

# Cainozoic biostratigraphy and palaeobathymetry, northern North Sea and Haltenbanken

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Gradstein, F. M. & Bäckström, S. A.: Cainozoic biostratigraphy and palaeobathymetry, northern North Sea and Haltenbanken. *Norsk Geologisk Tidsskrift*, Vol. 76, pp. 3–32. Oslo 1996. ISSN 0029-196X.

This study details the biostratigraphy and palaeobathymetry of Palaeogene bathyal and Neogene neritic strata in the North Sea and on Haltenbanken, using the 'tops' or last common presence of 190 benthic and planktonic foraminifers, dinoflagellates, and miscellaneous microfossils in 26 wells. Mathematical and graphical sequencing methods assisted with definition of the zones, and with the most likely order of the microfossil events within each zone. The interval zones are: Zone NSR13 – *Cassidulina teretis*, Pleistocene; Zone NSR12B – *Cibicides grossa*, late Pliocene; Zone NSR12A – *Monspeliensis pseudotepida*, early (part of) Late Pliocene; Zone NSR11 – *Neoglobobulimina atlantica*, Early Pliocene; Zone NSR10 – *Bolboforma metzmacheri*, Late Miocene; Zone NSR9B – *Martinotiella cylindrica*, late Middle to early Late Miocene; Zone NSR9A – *Globorotalia praescitula* gr., late Early to early Middle Miocene; Zone NSR8B – unnamed, Early Miocene; Zone NSR8A – *Globigerina* ex. gr. *officinalis*, Late Oligocene (Chattian); Zone NSR7B – *Turrilina alsatica*, Early Oligocene to early Late Oligocene; Zone NSR7A – *Adercotryma agterbergi*, Early Oligocene (Rupelian); Zone NSR6B – *Globorotalia cerroazulensis*, Late Eocene (Priabonian); Zone NSR6A – *Reticulophragmium ampletens*, late Middle Eocene (Bartonian); Zone NSR5B – *Ammomarginulina aubertae*, early Middle Eocene (Lutetian); Zone NSR5A – *Reticulophragmium intermedia*, late Early to early Middle Eocene; Zone NSR4 – *Subbotina patagonica*, Early Eocene (Ypresian); Zone NSR3 – *Coscinodiscus* spp., earliest Eocene; Zone NSR2B – *Reticulophragmium paupera*, Late Palaeocene (Selandian); Zone NSR2A – *Trochammina ruthvenmurrayi*, early Late Palaeocene; Zone NSR1 – *Subbotina pseudobulloides*, Early Palaeocene (Danian). Range charts give details of the stratigraphic extent of 140 foraminifers and other shelly microfossil taxa. The zonation is correlated to a seismic sequence stratigraphy with 14 depositional units. Palaeoecological analysis reveals five foraminiferal assemblages, which characterize inner shelf through middle slope (bathyal) depth regimes. The upper Oligocene–lower Miocene siliceous biofacies on Tampen Spur is thought to reflect slope upwelling. Upper Eocene strata appear to be largely missing in the central North Sea, as is part or all of the Upper Miocene.

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## Introduction

This study emphasizes the stratigraphic utility of foraminifers and dinoflagellate cysts in one integrated biozonation for the Cainozoic of the northern North Sea and Haltenbanken. The zonation is aimed at being practical and relatively robust, which means that zones can readily be recognized and apply over a wide range of palaeoenvironments. For that reason emphasis is on foraminiferal and dinoflagellate events that are relatively widespread and readily recognized, and that were observed in the same samples. Hence, a local absence of one or more zones can be interpreted confidently as the result of a hiatus. Mathematical and graphical sequencing methods were employed to calculate and outline the basic zonal succession in relative time. For each zone the most likely order of the microfossil events was established.

A second objective of this study is to outline palaeobathymetric trends, using foraminiferal ecology and palaeoecology from North Sea and Atlantic margin transects, visualized along seismic cross-sections. Using multiple fossil criteria, five depositional environments are recognized in the Cainozoic strata of the northern North Sea and Haltenbanken, classified in accordance with both water depth and distance from shore. The combina-

tion of chronostratigraphy and palaeobathymetry in chronograms highlights regional depositional trends in time, as does correlation of the biozones to the seismic sequences mapped in the central and northern North Sea (Jordt et al. in prep.).

The fossil record utilized in this study consists of the last stratigraphic occurrence (top) or last common stratigraphic occurrence of 299 taxa of foraminifers, dinoflagellate cysts and miscellaneous microfossils in ditch-cuttings, side-wall cores, and cores in 26 wells. In total, 1546 occurrences (events) of the 299 taxa were stratigraphically evaluated. The shelly microfossils (foraminifers, diatoms and miscellaneous taxa) in the wells were studied by the authors. The dinoflagellate and spore/pollen record is from R. Jan du Chene in unpublished reports for Saga Petroleum a.s. (1992), and from I. L. Kristiansen in Gradstein et al. (1992).

The biozonation was calculated with two quantitative stratigraphy programs that calculate and construct microfossil event sequences in relative time. The principal quantitative stratigraphic method utilized in this study is Ranking and Scaling (RASC; Agterberg 1992; Gradstein et al. 1985), which considers the stratigraphic order of all (pairs of) events in all wells simultaneously, and calculates the most likely sequence of events. In this optimum



sequence, each event position is an average of all individual positions encountered in the wells.

Scaling of the optimum sequence in relative time is a function of the frequency with which events in each pair in the optimum sequence cross-over their relative positions (observed records) from well to well; the more often any two events cross-over from well to well, the smaller their interfossil distance. Final distance estimates are expressed in dendrogram format, where tightness of clustering is a measure of nearness of events along a stratigraphic scale. The scaled version of the optimum sequence features time-successive clusters, each of which bundles distinctive events. Individual bundles of events are assigned zonal status. The process of zone assignment in the scaled optimum sequence is somewhat subjective, as guided by the stratigraphic experience of the users. Large interfossil distances between successive dendrogram clusters agree with zonal boundaries, reflecting breaks in the fossil record due to average grouping of event extinctions. Such extinctions occur for a variety of reasons. From a practical point of view it suffices to say that taxa in a zone on average group close together in relative time.

The RASC method features three tests to determine whether the individual well record differs from the most likely zonation; these tests guide the user to outliers as a result of event misidentification, reworking or sample contamination.

A second method, employed mainly to complement RASC, is probabilistic graphic zonation (program STRATCOR; Gradstein 1990). The event record in well 1 is cross-plotted with that in well 2; a best fit line through the events in common between both wells is used to interpolate the well 1 record in that of well 2; next well 3 is cross-plotted with the updated record in well 2 and interpolated in it, and so on. Cross-plotting and interpolation proceeds semi-automatically for all wells, until a final composite standard has been calculated. STRATCOR, like RASC, has several built-in normality tests to detect outliers in the well record. The method is more subjective than RASC, but can proceed with fewer wells (2–5).

Two range charts, displayed in fold-outs, show the stratigraphic distribution in time of foraminifers and miscellaneous shelly microfossils for the northern North Sea and Haltenbanken. The average stratigraphic range of taxa is indicated by a solid line; local extensions upward and downward in wells, reflecting local ranges, are indicated by a hatched line. Obviously, an average stratigraphic range and a maximum one will coincide if the scatter in relative last occurrence position of a taxon from well to well is small. The total, or complete range of a taxon can be observed only rarely, whereas there is more likelihood of finding specimens of a taxon in the interval covered by its average biostratigraphic range. Hence, the average biostratigraphic range of fossils is well suited for exploration stratigraphy.

## Well data

Here we focus on the fossil record that forms the basis for this study. The North Sea and Haltenbanken records consist of the highest (last) occurrence (LO or 'tops'), or last common occurrence (LCO) of calcareous and agglutinated benthic foraminifers, planktonic foraminifers, dinoflagellates and miscellaneous microfossils, including *Bolboforma* spp., diatoms and radiolarians. The data are from 26 selected wells (Fig. 1); the North Sea wells are between 55° and 62°N in the Central and Viking Grabens, and the Tampen Spur; the Haltenbanken wells, offshore mid-Norway, are at 64°–65°N.

The zonation directly derives from a study of 12 Norwegian sector wells by the authors at Saga Petroleum a.s. in Oslo, and 14, largely UK sector wells, studied previously by the senior author in Canada. The following wells were studied at Saga Petroleum a.s., Oslo: Hydro 6407/7-1, Saga 6407/2-3, Statoil 6407/4-1, Elf Aquitane 6406/8-1, Saga 35/3-1, Saga 34/7-1, 7-2, 7-4 and 7-15s, Saga 34/4-5, Hydro 34/8-1 and Saga 2/2-4. The foraminiferal analysis was done on samples largely processed and selected by J. Nagy's laboratory, University of Oslo. R. Jan du Chene, France analysed many of the same samples in seven of the wells for palynology; the palynology slides were processed by the well operators. The palynology in wells Hydro 6407/7-1 and 34/8-1 follows I. L. Kristiansen, in Gradstein et al. (1992), with minor updates.

In order to increase the number of observations on the relative stratigraphical order of all (pairs of) taxa, data were added from 14 North Sea wells (Gradstein et al. 1992; Fig. 1), including: Shell (UK) 9/32-1, Mobil (UK) 9/13-3A, Total (UK) 3/25-1, BP (UK) 15/20-2, Phillips (UK) 16/17-1, BP (UK) 21/10-1, BP (UK) 21/10-4, Esso 16/1-1, Shell (UK) 22/6-1, Phillips (UK) 23/22-1, Shell (UK) 29/3-1, Shell (UK) 30/19-1 and Amoco 2/8-1. The choice of these wells balances representation of the four areas under study: Haltenbanken, Tampen Spur, Viking Graben and Central Graben, with emphasis on the more northerly regions.

In addition, detailed observations on microfossil distributions in an additional 20 wells in the North Sea, and over 30 wells, offshore eastern Canada (Gradstein et al. 1994) assisted with zone definition and calibration in time. The Cainozoic record in the Canadian wells resembles that of the North Sea, but is less endemic. It contains more Cainozoic planktonic foraminifers assignable to standard Cainozoic zones, which helps with chronostratigraphic calibration of the proposed zonation.

The taxonomy of the foraminiferal taxa used in this study is relatively well known. For details the reader is referred to Stainforth et al. (1975), Gradstein & Agterberg (1982), Kennett & Srinivasan (1983), King (1983, 1989), Van Morkhoven et al. (1986), Gradstein & Kaminski (1989), Kaminski et al. (1989). The taxonomy of the 'cosmopolitan' agglutinated benthic foraminiferal record, which includes the North Sea, is treated in detail



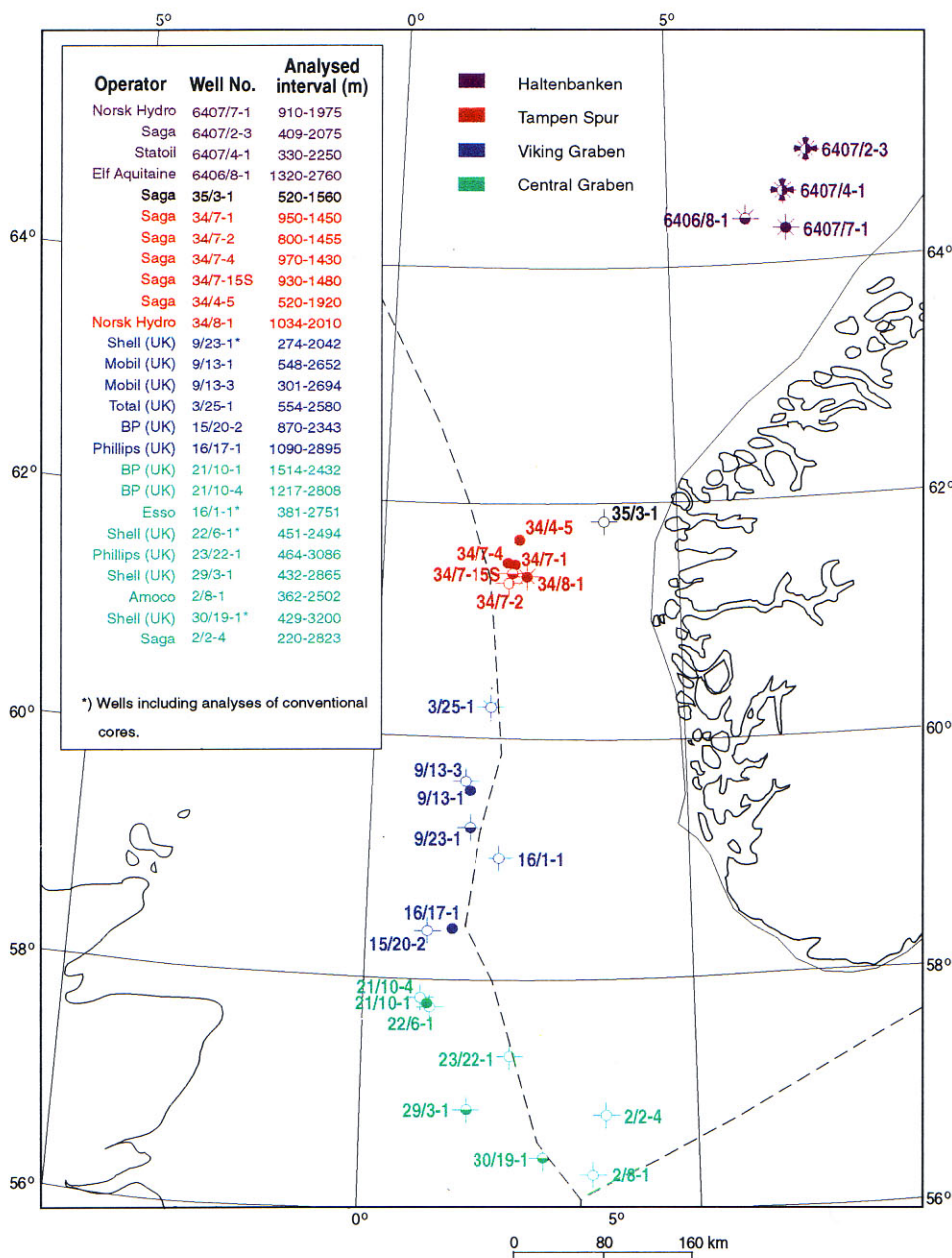


Fig. 1. Location of the northern North Sea and Haltenbanken wells, and the Cinozoic intervals studied. Wells denoted with an asterisk have a cored record.

by Charnock & Jones (1990), and Kaminski et al. (in prep.). Most shelly microfossils listed in the zonation are illustrated in King (1983, 1989), Gradstein et al. (1992, 1994), Charnock & Jones (1990), and Kaminski et al. (in prep.). Valuable references on taxonomy and zonation also include Van der Zwaan et al. (1986), which is the most authoritative study on the comparative taxonomy and stratigraphy of the multitude of Northwestern European uvigerinids, Doppert (1980), Doppert & Neele (1983) and Eidvin & Riis (1991, 1992). Details on dinoflagellate taxonomy can be found in Powell et al. (1992), and I. L. Kristiansen (in Gradstein et al. 1992).

In order to process the data with the RASC program, the microfossil record in each well was coded, using index numbers for each taxon and three rules that determine whether an event should be entered in the census

data: (a) a local identification with the qualifier aff. (affinis) is the same as the nominate taxon; (b) a local identification with the qualifier cf. (confer) for a regular dictionary taxon was omitted, or is a different taxon, e.g. *Areoligera* cf. *A. senonensis*; and (c) obviously reworked, or for other reasons (e.g. cavings) badly misplaced highest occurrences of taxa were eliminated as much as possible. 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, detected during ranking and scaling with the built-in stratigraphic normality tests (see discussion of the Cinozoic zonation). The record in well 6407/7-1, which has a well-defined Upper Oligocene through Miocene hiatus, for zonation purposes was actually coded as being from two separate wells: One 'well'



above and one 'well' below the hiatus. In such a way, RASC does not consider taxa across this hiatus as 'natural' pairs. In general, the database is robust enough to 'ignore' such stratigraphic 'noise', but it helps with resolution to segment wells in stratigraphically continuous units.

H. Jordt (Department of Geology, University of Oslo) provided the Cenozoic seismic sequence stratigraphy of the central and northern North Sea (Jordt et al. in prep). Fourteen mapped, seismic sequences are separated by seismic unconformities, as defined from reflection terminations, contrasts between adjoining sequences or regionally continuous reflections. Each sequence reflects a specific depositional trend, and is calibrated to a biostratigraphic framework, offshore Denmark (Michelsen et al. in press). The sequences are correlated to the zonation proposed in this study.

A. C. Morton & R. Knox (British Geological Survey, Keyworth, U.K.), provided depth picks for their log markers B–G in UK sector wells studied. According to Morton & Knox (pers. comm. 1984 and 1985) the log markers correspond to the following levels: Marker G – top Middle Miocene, Marker F – top Upper Eocene, Marker E – top Lower Eocene, Marker D – top Sele Formation or its equivalent, Marker C – base Sele Formation (top Palaeocene), Marker B – top Ekofisk Formation (top Lower Palaeocene). Inclusion of the log picks as events in the zonal model (Fig. 2) largely agrees with the inferred ages. Details are discussed with the zones.

The complete microfossil event data for wells listed in this study may be requested from the authors; for a file in ASCII format, users should forward a 3.5" microdisk.

## The Cainozoic biozonation

In this section, we propose a Cainozoic biozonation (Tables 1, 2; Fig. 2) using the microfossil events record in

the 26 wells from North Sea and Haltenbanken selected for this study. The record includes occurrences of 73 agglutinating and 55 calcareous benthic foraminifers, 61 planktonic foraminifers, 89 dinoflagellates and 21 miscellaneous events, such as *Bolboforma*, diatoms and some physical well log markers. In all, there are 299 dictionary entries, for a total of 1546 events, mostly last occurrences. The majority of events was recorded in a few wells only and the cumulative frequency distribution of events indicates that over half of them occur in fewer than 4 wells, and 30% in fewer than 8 wells; none of the taxa occur in all 26 wells.

The probabilistic RASC interval zonation shown in Fig. 2 was run with the thresholds  $k_c = 6$ ,  $m_{c1} = 0$  and  $m_{c2} = 3$ , where  $k_c$  represents the minimum number of wells in which each event must occur in order to be ranked,  $m_{c1}$  the number of wells in which each pair of events in the ranked optimum sequence must occur, and  $m_{c2}$  the minimum number of wells in which each pair of events in the scaled optimum sequence occurs. The RASC interval zonation contains 93 microfossil events that occur in at least 6 out of 26 wells, plus 19 'unique' events (listed below) that occur in 5 or fewer wells, for a total of 112 events. Average positions with a relatively large uncertainty were flagged in Fig. 2 with an x (not to be confused with 'unique' events in Fig. 2, marked with an asterisk).

The following 21 taxa were observed in 15 or more wells: *Elphidium* spp., *Cassidulina teretis*, *Neoglobobadrina pachyderma*, *N. atlantica*, *Cibicidoides grossa*, *Sigmoilopsis schlumbergeri*, *Globigerina praebulloides*, *As-terigerina gurichi*, *Spirosigmoilinella compressa*, *Cyclamira placenta*, *Reticulophragmium amplexens*, *R. paupera*, coarse agglutinated foram spp., *Spiroplectamina spectabilis* LO and LCO, *Subbotina pseudobulloides*, *Haplophragmoides walteri*, *H. kirki*, *Karreriella conversa*, *Cystammina pauciloculata*, *Ammosphaeroidina pseudo-pauciloculata*, *Coscinodiscus* spp.

As mentioned above, 19 unique events were added to the scaling solution of RASC in Fig. 2. These events

Table 1. Listing of the twenty interval zones for the Cainozoic of the northern North Sea and the Haltenbanken.

