponds to our *Coscinodiscus* spp. Zone (table 3). Traditionally, in subsurface stratigraphy, the top of the Balder Formation was used to delimit the Paleocene. This was a convenient practice, due to the presence of a significant log break and a good seismic reflector at this lithostratigraphic boundary. Costa and Manum (op. cit.) claim that the last occurrence of *A. augustum* coincides with that of the *D. oebisfeldensis* acme, the reason why these authors calibrate the *D. oebisfeldensis* acme to NP9. However, they also state that "*Apectodinium augustum* is absent or very

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Plate 4

1a,b *Trochammina ruthven murrayi* Cushman and Renz from Mobil 21/28-1, 3900′, North Sea; ×90.

2a,b *Trochammina* cf. *subvesicularis* Hanzlikova from Mobil 9/13-3A, 5840′; 2a ×145, 2b ×130.

3a-c, 4 *Reticulophragmium paupera* (Chapman). 3a-c from Mobil 9/13-3A, 5810′; 3a - optical photograph showing the concentration of alveoles along sutures and periphery, ×45; 3b,c - less disk-shaped than *R. amplectens,* both species have a simple, slit-like aperture, 3b - ×350, 3c - ×80. 4 from Mobil 9/13-3a, 5790′ - optical photograph, ×40.

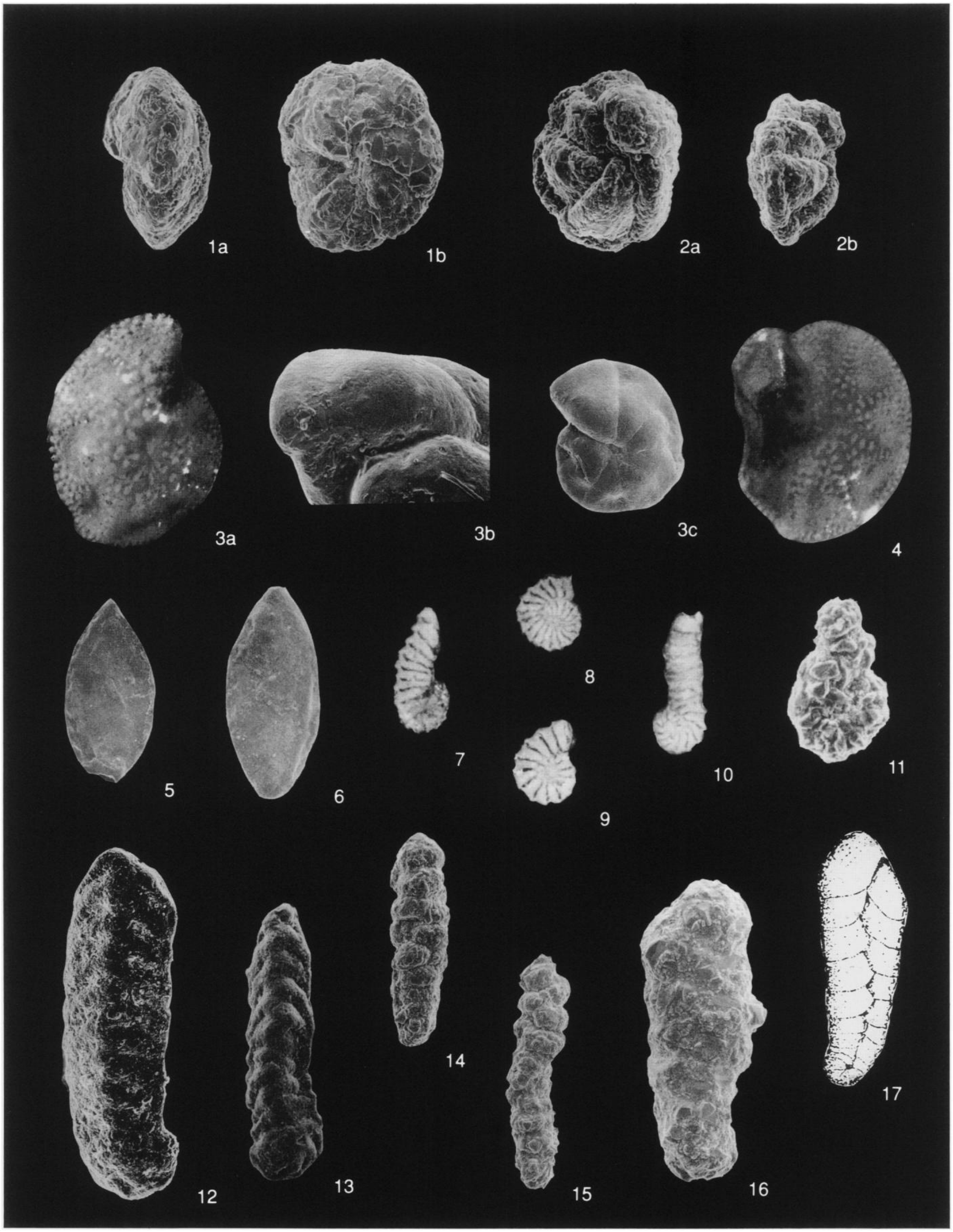
5, 6 *Rzehakina minima* Cushman and Renz. This species is smaller, more translucent, more delicate and more evolute than *R. epigona.* 5 from BP 15/20-2, 1880′; ×80. 6 from Danish Nordso A-2, 5940′; ×125.

