

# Foraminiferal, palynomorph, and diatom biostratigraphy and paleoenvironments of the Torsk Formation: A reference section for the Paleocene–Eocene transition in the western Barents Sea

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## ABSTRACT

A microfossil-based biostratigraphic reference section is selected for the Paleogene Torsk Formation in the 7119/9-1 well, located in the Tromsø Basin of the southwestern Barents Sea. Benthic foraminifera, dinoflagellate cysts, and diatom infillings indicate an early late Paleocene to early Eocene age for the Torsk Formation on the eastern flank of the basin. A comparison of benthic foraminiferal last occurrences in the reference section with that established in neighbouring wells illustrates the potential use of these events for high-resolution stratigraphic correlation. Though differing in detail, the record of microfossil last occurrences in the western Barents Sea compares well with the biostratigraphy of the Central North Sea area. A morpho-group analysis of the Paleogene foraminiferal succession of the Tromsø Basin reveals a bathymetric deepening of the depositional area culminating near the Paleocene-Eocene transition, followed by a shallowing.

## INTRODUCTION

The Barents Sea covers a continental shelf area that is of a comparable size to the entire North Sea, but the subsurface geology of the area is constrained by fewer than 53 wells, mostly concentrated in the Hammerfest and Tromsø basins (Fig. 1). This area has been subjected to intense Mesozoic and Cenozoic tectonic movements that have affected the configuration of seaways linking the North Atlantic with the Arctic Ocean. Therefore, studies of the sedimentary and biotic record preserved in the Barents Sea basins are important for reconstructing the history of faunal connections between the North Atlantic and Arctic oceans, and constraining paleobiogeographic patterns in the Boreal Realm.

Reconstructing the development and history of marine connections through the Norwegian-Greenland Sea is the prime objective of the „Arctic Gateways“ legs of the Ocean Drilling Program. As the oldest oceanic crust in the Norwegian Sea

region is of early Eocene age, the early Paleogene biotic record can only be obtained from continental margin wells. Fortunately, Paleocene to Eocene sediments have been recovered from a number of exploratory wells drilled in the Tromsø and Hammerfest basins, off the northern coast of Norway. These basins are situated just east of the oceanic areas of the Norwegian-Greenland Sea, and constitute the northernmost offshore basins of the North Sea / Norwegian Sea rift system explored by conventional drilling. The main objective of this study is to assess the stratigraphic and paleoenvironmental significance of early Paleogene benthic foraminifera, dinoflagellate cysts, and diatoms from a key section in the western Barents Sea. This study is intended to complement the assessment of microfossil assemblages from younger Cenozoic material carried out under the auspices of the ODP „Arctic Gateways“ initiative.

Among 12 wells that we have examined from

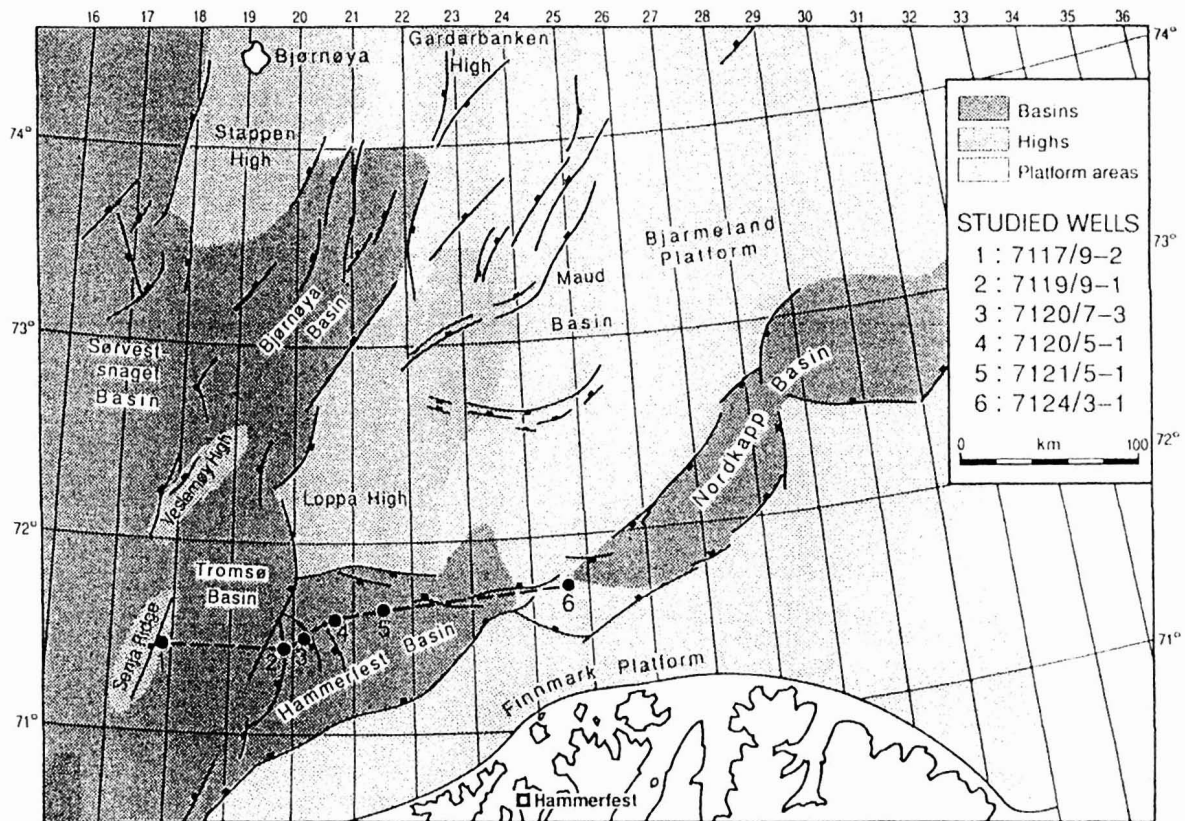


Figure 1. Location map of the western Barents Sea, with main structural features and locations of 6 of the studied wells.

the western Barents Sea area, well 7119/9-1 was chosen as a reference section because of the presence of a thick Paleogene succession (1030 m according to electric logs), rich microfossil assemblages, and the availability of continuous sampling. In addition, Knutsen *et al.* (1992) published a seismic line that crosses the well site and defined seismic units in this well, so it is now possible to more accurately assess the age and significance of regional seismic reflectors. Altogether, 129 ditch cutting samples were analysed from this well, with few exceptions spaced at 10 m intervals. The biostratigraphy from well 7119/9-1 is compared with data from nearby wells in the Hammerfest and Tromsø basins.

## STUDY AREA

### Geological Setting

The Barents Sea overlies an intracratonic area of structural basins, platforms, and highs. In the west, the area borders the oceanic Norwegian-Greenland Sea with a passive shear margin marked by the Senja Fracture Zone in the south and the Hornsund Fault Zone in the north. The Barents Sea margin started to develop in the early Paleogene in connection with the opening of the Norwegian-

Greenland Sea, but the structural basins on the Barents Sea platform were formed as a result of earlier (Cretaceous to Paleocene) rifting phases.

The geology and structural development of the Barents Sea has been the subject of numerous studies published mainly after drilling in the area commenced in the early 1980's. The subsurface geology of the area based on seismic evidence has been discussed by Rønnevik (1981), Rønnevik & Jacobsen (1984), Roufosse (1987), and Faleide *et al.* (1993a,b). Recently, Riis (1992), Cloetingh *et al.* (1992), Walderhaug (1992), and Richardsen *et al.* (1993) have provided estimates of the amount of Cenozoic uplift and erosion in the western Barents Sea based on geophysical and petrophysical evidence. The early Cenozoic sedimentary history of the area has been discussed by Knutsen & Vorren (1991).

The area of this study is located in the south-western part of the Barents Sea close to the continental margin. The region is divided into four main basins: Bjørnøya, Tromsø, Hammerfest, and Nordkapp, with intervening structural highs such as the Senja Ridge, Loppa High, and Veslemøy High (Fig. 1). The Tromsø Basin is connected with the Hammerfest Basin over the Ringvassøy-Loppa Fault

Complex. In an easterly direction, the Hammerfest basin is linked to the Nordkapp Basin over a shallow threshold on the southernmost extension of the Bjarmeland Platform. The reference well chosen was drilled on the eastern flank of the Tromsø Basin.

### Stratigraphical Framework

The Mesozoic and Cenozoic lithostratigraphy of the western Barents Sea was formally outlined by Worsley *et al.* (1988). The Paleogene Torsk Formation has a rather monotonous lithology consisting of light grey to greenish grey, essentially non-calcareous claystones. Thin beds of siltstone or limestone occur rarely throughout the formation, and tuffaceous horizons are commonly reported in the lower part. The thickness of the formation varies from 200–300 m in wells drilled in marginal areas of the Hammerfest Basin, to over 1 km in the central parts of the basin. The formation thickens to over 2 km in the undrilled deepest parts of the Tromsø Basin.