Zone NSR13	<i>Cassidulina teretis</i>	Pleistocene
Zone NSR12B	<i>Cibicidoides grossa</i>	late Pliocene
Zone NSR12A	<i>Monspelisina pseudotepida</i>	early (part of) Late Pliocene
Zone NSR11	<i>Neoglobobadrina atlantica</i>	Early Pliocene
Zone NSR10	<i>Bolboforma metzmacheri</i>	Late Miocene
Zone NSR9B	<i>Martinotiella cylindrica</i>	late Middle to early Late Miocene
Zone NSR9A	<i>Globorotalia praescitula</i> gr.	late Early to early Middle Miocene
Zone NSR8B		Early Miocene
Zone NSR8A	<i>Globigerina</i> ex. gr. <i>officinalis</i>	Late Oligocene (Chattian)
Zone NSR7B	<i>Turrilina alsatica</i>	Early to early Late Oligocene
Zone NSR7A	<i>Adercotryma agterbergi</i>	Early Oligocene (Rupelian)
Zone NSR6B	<i>Globorotalia cerroazulensis</i>	Late Eocene (Priabonian)
Zone NSR6A	<i>Reticulophragmium amplexens</i>	late Middle Eocene (Bartonian)
Zone NSR5B	<i>Ammomarginulina aubertae</i>	early Middle Eocene (Lutetian)
Zone NSR5A	<i>Reticulophragmium intermedia</i>	late Early to early Middle Eocene
Zone NSR4	<i>Subbotina patagonica</i>	Early Eocene (Ypresian)
Zone NSR3	<i>Coscinodiscus</i> spp.	earliest Eocene
Zone NSR2B	<i>Reticulophragmium paupera</i>	Late Palaeocene (Selandian)
Zone NSR2A	<i>Trochammina ruthvenmurrayi</i>	early Late Palaeocene
Zone NSR1	<i>Subbotina pseudobulloides</i>	Early Palaeocene (Danian)



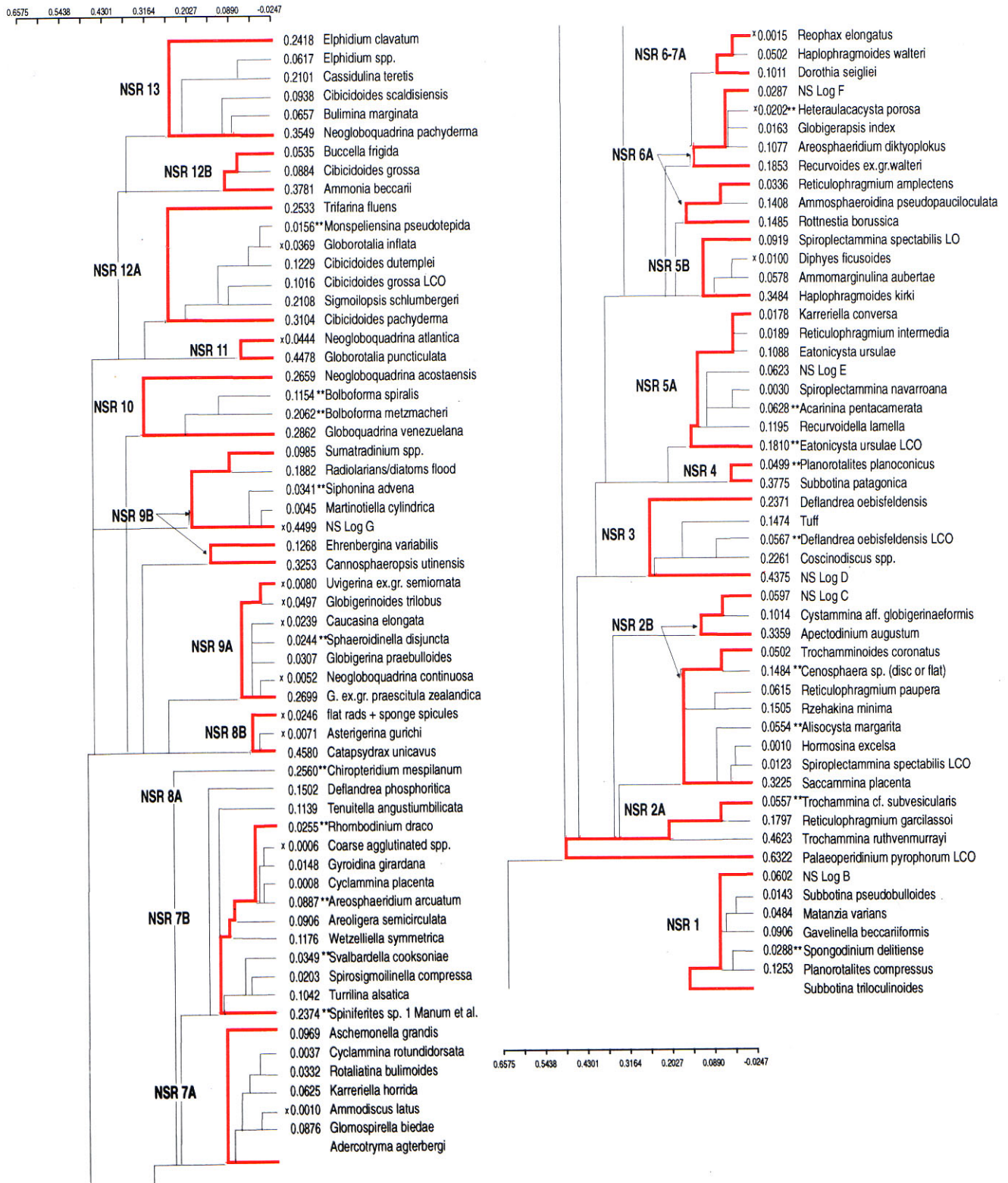


Fig. 2. Cainozoic interval zonation for the Central North Sea (Central Graben, Viking Graben and Tampen Spur), showing the average last occurrence of 93 foraminifers, dinoflagellates, miscellaneous microfossils and physical log markers B-G. It was calculated with program RASC (Ranking and Scaling). Each zonal event occurs in a minimum of 6 out of 26 wells examined, with the exception of 16 unique (rare) events shown as \*\*, which occur in fewer than 6 wells. 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. Average interfossil distances with relatively large uncertainty are flagged with an X. The generalized 20-fold NSR (= North Sea RASC) zonation, Danian through Pleistocene in age, is representative of the regional Cainozoic stratigraphy (see text). Relatively large interfossil distances in the mid- and latest Palaeocene, near the top of the early Middle Eocene, and in the earliest, Middle and latest Miocene correspond to major stratigraphic facies changes, with relatively large turnover of assemblages. The quantitative zonation does not aim at maximum stratigraphic resolution, but emphasizes zonal recognition and its widespread correlation through many well sites; hence, local absence of a zone can with confidence be assigned to a sedimentary hiatus. In the text, zonal detail is discussed and other taxa are merged in the zones that could not be accommodated in the RASC run.



occur in fewer than  $k_c$  ( $= 6$ ) wells, and up to 20 of those may be added to the scaled optimum sequence, using a simple insertion procedure built in the computer routine (Gradstein et al. 1985). The unique events assist with stratigraphical integration of the dinoflagellate and foraminiferal record, and with chronostratigraphic interpretation of the RASC zones. The unique events, listed in descending stratigraphic order, and their record are: *Monspeliensis pseudotepida* – 5 wells; *Bolboforma metzmacheri* – 4 wells; *Bolboforma spiralis* – 1 well; *Siphonina advena* 5 wells; *Sphaeroidinella disjuncta* – 5 wells; *Chiropteridium mespilanum* – 5 wells; *Rhombodinium draco* – 4 wells; *Areosphaeridium arcuatum* – 5 wells; *Svalbardella cooksoniae* – 4 wells; *Spiniferites* sp. 1 Manum et al. – 3 wells (*Spiniferites* sp. 1, also includes *S.* sp. 2 Manum et al. 1989, and *S. rugulatus* of well consultants); *Globigerinatheka index* – 3 wells; *Eatonicysta ursulae* LCO – 2 wells; *Acarinina pentacamerata* – 3 wells; *Deflandrea oebisfeldensis* LCO – 4 wells; *Planorotalites planoconicus* – 2 wells; *Cenosphaera* (disk or flat) – 3 wells; *Trochammina* cf. *subvesicularis* – 4 wells; *Alisocysta margarita* – 5 wells; *Spongodinium delitiense* – 1 well.

Owing to limitations in the number of unique events per RASC run ( $< 21$ ), observations remain that cannot be added directly to the zonal model. The limitation protects a computed zonal model from an 'overdose' of rare events, with insufficient pairwise event comparison information in the wells. Such events, 78 in all, were placed in a separate column, adjacent to that derived from the RASC zonation (Table 2, right column). Hence, the total number of taxa in the zonation of Table 2 is 190, details of which are discussed below.

Normality testing with RASC of the individual sequences in the 26 wells relative to scaled optimum sequences led to re-examination of scores of fossil tops, placed wrongly. Below follows a listing of emendations that 'cleaned' the large file of more obvious out-of-place events. As a result, wells were examined more than once to ascertain consistent assignments of as many taxa as possible. Emendations and deletions are discussed below. The final quantitative zonation presented here is based on the filtered data.

*Reticulophragmoides jarvisi*, *Cystammina pauciloculata*, *Cyclammina cancellata*, and *Cenosphaera* spp. LCO occur in more than 6 wells, but tops for each taxon in individual wells have such a wide stratigraphic range that the calculated average top is meaningless. We deleted these taxa from the data set. In well 6407/4-1, an occurrence of *Karreriella conversa* in the lower Palaeocene was deleted, because its range extends well into the Eocene in the North Sea. In well 35/3-1 *Adercotryma agterbergi* was deleted because of an uncertain taxonomic determination at an anomalously low stratigraphic level. In well 3/25-1, in Oligocene strata at 1100 m, we deleted the presence of lower-middle Eocene acarininids *A. lozanei* and *A. broedermanni*. A single occurrence of *Elphidium* spp. below NS log marker G was also deleted. In well 34/7-1, samples 1070 and 1110 m, with reworked Oligocene taxa,

were deleted. In well 34/8-1, the last occurrence of *A. aubertae* was found three zones lower than expected and was deleted. In well (UK) 9/23-1 and other 9-block wells, A. C. Morton (pers. comm. 1988) reported difficulty in picking NS log marker G ('middle Miocene'), as borne out by the presence of a diversified Pliocene assemblage below its pick at 290 m. This log level was thus deleted. In wells (UK) 15/20-2 and 2/7-1X, a determination of *Cystammina pauciloculata*, respectively at 1510 m and 2557 m, was changed to *Ammosphaeroidina pseudopauciloculata*. In well 16/1-1, the anomalously low occurrence of *S. advena* and *C. rotundidorsata* in 16/1-1 was verified using normality testing; these events were suppressed in the data set. In well (UK) 16/17-1, a determination of *Rzehakina minima* at 1603 m was changed to *Spirosigmoilinella compressa*. In well (UK) 23/22-1, the scattered occurrences of *Turrilina alsatica*, *Rotaliatina bulimoides* and *Haplophragmoides walteri* between 1859 m and 2438 m make it difficult to assign firm (Oligocene) last occurrence levels. The tops used are provisional. Since the NS log F marker ('top Eocene') was assigned at 2468 m, we consider the presence of *Reticulophragmium amplectens*, *Acarinina* sp., *Subbotina patagonica* and *Turrilina robertsi* (all Eocene taxa) between 2182 m and 2292 m to be due to reworking. These tops were ignored. Similarly, a late Palaeocene assemblage with *Subbotina trilocolinoides*, *S.* aff. *variata*, *S. velascoensis*, *S. triangularis* and *Acarinina mckannai* at 2761 m, above the tuffs of the Balder Formation of NP10-11 age at 2773–2791 m, is thought to be due to reworking; the taxa were deleted from the sequence file. In well (UK) 30/19-1, the top of *Cystammina pauciloculata* at 2661 m scored six penalty points in the RASC stepmodel, which means its occurrence is considerably out of place in a stratigraphic sense; the occurrence was re-examined and it was found to be the top of *Ammosphaeroidina pseudopauciloculata*, with which it is easily confused. The latter has no visible aperture, and attains a larger size. In well 2/2-4, in Middle Eocene sediments, *Gyroidina girardana* was deleted; it likely is caved.

In order to provide an independent, semi-objective verification of the RASC zonation, we also performed a biostratigraphic analysis of the 26 wells with the STRATCOR program. Threshold conditions and unique events are the same as those for RASC (see above); minimum smoothing of best fits and weighted average interpolation were selected for cross-plotting. Not surprisingly, the calculated regional composite standard using STRATCOR correlates in detail to the (scaled) optimum sequence using RASC, with only minor interchange of event positions. Position shuffles, as expected, are mostly from events that occur in relatively few wells (e.g. the unique events). Stratigraphically, there is little difference between the RASC and STRATCOR optimum sequences and the same zones are distinguished, which is why they have been omitted from the discussion.



As a result of the quantitative analysis, we propose 20 interval zones for the North Sea and Haltenbanken that detail the average last occurrence of taxa. As mentioned earlier, an average stratigraphic top and a maximum one will 'coincide' if the scatter in relative last occurrence position of a taxon from well to well is small. The very top of a taxon may be observed rarely, whereas there is more likelihood of finding specimens of a taxon close to its average biostratigraphic top. Hence, the average biostratigraphic top of fossils, with an errorbar attached, is well suited for exploration stratigraphy.

The zonation does not aim at maximum stratigraphic resolution but at being widespread and being readily recognized in North Sea wells. Microfossil events in each zone are listed in descending average stratigraphic order. The zones are numbered NSR (North Sea RASC) 1–13, with some zonal units further subdivided, using the letters A or B. Zonal units indicated with a letter extension are less readily recognized in the wells than the (stratigraphically wider) numerical zonal unit. The reason for this is largely because of limited stratigraphical resolution in wells with ditch-cutting samples only. For example, it is easy to recognize Zone NSR2, Late Palaeocene, but the distinction of a lower zonal unit NSR2A with the average last occurrence of *T. ruthvenmurrayi* and *R. garcilasso* is less obvious. This is also due to the fact that in a few wells in the Norwegian 35 exploration block, these two events have been recorded with other NSR2A events near the top zone NSR2, without obvious indication of possible reworking.

The proposed depth distribution of the Cenozoic NSR zones through selected wells in the North Sea and the Haltenbanken can be found in Table 3. Absence of a zone, indicative of a hiatus in relative time, is shown as a blank entry. Sampling resolution on average is 10 m.

The North Sea dinoflagellate cyst T zonation, to which this microfossil zonation is directly correlated is from Gradstein et al. (1992), whose study also calibrates the zonations of Costa & Manum (1988) and King (1989), (see Fig. 5). Further details are given in the text below. The North Sea CSS (Cenozoic seismic sequences) units 1 through 10 in Fig. 5, which are correlated to our zonation, are from Jordt et al. (in prep.). The linear scale in m.y. units, to which the zonation is tentatively calibrated, follows Cande & Kent (1992), with the base Cainozoic now drawn at 65.0 Ma.

#### RASC interval zone: *Subbotina pseudobulloides* (NSR1)

*Type section:* Well 16/1-1, 2760–2600 m (ca. 8924–8460 feet); co-type section in well 34/8-1 from 2010–1995 m.

*Definition:* Interval in the wells with the last occurrences of *Subbotina pseudobulloides*, *Spongodinium delitiense* LCO, and associated taxa listed below, immediately above the upper limit of Cretaceous (or older) strata.

*Age:* Danian, Early Palaeocene.

*Corresponding Dinoflagellate Zones:* T1A and B.

*Corresponding Seismic Sequence:* The lower boundary of CSS-1 is the Danian erosion surface, which roughly corresponds to the upper limit of Zone NSR1.

*Taxa:* The following taxa or log events, listed in descending average stratigraphic order, have their last occurrence in this interval zone: North Sea log marker B, *Subbotina pseudobulloides*, *Matanzia varians*, *Gavelinella beccarii-formis*, *Spongodinium delitiense*, *Planorotalites compressus* and *Subbotina triloculinoides*; taxa occurring less commonly are from younger to older: *Alisocysta reticulata*, *Clavulinoides globulifera*, *Globoconusa daubjergensis* and *Globigerina fringa*.

*Discussion:* The *S. pseudobulloides* Zone is present in the carbonate-bearing Ekofisk Formation, in agreement with the average position of log marker B that Morton & Knox (pers. comm. 1984) in UK sector wells assign to the top Ekofisk Formation (Danian). In a few wells, such as 16/1-1 at 2740 m, the basal part of the zone contains abundant small globigerinids, including *Globoconusa daubjergensis*, which indicates Zone P1. *Dorothia oxycona*, *Arenobulimina* sp., including *A. dorbignyi* and *Clavulinoides globulifera*, also disappear in this zone. In well 35/3-3 + 4 at 1420 m the tiny *Globigerina fringa* occurs. *S. pseudobulloides* itself may extend above the Ekofisk Formation, and into the overlying Maureen Formation (J. Stein, pers. comm. 1995).

Frequent reworking of Ekofisk sediment in the overlying terrigenous clastics obscures precise delineation of the top of the *S. pseudobulloides* Zone, and we include isolated specimens of *Morozovella* aff. *angulata* of Zone P3 that were found in the overlying Maureen Formation, in the *S. pseudobulloides* Zone. The Maastrichtian strata underlying the *S. pseudobulloides* Zone, are readily identifiable in most wells from the highest occurrence of globotruncanids, incl. *G. contusa*, and *Abathomphalus mayaroensis*, *Globotruncanella havanensis*, *Pseudotextularia*, *Globigerinelloides*, *Heterohelix* and *Rugoglobigerina*. The palynological top for the Maastrichtian is based on the highest occurrence of *Palynodinium grillator*.

The *S. pseudobulloides* zone (NSR1) corresponds to King's (1989) Zone NSP1 of the same name; *Planorotalites chapmani* is reported by King (op. cit.) to be widespread in the upper part of NSP1, but in the wells analysed by us it is rare or absent. The observation appears valid only for the southern North Sea region, where it may indicate that NSP1 ranges upward in the Selandian.

In the Atlantic Ocean, *Gavelinella beccarii-formis* has been reported from sediments as young as Zone P5 (Tjalsma & Lohmann 1983). This is in agreement with its disappearance along the Canadian Atlantic margin together with *Aragonia velascoensis*, just below the appearance of the genus *Pseudohastigerina* (post P5), (Gradstein

Table 2. Listing of the Cainozoic zones for the northern North Sea and the Haltenbanken, and their microfossil record. Last occurrence events in time are defaults. To the left are the taxa in the RASC zonal model of Fig. 2; to the right are listed taxa that assists in recognizing and correlating the zones, but are either rare in the wells studied with RASC, or occur in wells listed in the text, but not utilized in the RASC run.