7-11 *Ammomarginulina aubertae* Gradstein and Kaminski. 7-10 - optical photographs of paratypes from Shell 22/6-1, 6356-6820′; ×50. 11 from Amoco Norway 2/8-1, 7580′; ×55.

12, 13 *Spiroplectammina spectabilis* Grzybowski. 12 from Esso Norway 16/1-1, core 7958′; ×80. 13 from Mobil 21/28-1, 3500-4500′; ×100.

14, 15 *Karreriella conversa* (Grzybowski) from Esso Norway 16/1-1, core 4, 7060′; ×85.

16, 17 *Spiroplectammina navarroana* Cushman. 16 from Esso Norway 16/1-1, core 4, 7060′; ×80.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rare" at that level. None of our records show *A. augustum* within the *D. oebisfeldensis* acme interval, the reason why we support the indirect calibration of the *D. oebisfeldensis* acme to NP10 (Powell 1988).

T3B Zone

Top defined on: top acme of *Areoligera/Glaphyrocysta*

Age: Ypresian, Early Eocene

Discussion: The zone is characterized by the abundance of the *Areoligera/Glaphyrocysta* complex and the common occurrence of *Dracodinium varielongitudum* and *D. samlandicum.* Our record shows that zone T3B correlates with the foraminiferal North Sea zone of *Subbotina patagonica* (table 3), of Ypresian age.

T3C Zone

Top defined on: top acme *Dracodinium pachydermum* and/or top acme *Eatonicysta ursulae*

Age: late Ypresian-earliest Lutetian, late Early Eocene-earliest Middle Eocene

Discussion: The zone is characterized by the common occurrence of *E. ursulae.* In the upper part of T3C *D. pachydermum* is also common. According to Williams and Bujak (1985), *E. ursulae* has its stratigraphic top at the upper boundary of NP14, while Costa and Manum (in Vinken 1988) claim it ranges into but not to the top of NP14. The top of our zone T3C is believed to be close to the Ypresian/Lutetian boundary (earliest NP14). Direct comparison with onshore sections is difficult because of a widespread stratigraphic hiatus in northwest Europe. Zone T3C equates with the uppermost part of North Sea foraminiferal zone *Subbotina patagonica* and the basal part of the North Sea foraminiferal zone of *Ammomarginulina aubertae* (table 3).

T4A/B Zone

Top defined on: last stratigraphic occurrence of *Diphyes ficusoides*

Age: Early Middle Eocene (Lutetian, pars)

Discussion: The following events were observed to occur within the zone: top abundant *Systematophora placacantha* (labelled LCO), *Dracodinium pachydermum* LO and *E. ursulae* LO. The index fossil for the zone, *D. ficusoides,* is rarely encountered in the literature and is probably often recorded as *D. colligerum. D. ficusoides,* however, is the easiest of the two to record with "ordinary magnification". Goodman and Witmer (1985), who have emended *D. colligerum,* distinguish *D. colligerum* from *D. ficusoides* "by the shape of the antapical process, which is bell shaped to cylindrical on the former, and fig-shaped with a biconvex margin" on *D. ficusoides* (see pl. 2, figs. 4, 5 and 8). According to our records, *D. colligerum* s.s. has a younger stratigraphic last occurrence than *D. ficusoides.*

In the present study, the last occurrence of *D. ficusoides* is encountered above *E. ursulae* LO and below *Heteraulacacysta porosa* FO. In view of the known stratigraphic top and base for these two species (see zones above and below), the last occurrence of *D. ficusoides* is believed to be in NP15. Manum et al. (1989) have also encountered the top of *D. ficusoides* (as *D.* cf. *D. colligerum*) in the lower part of Middle Eocene at the outer Vøring Plateau.

The middle part of foraminiferal North Sea zone *Ammomarginulina aubertae* equates to all of zone T4A/B.

T4C/D Zone

Top defined on: last stratigraphic occurrence of *Heteraulacacysta porosa*

Age: Late Lutetian-Bartonian, Late Middle Eocene

Discussion: A thick and well developed late Middle Eocene sequence is encountered in wells 34/8-1 and 6407/7-1. *Diphyes colligerum* and *Rhombodinium porosum* have their last occurrence within this zone. *Rhombodinium porosum* has a range restricted to NP17 (Williams and Bujak 1985; Costa and Manum, in Vinken 1988) and should be a good upper Middle Eocene marker (zone D11 of Costa and Manum). This species is, however, very rarely recorded in offshore wells, and is therefore very inconvenient to use as a zone criteria.