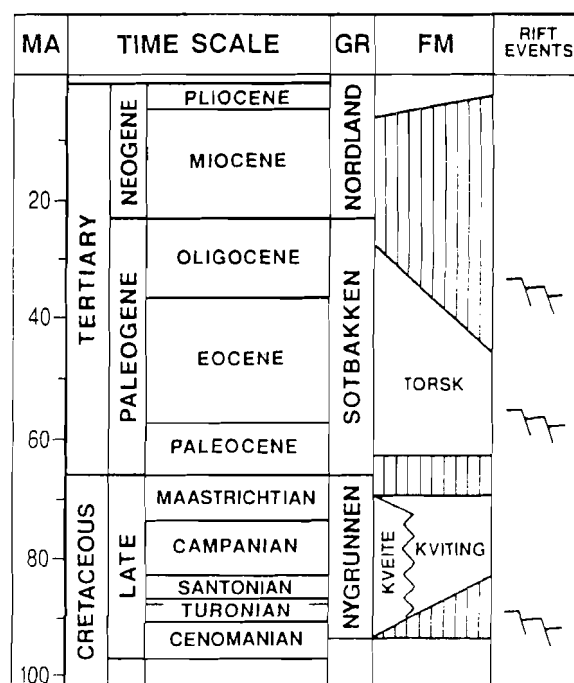


Figure 2 Lithostratigraphic scheme of Upper Cretaceous and Cenozoic deposits of the southwestern Barents Sea (modified after Worsley *et al.* (1988) and Faleide *et al.* (1993)).

The basal contact of the Torsk Formation is unconformable, and represents an important depositional hiatus encompassing the latest Cretaceous and early Paleocene (Fig. 2). This hiatus can be traced on seismic lines throughout the southwestern Barents Sea (Rønnevik, 1981; Faleide *et al.*,

1993a,b). The top of the Torsk Formation is cut by an erosional unconformity, and it is overlain by Plio-Pleistocene glacial and glacial-marine sediments.

Large areas of the Barents Shelf east of the Senja Ridge were uplifted and subjected to multiple phases of erosion, lasting to the early Pliocene. As a result, the upper parts of the Torsk Formation (as much as 1500 m) have been removed, particularly in marginal parts of the basins where the formation thickness is strongly reduced.

### MATERIAL & METHODS

Well 7119/9-1 was a wildcat well drilled in the summer of 1984 at 71°24'53.19"N, and 19°49'43.26"E in 201 m of water, with Elf Aquitaine Norge a.s. acting as the operator. Samples for this micropaleontological study were provided by the Norwegian Petroleum Directorate in Stavanger. The material analysed consists wholly of washed ditch cutting samples ranging in dry weight from 25 to 45 grams. The micropaleontological samples were disintegrated by boiling in sodium carbonate, and washed over a 63µm sieve. Foraminifera and diatoms were picked from the >125µm fraction and mounted on cardboard slides. Palynological samples were analysed in accordance with standard techniques. All depths reported in this paper are quoted below rotary kelly bushing (therefore, a value of 226 m must be subtracted from the reported depth to convert to depth below sea floor).

### RESULTS

The succession of palynomorphs, diatoms, and benthic foraminifera in the 7119/9-1 well can each be subdivided into distinct assemblages based on the distribution of dominant taxa, the occurrences of stratigraphically important species, and fluctuations in diversity and abundance (Fig. 3). The chronostratigraphy of the well is based primarily on palynomorph assemblages, which can be correlated with the zonations of the northern North Sea published by Schröder (1992) and Mudge & Bujak (1994, 1996).

#### a. Palynomorph assemblages

Altogether, 70 samples have been analysed for palynomorphs with a spacing of 10 m except in the upper 400 m of the well, where the sample spacing is mostly 30 m. The studied interval contains 99 palynomorph taxa, and their stratigraphical distribution is presented in Table 1. The palynomorph succession is subdivided into six stratigraphically significant assemblages (Fig. 3).

From the uppermost part of the formation (at 330 m), a single sample was analysed which contains a poor palynomorph assemblage. No age-dia-

gnostic species were recorded, and most of the palynomorphs present are reworked from Cretaceous deposits, a feature that is typical of the Pliocene – Pleistocene deposits of the area. The palynomorph succession from the 7119/9-1 well is discussed below in order from youngest to oldest.

### 1. *Alisocysta* sp. 2 assemblage

Interval: 405-720 m.

Age: early Eocene

Samples from this interval contain rich and diverse palynomorph assemblages. The persistent occurrence of *Alisocysta* sp. 2 (Heilmann-Clausen, 1985) and *Deflandrea oebisfeldensis* below 405 m suggest an age no younger than early Eocene. This age assignment is supported by the presence of *Charlesdownia edwardsii* at 435 m and *Charlesdownia crassiramosa* at 570 m. The persistent occur-

rence of *Alisocysta* sp. 2 and *D. oebisfeldensis* and the high content of terrestrial material (pollen, spores, plant tissue fragments) indicates that the interval belongs to the lower part of the lower Eocene, and corresponds to the top of the lower Eocene Subzone E2A of Mudge & Bujak (1994) in the northern North Sea.

*Dracodinium varielongitudum* was recorded at 405 m and below. This species is characteristic of the early Eocene. However, *D. varielongitudum* is thought not to coexist with *Alisocysta* sp. 2, but in slightly younger sediments (Heilmann-Clausen, 1985). Younger early Eocene sediments are therefore thought to be present between 405 and 330 m.

A certain number of species occurring in the assemblage are probably caved. The presence of *Rhombodinium draco* at 435 and 470 m suggests that sediments younger than the middle part of the Middle Eocene (Costa & Manum, in Vinken, 1988) are present above 405 m. *Svalbardella cooksoniae* was recorded at 405 m. This species has a known strati-