AGE	NSR ZONES	TAXA IN RASC ZONAL MODEL	TAXA OCCURRING IN FEW WELLS ONLY
Pleistocene	NSR 13	Elphidium clavatum Elphidium spp. Cassidulina teretis Cibicoides scaldisiensis Bulimina marginata Neogloboquadrina pachyderma	Nonionella labradoricum
Late Pliocene	NSR 12B	Buccella frigida Cibicoides grossa Ammonia beccarii	
	NSR 12A	Trifarina fluens ** Monspellensis pseudotepida Globorotalia inflata Cibicoides dutemplei Cibicoides grossa LCO Sigmioilopsis schlumbergeri Cibicoides pachyderma	Planulina ariminensis Hyalinea balthica Nonion affine LCO Globorotalia bulloides LCO Cibicoides scaldisiensis LCO Neogloboquadrina pachyderma (non-rugose, right colling)
Early Pliocene	NSR 11	Neogloboquadrina atlantica Globorotalia punctulata	Globorotalia crassaformis Neogloboquadrina humerosa Neogloboquadrina humerosa - acostaensis Globigerina apertura Orbulina universa
Late Miocene (pars.)	NSR 10	Neogloboquadrina acostaensis ** Bolboforma spiralis ** Bolboforma metzmacheri Globoquadrina venezuelana	
early Late Miocene to late Middle Miocene	NSR 9B	<i>Sumatradinium</i> spp. Radiolarians/diatoms flood ** Siphonina advena Martiniella cylindrica NS Log G Ehrenbergina variabilis <i>Cannosphaeropsis utinensis</i>	Alabamina scitula <i>Unipontidinium aquaeductum</i> <i>Palaeocystodinium</i> sp. A Costa & Downie Bolboforma reticulata Bolboforma fragori
early Middle Miocene to late Early Miocene	NSR 9A	Uvigerina ex. gr. semiornata Globigerinoides trilobus Caucasina elongata ** Sphaeroidinella disjuncta Globigerina praebulloides Neogloboquadrina continuaosa Globorotalia ex. gr. praescitula zealandica	Globoquadrina dehiscens coarse agglutinated benthics (Central Graben only)  Globorotalia praemenardii Orbulina suturalis
Early Miocene	NSR 8B	flat rads + sponge spicules Asterigerina gurichi Catapsydrax unicavus	Catapsydrax aff. dissimilis Globoquadrina praedeheiscens Dentoglobigerina baremoensis Uvigerina ex. gr. basicordata
Late Oligocene (Chattian)	NSR 8A	** <i>Chiropteridium mesplanum</i> <i>Deflandrea phosphonica</i> Tenuitella angustiumbilicata	Globigerina officinalis group Almaena osnabrugensis Emslandia emslandensis Coscinodiscus sp. 4 King Globigerina ciperensis
Early Chattian to Early Oligocene (Rupelian)	NSR 7B	** <i>Rhomboidium draco</i> Gyroldina girardana coarse agglutinated spp. Cyclammina placenta <i>Areosphaeridium arcuatum</i> <i>Areoligera semicirculata</i> <i>Wetzeliella symmetrica</i> ** <i>Svalbardella cooksoniae</i> Spirosigmoilinella compressa Turrilina alsatica ** <i>Spiniferites</i> sp. 1 Manum & al.	<i>Homotryblium floripes</i> Cibicoides mexicanus <i>Wetzeliella gochtii</i>
	NSR 7A	Aschemonella grandis Cyclammina rotundidorsata Rotaliatina bulimoides Karrerella horrida Ammodiscus latus Glomospirella biedae Adercotryma agterbergi	<i>Reticulatosphaera actinocoronata</i> FO <i>Areoligera semicirculata</i> FO + LCO <i>Chiropteridium lobospinosum</i> FO Reticulophragmium amplexens var. Haplophragmoides walteri var. Globorotalia increbescens "Globorotalia" ampliapertura



to Early Oligocene (Rupelian)	NSR 7A	<p><i>Turritina asatica</i> ** <i>Spiniferites</i> sp. 1 Manum &amp; al.</p> <p>Aschemonella grandis Cyclammina rotundidorsata Rotaliatina bulimoides Karrerella horrida Ammodiscus latus Glomospirella biedae Adercotryma agterbergi</p> <p>Reophax elongatus Haplophragmoides walteri Dorothia seigliei</p>	<p><i>Reticulatosphaera actinocoronata</i> FO <i>Areoligera semicirculata</i> FO + LCO <i>Chiropteridium lobospinosum</i> FO <i>Reticulophragmium amplectens</i> var. <i>Haplophragmoides walteri</i> var. <i>Globorotalia increbescens</i> "Globorotalia" ampliapertura</p>
Late Eocene (Priabonian)	NSR 6B		<p><i>Globorotalia cerroazulensis</i> <i>Turborotalia pomeroli</i> <i>Globigerina linaperta</i></p>
late Middle Eocene (Bartonian)	NSR 6A	<p>NS Log F <i>Heteraulacacysta porosa</i> ** <i>Globigerapsis index</i> <i>Areosphaeridium diktyoplokus</i> <i>Recurvoides</i> ex. gr. walteri <i>Reticulophragmium amplectens</i> <i>Ammosphaeroidina pseudopauciloculata</i> <i>Rotnestia borussica</i></p>	<p><i>Cibicoides truncanus</i> <i>Marginulopsis decorata</i> <i>Operculodinium tiara</i> <i>Corrodinium incompositum</i> <i>Diphyes colligerum</i></p>
early Middle Eocene to late Early Eocene	NSR 5B	<p><i>Spiroplectammina spectabilis</i> LO <i>Ammomarginulina aubertae</i> <i>Diphyes ficusoides</i> <i>Haplophragmoides kirki</i></p>	
	NSR 5A	<p><i>Karrerella conversa</i> <i>Reticulophragmium intermedia</i> <i>Eatonicysta ursulae</i> NS Log E <i>Spiroplectammina navarroana</i> ** <i>Acarinina pentacamerata</i> <i>Recurvoidella lamella</i> ** <i>Eatonicysta ursulae</i> LCO</p>	<p><i>Phthanoperidinium echinatum</i> LCO <i>Systematophora placacantha</i> LCO <i>Dracodinium pachydermum</i> LCO + LO <i>Areoligera</i> spp. LCO <i>Turritina robertsi</i> <i>Charlesdowniea columna</i> <i>Karrerella coniformis</i></p>
Early Eocene (Ypresian)	NSR 4	<p>** <i>Planorotalites planoconicus</i> <i>Subbotina patagonica</i></p>	<p><i>Acarinina densa</i> <i>Reticulophragmium intermedia</i> FO <i>Cyclammina placenta</i> FO <i>Acarinina pseudotopilensis</i> <i>Glaphyrocysta ordinata</i> LCO <i>Planorotalites australiformis</i> <i>Morozovella formosa gracilis</i> <i>Acarinina soldadoensis</i> <i>Bulimina trigonalis</i></p>
earliest Eocene	NSR 3	<p><i>Deflandrea oebisfeldensis</i> Tuff ** <i>Deflandrea oebisfeldensis</i> LCO <i>Coscinodiscus</i> spp. NS Log D</p>	<p><i>Inaperturopollenites</i> (acme) <i>Glomospirella irregularis</i></p>
Late Palaeocene (Selandian)	NSR 2B	<p>NS Log C <i>Cystammina</i> aff. <i>globigerinaeformis</i> <i>Apectodinium augustum</i> <i>Trochamminoides coronatus</i> ** <i>Cenosphaera</i> sp. (disc or flat) <i>Reticulophragmium paupera</i> <i>Rzehakina minima</i> ** <i>Alisocysta margarita</i> <i>Hormosina excelsa</i> <i>Spiroplectammina spectabilis</i> LCO <i>Saccammina placenta</i></p>	<p><i>Kalamopsis grzybowskii</i> <i>Areoligera gippingensis</i> <i>Palaeocystodinium bulliforme</i> <i>Labrospira pacifica</i></p>
	NSR 2A	<p>** <i>Trochammina</i> cf. <i>subvesicularis</i> <i>Reticulophragmium garcilaso</i> <i>Trochammina ruthvenmurrayi</i> <i>Palaeoperidinium pyrophorum</i> LCO</p>	<p><i>Palaeocystodinium bulliforme</i> LCO <i>Alisocysta margarita</i> LCO</p>
Early Palaeocene (Danian)	NSR 1	<p>NS Log B <i>Subbotina pseudobulloides</i> <i>Matanzia varians</i> <i>Gavellinella beccariformis</i> ** <i>Spongodinium delitiense</i> <i>Planorotalites compressus</i> <i>Subbotina triloculinoides</i></p>	<p><i>Alisocysta reticulata</i> <i>Clavulinoides globulifera</i> <i>Globoconus daubjergensis</i> <i>Globigerina fringa</i></p>

\*\* Indicate unique (rare) events (occurring in less than 6 out of 26 wells). *Palynomorphs* are in italics.



et al. 1985, p. 346). In the Central North Sea the average disappearance of *G. beccariiformis* is ca. 5 m.y. earlier than in the Atlantic Ocean. This local disappearance relates to the change from predominantly carbonates of the Ekofisk Formation into overlying terrigenous clastic sediments of the Maureen, Andrew and Forties Formations, at the transition from the Danian into the Late Palaeocene.

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

In 16/1-1, the interval of about 2760–2600 m (ca. 8924–8460 ft in the original scale of measurement), including cores 17 through 14, is Danian in age; here the basal Palaeocene beds with *Globoconusa daubjergensis* (P1) at 2760–2677 m contain reworked Maastrichtian, Jurassic and Triassic dinoflagellate flora, assigned by Ioakim (1979) to the Maastrichtian dinoflagellate zone of *Palynodinium grallator*. The overlying Danian–lower Selandian dinoflagellate zone *Cerodinium striatum*–*Palaeoperidinium pyrophorum* of Ioakim (op. cit.) at 2658–2496 m corresponds to our Danian zone of *S. pseudobulloides* (P1–P2) and the lowermost part of our overlying Selandian, Late Palaeocene zone. The Danian microfossil slides contain reworked Upper Cretaceous carbonate fragments with Maastrichtian *Inoceramus* and globotruncanids (found as high as core 14).

In Viking Graben well 34/8-1 and Haltenbanken well 6407/7-1, *Palynodinium grallator*, the LO of which defines the base of North Sea dinoflagellate Zone T1A (Fig. 5), occurs at the base of the *S. pseudobulloides* zone of Danian age. The last occurrence of *Spongodinium deltiense*, which defines the top of North Sea dinocyst Zone T1A, is within the lower part of the *S. pseudobulloides* zone (Gradstein et al. 1992). In the four Halten-banken wells examined, the *S. pseudobulloides* Zone was not recognized; Danian sediments are very thin or absent.

In the southern Central Graben well (UK) 30/19-1 the lower Palaeocene (Danian and slightly younger strata?) was recovered in cores 2 through 8 at 3050–3128 m; the interval contains a melange of chalks of Maastrichtian and Danian age, and sands and dark shales, assigned to the Maureen Formation. The stratigraphic melange of carbonates and siliciclastics is due to tectonic ‘collapse’ of the Upper Cretaceous–lower Danian chalk platform. The shales contain rather 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.

**RASC interval zones:** *Trochammina ruthvenmurrayi* (NSR2A)–*Reticulophragmium paupera* (NSR2B)

**Type section:** Well 34/8-1 from 1990–1875 m.

**Definition:** Interval in the wells with the last occurrence of *Apectodinium augustum*, *Reticulophragmium paupera*, *Trochammina ruthvenmurrayi* and associated taxa listed below, overlying Zone NSR1.

**Age:** Selandian, Late Palaeocene.

**Corresponding Dinoflagellate Zones:** T2A, B and C.

**Corresponding Seismic Sequence:** CSS-1.1 and part of CSS-1.2.

**Taxa:** The following last occurrence events, reported in descending average stratigraphic order belong in zonal units NSR2A and in NSR2B:

Zonal unit NSR2A – *T. cf. subvesicularis*, *Reticulophragmium garcilassoi*, *Trochammina ruthvenmurrayi* and *Palaeoperidinium pyrophorum* LCO; less common are *Palaeocystodinium bulliforme* LCO and *Alisocysta margarita* LCO.

Zonal unit NSR2B – Log marker C (base Sele Formation), *Cystammina aff. globigerinaeformis*, *Apectodinium augustum*, *Trochamminoides coronatus*, flat or disk-shaped *Cenosphaera* spp., *Reticulophragmium paupera*, *Rzehakina minima*, *Alisocysta margarita*, *Hormosina excelsa*, *Spiroplectammina spectabilis* LCO, *Saccamina placenta*; less common are *Areoligera gippingensis* (formerly *A. cf. senonensis*), *Palaeocystodinium bulliforme*, and *Labrospira pacifica*.

**Discussion:** Zonal unit NSR2 is readily recognized in the North Sea, Tampen Spur and Haltenbanken wells. It occurs in sediments assigned to the Maureen, Andrew and Forties Formations in the Central Graben and the fine-grained Lista Formation in the Viking Graben. The shelly microfossils in the zone exclusively are agglutinated benthic foraminifers, which are often abundant, and in the Lista Formation are often greenish in colour, relatively small 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.

Other, less common taxa which have their last occurrence in this zone include *Ammodiscus planus*, *Glomospira diffundens* and *Hyperammina rugosa*. *Hormosina excelsa*, *Kalamopsis grzybowskii* and *Cribrostomoides trinitatisensis* occur throughout this zone, but are only infrequently found higher in the (Eocene) well sections studied. *Spiroplectammina spectabilis* extends 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 Palaeocene 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 the upper Palaeocene to lower Eocene in Australia (Ludbrook 1979) and Tunisia (F. M. Gradstein, unpublished). In Trinidad, the earliest cyclamminids are post P1c in age, which appears to concur with the central North Sea record.

Although the exact last occurrence of the zonal taxa shows considerable scatter in the North Sea Palaeocene, the average last occurrences of *T. cf. subvesicularis* (probably a new species), *T. ruthvenmurrayi* and *R. garcilassoii* is immediately above Zone NSR1 (*S. pseudobulloides* zone) of Danian age. The average last occurrence of these three taxa clusters in the RASC zonation, together with *Palaeoperidinium pyrophorum* LCO (Fig. 2). This dendrogram cluster is considered as Zone NSR2A, and of the early part of the Late Palaeocene in age. In wells (UK) 30/19-1, 16/11-1, (UK) 3/25-1 34/8-1 (but not in 34/4-5 or 35/3-1), the taxa disappear at or below the highest occurrence of the Danian planktonics. In a few other wells, particularly (UK) 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. ruthvenmurrayi* and *R. garcilassoii* range into Zones P5 and P6a, at the top of the Palaeocene (Kaminski et al. 1988). The latter, on average is not true for the North Sea, where these events are older, and of middle Palaeocene age.

The upper stratigraphic ranges of *Cystammina* aff. *globigerinaeformis* (probably a new species) and *C. pauciloculata* are special cases. The latter extends into the Recent, while the former is best known from oceanic Upper Cretaceous strata. In some wells (like 34/4-5 and 34/8-1, 16/1-1) the two species disappear in the Upper Palaeocene Zone of *Reticulophragmium paupera* (NSR2B), in others (like 6407/2-3, 6407/4-1, and UK 30/19-1) both taxa extend into the Lower or even Middle Eocene. The average (!) tops are calculated by RASC to be just below the *Coscinodiscus* Zone, but these are stratigraphic midpoints with an 'errorbar' of one or more zones. The taxa only extend to the lower part of the Middle Eocene strata where relatively deep marine (middle or middle to upper bathyal) conditions continued (see section on Palaeobathymetry). Deletion of *C. pauciloculata* from the final RASC run led to better differentiation of NSR2 and 3.

In the four Haltenbanken wells examined, *Reticulophragmoides jarvisi* does not range above this zone; but southward it ranges into Eocene and (lower) Oligocene strata. The taxon was omitted from the zonation due to this diachronous correlation of its last occurrence event.

The *T. ruthvenmurrayi*–*R. paupera* zonal unit (NSR2) equates with King's (1989) calcareous benthic zones NSB1b (*Stensioeina beccariiiformis*) and the younger NSB1c (*Bulimina trigonalis*), and agglutinated benthic zones NSA1a (acme of *Spiroplectammina spectabilis*) and the younger NSA1b (*T. ruthvenmurrayi*). These four

(sub)zones span most of the Thanetian, Late Palaeocene. According to King (1989) *Bulimina trigonalis* is restricted to the Paleocene, whereas we observe it in zone NSR4, Early Eocene.

In the 16/1-1 well, Ioakim (1979) reported the Selandian (Thanetian) *Deflandrea (Cerodinium) speciosum* zone from approximately 2540 to 2300 m, which overlaps with our Zone NSR2 which extends from ca. 2628–2409 m (2307 m using quantitative interpolations of zonal boundaries with program STRATCOR).

In Viking Graben wells 34/8-1, 34/4-5, and in the Haltenbanken wells, the dinoflagellates *Palaeocystodinium bulliforme*, *Palaeoperidinium pyrophorum*, *Areoligera gippingensis* and *Alisocysta margarita* disappear in the lower or middle part of NSR2. According to Powell (1992) the taxa disappear approximately in nannofossil Zones NP6–8, middle Selandian. Their last occurrence levels define North Sea dinocyst Zone T2 (see below). The last occurrence of *Apectodinium augustum*, which defines North Sea dinoflagellate (sub)Zone T2C, is positioned at the top of NSR2. This is in good agreement with its use as a marker event for the top of the Selandian or Thanetian stages, at the Palaeocene–Eocene boundary (Powell, 1992).

*RASC interval zone: Coscinodiscus spp. (NSR3)*

*Type section:* Well 16/1-1 from 2258–2223 m (ca. 7411–7296 ft).

*Definition:* Interval in the wells with the last occurrences of *Deflandrea oebisfeldensis*, *Coscinodiscus* spp., and associated taxa listed below, immediately above Zone NSR2.

*Age:* Earliest Eocene (early Ypresian).

*Corresponding Dinoflagellate Zone:* T3A.

*Corresponding Seismic Sequence:* Upper part of CSS-1.2  
*Taxa:* The following taxa or physical events, listed in average, descending stratigraphic order occur in this interval zone: *Deflandrea oebisfeldensis*, tuffaceous sediments (Balder unit), *D. oebisfeldensis* LCO, *Coscinodiscus* spp. (often pyritized), and North Sea log marker D (top Sele Formation); less common *Inaperturopollenites* spp. (acme), *Taxodiaceae* spp., *Cerodinium wardenense* and *Glomospira irregularis*.

*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 foraminifers, directly in the sediments, and on the physical well logs. The agglutinated benthic assemblage is of low diversity, with few taxa only, as compared to diverse and rich assemblages below in Zone NSR2, and above in Zones NSR5 and 6; locally, there is an acme of *Trochamminoides coronatus*. Similar diatoms such as *Coscinodiscus* spp. also occur in younger strata in the wells examined, but not so commonly and consistently and with such relatively large test size. 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 & Morton 1983). The predominance of the large, pyritized *Coscinodiscus* is often accompanied by a characteristic preservation of agglutinated foraminifers 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*. The preservation, including a typically light-grey test colour, assists in distinguishing *in situ* from caved taxa, which helps in determining that *Reticulophragmium amplexens* and *Cyclammina placenta* do not extend down into this zone, but have their first stratigraphic appearance in the overlying *Subbotina patagonica* zone.

From the record in wells 2/2-4, 6407/4-1 and 6406/8-1 *Cerodinium wardenense* and *Wetzelliella astra* disappear in Zone NSR3, correlative with the upper part of the Balder Formation.

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 places North Sea log marker C on average at the top of the underlying zone of *Reticulophragmium paupera*, and North Sea log marker D immediately 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 (see below) is within it. Following Powell (1988), this correlation helps to equate the *Coscinodiscus* zone with uppermost NP9 and NP10 nannofossil zones, of earliest Ypresian age.

The *Coscinodiscus* zone (NSR3) correlates to Zone NSP4 (*Coscinodiscus* sp. 1 and 2) and Zone NSA2 (*Verneuilinoides subeocaenus*) of King (1989); Zone NSA2 is restricted to the southern North Sea only, and is not recognizable in the wells examined in this study.

#### RASC interval zone: *Subbotina patagonica* (NSR4)

*Type section*: Well 2/2-4 at 2660 m; co-type section in 6407/2-3 from 1960–1940 m.

*Definition*: Interval in the wells with *Subbotina patagonica* and associated taxa listed below, immediately overlying interval Zone NSR3.

*Age*: Ypresian, Early Eocene (Zones P6b–P8).

*Corresponding Dinoflagellate Zone*: T3B.

*Corresponding Seismic Sequence*: CSS-2.1 (p.p.).

*Taxa*: This zone is characterized by the presence of *Subbotina patagonica*. Less commonly occur: *Glaphyrocysta ordinata* LCO, *Subbotina eocaena*, *Planorotalites planoconicus*, *Acarinina pseudotopilensis*, *A. densa*, *A. soldadoensis*, *Planorotalites australiformis*, *Morozovella formosa gracilis*, *Pseudohastigerina wilcoxensis* and *Bulimina*

*trigonalis*. The lowest occurrence of *Reticulophragmium intermedia* (the forerunner of *R. amplexens*) and *Cyclammina placenta* (rare) is also observed in this zone. *Acarinina pentacamerala* occurs in this zone and the lower part of the overlying one (Zone NSR5a).

*Discussion*: This zone is easily identified by the occurrence of (sometimes reddish-coloured) 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 (as in 6407/2-3 at 1940 m; in 6407/4-1 at 2070 m, and in 2/2-4 at 2660 m). Other planktonic foraminifers listed above are rare and only occur in a few (mostly Central or Viking Graben) wells, such as (UK) 15/20-1, 16/1-1, (UK) 22/14-1x, and (UK) 9/13-1. Rare calcareous benthic foraminifers in this zone in some wells include *Turrilina robertsi*, *Bulimina trigonalis* and *Nuttalinella florealis*.