Plate 5

1, 2 *Reticulophragmium amplectens* (Grzybowski) from Norsk Hydro 34/8-1, 1660 m; 1, ×80, this is not a most typical shape, ideally specimens are strongly disk-shaped with umbilical depression; 2, ×150, detail of apertural face, showing basal slit with rim.

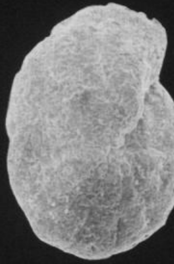
3, 4, 5 *Haplophragmoides kirki* Wickenden. 3,4 from Esso Norway 16/1-1, core 4, 7080′; 3×110; 4×105. 5 from Conoco 211/19-1, swc, 5840′; ×160.

6, 7 *Ammosphaeroidina pseudopauciloculata* (Mjatliuk) from Shell 29/3-1, 7569′; 6, ×110; 7, ×85. This taxon differs from *Cystammina* in its (often poorly visible) basal apertural slit, without a lip. *Cystammina* has an areal aperture, which generally can be easily observed, with a lip or a rim.

8, 9a-c *Dorothia seigliei* Gradstein and Kaminski from Shell 30/19-1, 8200′; 8, ×100; 9a,b,c are optical photographs of the holotype, ×100.

10a-c, 11a-c Drawings of paratypes of *Adercotryma agterbergi* Gradstein and Kaminski from Shell 29/3-1, 7110-7410′, North Sea; ×150.

12-15 *Spirosigmoilinella compressa* Matsumaga optical photograph of specimens in Shell 29/3-1, 5830-6030′; ×45.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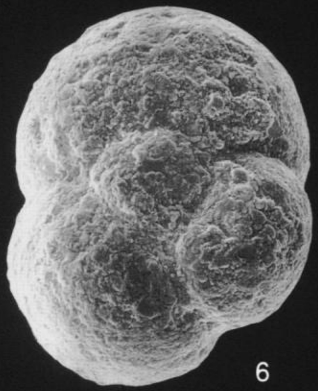
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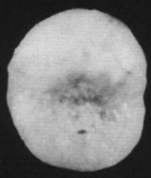
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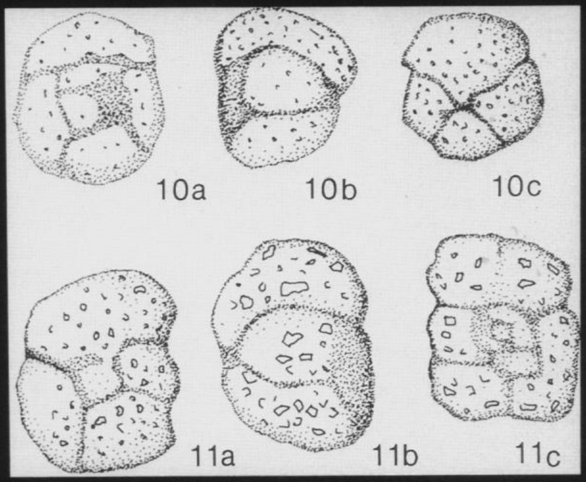

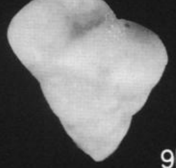
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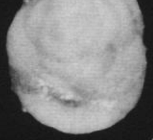
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H. porosa is easily recognizable and occurs more frequently in Eocene deposits. We therefore suggest this species as a index taxa for the zone. Unfortunately, the age of the last occurrence of *H. porosa* is slightly problematic at present.

In the type section in southern England, Bujak et al. (1980) recorded *H. porosa* from the lower Barton Beds (NP16 of Aubry et al. 1988), of late Middle Eocene age. Dinoflagellate cyst studies of other European sections covering this interval are few, and rather preliminary. *H. porosa* is reported from Late Eocene in the Netherlands (De Coninck 1986), Denmark (Heilmann-Clausen,1983) and North Atlantic DSDP sites (Damassa et al. 1990). Head and Norris (1989) propose a range for *H. porosa* from upper Middle Eocene (NP16) to uppermost Eocene (NP20), where the Upper Eocene part is mainly based on offshore eastern Canadian records.

In the present study, *H. porosa* and *R. porosum* are recorded in the same samples (swc), and *H. porosa* extends higher than *R. porosum*. In view of the above data, we conclude that *H. porosa* in the North Sea ranges from NP16 throughout NP17, and possibly slightly higher into lower Upper Eocene.

Zones T4C/D overlap with the upper part of the *Ammomarginulina aubertae* Zone and with all of the *Reticulophragmium amplectens* Zone (table 3).