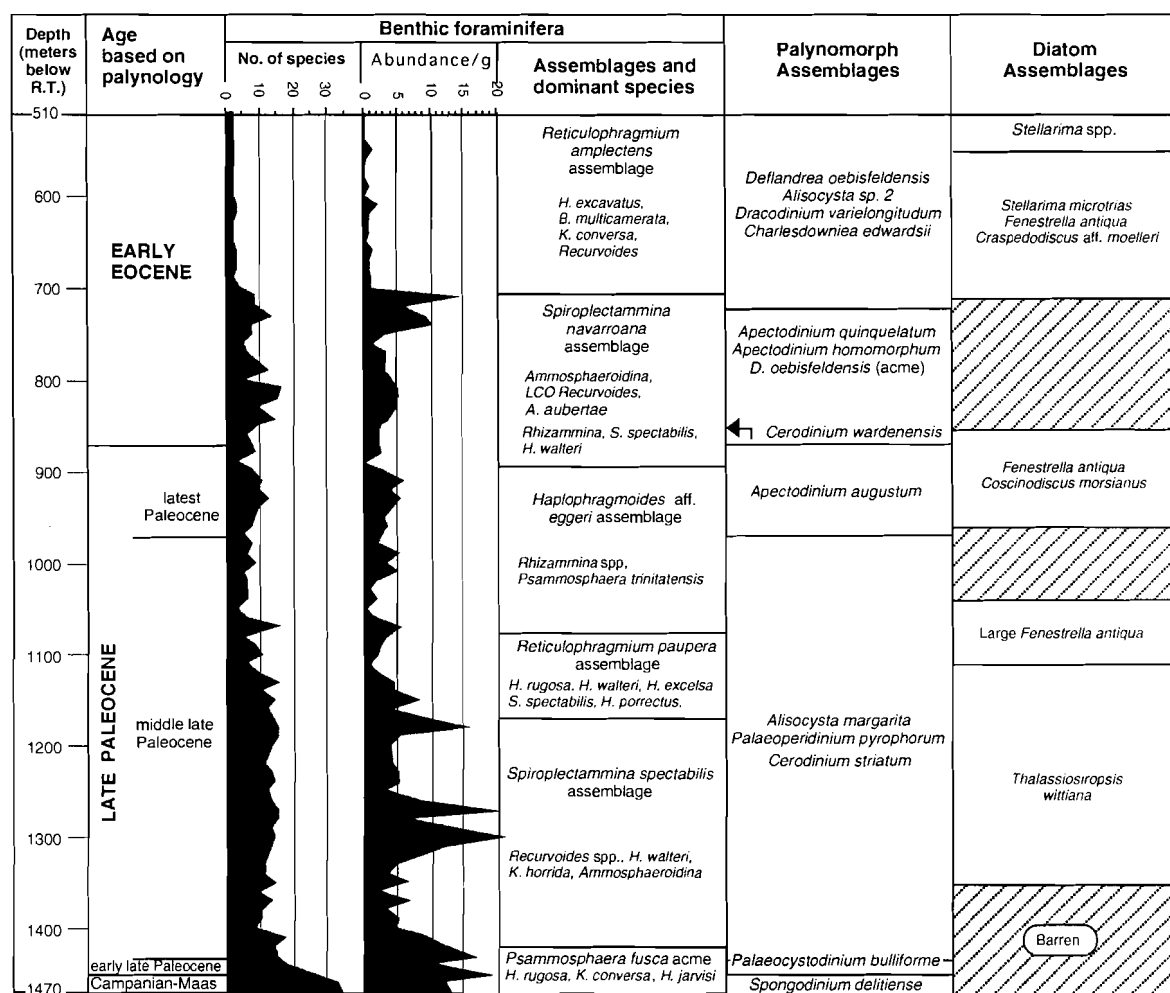


Figure 3. Chronostratigraphy, foraminiferal distribution, palynomorph assemblages, and diatom assemblages in well 7119/9-1.

graphic range spanning from late Eocene to early Oligocene (Costa & Manum, in Vinken, 1988). In this assemblage there is also evidence of reworking from the Cretaceous.

## 2. *Deflandrea oebisfeldensis* assemblage

Interval: 720-890 m.

Age: earliest Eocene

The consistent occurrence of *Apectodinium quinquelatum* below 720 m and the presence of the *Apectodinium homomorphum*/*parvum* complex at 720 m suggests an early Eocene age. The relatively common occurrence of *Deflandrea oebisfeldensis* at 720 m supports this age assignment. The top of the *D. oebisfeldensis* acme defines the top of the lowermost Eocene Subzone E1c of Mudge & Bujak (1994), and correlates with the top of the Balder Formation in the northern North Sea.

The LO of *Cerodinium wardenense* is observed at 845 m and it occurs consistently below 850 m. The LO of *C. wardenense* defines the top of the lowermost Eocene E1b Subzone of Mudge & Bujak (1994).

## 3. *Apectodinium augustum* assemblage

Interval: 890-970 m.

Age: latest Paleocene

The LO of *Apectodinium augustum* at 890 m indicates the latest Paleocene „P6“ palynomorph zone of Mudge & Bujak (1996). The individuals reveal considerable morphological variability. Some specimens have less well-developed horns, and especially the apical horn displays variation in size. The characteristic acme of *Apectodinium* spp. was not recorded in this well.

## 4. *Alisocysta margarita* assemblage

Interval: 970-1420 m.

Age: middle late Paleocene

The LO of *Alisocysta margarita* at 970 m together with the occurrence of *Palaeoperidinium pyrophorum* at 1020 m suggests a middle late Paleocene age, corresponding to the „P5“ palynomorph zone of Mudge & Bujak (1996). Schröder (1992) noted that the range of *A. margarita* is limited to the lowermost part of the Lista Formation in the southern Viking Graben. In the studied well, the species *Areoligera* cf. *senonensis* displays an acme at 1000

m. This species usually occurs in high numbers in the middle part of the upper Paleocene, and this event probably corresponds to dinoflagellate cyst zone 4 of Heilmann-Clausen (1985). The common occurrence of *Palaeoperidinium pyrophorum* at 1370 m probably corresponds to the upper part of dinoflagellate cyst zone 3 of Heilmann-Clausen (1985), which is equivalent to the middle part of the „P4“ palynomorph zone of Mudge & Bujak (1996).

## 5. *Palaeocystodinium bulliforme* assemblage

Interval: 1420-1450 m.

Age: early late Paleocene

The LO of the species *Palaeocystodinium bulliforme* (= *P. australinum* of Mudge & Bujak, 1996) at 1420 m indicates an early late Paleocene age. The common occurrence of *P. bulliforme*, *P. pyrophorum* and *Isabelidinium* cf. *viborgense* below 1440 m supports this age assignment. This interval corresponds to dinoflagellate cyst zone 3 and the upper zone 2 of Heilmann-Clausen (1985).

The presence of *Spongodinium delitiense* at 1450 m may be due to reworking. This species is known to have its last occurrence in the earliest early Paleocene (Hansen, 1977). According to Schröder (1992) it ranges only to the top of the Ekofisk Formation in the southern Viking Graben.

## 6. *Spongodinium delitiense* – *Odontochitina* cf. *costata* – *Cleistosphaeridium* sp. 1 assemblage

Interval: 1460-1570 m.

Age: late Campanian

An abrupt change in the organic content of the samples takes place at 1460 m, with an increase in the amount of coal particles and the occurrence of abundant *Cleistosphaeridium* sp. 1 and common *Chatangiella* spp.

*Spongodinium delitiense* is relatively common at 1460 m. This species is known to occur in the upper Campanian (Lucas-Clark, 1987), but is more characteristic of sediments of Maastrichtian and early Paleocene age (Hansen, 1977). The LO of *Odontochitina* cf. *costata* at 1460 m suggests an age not younger than the late Campanian or early Maastrichtian (Tocher, 1987).

## b. Benthic Foraminiferal Assemblages

Samples examined from the uppermost part of the Torsk Formation (410-500 m) were barren of foraminifera. Ninety-three samples were analysed in the interval from 510 to 1470 m, mostly at a sample

spacing of 10 m. A total of 84 species and open nomenclature taxa were recognised, all of which are agglutinated (Table 2). The succession of foraminiferal events can be compared with the integrated microfossil zonation of the northern North Sea and Haltenbanken areas recently established by Gradstein *et al.* (1994) and by Gradstein & Bäckström (1996). The benthic foraminiferal succession in the well can be subdivided into six main assemblages:

#### 1. *Reticulophragmium amplexens* assemblage

Interval: 510-710 m.

Age: early Eocene

At the top of the Torsk Formation from 510 m to 700 m, both abundance and diversity are low. The assemblage consists mainly of *Haplophragmoides excavatus* and *Budashevaella multicaerata*. At 710 m there is a sharp increase in foraminiferal abundance, and a peak in the frequency of *Reticulophragmium amplexens* (= the early Eocene morphotype called *Reticulophragmium intermedium* (Mjatluk)) is observed. This assemblage also contains common *Rhizammina* spp., *Recurvoides* spp., *Karrerulina* spp., *Haplophragmoides excavatus*, and *Budashevaella multicaerata*. The species *R. intermedium* is the nominate taxon of the late early Eocene to early middle Eocene Zone NSR5A of Gradstein & Bäckström (1996).

#### 2. *Spiroplectammina navarroana* assemblage

Interval: 710-890 m.

Age: latest Paleocene to earliest Eocene

The LOs of many taxa are observed near 710 m, including that of *Spiroplectammina navarroana*, *Ammosphaeroidina pseudopauciloculata*, *Haplophragmoides kirki*, and *Ammodiscus macilentus*. In the Central North Sea, the LO of *S. navarroana* is an important event within the lower Eocene *Subbotina patagonica* Zone of Gradstein *et al.* (1994). In the Haltenbanken area of offshore Norway, the LO of *S. navarroana* is observed within the middle part of Zone NSR5A of Gradstein & Bäckström (1996). Mudge & Bujak (1996) correlate the LO of *S. navarroana* with the top of the Ypresian.

The interval from 790 to 890 m is characterised by the occurrence of a diminutive form of *Ammonia marginulina aubertae*, a species first described from the North Sea and Labrador Shelf by Gradstein & Kaminski (1989). This species is apparently

diachronous in offshore Norway, as it characterises the late middle Eocene Zone NSR6 of Gradstein & Bäckström (1996) in Haltenbanken and in the northern North Sea. It is rare in our samples. The assemblage is numerically dominated by *Rhizammina* spp., with *Recurvoides* spp., *Karrerulina* spp., and *Spiroplectammina spectabilis* present in low numbers. The whole interval is characterised by a taxonomic turnover, and a plateau in the species range chart occurs near 810 m, coincident with a peak in the abundance of tubular forms. At this level the LOs of several typically Paleocene to lower Eocene species are observed, including *Saccammina placenta*, *Sphaerammina* sp., *Kalamopsis grzybowskii*, and *Glomospira* spp. Both diversity and abundance decrease to minimum values near the base of this assemblage.