*Turrilina robertsi* (previously named *T. brevispira*) is distinguished from *T. alsatica* by the granular extinction pattern of the test wall under crossed nichols; *T. alsatica* has a radial extinction pattern of the wall under polarized light. Some details on taxonomy and illustrations of morphology are presented in Gradstein et al. (1994).

The lowest stratigraphic range of *Reticulophragmium amplexens* 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; we refer to such an older morphotype as *R. intermedia* (see overlying subzone).

The reddish colour of *S. patagonica* refers to 'The Red Shale' interval at the base of the Hordaland Group, which correlates with units D and E of the London Clay in the southern UK and the Rosnaes Clay of Denmark (Gradstein et al. 1994). 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; Zone NP12) of Denmark and in the Ypresian of Belgium. It is also known from DSDP sites on the Vøring 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 (Baldauf et al. 1989). The interval of time represented by the relatively calcareous sediments of the *S. patagonica* zone reflects a large productivity increase of pelagic biogenic carbonate, preserved at the sea floor.

In the 16/1-1 well Ioakim (1979) assigned the interval from about 2000 to 2200 m, including core 4, to the *Charlesdownia edwardsii*–*Eatonicysta ursulae* zone and the interval from about 2200 m to 2220 m to the *Glaphyrocysta ordinata* zone, both Early Eocene. This correlates with our Lower Eocene *S. patagonica* zone, which extends from 2152 to 2242 m. In Viking Graben well 34/8-1, the *S. patagonica* zone includes the first occurrence of *Dracodinium pachydermum*. The *S. patagonica* zone correlates to the North Sea dinoflagellate zone T3B, defined on the upper limit of the acme of the *Areoligera*



*Glaphyrocysta* complex, together with the common occurrence of *Dracodinium varielongitudum* and *Wetzeliella samlandica*.

The *S. patagonica* zone correlates with Zone NSP5 (*G. ex gr. linaperta*) of King (1989).

**RASC interval Zones:** *Reticulophragmium intermedia* (NSR5A)-*Ammomarginulina aubertae* (NSR5B)

**Type-section:** Well 6407/4-1 from 2050–1790 m; co-type section in well 2/2-4 from 2620–2560 m.

**Definition:** Interval in the wells with the last occurrence of *Diphyes ficusoides*, *Spiroplectammina spectabilis*, *Ammomarginulina aubertae*, *Reticulophragmium intermedia*, *Eatonicysta ursulae* LCO, and associated taxa listed below, overlying Zone NSR4.

**Age:** Latest Early Eocene to early Middle Eocene.

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

**Corresponding Seismic Sequence:** Lower part of CSS-2.2.  
**Taxa:** The following taxa, listed in descending average stratigraphic order, have their average last occurrence in the zonal units NSR5A and NSR5B:

Zonal unit NSR5A – *Karriella conversa*, *Reticulophragmium intermedia*, *Eatonicysta ursulae*, North Sea Log marker E, *Spiroplectammina navarroana*, *Recurvoidella lamella* and *Eatonicysta ursulae* LCO; less commonly occur *Phthanoperidinium echinatum* LCO, *Systematophora placacantha* LCO, *Dracodinium pachyderma* LCO and LO, *Acarinina pentacamerata*, *Areoligera* spp. LCO., *Turrilina robertsi*, *Charlesdownia columna* and *Karriella coniformis*.

Zonal unit NSR5B – *Spiroplectammina spectabilis* LO, *Diphyes ficusoides*, *Ammomarginulina aubertae*, and *Haplophragmoides kirki*. Also present is *Areosphaeridium fenestratum*; *Spirosigmoilinella compressa* first occurs in the younger part of this zone.

**Discussion:** The foraminiferal part of this zonal unit is almost exclusively composed of agglutinated benthic foraminifers, typical of the relatively thin Eocene mudstone intervals, overlying the lower Eocene *S. patagonica* zone. It is virtually devoid of calcareous benthic or planktonic foraminifers.

Although both RASC and particularly STRATCOR indicate a distinct break between this zone and the overlying *R. amplexens* zone, it may not be possible to draw a distinct boundary between the two zones in some wells. The reason is local scatter in the tops of the constituent taxa. In a previous zonation using fewer wells, the *A. aubertae* and *R. amplexens* zones were not separated for that reason (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 of *Spiroplectammina spectabilis* in the wells (albeit with isolated

specimens) is a reliable indicator for the middle part or upper part of Zone NSR5, and *S. navarroana* (without the presence of *Subbotina patagonica*) indicates that it is the basal part.

The lowest stratigraphic range of *Reticulophragmium amplexens* is in the *R. intermedia* and *S. patagonica* zones 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 *R. intermedia*, after which Zone NSR5A is named.

The age of zonal unit NSR5 is determined through superposition, the presence of rare planktonic foraminifers, calibration to ODP Site 647A, and correlation of palynological events (see below). First, the zone occurs above the underlying Lower Eocene zone of *S. patagonica* and below the overlying zone of *R. amplexens*, of (largely) late Middle Eocene age. This interpolated age of latest Early Eocene to early Middle Eocene agrees with the highest occurrence of *Acarinina pentacamerata* in a few wells (e.g. UK 9/13-1 at 1225 m) in this zone. Also, *Spiroplectammina navarroana* in the 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 & 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 a gamma ray log spectrum to lower values in core hole (UK) 81/46A off northeast Yorkshire (Lott et al. 1983); it was dated to early Middle Eocene, close to the top of the Lower Eocene, based on its position slightly above the base of *Areosphaeridium diktyoplokus*, in the *Charlesdownia coleothrypa* zone, and slightly above the *G. gr. linaperta* zone (=our *Subbotina patagonica* zone). Log marker E is slightly time-transgressive, being older in the south and younger in the northern part of the North Sea basin; inspection of the original well data indicates that the range is from Early Eocene to late Middle Eocene time; the average age is early Middle Eocene.

*Spiroplectammina spectabilis* does not extend above the *A. aubertae* zone in the central North Sea, in agreement with the observation along the Canadian Atlantic margin that *S. spectabilis* also extends 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. The total stratigraphic range of *S. spectabilis* is Campanian through latest Eocene.

The average last occurrence of *Karriella conversa* is a useful marker for the *A. aubertae* zone. In some wells this species is accompanied by rare *Karriella coniformis*, distinguished by its rather elongated, elliptical outline. On Haltenbanken *Karriella conversa* and *K. coniformis* may not extend above the Palaeocene.







<i>Tarminia roseni</i>									
<i>Nuttallinella florealis</i>									
<i>Bulimina trigonalis</i>									
<i>Gavelinella beccariformis</i>									
<i>Sigmoilopsis schlumbergeri</i>									
<i>Martinitella cylindrica</i>									
<i>Spiroplectammina carinata</i>									
<i>Coarse agglutinated forams spp.</i>									
<i>Cyclammina placenta</i>									
<i>C. rotundiborsata</i>									
<i>C. cancellata</i>									
<i>Glomospira spp.</i>									
<i>Aschermonella grandis</i>									
<i>Anmodiscus latus</i>									
<i>Spirostigmimella compressa</i>									
<i>Glomospirella biedae</i>									
<i>Karreriella horrida</i>									
<i>Reophax elongatus</i>									
<i>Adercoryma agerbergi</i>									
<i>Haplophragmoides walteri var.</i>									
<i>Dorothyia seigliei</i>									
<i>Reitculophragmium amplexens var.</i>									
<i>Ammosphaeroidina pseudopauciloculata</i>									
<i>Haplophragmoides walteri</i>									
<i>Reitculophragmium amplexens</i>									
<i>Reitculophragmoides jarvisi</i>									
<i>Spiroplectammina spectabilis</i>									
<i>Recurvirodesex. gr. walteri</i>									
<i>Haplophragmoides kirki</i>									
<i>Ammonia marginulina aubertae</i>									
<i>Reitculophragmium intermedia</i>									
<i>Spiroplectammina navarroana</i>									
<i>Recurvirodella lamella</i>									
<i>Karreriella conversa</i>									
<i>Karreriella coniformis</i>									
<i>Cystammina pauciloculata</i>									
<i>Cystammina afr. globigerinaeformis</i>									
<i>Trochammina cf. coronatus</i>									
<i>Reitculophragmium paupera</i>									
<i>Saccammina placenta</i>									
<i>Homosina excelsa</i>									
<i>Rzehakina minima</i>									
<i>Cribrosomoides trinitatis</i>									
<i>Kalamopsis grzybowski</i>									
<i>Labrosira pacifica</i>									
<i>Reitculophragmium garciasoi</i>									
<i>Trochammina rufhenmurrayi</i>									
<i>Trochammina cf. subvesicularis</i>									
<i>Dorothyia oxycona</i>									
<i>Clavulinoides globulifera</i>									
<i>Neogloboquadrina pachyderma</i>									
<i>Globotallia inflata</i>									
<i>Globigerina bulloides</i>									
<i>Globotallia puncticulata</i>									
<i>Globotallia crassaformis</i>									
<i>Neogloboquadrina atlantica</i>									
<i>N. humerosa</i>									
<i>N. acostaensis</i>									
<i>N. confinosa-acostaensis</i>									
<i>Globoquadrina venezuelana</i>									
<i>Neogene planktonic foram flood</i>									
<i>Globoquadrina confinosa</i>									
<i>Globigerinoides spp.</i>									
<i>Orbulina suturalis</i>									
<i>Globotallia mayeri</i>									
<i>G. ex. gr. praescitula</i>									

Central Graben only



Globoquadrina venezuelana								
Neogene planktonic foram flood								
Globoquadrina continuosa								
Globigerinoides spp.								
Orbulina suturalis								
Globorotalia mayeri								
G.ex.gr. praescitula								
G. praemenardii								
Globigerina praebulboidea								
Sphaeroidinella disjuncta								
Catapsydrax unicavus								
C. aff. dissimilis								
Globoquadrina dehiscens								
Globigerina ex. gr. officinalis								
G. cipercoensis								
Tenuitella angustilumbicata								
*Globigerina* aff. ampliapertura								
Globorotalia increbescens								
Turborotalia pomeroli								
T. cernozulensis								
Globigerinatheka index								
G. kugleri								
Subbotina linaperla								
Acarinina ex. gr. spinulosa								
Acarinina pentacamerata								
A. densa								
A. soldadoensis								
Subbotina patagonica								
S. eocaena								
Acarinina pseudolopi lensis								
Morozovella formosa gracilis								
Planorotalites australiformis								
P. planoconvexus								
Pseudohastigerina wilcoxensis								
Subbotina trilobuloides								
S. pseudobulboidea								
Planorotalites compressus								
Globoconusa daubergensis								
Globigerina fringa								
Boibolorma metzmacheri								
Radiolarian/diatom flood								
Boibolorma fragori								
Boibolorma reitculata								
Coccinodiscus sp. 4								
Siliceous biofacies/sponge spic.								
Cenosphaera spp.								
Coccinodiscus spp.								
Cenosphaera (disc or flat)								



Frequent hiatus, see text



The tops of *Cystamina pauciloculata* and *C. aff. globigerinaeformis* are a special case. As discussed under the *R. paupera* zone, these taxa on average disappear in that zone, but the average tops have large errorbars. In several Haltenbanken and North Sea wells with mid-upper bathyal Eocene, these taxa range into the *R. intermedia*–*A. aubertae* zone; the taxa are rare.

*A. aubertae* is apparently a higher-latitude species, restricted to the North Sea, Norwegian and Labrador Sea margins, where it ranges from the Maastrichtian (*A. mayaroensis* zone) through part or all of the Middle (in the North Sea and Haltenbanken) to Late Eocene.

The following dinoflagellates range into the *R. intermedia*–*A. aubertae* zone: *Eatonicysta ursulae* (LCO + LO) and *Dracodinium pachydermum* (LCO + LO), the LCO events of which define Zone T3C, *Charlesdownia columna*, *Systematophora palcacantha* LCO, *Phthanoperidinium echinatum* LCO, *Diphyes ficusoides* (its LO defines Zone T4A/B, see below), and *Areosphaeridium fenestratum*. *Deflandrea phosphoritica* FO does not range below this zone. *Eatonicysta ursulae* extends into NP14 (Costa & Manum 1988) to NP16 (Head & Norris 1989). From its position in the lower *R. intermedia* subzone, immediately above the *S. patagonica* zone, we conclude it to be more likely that in the North Sea *E. ursulae* disappears in NP14. Accordingly, we assign an age of NP14 through NP16 (pars), Lutetian, to the *R. intermedia*–*A. aubertae* zone.

The *R. intermedia*–*A. aubertae* zone in the Esso Norway 16/1-1 well, at approximately 1584–2152 m, overlaps with the upper half of the *Charlesdownia edwardsii*–*Eatonicysta ursulae* zone and all of the *Dracodinium 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. amplexens* zone missing, makes the Bartonian age less likely.

The *R. intermedia*–*A. aubertae* zone (NSR5A + B) probably largely overlaps with zone NSP7 (last consistent occurrence of *Pseudohastigerina micra*) and NSB5a (*Neoeponides karsteni*) of King (1989), both of which can be recognized in relatively shallow marine Eocene environments, outside the Central and Viking Grabens. The NSR5 zone also correlates in time with most or all of King's (1989) zones NSA5 (top of *S. aff. spectabilis*), NSA4b (last consistent occurrence of *Reticulophragmium amplexens*) and NSA4a (last consistent occurrence of *Textularia plummerae*). Reference to *Textularia plummerae* in this zone equates with our *Spiroplectamina navarroana* at the base of the *R. intermedia*–*A. aubertae* zone.

*RASC interval zone: Reticulophragmium amplexens*  
(NSR6A)

*Type section:* Well 6407/2-3 from 1780–1720 m; co-type section well 2/2-4 at 2340 m.

*Definition:* Interval in the wells with the last occurrences

of *Heteraulacysta porosa*, *Reticulophragmium amplexens*, *Rottnestia borussica* and associated taxa listed below, immediately above Zone NSR5.

*Age:* Late Middle Eocene, possibly extending into Late Eocene.

*Corresponding Dinoflagellate Zone:* T4C/D.

*Corresponding Seismic Sequence:* Upper part of CSS-2.2.

*Taxa:* The following taxa or log events, listed in descending average stratigraphic order, have their last occurrence in this interval zone: North Sea log marker F, *Heteraulacysta porosa*, *Globigerapsis index*, *Recurvoides* ex. gr. *walteri*, *Reticulophragmium amplexens*, *Ammosphaeroidina pseudopauciloculata*, and *Rottnestia borussica*; less commonly occur *Cibicidoides truncanus*, *Marginulinopsis marginata*, *Operculodium tiara*, *Corodinium incompositum* and *Diphyes colligerum*. A listing in Fig. 2 of the disappearance of *A. diktyoplokus* in Zone NSR6A is due to the common presence of a Late Eocene hiatus between Zones NSR6 and NSR7 (see below).

*Discussion:* *Marginulinopsis decorata* extends through this zone, but it occurs only in a few wells, as it is commonly found in a shallower environment of deposition than that penetrated by the wells studied. *Haplophragmoides walteri*, *Reophax elongatus*, and *Recurvoides* ex. gr. *walteri* rarely extend above this zone, but are more common in the Central Graben. On Haltenbanken, *Dorothia seigliei* does not extend above the *R. amplexens* zone, but it does southward, which is why the RASC program groups the last three taxa in a separate cluster between our Zones NSR6A and NSR7A, indicative of the large stratigraphic spread in average 'top' of the three taxa.

*R. amplexens* disappears in a few wells in the underlying zone of *A. aubertae*, but the last consistent occurrence of *R. amplexens* (with disk-shaped test, sharp, circular periphery and umbilical depression) extends above the *A. aubertae* zone, into the nominate Zone NSR6A. Typical specimens have not been observed in the overlying zone of *Adercotryma agterbergi*–*Turrilina alsatica*. The zone may also be assigned on the highest occurrence in many wells of *Ammosphaeroidina pseudopauciloculata*. Unfortunately, the latter taxon may be easily confused with *Cystamina pauciloculata*. The latter taxon has an (areal) aperture, often with a lip, whereas *Ammosphaeroidina pseudopauciloculata* has a poorly visible, basal apertural slit, without a lip.

We have not been able to determine whether isolated specimens in a few wells of *Ammosphaeroidina pseudopauciloculata* and of *Reticulophragmium amplexens* var., with a more rounded periphery and larger size, in the overlying *A. agterbergi* zonal unit are due to reworking or are in fact stratigraphic events. Locally, *Haplophragmoides walteri* also extends up into the overlying (Oligocene) zone, but its average last occurrence is in the *R. amplexens* zone; its relatively rare subspecies *H. walteri* var., with more pronounced keel, evolute coiling and more 'caved-in' chambers, extends well into Oligocene strata.



*R. amplexens* var. 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 those known from regular Eocene occurrences. These particular forms may be morphologically close to *R. acutidor-sata* (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. 1992).

In the outer Carpathians the total range of *R. amplexens* is given as Lower to Upper Eocene (Morgiel & Olszewska 1981); in Poland the peak occurrence of *R. amplexens* is in Middle Eocene strata, where it defines the Middle Eocene *R. amplexens* zone of Geroch & Nowak (1984). In the Labrador Shelf–Grand Banks wells, the average disappearance of *R. amplexens* and other agglutinated taxa in this zone is well below the tops of *Turborotalia pomeroli* and *Globorotalia cerroazulensis* of Priabonian (Late Eocene) age. In well 35/3-3, 4, on the Tampen Spur, *T. pomeroli* and *G. cerroazulensis* occur together at 1040 m, but agglutinated taxa (without *R. amplexens*) occur only deeper down in the well. In the Labrador Sea Ocean Drilling Site 647, the acme of *R. amplexens* is in the Middle Eocene. For this reason, the *R. amplexens* zone may be largely Middle Eocene in age, possibly extending into Late Eocene.

The last occurrence of *Globigerapsis index*, which on average occurs near NS log marker F (Fig. 2), was observed in five wells. Thin sediments at this stratigraphic level in the wells suggest a regionally condensed section. In (UK) 9/13-1, *G. index* occurs at 1188 m, just above the top of *R. amplexens*; in (UK) 9/13-3A at 1103 m below the top of *Ammosphaeroidina pseudopauciloculata* and above the top of *Spiroplectamina spectabilis* LO; in Danish North Sea well E-1 at 1911 m below the top of *Reticulophragmium amplexens* at 1883 m and above the Lower Eocene tuff at 1950 m; in (UK) 23/22-1 *G. index* was found at 2468 m between NS log marker F and *Reticulophragmium amplexens*, and in well (UK) 38/16-1 it occurs at 859 m below *Cibicidoides truncanus* and above *Reticulophragmium amplexens*. *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 is equated with NP16 and P13, Middle Eocene. This interpretation is in accordance with information provided by P. Spaak (pers. comm., 1989) that the *G. index* influx in the southern North Sea occurs consistently in the upper part of NP16, and with the age of NP16-17 for this event in the Danish Søvind Formation. According to Gallagher (1990) nanofossil zones NP17/18 were not observed in the North Sea wells examined, which might indicate a regional Late Eocene hiatus. Nevertheless, King (1989) favours extension of the range of *G. index* in the North Sea into NP19/20, at the top of the Eocene, using new evidence from Danish strata. In the North Atlantic Ocean, the

taxon extends into P17, Late Eocene (Gradstein et al. 1994).

According to the stratigraphic information provided by A. C. Morton (pers. comm., 1985), 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. amplexens* zone, and may well be associated with a regional hiatus.

Based on the dinoflagellate determinations in the wells examined, the *R. amplexens* zone includes the highest occurrences of *Rhombodinium porosum*, *Rottnestia borussica*, *Diphyes colligerum*, *Heteraulacacysta porosa* (the LO of which defines North Sea Zone T4C/D, see below), *Corrudinium incompositum* and *Operculodinium tiara*. The RASC zonal model groups the LO of *A. diktyoplokus* into Zone NSR6A, because the studied wells provide insufficient resolution to extend its range upwards above the other dinoflagellates listed (see Zone NSR6B). We assign a late Middle Eocene age (Bartonian) for the listed dinocyst events, which provides an upper limit for the *R. amplexens* zone (NSR6A).