T5 (tentative) Zone

Top defined on: first consistent stratigraphic occurrence of *Reticulatosphaera actinocoronata*, or last stratigraphic occurrence of *Areosphaeridium diktyoplokus*

Age: (?) Priabonian, Late Eocene

Discussion: R. actinocoronata (*Impletosphaeridium* sp. 1, Manum 1976) is reported to have its lowermost occurrence in NP23 (Williams and Bujak 1985; Biffi and Manum 1988). On the outer Vring Plateau, Manum et al. (1989) reports the lowermost occurrence of this species from the upper part of Lower Oligocene. Recent studies in Italy indicate that *R. actinocoronata* ranges consistently down to base Oligocene (top NP21; H. Brinkhuis, pers. comm. 1991). This species is recorded regularly in the present study, and we propose its use as a reliable indicator for lowermost Oligocene strata.

Williams and Bujak (1985), Haq et al. (1987) and Costa and Manum (in Vinken, ed. 1988) all indicate that *Areosphaeridium diktyoplokus* has its highest occurrence near the Eocene/Oligocene boundary. Stover et al. (1988), in their morphologic and stratigraphic review of *Areosphaeridium* spp. also indicated that *A. diktyoplokus* was restricted to the Eocene. On the Norwegian Shelf *A. diktyoplokus* is used as an indicator for penetration of Eocene sediments, although specimens are invariably rare.

As shown in text-figures 5 and 6, we encountered a thin interval in wells 34/8-1 and 6407/71, between the last stratigraphic occurrence of *H. porosa* and the first occurrence of *R. actinocoronata*. Although *A. diktyoplokus* is absent, and no positive criteria for Eocene deposits have been recognized, we deem it possible that the interval represents a zone T5, that might correspond to part or all of the Priabonian stage. The poor stratigraphic resolution may be explained from regional condensation or a hiatus, as observed in the 16/1-1 well (text-fig. 7) during the Late Eocene.

T6A Zone

Top defined on: last stratigraphic occurrence of *Svalbardella cooksoniae*

Age: Rupelian (lower part), Early Oligocene

Discussion: The zone is characterized in its upper part by common *Chiropteridium* spp. *Reticulatosphaera actinocoronata* (see the discussion earlier for its stratigraphic range) has its first stratigraphic occurrence (as observed in swc) below common *Chiropteridium mespilanum*. Well preserved specimens of *Wetzeliella symmetrica* and *W. gochtii* are rare in the wells analyzed by us.

According to the literature review in Head and Norris (1989), the index taxa of the zone, *S. cooksoniae* has not been recorded younger than early Oligocene in the Norwegian Sea (Manum et al. 1989) and in the North Sea. Offshore eastern Canada, however, it has been recorded from so-called middle or upper Oligocene (Barss et al. 1979), but we consider that assignment as too young, and the result of reworking of specimens in younger strata. We base this interpretation on the Rupelian range of *Turrilina alsatica* (see previous section). Note that in the present study, the top of *S. cooksoniae* is encountered higher than the base of *R. actinocoronata*, in contrast to what Manum et al. found at the Vøring Plateau.

Zone T6A correlates to the lower part of the *Rotaliatina bulimoides-Dorothia seigliei* Zone (table 3).

T6B/C Zone

Top defined on: last stratigraphic occurrence of *Areoligera semicirculata*

Age: Rupelian (upper part), Early Oligocene

Discussion: The lower part of zone T6B/C is characterized by an acme of *A. semicirculata*. Species other than *A. semicirculata* that, according to the literature, have their last occurrence close to the Rupelian/Chattian boundary are *Wetzeliella symmetrica, W. gochtii* and *Rhombodinium draco*. Although useful as additional criteria, we find these species inconvenient as index taxa for the identification of upper Rupelian in offshore sections, partly because they occur rarely and partly because intermediate morphological forms are common. According to Williams and Bujak (1985), *W. gochtii* has its LO at the Rupelian/Chattian boundary. Costa and Manum (in Vinken 1988) show the LO of *A. semicirculata* together with *W. gochtii* LO; we therefore regard the upper limit of zone T6B/C as close to the Rupelian/Chattian boundary. The upper limit of the Middle Oligocene zone D14 (defined by *W. symmetrica* LO) of Costa and Manum (in Vinken 1988) is probably slightly higher than that of our zone T6B/C.

Zone T6B/C correlates to the upper part of the North Sea foraminiferal zone of *Rotaliatina bulimoides-Dorothia seigliei* of Rupelian age (table 3).

T7 Zone

Top defined on: last stratigraphic occurrence of *Chiropteridium lobospinosum*

Age: Chattian, Late Oligocene

Discussion: The highest occurrence of *Chiropteridium* spp. has been regarded as a reliable marker for the upper limit of the Oligocene, but there are several records showing that *C.*

Plate 6

1-6 *Subbotina patagonica* Todd and Kniker from Shell 29/3-1, 8390′; 1, ×145; 2, ×80; 3, ×100; 4, ×85; 5, ×70; 6, ×100.