We did not observe any planktonic foraminifera or calcareous benthic foraminifera in the lower Eocene interval of the well, nor did we find any calcareous specimens in adjacent wells in the western Barents Sea. Calcareous assemblages belonging to the *Subbotina patagonica* Zone of Gradstein *et al.* (1994) have been observed as far north as Haltenbanken (Gradstein & Bäckström, 1996) and the outer Vøring Plateau (Hulsbos *et al.*, 1989). Either the northern boundary of the early Eocene planktonic foraminifera must have existed south of the Barents Sea area, or the deep waters of the basin were too corrosive to allow the preservation of calcareous microfossils.

#### 3. *Haplophragmoides* aff. *eggeri* assemblage

Interval: 890-1070 m.

Age: late Paleocene

From 890 m to ca. 1070 m the diversity of benthic foraminifera is low, and the assemblage is dominated by tubular forms and a species of *Haplophragmoides* tentatively designated *H. aff. eggeri*. The LO of this species was observed at 910 m, but foraminiferal abundance near the top of this interval is especially low. We therefore arbitrarily placed the top of this assemblage at the abundance minimum at 890 m. The foraminifera in this interval are not age-diagnostic.

#### 4. *Reticulophragmium paupera* assemblage

Interval: 1080-1160 m.

Age: middle late Paleocene

Between 1080 and 1160 m, both the abundance and diversity of the benthic foraminifera steadily

increase downhole. This interval is characterised by the consistent common occurrence of *Reticulophragmium paupera*, an index taxon for the upper Paleocene in the North Sea and Haltenbanken. It is the nominate taxon of the late late Paleocene Zone NSR2B of Gradstein & Bäckström (1996). Other important species include *Haplophragmoides walteri* and tubular forms belonging mainly to *Rhizammina*. *Spiroplectammina spectabilis* is occasionally present in this interval in low numbers. The LO of *Hyperammina rugosa* is observed together with that of *R. paupera* at 1080 m.

#### 5. *Spiroplectammina spectabilis* assemblage

Interval: 1180-1400 m.

Age: middle late Paleocene

A distinct maximum in the abundance of *Spiroplectammina spectabilis* is observed in the interval from 1180 to 1400 m. The last common occurrence (LCO) of *S. spectabilis* occurs within the upper Paleocene in the North Sea, and is placed near the base of Zone NSR2B of Gradstein & Bäckström (1996). In the studied well, this event occurs between the LO of *Alisocysta margarita* and the LCO of *Palaeoperidinium pyrophorum* (at 1370 m), which agrees with its relative position in the RASC zonal model of Gradstein & Bäckström. One unusual feature of this assemblage is the large proportion of juvenile forms of *S. spectabilis*. Other common taxa include *Rhizammina* spp., *Ammosphaeroidina pseudopauciloculata*, *Haplophragmoides walteri*, and *Reticulophragmium paupera*. In the lower part of the interval, single occurrences of the species *Rzehakina minima* and *Reticulophragmoides jarvisi* were observed.

In the studied western Barents Sea wells, the species *Ammonia ruthvenmurrayi* (the nominate taxon of the mid Paleocene Zone NSR 2A of Gradstein & Bäckström) is rare or absent. We therefore selected an event that occurs regionally in the western Barents Sea to characterise this assemblage. Our *S. spectabilis* assemblage is roughly equivalent to the *T. ruthvenmurrayi* Zone in the North Sea and Haltenbanken.

#### 6. *Psammosphaera fusca* assemblage

Interval: 1410-1450 m.

Age: early middle Paleocene

The benthic foraminiferal assemblage at the base of the Torsk Formation (1430-1480 m) displays strongly increased abundance and the highest diversity

in the well. There is an abrupt downhole expansion in abundance at 1410 m. The assemblage is distinguished from overlying assemblages because it is dominated by species that agglutinate coarse material for the construction of their test, such as *Hyperammina rugosa*, *Psammosphaera fusca*, and an unnamed species of *Recurvoides*. *Psammosphaera fusca* increases in relative abundance at 1430 m, near the base of the Torsk Formation. Other common forms in this interval include *Recurvoides* spp., *Rhizammina* spp., *Karrerulina* sp., and *Ammosphaeroidina pseudopauciloculata*. Three distinctive species are restricted to this assemblage: *Præcystammina* sp., *Caudammina ovulum*, and *Rzehakina epigona*.

Samples from the underlying Cretaceous Kviting Formation display further increased abundance and diversity compared with the Torsk Formation. The species *Ammodiscus glabratus*, *Spirosigmolinella* sp. 1, *Hormosina velascoensis*, and *Trochammina* cf. *subvesicularis* display LOs at 1460 m, coincident with the top of the Kviting Formation. However, these are taxa that are known to range into younger stratigraphic levels in other areas of the North Atlantic. The Upper Cretaceous index form *Caudammina gigantea* was observed at 1470 m, confirming a Campanian to Maastrichtian age for this level.

#### c. Diatom assemblages

A total of 35 diatom taxa were identified from 70 samples. Although poorly preserved (being infilled and/or replaced by pyrite) and in relatively small numbers (due to the effects of differential preservation bias towards more robust forms), enough stratigraphically important taxa were present to enable the Paleogene succession to be subdivided into five stratigraphically significant assemblages (Fig. 3). Diatoms occur sporadically in the samples studied, with a major abundance peak developed between 850 and 870 m, at around the Paleocene/Eocene boundary. This correlates with a similar abundance peak in the North Sea Basin. Diatoms are also relatively abundant between 1110 and 1310 m. The diatom succession is discussed below in order from youngest to oldest.

##### 1. *Stellarima* spp. assemblage

Interval: 510-550 m.

Various morphologies belonging to the genus *Stellarima* occur in the uppermost diatomaceous samples studied. Although some of these are difficult to identify to species level due to poor preservation, their biconvex shape, small size (<100 µm) and centrally-positioned labiate processes, are

characteristic of *Stellarima*. Usually these are normal (i.e. vegetative) cells of the species *S. microtrias*, but sometimes resting spores are encountered, distinguished by having a depression at the centre of the valve face. The latter are a morphological adaptation found in many diatom species, and are formed in response to seasonal depletions of nutrients (see Round *et al.* 1990, pp. 37-40 for a fuller discussion). Smaller morphologies bearing a strong resemblance to *S. microtrias* also occur in some samples in the lower Eocene interval.

2. *Stellarima microtrias*, *Fenestrella antiqua*, *Craspedodiscus* aff. *moelleri* assemblage

Interval: 560-710 m.

This assemblage is characterised by the continued presence of *Stellarima microtrias*, though in low abundance; in addition to the first occurrence of the large, biconvex species *Fenestrella antiqua*, also in small numbers. Sporadic appearances of the „doughnut-shaped“ genus *Craspedodiscus* (which bear a resemblance to the species *C. moelleri*.) are also present in this assemblage. Poor preservation precludes species determination. In the interval 720 to 810 m, diatoms are completely absent.

3. *Fenestrella antiqua*, *Coscinodiscus morsianus* assemblage

Interval: 850-960 m.

Diatoms reappear at 820 m, slightly above the Paleocene/Eocene boundary as delimited by palynomorphs. From 850 m, a rich diatom assemblage is present, dominated by *Fenestrella antiqua*. Other species include *Stellarima microtrias*, the biconcave species *Coscinodiscus morsianus*, the triangular taxon *Triuacria regina*, and sporadic occurrences of *Thalassiosiropsis wittiana*. The latter is similar in shape to *Stellarima microtrias* but much larger, with an extremely smooth surface and with a pronounced dimple at the centre of the valve. Other species include the benthic taxa *Actinoptychus senarius* and *Aulacodiscus hirtus*, indicative of shallowing conditions. Diatoms appear only sparsely between 970 and 1030 m.

4. *Fenestrella antiqua* assemblage

Interval: 1040-1110 m.

Huge (<250 µm) specimens of *F. antiqua* dominate this assemblage, often characterised by the presence of a veneer of original silica on the surface. Both vegetative cells and resting spores are found;

the latter distinguished by their lenticular shape, smooth surface and lack of a girdle. Auxospores of *F. antiqua* also occur, which are barrel-shaped with a very wide girdle. Other species present in the assemblage include *Stellarima* sp. and *Coscinodiscus morsianus*.

5. *Thalassiosiropsis wittiana* assemblage

Interval: 1120-1350 m.

The late Paleocene interval is dominated by relatively great numbers of the large, discoidal species *Thalassiosiropsis wittiana*. This taxon is found in other areas during this interval, including the Russian Platform and the North Sea, and indicates fairly unrestricted connections between these areas. The interval from 1350 to 1470 m is barren of diatoms.