#### RASC interval zone: (NSR6B)

*Type Section:* Well 35/3-4 at 1040 m; co-type section in well 2/2-4 at 2240 m.

*Definition:* Interval in the wells with the presence of *Turborotalia pomeroli* and *Globorotalia cerroazulensis*, overlying Zone NSR6A.

*Age:* Late Eocene (Priabonian).

*Corresponding Dinoflagellate Zone:* T5.

*Corresponding Seismic Sequence:* Uppermost part of CSS-2.2.

*Discussion:* In a few wells, e.g. 35/3-3, 4 and 2/2-4, a calcareous planktonic record is observed with *Turborotalia pomeroli*, *Globorotalia cerroazulensis*, and *Globigerina linaperta*. This assemblage is of Late Eocene (Priabonian) age.

In most wells, particularly those more centrally situated in the Central and Viking Grabens and on Haltenbanken, the Eocene/Oligocene boundary is not clearly and definitively recognizable. Indeed, our studies suggest that sediments recording the Eocene–Oligocene transition may be thin or absent in most, if not all of the deeper parts of the North Sea Basins. The hiatus may be relatively short (about 1 or 2 my). As discussed above, the LO of *Globigerinatheka index* and *Cibicidoides truncanus* in North Sea RASC Zone NSR6 correlate to Zone NP16/17, in agreement with correlation to North Sea dinoflagellate cyst zone T4C/D, late Middle Eocene. The top of the Eocene is generally placed at log marker F (which occurs in Zone NSR6) in the North Sea. This suggests that the so-called top of the Eocene, as recognized by log marker F, is probably within the upper part of the middle Eocene or basal part of the upper Eocene.

Zone NSR6B corresponds to dinoflagellate cyst zone T5 of Gradstein et al. (1992), defined on the basis of the



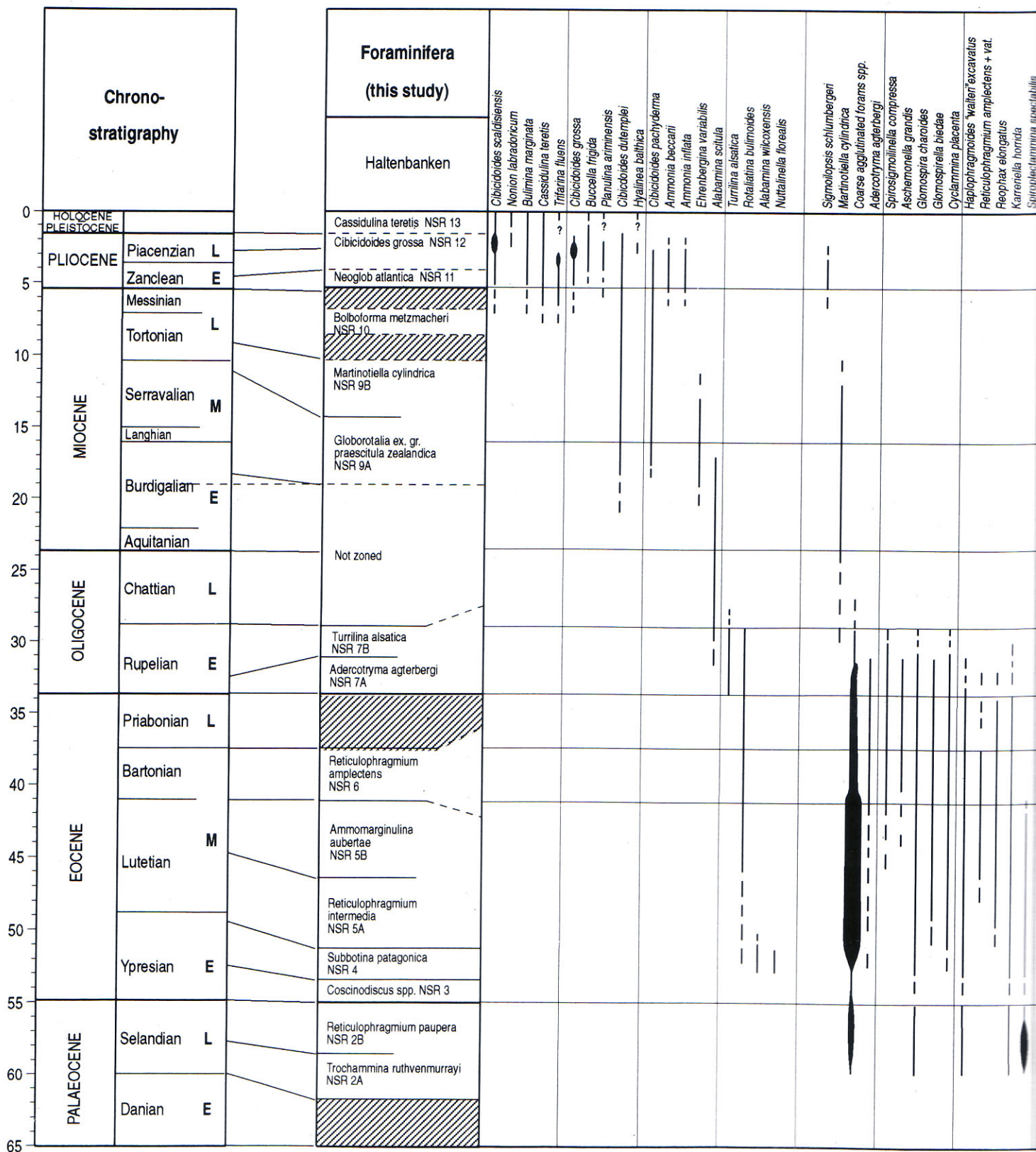


Fig. 4. Stratigraphic range chart for foraminifers and miscellaneous shelly microfossils on Haltenbanken. The average stratigraphic range is in solid, local extensions upward and downward in wells (shown dashed); fully dashed ranges are tentative. The same North Sea foraminiferal zonation of Fig. 2, albeit less detailed, applies to the Haltenbanken area; Lower Palaeocene strata are absent in the wells examined. *Dorothyia seigliei*, *Reticulophragmium jarvisi*, *Karreriella conversa*, and *Cystammina* spp. have different local ranges from those of the North Sea.







upper occurrence of *A. diktyoplokus*, above the last occurrence of *H. porosa*, and below the first occurrence of *A. arcuatum*. Bujak & Mudge (1994) also follow this concept to define North Sea Priabonian strata. We have not been able to confirm that the planktonic foraminifers of Zone NSR6B actually co-occur in wells with the dinoflagellates typifying Zone T5; correlation of Zones NSR6B and T5 is based on their assumed relative stratigraphic positions.

*RASC interval zones: Adercotryma agterbergi*  
(NSR7A) – *Turrilina alsatica* (NSR7B)

*Type-section:* Well 6407/2-3 from 1700–1580 m.

*Definition:* Interval in the wells with the last occurrence of *Areoligera semicirculata*, *Turrilina alsatica*, *Rotaliatina bulimoides* and *Adercotryma agterbergi*, above interval Zone NSR6.

*Age:* Early Oligocene (Rupelian)–early Late Oligocene (early Chattian).

*Corresponding Dinoflagellate Zones:* T6A and TB/C.

*Corresponding Seismic Sequence:* Zone NSR7A probably corresponds to CSS-3, and Zone NSR7B to the lower part of CSS-4.

*Taxa:* The following taxa, listed in descending average stratigraphic order, have their last occurrence in the zonal units listed:

Zonal unit NSR7A – *Aschemonella grandis*, *Cyclamina rotundidorsata*, *Rotaliatina bulimoides*, *Karrerella horrida*, *Ammodiscus latus*, *Glomospirella biedae*, *Adercotryma agterbergi*. Taxa listed in a few of the wells studied include '*Globorotalia*' *ampliapertura* and *G. increbescens* (both limited to the southern part of the region studied), *Reticulosphaera actinocoronata* FO, *Areoligera semicirculata* FO + LCO, *Chiropteridium lobospinosum* FO, *Distatodinium biffii* FO, *Gyroidina girardana mamillata*, *Dorothia seigliei* (Central Graben), *Reticulophragmium amplexens* var. (rare), *Haplophragmoides walteri* (rare), *H. walteri* var. (rare), *Reophax elongatus* (rare).

Zonal unit NSR7B – *Rhombodinium draco*, coarse agglutinated foraminifers spp. (Haltenbanken/Viking Graben only), *Gyroidina girardana*, *Cyclamina placenta*, *Areosphaeridium arcuatum*, *Areoligera semicirculata*, *Wetzeliella symmetrica*, *Svalbardella cooksoniae*, *Spirosigmoilinella compressa* (Haltenbanken/Viking Graben), *Turrilina alsatica*, *Spiniferites* sp. 1 Manum et al. (1989). Taxa listed in a few of the wells studied include *Cibicidoides mexicanus*, *Uvigerina gallowayi*, *Homotryblium floripes* LCO, and *Wetzeliella gochtii*.

*Discussion:* The taxa in the *A. agterbergi* – *T. alsatica* zones are readily recognized, but individual 'Oligocene' North Sea well records may be 'confusing', the result of both scatter in the tops of some taxa and reworking across the mid-Oligocene disconformity related to a major erosional event in relatively shallow marine environments (e.g., on Tampen Spur). For this reason, users

may want to combine zonal units NSR7A and NSR7B in one larger, and stratigraphically easier to correlate, interval zone NSR7.

In the (UK) 3/25-1 (860 m) and 2/8-1 (1981 m) wells, the NSR7A zonal interval contains rare specimens of *Turborotalia* aff. *ampliapertura*, probably of P19 age. The lower Oligocene marker *Cibicidoides mexicanus* was found in several wells. The zonal interval is (also) represented by the Upper Eocene – (lower?) Oligocene marker *Gyroidina soldanii mamilligera*, e.g. in wells (UK) 9/23-1 at 844 m, (UK) 9/13-3A at 1006 m, and (UK) 15/20-2 at 1260 m.

*Recurvoides* ex. gr. *walteri*, *Haplophragmoides walteri* and *Reophax elongatus* rarely range into this zone (NSR7A), but are more common in the Central Graben. *Dorothia seigliei* does not range above the Eocene *R. amplexens* zone in wells on Haltenbanken, but it does in wells southward.

*Rotaliatina bulimoides* is known from the Rupel Formation, including the Boom Clay, Lower Oligocene of Belgium; we are not aware of Chattian records for this readily recognizable taxon. The top of *R. bulimoides* is a reliable indicator of zonal unit NSR7A, where it disappears stratigraphically below *Turrilina alsatica*. In North Sea/Haltenbanken wells *R. bulimoides* is also found rarely in the calcareous benthic assemblage of the red shale unit assigned to the *S. patagonica* zone of Early Eocene age.

*Turrilina alsatica* (with radiate extinction pattern of test wall in polarized light, to distinguish it from granular patterned and Eocene *T. robertsi*) together with *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 & Neele 1983). *T. alsatica* is also known from the Viborg Formation of Denmark (Lower Oligocene). We are not aware of on-shore records in Chattian (or younger age) strata. In the North Sea it is widely used by consultants to denote undifferentiated Oligocene, without providing evidence for calibration to Chattian strata.

Feyling-Hansen & Ulleberg (1984) found *T. alsatica* together with *Rotaliatina bulimoides* and *Gyroidina soldanii mamillata* in the Sarsbukta locality at Forlandsundet, Svalbard (Spitsbergen). From this evidence the author concluded that the beds are probably Middle to Late Oligocene in age. Manum & Thronsen (1986) assigned the same strata to the upper Eocene, based on finding *Cribopteridium giuseppi*, '*Kisselovia*' *crassiramosa* and *Svalbardella cooksoniae*. If the first two palynomorphs are indeed reworked into younger strata, the beds might belong in dinoflagellate cyst Zone T6A, with the upper range of *Svalbardella cooksoniae* (Gradstein et al. 1992), a zone which is calibrated with our Zone NSR7A, Rupelian, Lower Oligocene. In Zone NSR7A, *Rotaliatina bulimoides* and *T. alsatica* overlap in stratigraphic range, hence the Sarsbukta strata of Svalbard are assigned to this zone.



*Turrilina alsatica* occurs in 13 of the 26 North Sea wells studied. A close inspection of its stratigraphic range, using associated assemblage taxa, reveals that it appears in Zone NSR7A, extends through Zone NSR7B, and locally into strata belonging in Zone NSR8A. The NSR8 record is seen in the Norwegian blocks 34 and 35, although severe sediment condensation and fossil reworking across the mid-Oligocene erosional boundary limit stratigraphic detail and confuse the fossil record. RASC calculates average *T. alsatica* top in the NSR7B zone, which is its most likely and well-documented upper range. The presence of *Rhombodinium draco* in the upper part of Zone NSR7B indicates that the NSR7B zone extends into early Chattian (Powell 1992), in agreement with the Atlantic realm calibration of the range *T. alsatica*, presented below.

Calibration of the range of *T. alsatica* to standard planktonic foraminiferal zones is feasible in the Atlantic Ocean and its western continental margin (Gradstein et al. 1994). Along the Canadian Atlantic margin, *T. alsatica* is widespread in the *Turrilina alsatica* zone, directly calibrated to the *Globigerina ampliapertura* zone (P19) and the *Paragloborotalia opima opima* zone (P20–P21). Strontium isotope analyses of mollusc and foraminiferal tests at levels with *T. alsatica* give values compatible with a late Rupelian to earliest Chattian age, across the early to late Oligocene boundary, in the sense of the time-scale of Cande & Kent (1992). 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, but it is not clear whether it actually extends throughout the P21 zone. As a result we postulate that North Sea Zone NSR7B extends from upper Rupelian, the upper part of the Lower Oligocene, into (but not throughout) Chattian strata, the lower part of the Upper Oligocene. Thus, Zone NSR7 as a whole extends from the Lower Oligocene into the lower part of the Upper Oligocene.

*Dorothia seigliei* in the Norwegian Sea ODP Site 643A appears to extend into the early Miocene, if a palynomorph age is used. We cannot exclude the possibility that its total stratigraphic range in the relatively restricted deep Norwegian Basin, behind the shallower Faeroe Island sills, is greater than that in the North Sea. *Tenuitella angustiumbilocata* extends in the overlying zone of *G. ex. gr. officinalis*. The top of the coarse agglutinated foraminifer biofacies is diachronous; in Central Graben wells it extends in the Middle Miocene (with taxa like *Cyclammmina placenta*, *C. rotundidorsata* and *Karrerella horrida*), but along wells around the (deeper marine) grabens it disappears in the Eocene (eastern Tampen Spur), or even the Palaeocene (upper Moray Firth)). The RASC program calculates an average disappearance in Oligocene strata.

In the 16/1-1 well, zonal unit NSR7, at about 1396–1585 m, corresponds to the Lower Oligocene (Rupelian) dinoflagellate zone of *Wetzeliella gochtii* – *Samlandia*

*chlamydothora* at 1372–1592 m (Ioakim 1979). In Haltenbanken well 6407/7-1, I. L. Kristiansen (in Gradstein et al. 1992) determined a diversified Rupelian dinoflagellate assemblage at between 1100 and 1200 m. It incorporates the lowest occurrences of *Reticulosphaera actinocoronata*, *Areoligera semicirculata* and *Chiropteridium lobospinosum*, and the highest occurrences of *Spiniferites* sp. 1 Manum et al. (1989), *Svalbardella cooksoniae* (the last-mentioned defining North Sea Zone T6A), *Areoligera semicirculata* LCO and LO (which defines North Sea Zone T6B/C), and *Wetzeliella symmetrica*. The last occurrences of *Chiropteridium lobospinosum* and *Deflandrea phosphoritica* at 1100 m are truncated below the Rupelian/Pliocene hiatus at 1100 m.

In Haltenbanken wells 6407/2-3, 6407/4-1 and 6406/8-1 the same dinocyst taxa occur in this zone as in well 6407/7-1.

In Viking Graben well 34/8-1, the lower part of zonal unit NSR7, between 1497 and 1400 m, corresponds to the interval with the disappearance of *Svalbardella cooksoniae*, *Areoligera semicirculata* LCO and LO, and *Wetzeliella symmetrica* of Rupelian age (Gradstein et al. 1992). In this well, the zone might extend to 1161 m using the top of *Dorothia seigliei* at 1220 m, and that of *Turrilina alsatica* at 1161 m. The latter may concur with the presence of *Distatodinium biffii* between 1422 m and 1194 m, and the last occurrences of *Homotryblum floripes*, *Chiropteridium lobospinosum* and *Deflandrea phosphoritica* between 1220 m and 1161 m, which suggests a Chattian age above 1220 m. Since the NSR7 zone, as discussed, extends into Chattian strata, we postulate that the lower Chattian is present in the 34/8-1 well, disconformably overlain by sediments assigned to Zone NSR8B, Early Miocene.

Zone NSR7 correlates to Zone NSB7 of King (1989), which includes the highest occurrences of *C. mexicanus* and *R. bulimoides*, as also observed in our data. King's (1989) reference to a *Karrerulina conversa* zone (NSA6) for the interval assigned by us to zonal unit NSR7A probably correlates to a level with the average last occurrence of *Karrerella horrida*.

*RASC interval zone: Globigerina ex gr. officinalis (NSR8A)*

*Type section:* Well (UK) 3/25-1 from 720–650 m; co-type section in well 6406/8-1 from 1860–1800 m.

*Definition:* Interval with the last occurrence of *Globigerina officinalis* group, *Chiropteridium mespilanum*, and associated taxa listed below, above Zone NSR7.

*Age:* Late Oligocene (Chattian).

*Corresponding Dinoflagellate Zone:* T7.

*Corresponding Seismic Sequence:* CSS-4 overlaps in part with Zone NSR8, but the detailed correlation has still to be investigated.

*Taxa:* The following taxa have their (average) last occurrence in this interval zone, listed in descending strati-



graphic order: *Chiropteridium mespilanum*, *Deflandrea phosphoritica* and *Tenuitella angustumbilicata*; less commonly occurring are *Globigerina officinalis* group, *Almaena osnabrugensis*, *Emslandia emslandensis*, *Chiropteridium lobospinosum*, *Coscinodiscus* sp. 4 King, *Globigerina ciperoensis*, and *Spiroplectammina carinata*.

In the Central Graben, some coarse agglutinated benthic taxa occur in this zone that further north disappear in the underlying zone NSR7 (see below). *Globigerina ciperoensis* occurs in this zone, or slightly higher in Central Graben wells (Eidvin et al. 1993). In Viking Graben well (UK) 3/25-1, there is a record of the late Oligocene marker *Almaena osnabrugensis* (Doppert 1980) at 650 m, immediately above *Globigerina officinalis* at 720 m.

In several wells this zonal interval contains common to abundant small and largely nondescript globigerinids. These include the nominate zonal species, *T. angustumbilicata*, *P. opima nana*, *Catapsydrax unicavus* and rarely *G. ciperoensis*, assigned a Late Oligocene age (P22). Sampling resolution is low in this interval and Miocene cavings hamper easy recognition of this interval zone. Floods of small, flat 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 m and 1396 m; it overlaps with the *C. lobospinosum* zone of late Oligocene age (Ioakim 1979). In Viking Graben well 34/8-1 and Haltenbanken well 6407/7-1, discussed in Gradstein et al. (1992), a hiatus between Upper Oligocene and Pliocene strata truncates microfossil ranges and makes integration of late Oligocene dinoflagellate and foraminiferal events difficult. A detailed analysis of the wells studied indicates that *Deflandrea phosphoritica*, *Chiropteridium lobospinosum* (the LO of which defines North Sea Zone T7), *Distatodinium biffii* and *Homotryblidium floripes* all extend into the zone of *G. officinalis* (NSR8A). According to Head & Norris (1989) the upper range of *Chiropteridium lobospinosum* is in the Upper Oligocene, in agreement with the correlation to the *G. ex gr. officinalis* zone.