7-11 Ex group *Globorotalia praescitula* Blow - *G. zealandica* Hornibrook from Shell 30/19-1, swc, 5850′; 7 ×90; 8 ×95; 9 ×110; 10 ×145; 11 ×125.

mespilanum ranges into the lowermost Miocene (see Manum et al. 1989). These authors recommend using *C. partispinatum* LO to delimit the Upper Oligocene, and Costa and Manum (in Vinken 1988) use the highest occurrence of *C. partispinatum* and *C. lobospinosum* as indicative of Upper Oligocene (top zone D15). Brinkhuis et al. (in press) use *Chiropteridium* spp. LCO as indicative for the Oligocene/Miocene boundary. Haq et al. (1987) indicate that *D. phosphoritica* has its highest occurrence at the Oligocene/Miocene boundary, but Brinkhuis et al. (in press) show that *Deflandrea* spp. probably range into basal Miocene strata.

In our study of the 34/8-1 and 6407/7-1 wells, the evaluation of the Oligocene/Miocene transition is hampered by a basal Miocene unconformity (see discussion of foraminiferal record in previous chapter). In Northern North Sea well 34/8-1, *C. lobospinosum* and *D. phosphoritica* have their highest occurrence in the same sample, while in the 16/1-1 well, *D. phosphoritica* ranges high up in the *Tuberculodinium vancampoae* Zone of early Miocene age (Ioakim 1979). For this reason, we consider the LO of *C. lobospinosum* (and *C. partispinum*) as most suitable for indicating the upper boundary of the Chattian.

Zone T7 is characterized by common *C. mespilanum* and *Homotryblium floripes* in the lower part. The characteristic dinocyst *Distatodinium biffii* (Brinkhuis et al. in press) is present almost throughout the zone. At the Monte Conero section of central Italy, this species (called *Distatodinium paradoxum* sensu Gocht) is reported from the base of NP25 and almost to the top of this nannoplankton zone (Biffi and Manum 1988). In a recent study in Italy, Brinkhuis et al. (in press) found the lowermost occurrence of *D. biffii* in mid NP24, or slighty lower. *D. biffii* thus seems to be a marker for Chattian, Late Oligocene.

Zone T7 probably corresponds to the central North Sea foraminiferal zone of *Globigerina* ex gr. *officinalis* of Chattian age (see discussion in previous section).

ZONAL CORRELATIONS

A combination of several strategies is generally the best approach to obtain information or solve a problem. This is particularly true for stratigraphy in offshore basins, where sampling is limited and of mediocre quality. This is the reason why we combine palynological and foraminiferal distributional data to provide a multiple stratigraphic framework for the North Sea. In table 3 we present the interrelation, as outlined in the previous sections of our Paleogene dinoflagellate and foraminiferal zonations in the northern North Sea and Haltenbanken. The indirect calibration to the standard NP nannofossil zones and standard planktonic foraminiferal zonations (taken from Berggren et al. 1985a, 1985b; Aubry et al. 1988) has also been discussed in the previous chapters and will not be repeated here. Correlations of our dinoflagellate zonation to that of Costa and Manum (in Vinken 1988) for the North Sea are also shown in table 3. This comparison is somewhat hampered because Costa and Manum (in Vinken 1988) lacks documentation of the well sites and depth intervals and detailed onshore correlations of the zones proposed.

Comparison of our foraminiferal events to the zones proposed for the circum central North Sea by King (1983) and Gramann and von Daniels (in Vinken ed. 1988) enabled us in table 3 to propose an interrelation of King's (1983) and Costa and Manum (in Vinken 1988) zonal schemes, not previously attempted in the literature.

As a result of our detailed study, we suggest that improvements to the regional Cenozoic biochronostratigraphic framework will come from more detailed investigation of the dinoflagellate and foraminiferal record in the same North Sea wells.

CONCLUSIONS

We use Ranking and Scaling (RASC), a new method of zonation and correlation called STRATCOR and conventional comparison of foraminifer and dinoflagellate cyst events in the same well sites to arrive at a detailed Cenozoic biostratigraphy for Paleogene bathyal and Neogene neritic strata, north of 55° in the central North Sea, and offshore central Norway. We emphasize ease of zonal recognition and reliability in correlation rather than maximum stratigraphic resolution. All zones are calibrated to standard planktonic zonations.