## DISCUSSION

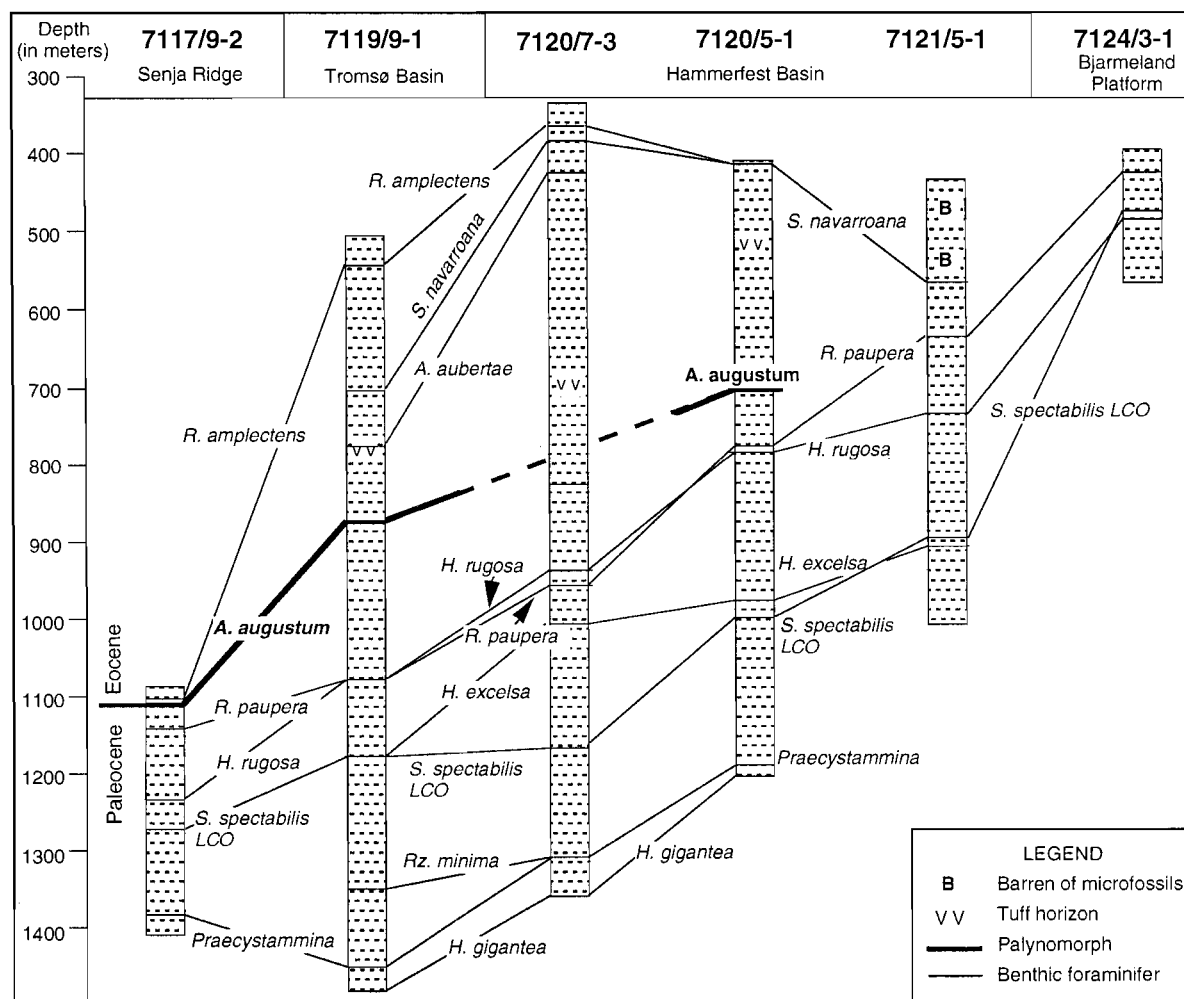
### a. Stratigraphic Correlation

For the purposes of assessing the utility of the assemblages observed in the 7119/9-1 well for regional stratigraphic correlation, we compiled a graphic overview of foraminiferal stratigraphic events that were observed in six wells comprising an east-west transect from the Senja Ridge to the transition between the Hammerfest and Nordkapp basin (Fig. 1). For these purposes, only the last occurrences (LO) and last common occurrences (LCO) of selected common, cosmopolitan, deep-water benthic foraminifera were included (Fig. 4).

Parts of the well sections analysed display low abundance and diversity of benthic foraminifera. In spite of this, the strata reveal several important biostratigraphical events, such as the LOs of *Reticulophragmium amplexans*, *Spiroplectammina navarroana*, and of the dinoflagellate cyst *Apectodinium angustum*. In the Paleocene part of the transect the LOs of *Reticulophragmium paupera*, *Hyperammina rugosa*, and the LCO of *Spiroplectammina spectabilis* are observed in all wells, whereas the LOs of *Hormosina excelsa*, *Rzehakina minima*, *Praecystammina* sp., and *Caudammina gigantea* are restricted to fewer wells. The events included in the transect have also been recorded from in the Viking Graben of the Central North Sea (i.e. Gradstein *et al.*, 1994), and may serve as the basis for a wider foraminiferal zonation of the lower Paleogene of offshore Norway.

In the three westernmost wells, the LO of *R. amplexans* is observed near the eroded upper contact of the Torsk Formation, therefore its last stratigraphic occurrence in this area is probably not correlative to its true extinction. The occurrence of *S. navarroana* near the top of the studied interval in





**Figure 4.** Foraminiferal last occurrences in an W-E transect of wells from the Tromsø and Hammerfest basins, plotted at a common depth scale (meters below rig floor) to give an impression of the subsurface geometry of the Torsk Formation. The position of a distinctive tuff horizon and the LO of a dinocyst approximating the Paleocene/Eocene boundary is also indicated.

the three western wells suggests correlation with the lower Eocene *Subbotina patagonica* Zone of Gradstein *et al.* (1988; 1994), although we did not observe any specimens of the nominate species of this zone, or any other calcareous benthic foraminifera that are known to occur in the lower Eocene of the North Sea.

East of Block 7120, the Eocene sediments have been removed by erosion, and the Torsk Formation penetrated by the two eastern wells is dated as wholly within the late Paleocene according to palynomorphs. The top of the *R. paupera* assemblage in the studied wells is easily recognised by an abrupt change to more a diversified foraminiferal assem-

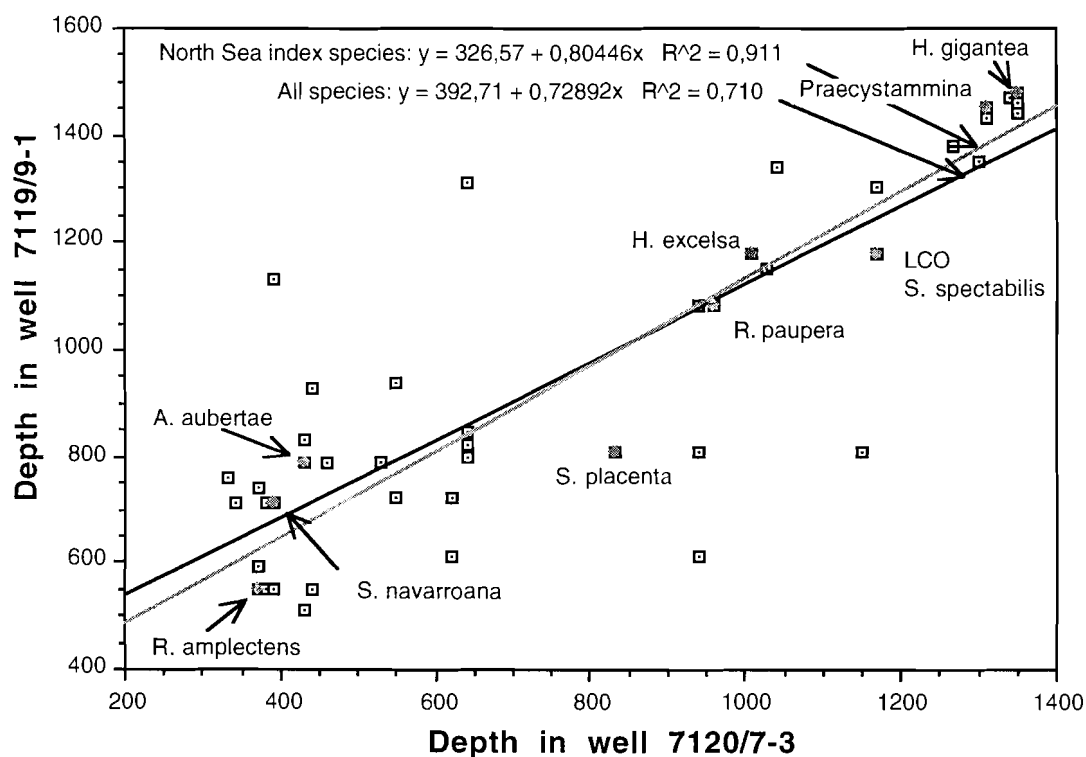
lage downhole. The LO of a distinct, very coarsely agglutinated tubular species, here identified as *H. rugosa*, is closely associated with that of *R. paupera*. These events, together with the last common occurrence of *S. spectabilis* are remarkably continuous over the whole study area despite obvious variations in sedimentation and paleobathymetry. However, the earliest late Paleocene *Psammospaera* assemblage (indicated in Fig. 4 by the LO of *Praecystammina* sp.) is not present in the two easternmost wells, suggesting that the pre-Cenozoic topography of the basin did influence the composition of the benthic foraminiferal assemblages. In the North Sea region, *Praecystammina* sp. is regarded to

be a deep-water species (middle bathyal) in the Paleocene, therefore, its absence from the eastern wells may be a result of ecological exclusion.