The upper stratigraphic extent of the coarse agglutinated benthic foraminiferal assemblage is an important biofacies event in the Central North Sea. In Central Graben wells, e.g. from the 2 (Norwegian), 21, 29 and 30 (UK) blocks, there is an interval of several hundreds of metres of claystone above the *A. agterbergi* – *T. alsatica* 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 foraminifers of the *G. ex gr. officinalis* zone were also found (e.g. in the (UK) 22/6-1 well at approximately 1402 m), which locally places the top of the agglutinated/radiolarian biofacies into the Oligocene. We did not observe *Spirosigmoilinella compressa* or *Ammodiscus latus* as young as the *G. praescitula* zone, of late Early to

Middle Miocene age. This zone contains a nondescript, agglutinated benthic component in its assemblage, largely comprising fragments of tubular taxa, *Cribrostomoides* sp. and *Cyclammina* spp.

On the Tampen Spur, in wells of the Norwegian block 34, the agglutinated biofacies disappears two or more zones earlier (in time) than in the Central Graben, (in Zone NSR7), reflecting earlier shallowing. In the Norwegian block 35, the agglutinated biofacies does not extend above Zone NSR6 or lower NSR7 (Eocene–lower Oligocene), probably due to a combination of mid-Oligocene eustatic shallowing and subsequent uplift, which may have removed some sections subaerially. Above the agglutinated biofacies, and in or below the *G. ex. gr. praescitula* zone of late Early to early Middle Miocene age, there are abundant radiolarians (see section on Palaeobathymetry). In part of the stratigraphic section of the 34 and 35 block wells, the siliceous biofacies predominates with flat and spherical radiolarians and with sponge spicules. This exclusively siliceous interval is older than late Early Miocene (Zone NSR9) and younger than NSR7A (Early Oligocene). The biofacies includes the LO of the dinocysts *Emslandia emslandensis*, *Chiropteridium mespilanum* and *Deflandrea phosphoritica*, of Chattian (Late Oligocene) age, according to R. Jan du Chene. The reason for the local geographic and stratigraphic extent of this siliceous biofacies is thought to reflect the Tampen Spur position as a local high between the North Sea and Norwegian Sea, potentially inducing upwelling. Details on Oligocene uplift, sedimentation and erosion on and along this high have still to be elucidated.

#### RASC interval zone: NSR8B

*Type-section:* Well 34/4-5 from 1360–1320 m.

*Definition:* Interval in the wells with *Catapsydrax unicavus*, flattened radiolarians and sponge spicules and associated taxa listed below, above Zone NSR8A.

*Age:* Probably largely Early Miocene.

*Corresponding Seismic Sequence:* CSS-5 (p.p.).

*Taxa:* The following taxa have their average last occurrence in this interval zone, as listed in descending stratigraphic order: Flattened radiolarians and sponge spicules (siliceous biofacies), *Asterigerina gurichi*, *Catapsydrax unicavus* and *C. aff. dissimilis*; less commonly *Globotrifarina praedeheiscens*, *Uvigerina ex. gr. basicordata*, *Dentoglobigerina baroemoensis* and *Sphaeroidinella disjuncta*. The last-mentioned taxon and *Asterigerina gurichi* rarely, and with few specimens, extend through the upper part of this interval zone, and slightly above it in the overlying zone NSR9A.

One or more of the taxa listed above, which are characteristic of the early Miocene or slightly older strata, occur in wells 6407/2-3 (1450 m), 6406/8-1 (1780 m) and 34/4-5 (1360–1320 m). However, if the Lower Miocene was relatively continuously depositional



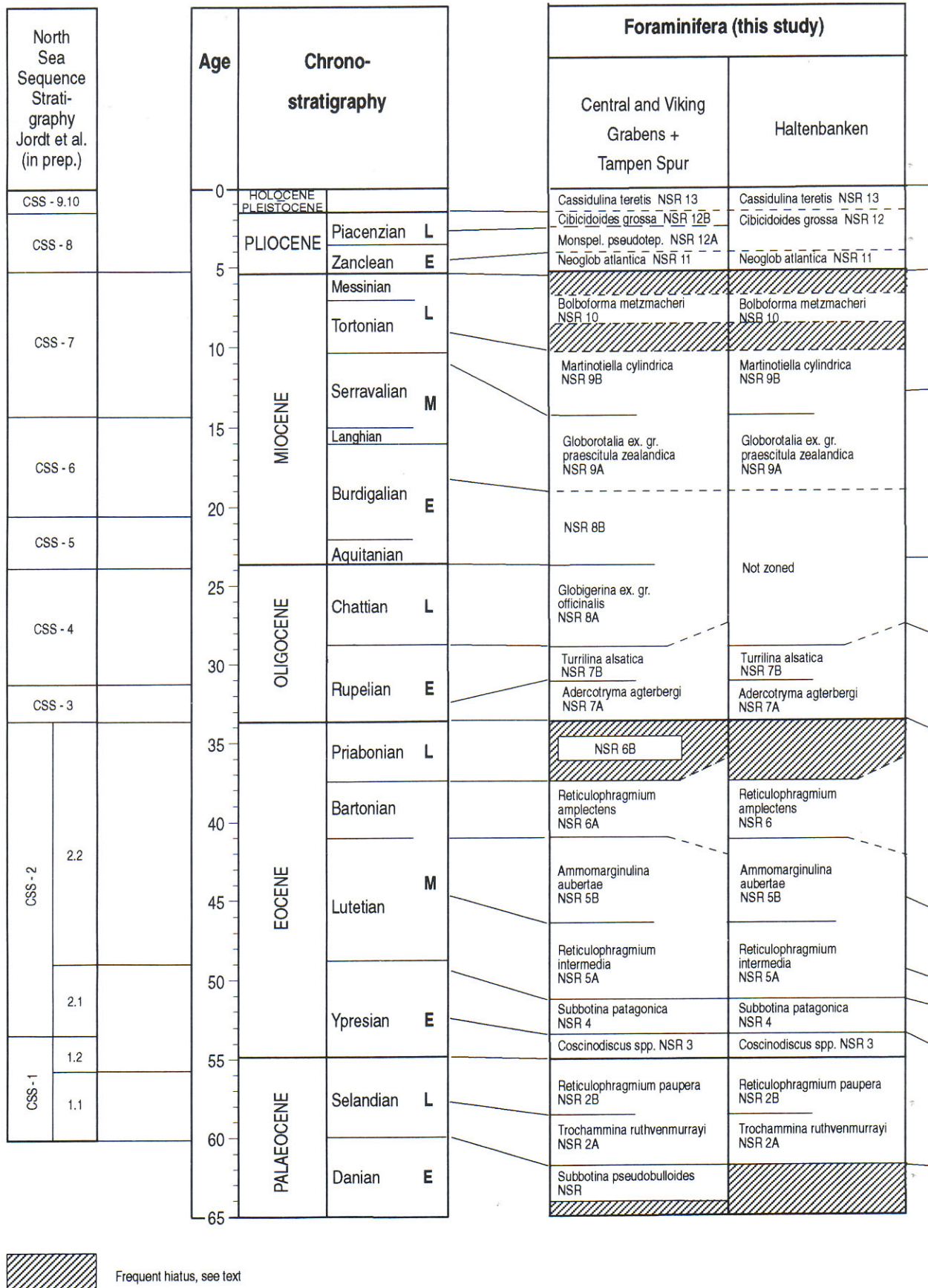


Fig. 5. Interrelation between the integrated foraminifer/dinoflagellate cyst (NSR) zonation for the North Sea and Haltenbanken, and the dinoflagellate cyst (T) Northwestern European dinoflagellate cyst zonation of Costa & Manum (1988) and the (circum central) North Sea foraminiferal zonation of King (1989). The column



Gradstein et al- (1992)	Costa & Manum (1988)	King (1989) North Sea			
		Dinoflagellates	Planktonic forams	Calcareous benthic forams	Aggl. forams
			NSP16	NSB 14-16	NSA12
			NSP15	NSB13	NSA11
	D20	NSP 12-14	NSB 11-12		
	D19				
	D18	NSP11	NSB10		
	D17				
	D16	NSP10	NSB9	NSA10	
			NSB8	NSA9	
T7	D15			NSA8	
T6B/C	D14	NSP9	NSB7	NSA7	
T6A	D13	NSP8	NSB6	NSA6	
TS	D12				
T4C/D	D11				
	D10	NSP7	NSB5	NSA5	
T4A/B					
T3C	D9	NSP6	NSB4	NSA4	
T3B	D8	NSP5	NSB3	NSA3	
	D7				
T3A	D6	NSP4	NSB2	NSA2	
T2C	D5				
T2B	D4	NSP3	NSB1	NSA1	
T2A	D3				
T1B	D2	NSP1	NSB1	NSA1	
T1A	D1				

(Eidvin & Riis 1991, 1992)		
NORTHERN PART OF THE NORTH SEA 34/4-6 & 34/8-1	MID-NORWAY (6506/12-4 & 6607/5-1) (Eidvin & Riis 1991)	
	Nonion labradoricum zone (A)	PLEISTOCENE
	Cibicides grossus zone (B)	UPPER PLIOCENE
Cibicides grossus-Elphidiella hannai-Globigerina bulloides zone (A)	Cibicides grossus-Globigerina bulloides zone (C)	
	Nonion affine zone (D)	UPPER MIOC./ LOWER PLIOC.
Eponides pygmeus zone (B)	Cibicides telegdi-Eponides pygmeus zone (E)	UPPER MIOCENE
Ehrenbergina variabilis zone (C)	Ehrenbergina variabilis-Globocassidulina subglobosa zone (F)	
	Bolboforma metzmacheri zone (G)	
	Bolboforma subfragori zone (H)	
Diatom sp. 4 zone (D)		LOWER MIOCENE
Diatom sp. 3 - Turritina alsatica zone (E)	Diatom sp. 3 zone (I)	LOWER MIOC./ UPPER OLIG.

zonation for some of the same wells by I. L. Kristiansen in Gradstein et al. (1992), the offshore Norway Neogene zonation of Eidvin & Riis (1991, 1992), the with the late Paleocene through Pleistocene seismic sequences CSS-1 through 10 is after Jordt et al. (in prep).



and thicker, many more taxa would be expected. One problem is that some overlap in actual depth exists with tops of taxa assigned to the overlying zone of *Globorotalia* ex. gr. *praescitula*. This mixing may be a function of reworking or a combination of condensation in a stratigraphic sense, with too wide a sample spacing (10–20 m). The lower Miocene (Aquitanian–lower Burdigalian), if and when present, is undoubtedly relatively thin (tens of metres or less).

*RASC interval zones: Globorotalia praescitula group (NSR9A) – Martinotiella cylindrica (NSR9B)*

*Type-section:* Well 2/2-4 from 1753–1460 m.

*Definition:* Interval in the wells with the last occurrence of *Globorotalia* ex. gr. *praescitula zealandica*, *Neogloboquadrina continua*, *Uvigerina* ex. gr. *semiornata* and associated taxa listed below, above Zone NSR8.

*Age:* Late Early, Middle and probably early Late Miocene.

*Corresponding Seismic Sequence:* CSS-6 and lower part of CSS-7.

*Taxa:* The following taxa or log events, listed in descending stratigraphic order, have their last or average last occurrence in this interval zone:

Zonal unit NSR9A – *Uvigerina* ex. gr. *semiornata*, *Globigerinoides trilobus*, *Caucasina elongata*, *Sphaeroidinella disjuncta* (rare), *Globigerina praebulloides*, *Neogloboquadrina continua*, and group of *Globorotalia praescitula* – *G. zealandica*. Common to abundant planktonics in this zone in Central Graben wells also include: *Globigerinoides* spp., *Globoquadrina dehiscens*, *Globorotalia praemenardii*, and *Globorotalia mayeri*. The upper part of the *G. praescitula*–*zealandica* zone yields *Orbulina suturalis*, but there is no record of *Neogloboquadrina acostaensis*.

Zonal unit NSR9B – *Sumatradinium* spp., radiolarian/diatom flood, *Siphonina advena*, *Martinotiella cylindrica*, North Sea log marker G, *Ehrenbergina variabilis*, *Cannosphaeropsis utinensis*. Less common are occurrences of *Alabamina scitula*, *Unipontidinium aquaeductum*, *Palaeocystodinium* sp. A Costa and Downie, *Bolboforma reticulata*, *B. fragori*, *Globocassidulina subglobosa* var., and *Globoquadrina venezuelana*.

*Discussion:* The planktonic assemblage listed above for NSR9A correlates to the upper part of the Lower Miocene and the lower part of the Middle Miocene (probably N6 or N7 to N11 or slightly younger), which agrees with the assignment by A. C. Morton of NS log marker G as the top of the Middle Miocene (?Upper Miocene hiatus on logs). Since the average position of log marker G occurs virtually between zonal units NSR9A and B, a hiatus may generally be present near that level. Although the total range of *G. praebulloides* is from P22 to N18 (Kennett & Srinivasan 1983), this species does not extend above the Lower to Middle Miocene of the North Sea and the Canadian margin.

North Sea specimens examined by us, listed as a record of *G. praebulloides* in the Upper Miocene strata, would be better assigned to atypical *G. bulloides*, or to *G. opimana*. The LO of *G. praescitula* and that of *S. disjuncta* may be slightly older than in the Atlantic Ocean, and are at N8 and N10 respectively (Gradstein et al. 1994).

*Asterigerina staeschi* (rare), *A. gurichi* (rare), *Alabamina scitula*, and *Caucasina elongata* are among the calcareous benthic foraminifers in Zone NSR9. The presence of *Sumatradinium* spp. and *Cannosphaeropsis utinensis* in Zone NSR9B is taken as indicative of either Late Miocene (R. Jan du Chene, pers. comm. 1992), or Middle Miocene (H. Brinkhuis, pers. comm. 1992). More studies may be needed to make an unequivocal determination of their ranges in the North Sea.

Agglutinated foraminifers are common in this zone in Central Graben wells, particularly around the Ekofisk area, with taxa such as *Cribostrumoides*, *Glomospira*, *Bathysiphon*, *Hyperammina*, *Martinotiella cylindrica*, *Trochammina*, *Reophax* and *Cyclammina*, including *C. cancellata*, *C. placenta* and the rare *C. rotundidorsata*. *Martinotiella cylindrica* is a more slender form than its coeval *M. communis* in Norwegian Sea DSDP and ODP sites. As mentioned above, in the southern North Sea wells, e.g. (UK) 22/6-1, (UK) 29/3-1 and (UK) 30/19-1, the zone is associated with common to abundant planktonic taxa, both foraminifers and radiolarians. These Miocene sediments were laid down in a bathyal depo-centre and are thick and fossiliferous.

In northern North Sea wells, the Miocene interval is either missing, due to uplift and erosion, or is relatively thin and shallow marine (mostly neritic), as in the (UK) 9/23-1, 34/4-5, 34/7-1, and 34/8-1 wells. Jordt et al. (in prep.) similarly note a northward thinning and absence of CSS-6, approximately correlative to Zone NSR9A. Zones NSR9A and B are more difficult to distinguish than those further south. We observed planktonic foraminifers including *Globigerinoides obliquus*, *Globigerina praebulloides*, *Globorotalia* ex. gr. *praescitula*, *Globoquadrina venezuelana*, *Catapsydrax unicavus* (?reworked), together with a few specimens of the benthics *Uvigerina* ex. gr. *semiornata*, *Nonion granosum*, *Epistomina elegans*, *Caucasina elongata*, *Martinotiella cylindrica*, *Ehrenbergina variabilis*, *Alabamina scitula* and *Asterigerina gurichi*.

On Haltenbanken, Zone NSR9 yields taxa similar to those found in the northern North Sea, but planktonic foraminifers are relatively rare, and less diverse. *Globocassidulina subglobosa* var. was not observed, but *Bolboforma* events (*B. reticulata*, *B. fragori*) occur and are stratigraphically useful (Spiegler & von Daniels 1991).

The *G. praescitula* zone NSR9A probably corresponds to NSP11 and 12 of King's (1983) zones, which list fewer planktonics, but assign a comparable age range for the zone. The relation of zone NSR9B to the *Ehrenbergina variabilis* assemblage of Eidvin & Riis (1991, 1992) is the subject of further discussion.



**RASC interval zone: *Bolboforma metzmacheri* (NSR10)**

**Type-section:** Well (UK) 29/3-1 from 1378–1370 m; co-type section in well (UK) 22/6-1 from 1186–1155 m.

**Definition:** Interval in the wells with the last occurrence of *Bolboforma metzmacheri*, above Zone NSR9.

**Age:** Late Miocene.

**Corresponding Seismic Sequence:** ? Middle part of CSS-7; Jordt et al. (in prep.) indicates that CSS-7 spans the upper part of the Middle and Upper Miocene, but in view of postulated hiatuses (see below), we consider CSS-7 to be overextended in time.

**Taxa:** The following taxa have their highest occurrence in this interval zone: specimens belonging to the group *Neogloboquadrina continua-acostaensis-humerosa*, *Bolboforma spiralis*, *Bolboforma metzmacheri*, *Globoquadrina venezuelana* (Central Graben), *N. atlantica* (right coiling).

**Discussion:** In a few wells, e.g. (UK) 29/3-1 at 1378 m, (UK) 22/6-1 at 1155–1186 m, 34/4-5 at 1040 m, 6407/4-1 at 1290 m and 6404/8-1 at 1440 m, there is an interval with taxa listed above, below the occurrence of *Globorotalia puncticulata* and above the presence of taxa in the *G. praescitula*–*M. cylindrica* zone. The sediment interval is relatively thin, probably less than 100 m, and corresponds to a time interval between the Middle Miocene and Early Pliocene. Following Doppert (1980) and King (1983, 1992), taxa in this interval are Late Miocene in age; zone NSR10 equates with NSP14 of the latter author. Spiegler & von Daniels (1991) also define the *B. metzmacheri* zone as part of a series of 12 Cainozoic *Bolboforma* zones with widespread, 'global' correlation potential, extending into the North Sea Basin. The *B. metzmacheri* zone extends from the first common to the last common occurrence of the nominate species, and is calibrated to part of Zones N16 and N17, and part of NN10 and NN11, the middle part of the Late Miocene. The NSR zonation presented here follows this calibration.

King (1992) calibrates the disappearance of *B. metzmacheri* in Zone NN9 significantly below NN10–11; in our opinion this calibration should be revised stratigraphically upward. Eidvin & Riis (1991, 1992), and Eidvin et al. (1993) also calibrate a *B. metzmacheri* zone for mid-Norway as being older than the same zone in Spiegler & von Daniels (1991).

Eidvin & Riis (1991, 1992) make the observation that an assemblage with *E. variabilis* (probably belonging in zone NSR9B), offshore mid-Norway, occurs above (not below, as postulated here) the zone with *B. metzmacheri*. The latter does not appear to be borne out by observations, as explained below.

Specifically, Eidvin & Riis (1991, 1992) detail that:

- (a) In the 6607/5/1 well, the occurrences of *B. metzmacheri* and *E. variabilis* overlap, with the latter extending slightly lower and also higher in the section.

- (b) In the 34/8-1 well, *E. variabilis* extends below and (one sample) also above the range of *B. metzmacheri*, with *B. subfragoris* occurring in the youngest sample with *E. variabilis*. According to Spiegler & von Daniels (1991), the range of *B. subfragoris* possibly slightly overlaps with that of *B. metzmacheri*, but extends largely into older strata. Hence, in well 34/8-1, our Zone NSR10 with *B. metzmacheri* appears to be absent.

- (c) In the 2/4-C11 well, *E. variabilis* occurs at the base of the *B. metzmacheri*/*B. laevis* assemblage of Eidvin & Riis (1991, 1992), below the occurrence of *Martinotiella communis* (which belongs in our Zone NSR9), and below a level with *B. metzmacheri* and *B. laevis*, and together with *Siphonina reticulata* (probably our *S. advena* event of Zone NSR9). The data from this well are in agreement with results calculated with RASC.

The above observations suggest that the stratigraphic relationship of the two taxa is not unequivocal, and not in conflict with RASC results that consider all (co-) associations in 26 wells. According to our observations, weighted towards the North Sea Basin, the last occurrences of *B. metzmacheri* and *E. variabilis* do not overlap, with the latter occurring in older strata, assigned to NSR9 using other taxa listed for that zone. A scan of Haltenbanken (offshore mid-Norway) and North Sea well reports in the Saga Petroleum library did not reveal any obvious discrepancy to this observation. However, we do not rule out that, as quoted by Eidvin & Riis (1991, 1992), *E. variabilis* extends stratigraphically younger from south to north, offshore Norway. Further studies are warranted, also with respect to the mentioned discrepancy in chronostratigraphic calibration of the *B. metzmacheri* zone.