Eight Paleogene and four Neogene interval zones of benthic and some planktonic foraminifera involve the average last occurrence of 64 taxa present in a minimum of 7 of 33 wells studied. Eighteen rare but stratigraphically important shelly microfossils and dinoflagellate cyst taxa were inserted as "unique events". The zones are from oldest to youngest: (1) *Subbotina pseudobulloides* Zone, Danian; (2) *Trochammina ruthven murrayi-Reticulophragmium paupera* Zone, Selandian; (3) *Coscinodiscus* Zone, early Ypresian; (4) *Subbotina patagonica* Zone, late Ypresian; (5) *Ammomarginulina aubertae* Zone, Lutetian; (6) *Reticulophragmium amplectens* Zone, late Lutetian-Bartonian; (7) *Dorothia seigliei-Rotaliatina bulimoides* Zone, Rupelian; (8) *Globigerina* ex gr. *officinalis* Zone, Chattian; (9) *Globorotalia* ex gr. *praescitula* Zone, early-middle Miocene; (10) *Bolboforma metzmacheri* Zone, late Miocene; *Neogloboquadrina atlantica* Zone, early Pliocene; (11) *Cibicidoides grossa* Zone, late Pliocene.

Thirteen Paleogene dinoflagellate cyst interval and peak zones are defined, using our detailed record in 3 wells and literature-based range charts: Zone T1A - earliest Danian; Zone T1B - late Danian; Zone T2A - early Selandian; Zone T2B - middle Selandian; Zone T2C - late Selandian; Zone T3A - earliest Ypresian; Zone T3B - Ypresian; Zone T3C - Ypresian/Lutetian boundary; Zone T4A/B - early Lutetian; Zone T4C/D - late Lutetian/Bartonian; Zone T6A - early Rupelian; Zone T6B/C - late Rupelian; Zone T7 - Chattian.

A composite standard sequence of 60 foraminiferal and 39 dinoflagellate cyst species events in 3 of the same wells greatly facilitates interrelation of the foraminiferal and dinoflagellate cyst zonations, and assists with chronostratigraphic calibration. The last occurrence of *Apectodinium augustum* (T2C) at the top of the *Reticulophragmium paupera* (sub) Zone correlates to the Paleocene/Eocene boundary. The overlying volcanic tuffs of the Balder Formation correspond to the *Coscinodiscus* Zone and the acme of *Deflandrea oebisfeldensis* (T3A), in uppermost NP9 and NP10, early Ypresian. The last common occurrences of *Eatonicysta ursulae* and *Dracodinium pachydermum* (T3C), in or just below NP14, are in the basal part of the *Ammomarginulina aubertae* Zone, which probably extends throughout the Lutetian. The overlying *Reticulophragmium amplectens* Zone contains *Globigerapsis index* of NP16 age, and the last occurrence of *Heteraulacysta porosa* (T4C/D), also of NP16 or possibly NP17 age. The *Reticulophragmium amplectens* Zone probably is not younger than Bartonian. Above it occurs a widespread regional hiatus, equating to the Priabonian. The appearances of *Areoligera semicirculata, Reticulatosphaera actinocoronata* and *Chiropteridium lobospinosum* (T6A), in the lower part of *Dorothia seigliei-Rotaliatina bulimoides* Zone, correlate to NP22. The younger part of this foraminifer zone contains the last occurrences of *Svalbardella cooksoniae* and *Wetzelliella symmetrica* (T6B/C); it is Rupelian in age, possibly extending slightly in Chattian strata (younger P21). The overlying zone of *Globigerina* ex gr. *officinalis* contains most or all of the range of *Distatodinium biffii* (T7); *C. lobospinosum* and *Deflandrea phosphoritica* also disappear in this zone, which is assigned a Chattian age. Many well sites have a late Miocene hiatus. The disappearance of *Neogloboquadrina atlantica* and *Globorotalia puncticulata* and the appearance of *G. inflata* are used in zoning thick Pliocene deposits.

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Appendix 1

Listing of Cenozoic foraminifers, dinoflagellate cysts, spores and miscellaneous microfossils in the wells Norsk Hydro 6407/7-1 (Haltenbanken), Norsk Hydro 34/8-1 (northern Viking Graben), and Esso Norway 16/1-1 (southern Viking Graben). This data is used to calculate the composite standard sequence in Figure 8 (right). Samples are ditch cuttings, unless shown otherwise; swc = sidewall cores, c = cores. The depths of the log markers B through G are based on the log picks by A. C. Morton and R. Knox (BGS, Keyworth).

Norsk Hydro 6407/7-1, Haltenbanken (m)