A total of 74 stratigraphic last occurrences of foraminifera were recorded in the nearby 7120/7-3 well in the western Hammerfest Basin, with 50 events in common with those in the 7119/9-1 well. These two wells give the best correlation of last occurrence data observed between any two records investigated so far from the Torsk Formation. When the depths of all shared LOs are plotted in a standard graphic correlation plot, a regression equation can be calculated (Fig. 5). The regression coefficient can be interpreted as a measure of the „reliability“ of the last occurrence events. The correlation between the LOs in the two holes can best be described by a linear regression. Polynomial and exponential solutions of the regression equation did not yield markedly higher regression coefficients, suggesting that there were no observable significant hiatuses or changes in sedimentation rate between the two sites. In this solution, the regression coefficient calculated using all the observed LOs gave a value of  $R^2=0.71$ . Outliers from the regression line in all cases consist of rare species. In a later stage of biostratigraphic analysis, these outliers are normally deleted from the data set. The „scatter“ in the data points is greater

among Eocene last occurrences than among events recorded from the Paleocene. However, in this case the outliers can be partially explained by sampling bias. This is attributed to the small size of the studied samples resulting in low specimen numbers in many Eocene samples.

A second regression curve was calculated from a subset of data points, indicated as shaded squares in Fig. 5. These points represent species found in the Tromsø Basin, which are listed as stratigraphically important in the Paleocene to middle Eocene probabilistic stratigraphy of the Central North Sea by Gradstein *et al.* (1994). The regression line constructed from the important North Sea species alone does not differ greatly from the previous curve, but the regression coefficient is much higher ( $R^2=0.91$ ). This suggests that the North Sea benthic foraminiferal zonation of Gradstein *et al.* (1994) can give excellent stratigraphic results in the western Barents Sea. However, other points also fall close the correlation line as well, indicating that additional index forms are also present in the Tromsø-Hammerfest Basin area. A complete discussion of the stratigraphic utility of faunal events is beyond the scope of this study, and must be based on detailed analysis of a greater number of well sections.



**Figure 5.** Graphic correlation of foraminiferal LOs and LCOs in Wells 7119/9-1 and 7120/7-3 in the Tromsø and Hammerfest basins. Axes values are the depths in meters BKB of events observed in both wells.

### b. Unconformities

The benthic foraminiferal and dinoflagellate cyst biostratigraphy investigated here provides significant new constraints for the age and nature of unconformities, which are expressed as important seismic horizons in the western Barents Sea. Two seismic horizons were examined here in detail:

*The Basal Tertiary:* This is the „Sequence boundary B” horizon of Rønnevik (1981), which marks the top of the rotated fault blocks east of the contact between oceanic and continental crust. Rønnevik correlated this reflector with the oldest Tertiary sediments in Spitsbergen, and correctly regarded it as representing the base of the upper Paleocene. He added that older Paleocene sediments may be present in the eastern part of the Barents Sea area. Faleide *et al.* (1993b) recognised the regional nature of the „Base Tertiary” reflector, and noted that it constitutes a hiatus spanning the Cretaceous-Tertiary transition. On the southwestern Loppa High this reflector defines an angular unconformity truncating Cretaceous strata (Knutsen & Vorren, 1991).

Our observations suggest that the „Base Tertiary” reflector in the basin areas indeed represents a submarine hiatus. Earlier studies of the southwestern Barents Sea (e.g. Worsley *et al.*, 1988) have suggested an early Campanian age for the underlying Kviting Formation, but based on the occurrence of *Caudammina gigantea* and *Spongodinium deltiense* in our samples, the formation may include strata as young as late Campanian to Maastrichtian in places. In the wells where we sampled both the lowermost Torsk Formation and the uppermost Kviting Formation, we observed little change in the paleobathymetric significance of the benthic foraminiferal assemblage on either side of the disconformity. Assemblages from both formations in the Tromsø Basin and central part of the Hammerfest basin contain deep-water benthic foraminiferal taxa such as *Praecystammina*, *Caudammina*, *Pseudobolivina*, *Rzehakina*, and abundant tubular forms such as *Rhizammina* and *Rhabdammina*, which indicate a middle bathyal (or deeper) depositional environment.

In the Tromsø Basin and western part of the Hammerfest Basin, the basal assemblage of the Torsk Formation contains numerous tubular forms and several other taxa that utilize coarse agglutinated material in the construction of their test. At some localities, a maximum in *Psammospira fusca* is observed. The distinctive composition of the basal assemblage in the Torsk Formation invites comparison with areas affected by deep-sea bottom currents. In the modern North Atlantic, high abundances of coarsely agglutinated forms, sus-

pension-feeding tubular forms, and the opportunistic species *P. fusca* are found beneath the Western Boundary Undercurrent (Kaminski, 1985). The late Paleocene deep water conditions in the southwestern Barents Sea appear to have developed during a longer time period, because during the Late Cretaceous the Tromsø and Sørvestsnaget basins continued to subside (Faleide *et al.*, 1993a). It is likely that fine-grained sediments bypassed the area, and that the coarse agglutinated assemblage is testimony to the presence of periodic bottom currents that affected the sea floor.

*Top Torsk Formation:* The Torsk Formation is unconformably overlain by Plio-Pleistocene glacial marine and glacial sediments of the Nordland Group. Seismic lines interpreted by Faleide *et al.* (1993a,b) show truncation of seismic reflectors within the Torsk Formation in an easterly direction, indicating that the top of the Paleogene succession has been clearly eroded, while thicker and younger Paleogene sediments are present in the west. Our results confirm this interpretation. In the easternmost locality the top of the Torsk formation is within the middle late Paleocene *R. paupera* Zone (*sensu* Gradstein *et al.*, 1988), whereas in the west, sediments belonging to the late early Eocene *R. amplectens* Zone underlie the Cenozoic unconformity.

The timing and causes of the Cenozoic erosion is a matter of discussion. In the western part of the Barents Sea, in the region of the Sørvestsnaget Basin and the Senja Ridge, uplift of rift flanks is associated with Paleogene continental breakup. The main phase of deformation took place during initial breakup in the early Eocene, but some faults were active into early Oligocene times. Faleide *et al.* (1993b) estimated that as much as 1 km of Paleogene sediments were removed by erosion in this area. This erosion is related to uplift along the Senja Fracture Zone during Eocene time (Vignes, 1995). This event created a western source area for some sediments in the Tromsø Basin. Erosion in the Hammerfest Basin was of greater magnitude, according to estimates from vitrinite reflectance and fission track analysis in the range of 1200-1500 m. A study of the porosity, cementation, and oxygen isotopes in the Jurassic Stø Formation in the 7120/9-1 well (present depth = 1500 m) indicated that the at least 1500 m of overburden has been removed at this locality (Walderhaug, 1992). Regional uplift in the southwestern Barents Sea may have been associated with or caused by Oligocene volcanism (Faleide *et al.*, 1991), a Miocene sea-level fall (Reemst & Cloetingh, 1994), increased levels of intraplate compression in the Neogene (Cloetingh *et al.*, 1990, 1992), and neotectonic activity resulting from Pleistocene deglaciations (Karpuz *et al.*, 1991).

### c. Benthic foraminiferal paleoecology and paleobathymetry

A striking feature of the foraminiferal assemblages in the studied wells is the absence of calcareous taxa (both benthic and planktonic). The assemblages include significant proportions of deep-water agglutinated foraminifera belonging to the single-chambered (tubular and globular forms) and multichambered groups. The low availability of carbonate in the southwestern Barents sea during the early Paleogene has probably produced unfavorable conditions for the development of calcareous faunas, as well as for the preservation of any calcareous microfossil tests originally present. The wholly agglutinated nature of the assemblages and the presence of taxa that are known from basinal facies in the Central North Sea points to deep-water (middle bathyal) conditions in the Tromsø Basin. However, it is a well known fact that deep-sea organisms can be found living in shallower environments at high latitudes (Murray, 1895), so this estimate must be regarded as a lower limit.