The fact that Upper Miocene strata are relatively thin, the absence of immediately underlying and overlying *Bolboforma* or other standard planktonic zones in most wells, and the lack of more index taxa for this relatively long period of time indicate that the Upper Miocene is incompletely present in the North Sea region and Haltenbanken.

**RASC interval zone: *Neogloboquadrina atlantica* (NSR11)**

**Type-section:** Well 16/1-1 from 820–700 m; co-type sections in well (UK) 29/3-1 from 1350–1200 m, and well 34/7-4 at 1120 m.

**Definition:** Interval in the wells with *Globorotalia puncticulata*, *N. atlantica* (left coiling) and associated taxa listed below, above Zone NSR10.

**Age:** Early Pliocene (N19–N21)

**Corresponding Seismic Sequence:** Lower part of CSS-8.

**Taxa:** The following taxa, listed in descending stratigraphic order, have their last occurrence in this interval zone: *Neogloboquadrina atlantica* (left coiling), *Globorotalia puncticulata*, *G. crassaformis*, and the group of *Neogloboquadrina acostaensis-humerosa*.



*Discussion:* In several wells, notably (UK) 30/19-1 from about 762–1259 m, (UK) 29/3-1 from about 1350–1200 m, (UK) 22/6-1 near 1128 m, 16/1-1 from about 820–700 m, 2/2-4 at 740 m, (UK) 9/23-1 at 1500 m, 34/7-4 at 1120 m, 34/8-1 at 1080 m, 34/4-5 at 780 m and 6407/2-3 at 1040 m, an assemblage occurs with planktonic foraminifers assigned to the *N. atlantica* zone. In the Central Graben, the assemblage is diversified and specimen rich, changing to a much impoverished assemblage with few specimens further north, particularly in Haltenbanken. The assemblage contains the planktonics cited above plus *Neogloboquadrina pachyderma*, *N. humerosa*, *Globigerina apertura*, *G. bulloides*, and *Orbulina universa*. Jenkins et al. (1989) described a similar assemblage from the Coralline Crag of Suffolk, eastern England. The authors cite ranges throughout the Early Pliocene for these taxa, which agrees with our observations, albeit in well samples, that the range of *Globorotalia inflata* probably does not overlap with these taxa, but is restricted to the overlying zone. *N. atlantica* in the N. Atlantic Ocean disappears at 2.3 Ma (Baldauf et al. 1989).

Among benthic taxa 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 planktonic taxa are relatively abundant in this part of the stratigraphic column in 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 environment that supported only a few benthic species.

The *N. atlantica* zone correlates to the *G. puncticulata* zone of Weaver & Clement (1986), and NSP15 of King (1983), of Early Pliocene age.

*RASC interval zones: Monspeliensina pseudotepida (NSR12A) – Cibicidoides grossa (NSR12B)*

*Type-section:* Well 34/8-1 from 1040–440 m; co-type sections in well 6407/4-1 from 690–450 m.

*Definition:* Interval in the wells with the last occurrence of *Monspeliensina pseudotepida*, *Cibicidoides grossa* LCO and LO, and associated taxa listed below, above Zone NSR11.

*Age:* Late Pliocene.

*Corresponding Seismic Sequence:* Upper part of CSS-8.

*Taxa:* The following taxa, listed in descending stratigraphic order, have their last occurrence in this interval zonal unit:

Zonal unit NSR12A – *Cibicidoides pachyderma*, *Sigmoilopsis schlumbergeri*, *Monspeliensina pseudotepida* (rare), *Hyalinea balthica* (rare), *Planulina ariminensis* (rare), *Cibicidoides grossa* LCO, *C. scaldisiensis* LCO, *Trifarina fluens*, *Globorotalia inflata*; *Globigerina bulloides* may be abundant in this zone, which is a correlative

event (Eidvin & Riis 1991); *Neogloboquadrina pachyderma* extends through both zonal units NSR12A and B, and into Zone NSR13 (see below).

Zonal unit NSR12B – *Ammonia beccarii*, *Cibicidoides grossa*, *Buccella frigida*.

*Discussion:* The *M. pseudotepida*–*C. grossa* zonal unit generally characterizes the highest interval sampled in the wells examined. Limited sampling in the upper sediment section of wells often precludes separation of NSR12A and NSR12B. Several taxa in it are also known from the present, which means that their local disappearance may be the result of water mass cooling and shallowing throughout the late Neogene. The zonal interval is generally rich in *Cassidulina* and *Elphidium* with uvigerinids, miliolids and nonionids being less common. Planktonic taxa are rare in the majority of wells, and together with the benthics *Trifarina fluens*, *Monspeliensina pseudotepida* and *Sigmoilopsis schlumbergeri* are confined to the lower part of this zonal unit, named NSR12A; an exception is *N. pachyderma*, which occurs throughout NSR12.

The age of NSR12 is based on the presence of non-rugose and right-coiling *N. pachyderma*, which is older than 1.7 Ma (Weaver & Clement 1986), and the assumption that we are dealing with the lower range of *G. inflata*, which appears in the Late Pliocene at 2.1 Ma, as a descendant of *G. puncticulata*. *Cibicidoides grossa* is also thought to be restricted to the Pliocene and to 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.

*Hyalinea balthica* is a neritic to (upper) bathyal species widely known from N21–N23, late Pliocene through Pleistocene. In the wells examined it tops with *Planulina ariminensis*, below the extinction of *C. grossa*, although *H. balthica* is known from the present North Sea. Other extant taxa are *Trifarina fluens*, *Sigmoilopsis schlumbergeri* and *Cassidulina teretis*.

*RASC interval zones: Cassidulina teretis (NSR13)*

*Type-section:* Well 6407/4-1 from 450–330 m (= uppermost sample).

*Definition:* Interval in the wells with *Cassidulina teretis*, *Cibicidoides scaldisiensis* and associated taxa listed below, above Zone NSR12.

*Age:* Pleistocene.

*Corresponding Seismic Sequence:* ? CSS-9.

*Taxa:* The following taxa have their last occurrence in this interval zonal unit: *Nonion labradoricum*, *Cibicidoides scaldisiensis*, *Bulimina marginata*, *Cassidulina teretis*, *Elphidium* spp., *Buccella frigida* and rare *Neogloboquadrina pachyderma*. This assemblage is assigned a Pleistocene age. It was sampled in a few wells only, e.g. 6407/2-3 above 460 m, and 6407/4-1 above 450 m. The order of the events in the scaled optimum sequence of Fig. 2 has limited stratigraphic meaning, as



Table 4. Diachronous last occurrence of four taxa of agglutinated foraminifers, North Sea and Haltenbanken.

	Top in the North Sea	Top on the Haltenbanken
<i>Dorothia seigliei</i>	Lower Oligocene	Middle Eocene
<i>Reticulophragmium jarvisi</i>	Lower Oligocene	Upper Palaeocene
<i>Karrerriella conversa</i>	Middle Eocene	Upper Palaeocene
<i>Cystammina</i> spp.	Palaeocene	lower Middle Eocene

all taxa are extant, but the dendrogram cluster as a whole clearly stands out from underlying ones, testifying to the validity of this zone. Many more taxa may be determined in this interval, which is of limited value to routine stratigraphy in deep exploration wells.

### Foraminiferal zonation for Haltenbanken

The microfossil record in Haltenbanken wells 6407/7-1, 6407/4-1, 6407/2-3 and 6406/8-1 differs only in degree from that further south. Planktonic taxa are less common, and many benthic taxa which are rare in the North Sea did not colonize Haltenbanken. These rare taxa do not affect the zonation. Several benthic taxa show shorter stratigraphic ranges on Haltenbanken, as discussed below. Overall, the zonation proposed for the North Sea is also applicable to Haltenbanken (Fig. 3).

In order to highlight differences, a zonation was calculated using the STRATCOR program on the four wells examined. RASC is not suitable for a sample of four wells only. The same zones stand out as in the North Sea RASC zonal model of Fig. 2, except that of the *S. pseudobulloides* zone (Danian) is absent on Haltenbanken, and the *M. pseudotepida* subzone (Late Pliocene) is not differentiated.

The agglutinated benthic foraminifers *Dorothia seigliei*, *Reticulophragmoides jarvisi*, *Karrerriella conversa*, and *Cystammina* spp., have different local ranges from those of the North Sea (Figs. 3, 4; Table 4). Since *D. seigliei* in Norwegian ODP sites is found in the Oligocene–?Lower Miocene strata, it is assumed that a study of more Haltenbanken wells will update the stratigraphic range to agree with that in the North Sea. The ranges of *Cystammina* spp. are affected by changes in palaeobathymetry, as discussed for the *R. paupera* zone (see above). We expect that a study of more wells will also reveal that *K. conversa* extends into the Middle Eocene.

There is no foraminiferal record on Haltenbanken associated with the (informal) *G. officinalis* zone (upper Oligocene) of the North Sea. The absence of *M. pseudotepida* (Pliocene) is noted.

### Palaeobathymetry

Palaeobathymetry at well sites is an important parameter in depositional history, subsidence and burial analysis in

well sites. Estimates of changes in palaeobathymetry detail the amount of sediment underfill in basins.

In general, an overestimation of palaeo water depth may induce artificial uplifts through time in the subsidence model, whereas its underestimation artificially reduces subsidence rate. Ignorance of palaeobathymetric trends will generally lead to an underestimation of basin subsidence and incorrectly assigned palaeoslopes.

Using the multiple fossil criteria listed below, five depositional environments are recognized in the Cainozoic strata of the North Sea, classified according to both water depth and distance from shore:

- (1) Non-marine, terrestrial;
- (2) shallow neritic, less than 100 m deep;
- (3) deep neritic, 100–200 m deep;
- (4) upper bathyal (upper slope), 200–500 m deep;
- (5) middle bathyal (middle slope), 500–1000 or slightly deeper.

The palaeontological criteria, which are essentially based on the bottom dwelling foraminiferal assemblages encountered in the Palaeogene and Neogene North Sea marine sediments, are listed in Figs. 6a, b, and c. As a general rule, benthic foraminiferal diversity increases basinward, from shallower to deeper marine conditions. Radiolarian mudstones may be expected under upwelling conditions along shelf edge or deeper marine environments.

The criteria may be summarized as follows:

- (a) Non-marine, terrestrial: spores-pollen; no foraminifers.
- (b) Shallow neritic, less than 100 m: foraminiferal assemblages of low generic and species diversity; planktonic taxa are rare. *Elphidium* (sometimes monotypic), *Quinqueloculina*, *Nonion*, gastropods, and bryozoans occur in upper Neogene strata.
- (c) Deep neritic, 100–200 m; foraminiferal assemblages of varying diversity; planktonics locally common. *Uvigerina*, *Pullenia* (rare), *Sphaeroidina*, *Sigmoilopsis* (rare), and *Ceratobulimina* occur in Neogene strata. Palaeogene assemblages reflect the Midway formation-type faunas.
- (d) Upper bathyal (upper slope), 200–500 m or deeper (750 m?): foraminiferal generic and species diversity is high. *Uvigerina* is common to frequent in Neogene strata; other taxa include *Melonis barleanum*, *Cibicidoides pachyderma*, *Gyroidina girardana*, *Epistominina elegans*, *Pullenia bulloides* and common *Martinotiella*. Palaeogene benthic assemblages may be dominated by coarse, often large-sized agglutinated taxa, including cyclamminids and tubular forms. Under low sedimentation rate conditions planktonics and radiolarians may occur frequently.
- (e) Middle bathyal (middle slope), 500/750 m and deeper: foraminiferal diversity is high; calcareous Neogene benthics may include *Cibicidoides wuellerstorfi*, *Melonis pompilioides*, *Uvigerina* spp., and for



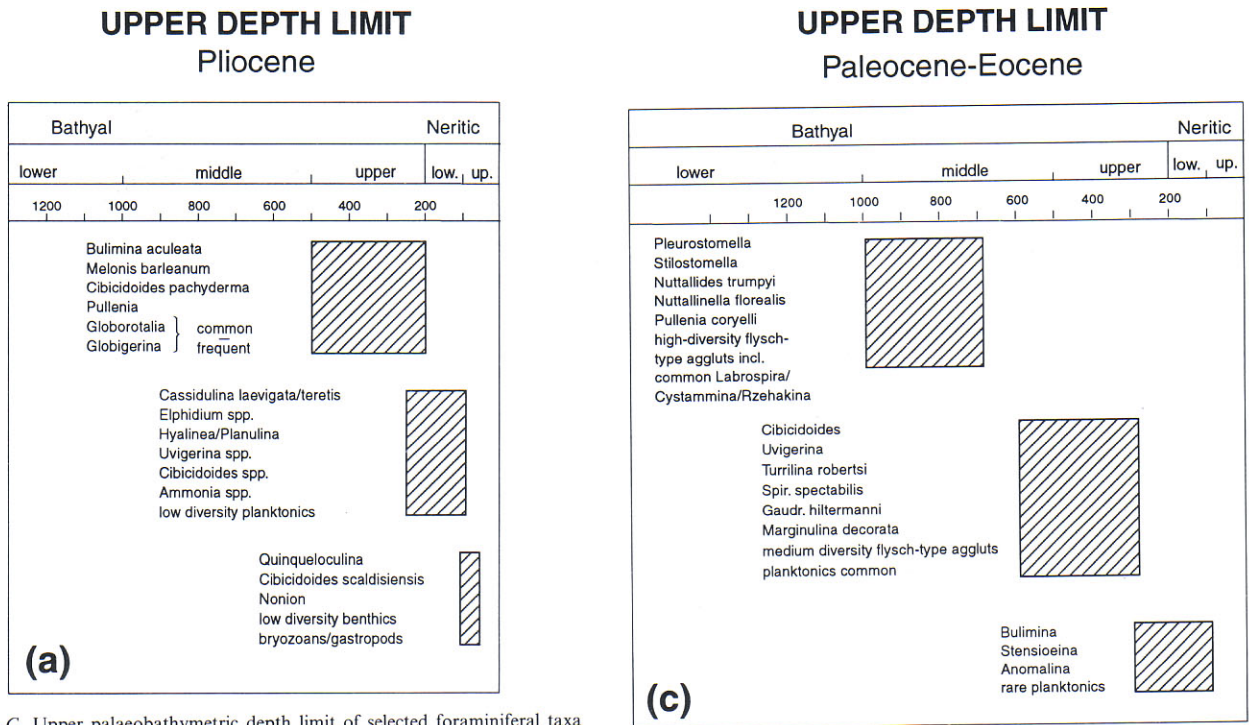


Fig. 6A - C. Upper palaeobathymetric depth limit of selected foraminiferal taxa or groups of taxa in the North Sea and Haltenbanken. For an explanation, see text.

the Palaeogene *Pleurostomella*, *Osangularia*, *Stilostomella* and *Nuttallides*. Agglutinated benthic assemblages are diverse and contain both finer- and coarser-grained, smaller-sized taxa, particularly *Cystammina*, *Rzehakina* and *Labrospira*. In the Palaeogene North Sea, the CCD (Calcium Carbonate Compensation depth) was relatively shallow, preventing calcareous sedimentation in the central (deepest) part of the basins. Such conditions were probably created by water-mass stratification in the semi-restricted basins that created an oxygen-minimum zone in the deeper water levels. Oxygen starvation resulted in limited organic matter oxidation, and led to higher levels of carbon dioxide, inducing carbonate corrosion and, ultimately, dissolution. The observation of calcareous assemblages with sparse planktonic and benthic taxa in basin-edge wells and on higher blocks (platforms) is in agreement with the restricted basin hypothesis.

More detailed information on neritic palaeobathymetry may be obtained from Murray (1991) and for bathyal and deeper environments from van Morkhoven et al. (1986).

Palaeogene sediments of the Central North Sea and Canadian Atlantic margin abound in predominantly agglutinated benthic foraminiferal assemblages. The fauna as a whole, probably encompassed up to 120 species and 65 or more genera from all major (ca. 9) families. As pointed out in a number of studies (Gradstein & Berggren 1981; Miller et al. 1982; Scott et al. 1983; Schroeder 1986), the diverse and abundant agglutinated assemblages found in the Palaeogene well sediments at



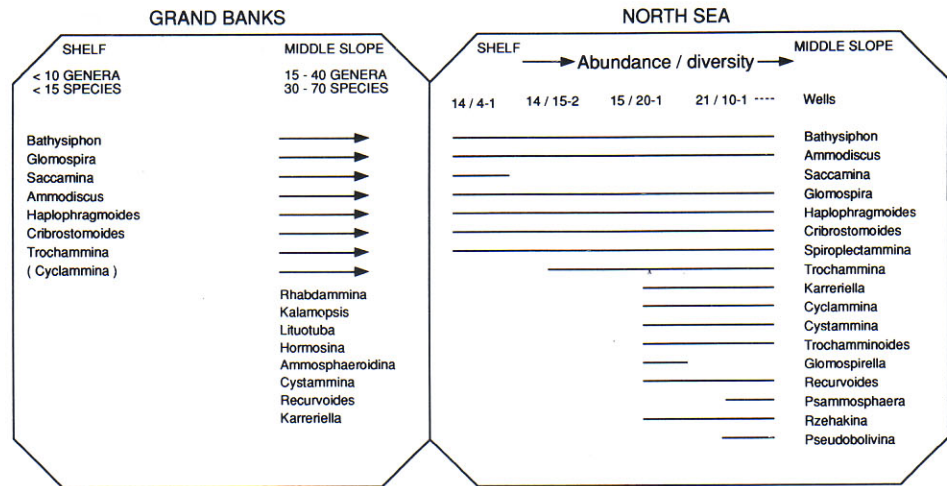


Fig. 7. Bathymetric distribution of selected coarse agglutinated benthic foraminiferal taxa, North Sea/Haltenbanken and Canadian Atlantic margin. For further information see text.

present occur on the modern continental slope, with their niches ranging down onto the abyssal plain. The fauna favours a fine-grained, low energy substratum, which is why it predominates in mudstone basins, where sediments may be generally enriched in organic matter. The fauna is not strictly bathymetrically controlled. On the other hand, this so-called flysch-type fauna, which we named after assemblages that are typical of some of the classical 'flysch' deposits in the Carpathians and Alps (Gradstein & Berggren 1981) from detailed observations on Recent slope fauna (Scott et al. 1983; Schafer et al. 1983; Schroeder 1986), has an upper depth limit of around 500 m. Few individual genera in it may dwell on the shelf, or even in marshes (e.g., some species of *Trochammina* and *Ammodiscus*), although on a species level, there is limited overlap between modern shelf and slope agglutinated faunas. In our concept of 'The Recent as a key to the Past', augmented with observations along palaeoslope transects (see below), the observed agglutinated benthic fauna in Palaeogene strata of North Sea and Canadian offshore wells is typical of middle- to upper-slope conditions. From recent observations, taxa such as *Cystammina*, *Labrospira* and *Pseudobolivina* are more typical of middle- to lower-slope conditions, which agrees with their absence in more updip, basin margin wells studied (see below).

In order to strengthen palaeobathymetric interpretations, Gradstein et al. (1994) analysed faunal trends along palaeoslope transects, using wells and long seismic lines in both the Central North Sea and northern Grand Banks. The objective was to assess lateral faunal changes along shelf to basin transects and enhance local palaeobathymetric models for these petroleum basins, applicable to realistic burial and subsidence analysis. Palaeoslope studies estimated the deepest part of the transects to be between 750 and 1000 m in water depth. The agglutinated benthic fauna not only becomes much more diversified basinward, but also extends into

younger strata in the deeper part of the North Sea Basin, from the Late Palaeocene along the basin edges to the Neogene in the central basin area. Cyclamminids, Rzehakinids, Cystamminids, *Recurvoides* and *Karrieriella* are confined to the basinal wells, with *Bathysiphon*, *Haplophragmoides*, *Cribrostomoides*, *Ammodiscus*, *Glomospira* and *Saccamina* being more opportunistic and extending to the margin. *Pseudobolivina* and (abundant) radiolarians, e.g. *Cenosphaera*, are also confined to the basinal mudstones. In general, the number of taxa of the family *Lituolidae* increases at the expense of the *Ammodiscidae*.