Depth	**Fossil Name**
910	*Cassidulina teretis*
	Cibicidoides grossa
	Elphidium spp.
940	*Globorotalia inflata*
	Neogloboquadrina pachyderma
970	*Globorotalia puncticulata*
1040	*Neogloboquadrina atlantica*
1100	*Turrilina alsatica*
1110	*Deflandrea phosphoritica*
	Chiropteridium lobospinosum
	Areoligera semicirculata
1120	*Wetzelliella symmetrica*
	Areoligera semicirculata LCO
1140	*Svalbardella cooksoniae*
1160	*Spiniferites* sp. 2 Manum et al.
1180	*Areoligera semicirculata* FO
	Chiropteridium lobospinosum FO
1199 swc	*Reticulatosphaera actinocoronata* FO
1200	*Alabamina scitula*
1210 swc	*Operculodinium tiara*
1230	*Aschemonella grandis*
	Coarse agglutinated foram spp.
1245 swc	*Reticulophragmium amplectens*
	Heteraulacacysta porosa
	Areosphaeridium cf. *diktyoplokus*
1250 swc	*Areosphaeridium diktyoplokus*
	Rottnestia borussica
	Rhombodinium porosum
1320	*Spiroplectammina spectabilis* LO
	Cyclammina placenta
1340	*Diphyes colligerum*
	Areosphaeridium fenestratum
	Phthanoperidinium echinatum LCO
1380	*Ammosphaeroidina pseudopauciloculata*
1460	*Karreriella horrida*
1540 swc	*Diphyes ficusoides*
1550 swc	*Systematophora placacantha* LCO
1570	*Reticulophragmium intermedia*
1600 swc	*Dracodinium pachydermum*
1630	*Eatonicysta ursulae*
	Dracodinium pachydermum LCO
1640	*Eatonicysta ursulae* LCO
1660	*Spiroplectammina navarroana*
	Haplophragmoides kirki
	Haplophragmoides walteri
1674 swc	*Karreriella conversa*
	Alabamina wilcoxensis
1675 swc	*Deflandrea phosphoritica* FO
	Areoligera spp. LCO
1690	*Haplophragmoides retroseptus*
	Karreriella coniformis
1710	*Subbotina patagonica*
	Subbotina eocaena
1730	*Cystammina* aff. *globigerinaeformis*
1739 swc	*Deflandrea oebisfeldensis*
	Inapertupollenites spp. LCO
1740	*Haplophragmoides decussatus*
1765 swc	*Glaphyrocysta ordinata* LCO
1820	*Deflandrea oebisfeldensis* LCO
1825 swc	*Trochamminoides coronatus*
1860	*Apectodinium augustum*
1870	*Reticulophragmium garcilassoi*
1895 swc	*Alisocysta margarita*
1898 swc	*Trochammina ruthven murrayi*
	Kalamopsis grzybowskii
	Cystammina pauciloculata
	Greenbug assemblage
	Saccammina placenta
1927 swc	*Spiroplectammina spectabilis* LCO
1940	*Areoligera* cf. senonensis
	Alisocysta margarita LCO
	Palaeoperidinium pyrophorum
	Palaeoperidinium pyrophorum LCO
1960	*Ammodiscus planus*
	Palaeocystodinium bulliforme
	Palaeocystodinium bulliforme LCO
1975 swc	*Rzehakina minima*

Norsk Hydro 34/8-1, Viking Graben (m)

Depth	**Fossil Name**
1034 swc	*Cassidulina teretis*
	Cibicidoides grossa
1040	*Trifarina fluens*
	Elphidium clavatum
	Neogloboquadrina pachyderma
1080	*Neogloboquadrina atlantica*
	Cassidulina islandica
	Caucasina elongata
1089	NS Log Marker G
1090	*Asterigerina gurichi*
1100	*Catapsydrax unicavus*
	Globigerina praebulloides
1150	Neogene radiolarian flood
1161 swc	*Deflandrea phosphoritica*
	Homotryblium floripes
	Chiropteridium lobospinosum
1194 swc	*Distatodinium biffii*
	Turrilina alsatica
	Uvigerina gallowayi
1220	*Homotryblium floripes* LCO
	Coarse agglutinated foram spp.
	Spirosigmoilinella compressa
	Cyclammina placenta
	Dorothia seigliei
1400	*Haplophragmoides walteri*
1410	*Haplophragmoides walteri excavatus*
1422 swc	*Distatodinium biffi* FO
1440	*Karreriella horrida*
	Adercotryma agterbergi
	Wetzeliella symmetrica
1458 swc	*Areoligera semicirculata*
	Areoligera semicirculata LCO
1480	*Svalbardella cooksoniae*
1497 swc	Eocene radiolarians flood
	Reticulophragmium amplectens
	Ammosphaeroidina pseudopauciloculata
	Reticulatosphaera actinocoronata FO
	Chiropteridium lobospinosum FO
	Areoligera semicirculata FO
	Spiniferites sp. 2 Manum et al.
1540	*Areosphaeridium diktyoplokus*
	Areosphaeridium cf. diktyoplokus
	Heteraulacacysta porosa
1580	*Rhombodinium porosum*
	Operculodinium tiara
1600 swc	*Glomospirella biedae*
	Diphyes colligerum
	Dracodinium spp.
1610	*Haplophragmoides kirki*