The accumulation rate of benthic foraminifera at a given locality can change in response to fluctuations in water depth, the flux of marine organic matter to the sea floor, as well as the sedimentation rate (Herguera & Berger, 1991). The foraminiferal abundance has been measured quantitatively in well 7119/9-1 (Fig. 3). The record displays fluctuations of two orders of magnitude within the Torsk Formation. Fluctuations of this magnitude cannot be explained by changes in surface productivity and water depth alone, and more likely reflect variations in the flux of terrigenous sediments. In sequence stratigraphic terms, inter-

vals with high benthic foraminiferal abundance and diversity reflect condensed horizons. The nature of the benthic foraminiferal abundance pattern in the 7119/9-1 well suggests cycles of higher sediment input, although changes in sediment texture are not apparent from gamma ray logs.

Knutsen & Vorren (1991) and Knutsen *et al.* (1992) noted that the Loppa High served as a sediment source area during the late Paleocene, and that in the northwestern part of the Tromsø Basin prograding clinoforms are visible in seismic reflection profiles. The decrease in foraminiferal abundance and diversity in this part of the section (above the *Spiroplectammmina spectabilis* assemblage) may reflect high terrigenous influx related to increased sediment supply from the north, which caused conditions unfavorable for the fauna.

The functional morphology of benthic foraminifera can provide important insights into the ecology of the benthic environment. Foraminiferal test shape is thought to reflect differences in life position and feeding strategy (Jones & Charnock, 1985). Changes in the relative proportions of the various morphogroups through time can reflect changes in environmental parameters such as water depth, current strength, and organic flux to the sea floor.

For this study, we have devised a morphogroup scheme for classifying the benthic foraminifera according to test morphology, and by analogy with modern faunas, for interpreting their paleoecology. Paleogene assemblages from the Barents Sea can be subdivided into four groups and nine subgroups (Fig. 6). Forms in Group 1 (tubular taxa) are normally found in higher abundance in bathyal to abyssal habitats, reaching an acme in the lower bathyal zone in the modern North Atlantic (Schroeder, 1986). Because they are epifaunal suspension feeders, they are adapted to life in areas of low organic flux. In the modern Norwegian-Greenland Sea, an abrupt shift from infaunal to predominantly epifaunal morphogroups is observed at a water depth of 1,500 m (Corliss & Chen, 1988). The infaunal Group 3, by contrast, is better adapted to life in areas of increased organic flux and high-

Morphogroup		Test morphology & Habitat	Examples
1	1 a	Rigid tubular Epifaunal, elevated, suspension feeding	<i>Bathysiphon</i> , <i>Rhabdammina</i>
	1 b	Flexible and flattened Epifaunal surficial, detritivores	<i>Rhizammina</i> , <i>Nothia</i>
2	2 a	Globular, surficial or shallow infaunal, feeding at the sediment surface	<i>Saccammina</i> , <i>Psammospaera</i>
	2 b	Rounded planoconvex, trocho- spiral, and streptospiral, surficial	<i>Recurvoides</i> & some <i>Trochammina</i>
	2 c	Keeled planispiral and elongated, surficial	<i>R. amplexens</i> <i>S. spectabilis</i>
3	3 a	Rounded planispiral, intermediate infaunal to surficial	<i>Haplo. eggeri</i>
	3 b	Elongated subcylindrical, tapered, deeper infaunal	<i>Karrerulina</i> , <i>Verneuilinoides</i>
4	4 a	Flattened planispiral and flattened irregular, epifaunal or climbing	<i>Ammodiscus</i> some <i>Glomospira</i>
	4 b	Flattened trochospiral Epifaunal or attached on elevated substrate	some <i>Trochammina</i>

**Figure 6.** Morphogroup scheme and inferred paleoecology of Paleogene agglutinated foraminifera from the western Barents Sea.

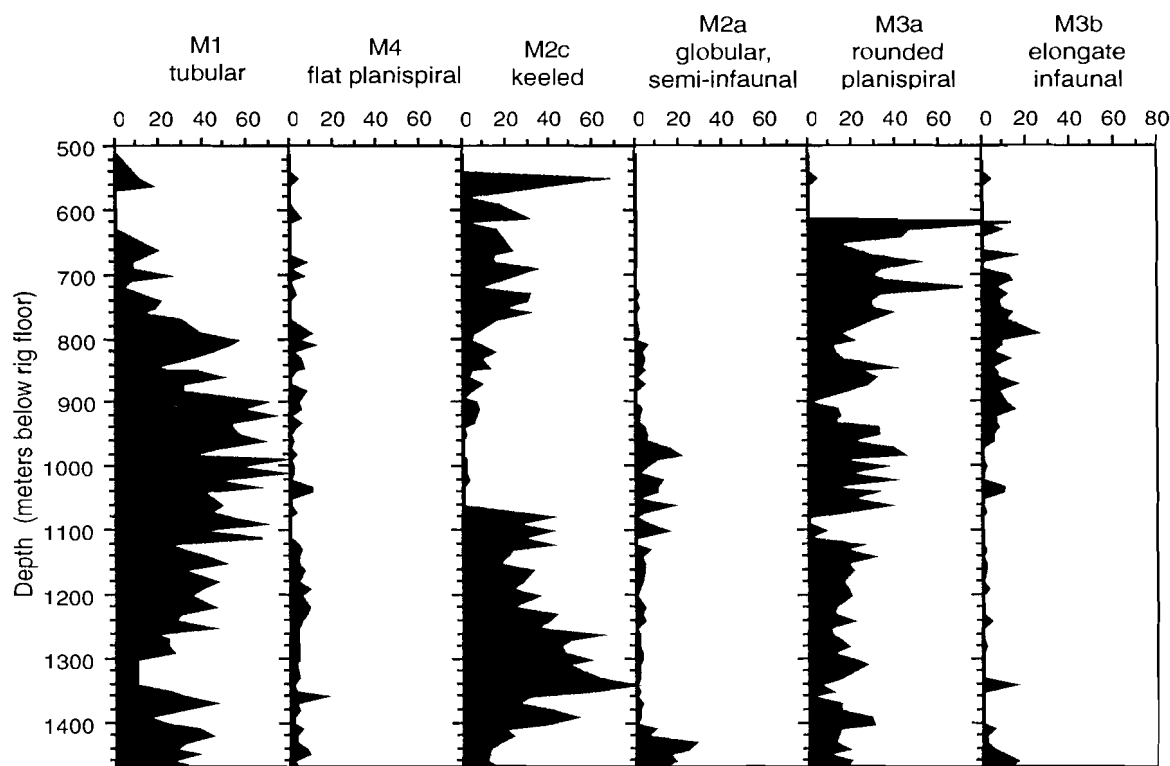


Figure 7. Relative proportions (in percent) of agglutinated foraminiferal morphogroups in the Paleogene of well 7119/9-1.

her nutrient supply. This group is often observed in large proportions near the shelf/slope break in the Gulf of Mexico, or in areas where the surface layer of the sea floor is affected by bottom currents (Kaminski, 1985).

We have undertaken a morphogroup analysis of the assemblages from the 7119/9-1 well, and results are shown in Figure 7. Taxa belonging to the tubular morphogroup 1a are common to dominant throughout the studied interval, except in the upper 170 m where they are rare or absent. High abundances of this group recalls the so-called flysch-type agglutinated assemblages of the Paleocene of the North Sea and Alpine-Carpathian regions. The frequency variations of the tubular morphogroup are interpreted as reflecting changes in the paleobathymetry of the site. In the lower part of the section, the relative proportion of tubes increases upsection, suggesting a gradual subsidence of the basin. Maximum water depth is represented by the interval between 900 and 1100 m, where the proportion of this morphogroup reaches 70%. It is natural to assume that the water depth during the latest Paleocene was middle bathyal or deeper. In the seismic section published by Knutsen *et al.* (1992, Fig. 11) a double high-intensity reflector is present between 900 and 1000 m which correlates precisely to our double peak in the proportions of

the tubular morphogroup. We believe that the maximum proportions of the tubular morphogroup at this level reflect the maximum extent of the Paleocene transgression in the Barents Sea area, and therefore represent a maximum flooding surface in sequence stratigraphic terms.