The above observations are in agreement with those of Jones (1988), who analysed agglutinated faunal changes along a Viking Graben palaeodepth transect, parallel to ours, but slightly to the north in the Frigg petroleum field area. Jones (1988) estimated the so-called basin floor assemblage to be 1000–1500 m deep, with our estimate favouring the shallow end of this bracket. There probably is an uncertainty of estimate in palaeo water depth, which may reach 25% or more of the depth estimate in metres on the middle to lower slope.

In order to summarize the agglutinated faunal trends along the Grand Banks and the North Sea transects from a shallow, proximal to deeper, distal facies, we have listed observed taxonomic and diversity trends in Fig. 7. There are less than 10 genera and 15 species up-slope and routinely 15–30 genera and 30–60 species or more down-slope. *Bathysiphon*, *Glomospira*, *Saccamina*, *Ammodiscus*, *Haplophragmoides*, *Cribrostomoides* and *Trochammina* are more opportunistic and widespread, and *Rhabdammina*, *Cyclammina*, *Kalamopsis*, *Lituotuba*, *Hormosina*, *Ammosphaeroidina*, *Cystammina*, *Recurvoides*, *Karrieriella*, *Rzehakina*, *Pseudobolivina* and *Labrospira* together are more typical for middle- or lower-slope conditions. As indicated earlier, there appears to be a local water depth difference of 500–1000 m along both transects basinward, which provides a (minimum) estimate of water depth difference between faunal end members.



### Stratigraphic distribution of sediment and burial history

Two stratigraphic displays that yield simple and informative overviews of regional geological trends through time are the stratigraphic distribution of sediments in several wells, and age-depth graphs for one or more wells or transects. The former graphs are chronograms, the latter burial graphs.

Chronograms display the distribution of sediments in wells, plotted against linear time; colours may differentiate time-successive palaeoenvironments, while the thickness of intervals is noted in metres. Burial is defined as the subsurface path (depth transect) through time of a horizon, from its original depth of deposition to its present subsurface depth. Tectonic subsidence is the residual subsidence left after the amount of sediment loading is subtracted from the amount of burial through time. Burial history uses all available data expressed in numerical units. Inputs are age, depth, palaeo water depth, eustatic sea-level height, lithology, depth porosity and grain densities, to yield information on vertical motion at well sites due to tectonic forces, sediment and waterfill and sediment loading (Stam et al. 1987; Gradstein et al. 1989).

Figures 8 and 9 show the distribution of sediment in time for the four Haltenbanken wells, ordered more or

less basinward, and six Viking Graben to Central Graben wells, ordered south-north. As far as possible, the stratigraphy reconciles all available microfossil ages and the sediment was classified into five categories based on palaeobathymetric interpretations (see previous section). Several trends stand out, and these will be discussed in conjunction with the burial history for wells in Figs. 10 and 11 and the seismic sequence stratigraphy for the central and northern North Sea, proposed by Jordt et al. (in prep.).

### Haltenbanken

In the four wells on Haltenbanken, the Danian, Upper Eocene, and part or all of the Upper Miocene are missing. The lack of palaeobathymetric detail for Cretaceous strata prevents an analysis of the history up to and including the Danian, but the two younger hiatuses are considered to be the result of a combination of regional uplift and of erosion due to eustatic sea-level changes (see below). We have taken into account that Late Palaeocene time saw major volcanic activity in the Norwegian Sea, at the onset of sea-floor spreading. Major subsidence progressed in late Palaeocene to Middle Eocene time from west to east away from the Vøring Plateau peripheral bulge. Overall, the basin shows a shallowing upward trend

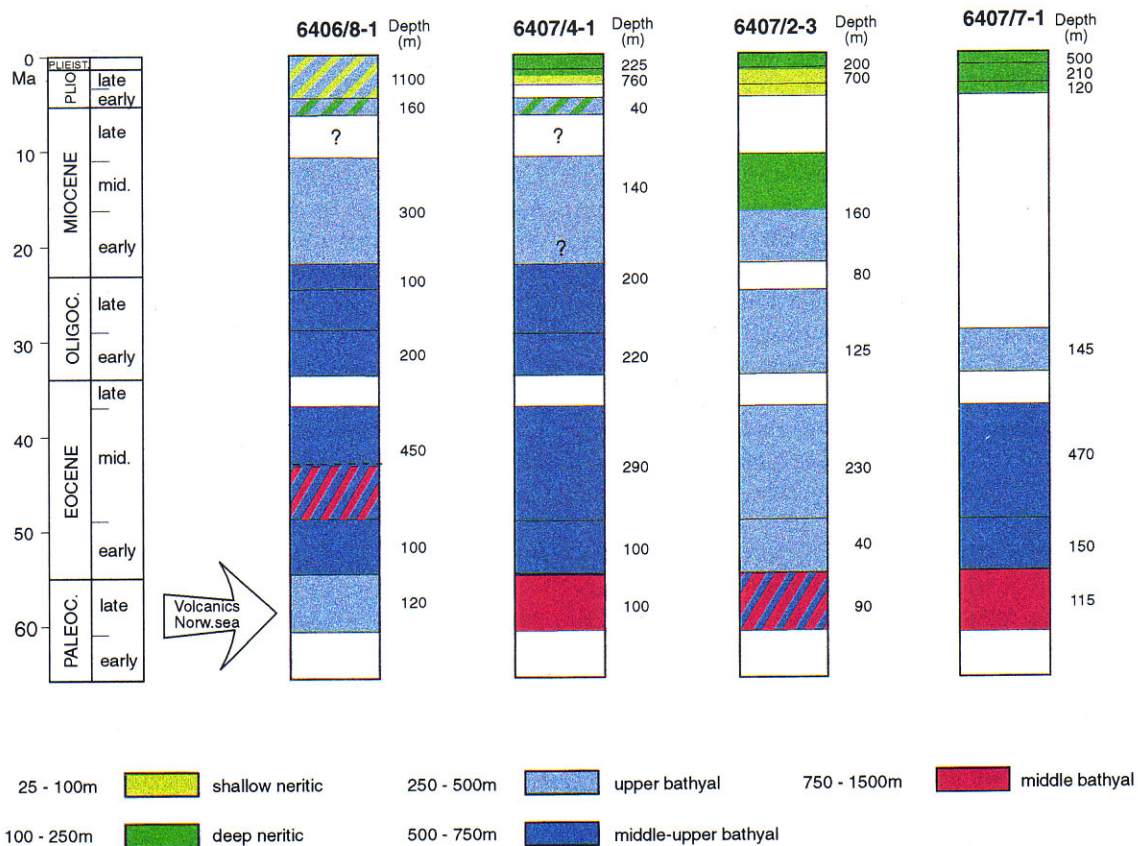


Fig. 8. Stratigraphic distribution of Cainozoic sediments in the Haltenbanken wells 6406/8-1, 6407/4-1, 6407/2-3 and 6407/7-1, classified according to five palaeo depth categories. For further information see text.



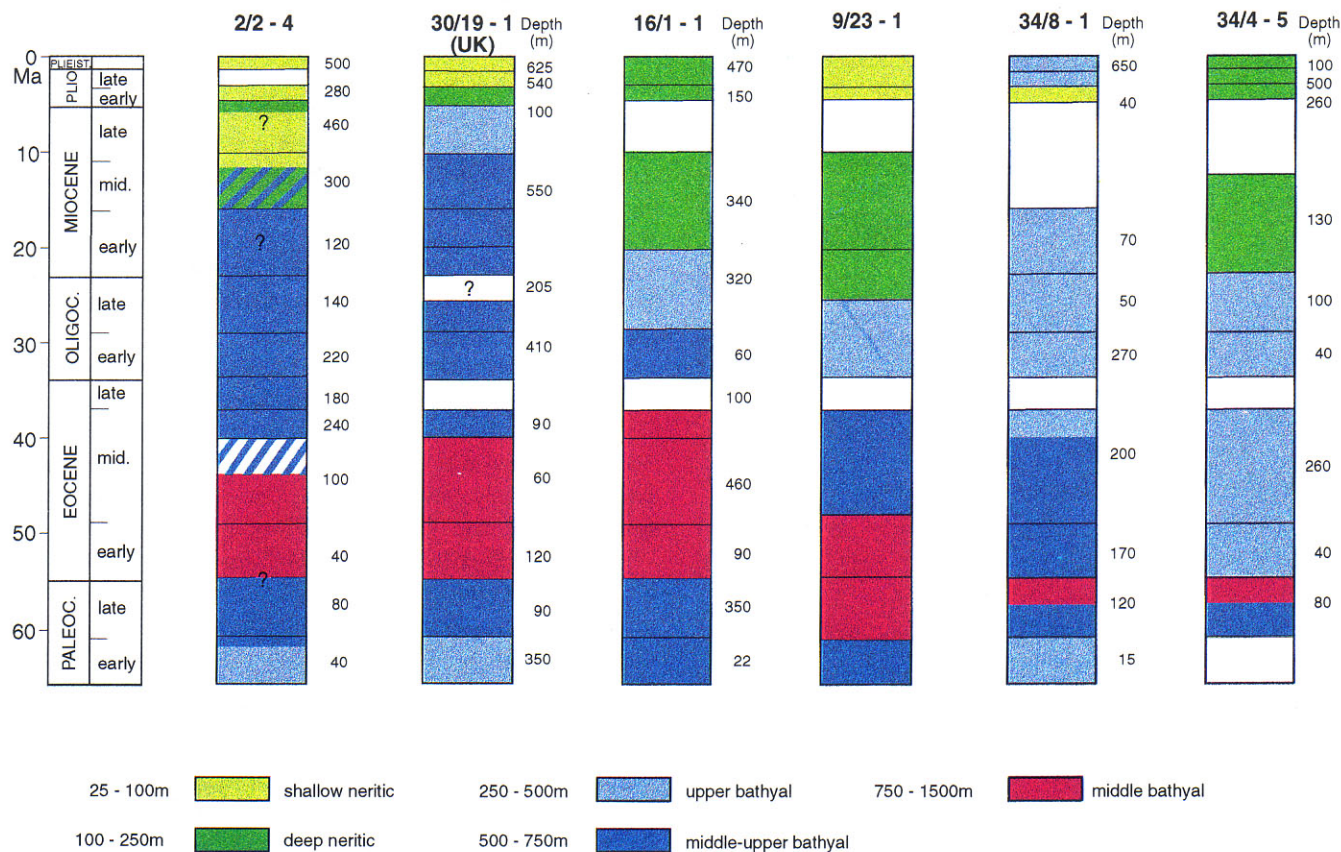


Fig. 9. Stratigraphic distribution of Cainozoic sediments in selected Viking Graben and Central Graben wells, classified according to five palaeo depth categories. For details, see text.

resulting from sediment filling at a low rate of 2 to 7 cm/ka. Late Eocene uplift, as seen in the 6406/8-1 well, may explain why Upper Eocene sediment is absent (see below). In Pliocene time, sediment rates reached a phenomenal 30–40 cm/ka; the Pliocene fill is a function of a new phase of Atlantic-wide tectonic subsidence (Cloetingh et al. 1990), concomitant with uplift of Scandinavia, which contributed to its glaciation.

*Viking Graben/Central Graben*

The sediment history for the Viking Graben and Central Graben of the North Sea in Cainozoic time is displayed in Fig. 9; for well 2/2-4, in the Central Graben, which has a remarkably complete Cainozoic record, the burial history is also shown (Fig. 11). Most of the sediment in the wells is mudstone. Three principal trends stand out in the wells.

First, following rapid subsidence and sedimentation exceeding 10 cm/ka, 65–60 Ma ago, in the mid-Palaeocene, the basins experienced virtually no further downdrop, only sedimentary fill. The latter situation ‘quickly’ brought the Viking Graben area in the northern North Sea to ‘sea level’ during the Eocene, possibly assisted by an inversion-type tectonic uplift. In the more southerly wells, sedimentation did not fill the basin until Middle Miocene time. Using the rule of thumb that

tectonic subsidence should account for approximately 60% of the observed subsidence signal, this mid-Palaeocene tectonic subsidence exceeded 500 m in 1–3 million years. Corresponding Upper Palaeocene fill rates reached 10–25 cm/ka.

Second, a major phase of late-stage subsidence and sedimentation under shallow marine conditions took place in the North Sea, starting in the Middle Miocene (Fig. 11). This phase, started in the North Sea a few million years before the renewed tectonic subsidence on Haltenbanken (Fig. 10). Although it is possible that this subsidence is a tectonic inversion event, we have argued in Cloetingh et al. (1990) that it is the result of a major plate reorganization in the Late Neogene, leading to an increase in compressional, intra-plate stresses that induce basin subsidence and margin uplift. Cloetingh et al. (1990) took into account that a similar late-stage basinal subsidence (and margin uplift) on the order of 0.5–1.5 km is observed in the West Greenland and Labrador/Grand Banks wells. Jordt et al. (in prep.) note a major shift in provenance area, to dominantly easterly sediment sources in Middle Miocene time, similarly pointing to basin margin (Scandinavia) uplift, relative to the northern North Sea.

Third, there are two widespread regional hiatuses in the Central North Sea (Fig. 9). The first is a late Eocene (Priabonian) hiatus, probably extending from ca. 37 to



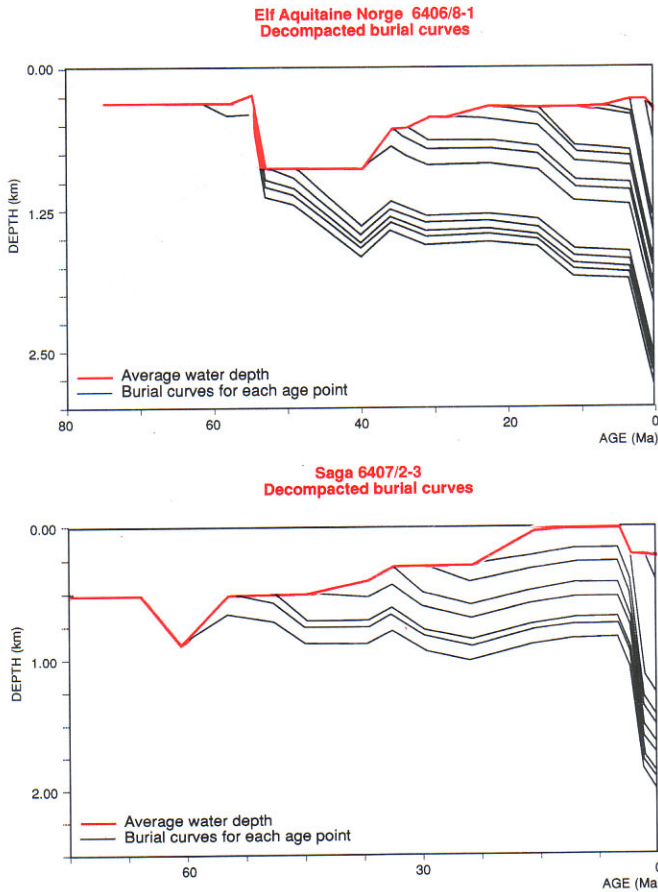


Fig. 10. Burial history of Cainozoic sediments in wells 6406/8-1 and 6407/2-3, Haltenbanken. For details on subsidence and sedimentation, see text.

34 Ma. The discontinuity in the sedimentary record is perhaps more prevalent in the deeper part of the basins. We speculate here that it may relate to the onset of widespread Alpine uplift, leading to an interruption in

relatively quiescent, deep marine sedimentation. The late Eocene uplift 'kicks' in the 16/1-1, (UK) 29/3-1 wells (Fig. 39 in Gradstein et al. 1994) and in well 6406/8-1 (Fig. 10) may thus be real events. Indeed, in the southern Central Graben wells (Fig. 11) a renewed sedimentation trend is observed in the Oligocene, consistent with an increase in hinterland relief (Alpine uplift) that increased erosion and fluviomarine sediment transport towards the Central Graben. These Central Graben sediments are found in seismic sequence unit CSS-3 of Jordt et al. (in prep.), which is absent in the north.

The second widespread hiatus is in Upper Miocene sediments. The fact that its lower boundary varies in age (Fig. 9) indicates that erosion plays a role in its creation, but local structural complications may have to be taken into account also. Nevertheless, the same hiatus is widespread along the Canadian Margin (Gradstein et al. 1994). In the North Sea wells, *Bolboforma metzmacheri* is of Late Miocene age, but its occurrence in a few wells only, without other Upper Miocene taxa, suggests a hiatus in most of the wells examined. The disconformity may be attributed in part to the effect of a global Messinian age sea-level drop. Since all well site sediments in the North Sea (and Haltenbanken) at that time are of a shallow marine environment, an offlap of the coastline and a dropdown of sedimentary base level easily affected the basins in an erosional or non-depositional manner. Rundberg et al. (1995) detail strong erosion of Oligocene strata between 61°25' and 62°N. The top Oligocene surface is here characterized by severe truncation, partly with deep scouring. By tracing the surface eastward into the 35/3 region, the authors suggest a Middle or Late Miocene age for the erosion, primarily controlled by tectonic uplift of the northernmost North Sea. This uplift and subsequent erosion is consistent with the effects from

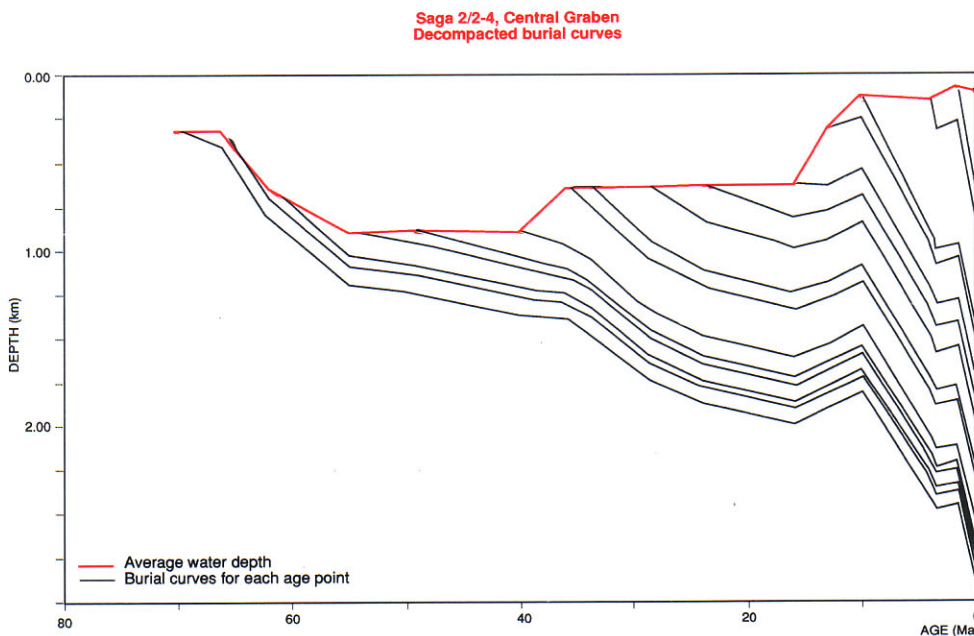


Fig. 11. Burial history of Cainozoic sediments in Central Graben well 2/2-4. For details on subsidence and sedimentation, see text.



both a Messinian sea-level drop and a regional uplift during a late stage, compressional tectonic phase of the Norwegian Sea passive margin. The details of the interaction of subsidence, sedimentation and erosion during this time have still to be investigated.

*Acknowledgements.* – The authors thank I. Thronsen, Y. Rundberg, S. Olaussen, T. Eidvin, B. Goll, M. Smelror, J. Stein, and the editors for comments on the manuscript, and Liv Ravdal for skilful preparation of the illustrations. Discussions with Henrik Jordt enhanced our insight in erosional events during Cenozoic time in the North Sea. R. Jan du Chene provided valuable palynological advice and cooperation during this study. We thank Saga Petroleum a.s. and the PL08, 066, 057, 131, 074 and 106 licensees for permission to publish the results of this study.

Manuscript received January 1995

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