1620	*Areosphaeridium fenestratum*
	Rottnestia borussica
1710	*Diphyes ficusoides*
1720	*Systematophora placacantha* LCO
1725 swc	*Haplophragmoides retroseptus*
1730	*Spiroplectammina spectabilis* LO
1740	*Dracodinium pachydermum*
	Eatonicysta ursulae
1760	*Reticulophragmium intermedia*
	Karreriella coniformis
	Pseudohastigerina wilcoxensis
1778 swc	*Dracodinium pachydermum* LCO
	Eatonicysta ursulae LCO
1786 swc	*Ammodiscus planus*
	Areoligera spp. LCO
	Dracodinium spp. LCO
1790	*Bulimina trigonalis*
	Planorotalites planoconicus
1805 swc	*Subbotina eocaena*
1815 swc	*Dracodinium pachydermum* FO
1820	*Subbotina frontosa*
	Subbotina patagonica
1829 swc	*Deflandrea oebisfeldensis*
	Deflandrea oebisfeldensis LCO
	Inapertupollenites spp. LCO
1830	*Coscinodiscus* spp.
1832	Tuff
1868 swc	*Apectodinium augustum*
1875 swc	*Glomospira irregularis*
	Glomospira diffundens
	Spiroplectammina navarroana
	Reticulophragmium garcilassoi
	Rzehakina minima
1884 swc	*Reticulophragmium paupera*
	Kalamopsis grzybowskii
	Saccammina placenta
	Alisocysta margarita
1890	*Labrospira pacifica*
1892 swc	*Spiroplectammina spectabilis* LCO
1898 swc	*Cystammina pauciloculata*
	Cystammina aff. globigerinaeformis
	Hormosina excelsa
	Areoligera cf. *senonensis*
1943 swc	*Palaeocystodinium bulliforme*
1950	*Trochammina ruthven murrayi*
1955 swc	*Palaeoperidinium pyrophorum*
1975 swc	*Alisocysta margarita* LCO
	Palaeoperidinium pyrophorum LCO
1995 swc	*Gavelinella beccariiformis*
	Palaeocystodinium bulliforme LCO
2006 swc	*Spongodinium delitiense*
2010	*Matanzia varians*
	Palynodinium grallator

Esso Norway 16/1-1, Viking Graben (f)

Depth	**Fossil Name**
1250	*Elphidium* spp.
	Cassidulina teretis
	Cassidulina islandica
	Cibicidoides grossa
2090	*Sigmoilopsis schlumbergeri*
	Neogloboquadrina pachyderma
	Globorotalia inflata
2110	*Martinotiella cylindrica*
2320	*Globorotalia crassaformis*
	Neogloboquadrina atlantica
2385 swc	*Globorotalia puncticulata*
2410	*Epistomina elegans*
2700	Neogene radiolarian flood
2950	*Globorotalia* ex. gr. *praescitula zealandica*
	Neogloboquadrina continuosa
	Globigerina praebulloides
2980	*Caucasina elongata*
	Asterigerina gurichi
3400	*Uvigerina* ex. gr. *miozea-nuttali*
3704	NS Log Marker G
4000	Coarse agglutinated foram spp.
4222	*Chiropteridium lobospinosum*
4502	*Wetzelliella symmetrica*
4580	*Rotaliatina bulimoides*
	Turrilina alsatica
	Spirosigmoilinella compressa
	Cyclammina placenta
5052	NS Log Marker F
5100 c	*Dorothia seigliei*
	Haplophragmoides walteri
	Adercotryma agterbergi
5200	*Haplophragmoides kirki*
	Karreriella horrida
5222 swc	*Areosphaeridium diktyoplokus*
5250	Eocene radiolarians flood
5643 c	*Ammomarginulina aubertae*
5665 c	*Spiroplectammina spectabilis* LO
5671 c	*Reticulophragmium amplectens*
6315 c	*Phthanoperidinium echinatum* LCO
6622 swc	*Eatonicysta ursulae* LCO
	Dracodinium pachydermum LCO
6923	NS Log Marker E
7060 c	*Karreriella conversa*
	Haplophragmoides retroseptus
	Spiroplectammina navarroana
	Dracodinium spp. LCO
7069 c	*Acarinina pentacamerata*
	Subbotina patagonica
7103 c	*Turrilina robertsi*
7222 c	*Glaphyrocysta ordinata* LCO
7296 c	*Pseudohastigerina wilcoxensis*
7354 swc	*Deflandrea oebisfeldensis*
	Tuff
	Apectodinium augustum
7375 c	*Coscinodiscus* spp.
7402 swc	*Trochamminoides coronatus*
7411	NS Log Marker D
7572	NS Log Marker C
7903 c	*Reticulophragmium paupera*
7940	*Cystammina pauciloculata*
7958 c	*Reticulophragmium garcilassoi*
8332 c	*Palaeoperidinium pyrophorum* LCO
8460 c	*Bulimina trigonalis*
8480	*Spiroplectammina spectabilis* LCO
8623 c	*Matanzia varians*
	Subbotina pseudobulloides
	Gavelinella beccariiformis
	Gaudryina aff. hiltermanni
8924 c	*Planorotalites compressus*
8990 c	*Subbotina triloculinoides*
	Globoconusa daubjergensis