Above this interval, a shallowing of the site is indicated by the decreasing frequency of the tubular morphogroup 1 and its partial disappearance in the later part of the early Eocene. The keeled morphogroup 2c displays a maximum in the lower and upper parts of the interval, expressing the first phases of the transgression and the subsequent regression, respectively. It is of interest to note that the infaunal rounded planispiral morphogroup 3a attains maximum frequency in the upper part of the interval, corresponding to the early Eocene portion of the Torsk Formation. As a general rule, infaunal organisms can only exist in large numbers in areas where organic matter is buried in sufficient amounts. This observation agrees with the general trend of increasing surface-water paleoproductivity in the North Atlantic region during the latter part of the early Eocene, reflected by the onset of biosiliceous sedimentation (Berggren & Olsson, 1985).

The „deep infaunal“ morphogroup 3b displays variable but low abundance throughout the

studied interval. Since this group normally reaches maximum proportions in eutrophic areas or in dysaerobic environments such as those found beneath the oxygen minimum zone (Kaminski *et al.* 1995), we conclude that the bottom water in the Tromsø Basin was not oxygen-deficient during the deposition of the Torsk Formation. However, increased numbers of the genus *Karreriulina* are observed in the *Psammosphaera* assemblage at the base of the Torsk Formation. This is consistent with the finding of elevated proportions of deep infauna in areas disturbed by bottom currents (Kaminski, 1985). The above patterns are complex, and analysis of additional sections is needed to provide a more complete picture of the subsidence history of the western Barents Sea.

#### d. Diatom paleoecology

The most commonly occurring diatom taxon in the samples studied is *Stellarima microtrias*, a species found intermittently through the entire Paleogene. It occurs in all of the samples from 510 to 710 m, and between 845 and 1240 m. This species also has an intermittent stratigraphic distribution in the Paleogene of the North Sea (Mudge & Bujak 1994; Mitlehner, 1994). Some of the diatom taxa recognised in well 7119/9-1 are more stratigraphically restricted. *Thalassioritopsis wittiana* occurs more or less continuously through the upper Paleocene section, but is absent thereafter; whilst appearing sporadically between 560 and 1100 m is the large (up to 300 µm diameter) species *Fenestrella antiqua* (= *Coscinodiscus* sp. 1 of Bettenstaedt *et al.*, 1962), a taxon which marks the base of the Eocene in the North Sea but which has a longer range in the Barents Sea, extending from the upper Paleocene through the lower Eocene. It has a similar range in the Paleogene of the Urals and Volga Basin (Glezer *et al.* 1974), suggesting a connection of the Barents Sea with the Turgai Sea which extended across the Russian Platform during the Paleogene. Other species co-occurring with *F. antiqua* include *Coscinodiscus morsianus* and *Trinacria regina*. This assemblage as a whole is very similar to coeval diatom assemblages from the North Sea area (Hughes, 1981; Malm *et al.*, 1984; Homann, 1991; Mitlehner, 1994) as well as the Arctic Ocean (Dell'Agnese & Clark, 1994), although there are fewer similarities to the Paleogene assemblages sporadically recovered by DSDP Leg 38 from the less restricted Norwegian Basin (Schrader & Fenner 1976; Dzinoridze *et al.*, 1978). This assemblage similarity documents the beginning of the early Eocene transgressive phase, related to a worldwide warming event which occurred in all areas (Rea *et al.*, 1990; Robert & Chamley, 1991). Other pyritised diatom assemblages, recovered from the Labrador Sea (Thomas &

Gradstein, 1981), and the MacKenzie Basin of offshore northern Canada (McNeil, 1990) have certain similarities with those from the Barents Sea, in particular the occurrence of *Stellarima* species.

The sporadic occurrence of diatoms in the samples studied is related to periods of restricted water circulation as a result of lowered sea-level, in conjunction with increased nutrient influxes leading to diatom blooms (Calvert, 1966; Thunell *et al.*, 1994) in a relatively small and insolated basin. These periods often coincide with a decline in both species numbers and diversity of benthic foraminifera, a pattern also found in the North Sea (Mitlehner, 1994; 1996). This phenomenon can be attributed to periods of high surface water productivity, with increased nutrient levels leading to diatom blooms and eutrophication in the upper water column, and oxygen depletion of the lower water column (Codispoti, 1989). Conversely, increased numbers of benthic foraminifera coincide with a general absence of diatoms, a situation which signifies improved water circulation and increased oxygenation in the lower water column.

A particularly significant period of increased diatom productivity occurred at the Paleocene-Eocene transition, and is represented in well 7119/9-1 by an abundant and diverse diatom assemblage. The presence of benthic species (*Actinopterychus senarius*, *Aulacodiscus* sp.) indicates that there were shallow neritic conditions in the vicinity. A similar diatom abundance peak is recorded in the North Sea at the same interval, and it is likely that similar mechanisms, involving a lowered sea-level with increased influxes of water-borne and windblown terrigenously and volcanically derived nutrients to a restricted basin led to the proliferation of diatoms at that time.

#### CONCLUSIONS

Among the six wells located along a transect from the Senja Ridge through the Tromsø Basin to the Hammerfest Basin, well 7119/9-1 is chosen as a stratigraphic reference section. Analysis of foraminiferal, palynomorph, and diatom assemblages in this well in the Tromsø Basin enable a reliable determination of the chronostratigraphy of the Torsk Formation. A total of 86 palynomorph, 84 foraminiferal, and 35 diatom taxa have been found. The succession of late Paleocene to early Eocene assemblages compares well with the North Sea zonations of Mudge & Bujak (1994, 1996), Gradstein *et al.* (1994), Gradstein & Bäckström (1996), and Mitlehner (1994). The stratigraphic occurrences of several foraminiferal and dinocyst last occurrence events are consistent in wells across the Senja Ridge - Hammerfest Basin transect, suggesting that the biostratigraphical record of the 7119/9-1 well

may serve as a standard for stratigraphic correlation in the southwestern Barents Sea. Micropaleontological and palynological evidence suggest that the top of the Kviting Formation may be as young as late Campanian to Maastrichtian.

The foraminiferal assemblages of the studied wells consist exclusively of agglutinated taxa, suggesting reduced availability of dissolved calcium carbonate in the depositional basins. The composition of the benthic foraminiferal assemblages at the base of the Torsk Formation and in the uppermost part of the underlying Kviting Formation reflects a deep-water (middle or upper bathyal) depositional environment. There is no paleontological evidence of a shallowing of the environment in connection with the „basal Tertiary unconformity“ in the Tromsø Basin. Analysis of the benthic foraminiferal morphogroups in the reference section indicates a deepening of the basin until the latest Paleocene, followed by a shallowing of the basin in the early Eocene. As with the benthic foraminifera, the Paleogene diatom assemblages recovered show marked similarities to those present in the North Sea, although there are a number of differences in the stratigraphic ranges of some taxa.

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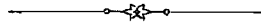
#### REFERENCES

- Barron, J.A. 1993. Diatoms. In: Lipps, J.H. (ed.) *Fossil Prokaryotes and Protists*, 155-167, Blackwell, Boston.
- Berggren, W.A., & Olsson, R.K. 1985. North Atlantic Mesozoic and Cenozoic paleoceanography. In: Vogt, P.R. & Tucholke, B.E. (eds.). *The Geology of North America, volume M, The North Atlantic Region*, 565-587, Geological Society of America.
- Bettenstaedt, F., Fahrion, H., Hiltermann, H., & Wick, W. 1962. Tertiär Norddeutschlands. In: Simon, W. & Bartenstein, H. (eds.) *Arbeitskreis deutscher Mikropaläontologen: Leitfossilien der Mikropaläontologie*, 432 pp. & pls., 2 vols. Gebrüder Bornträger, Berlin.
- Calvert, S.E. 1966. Accumulation of diatomaceous silica in sediments of the Gulf of California. *Bulletin of the Geological Society of America*, 77, 569-596.
- Cloetingh, S., Gradstein, F.M., Kooi, H., Grant, A.C., & Kaminski, M.A. 1990. Did plate reorganisation cause rapid late Neogene subsidence around the Atlantic? *Journal of the Geological Society of London*, 144, 43-58.
- Cloetingh, S., Reemst, P., Kooi, H., & Fanavoll, S. 1992. Intraplate stresses and the Post-Cretaceous uplift and subsidence in northern Atlantic basins. *Norsk Geologisk Tidsskrift*, 72, 229-235.
- Codispoti, L.A. 1989. Phosphorus vs. nitrogen limitation of new and export production. In: Berger, W.H., Smetacek, V.S. & Wefer, G. (eds.), *Productivity of the Ocean: Present and Past*, 377-394, Wiley & Sons, Chichester.
- Corliss, B.H., & Chen, C. 1988. Morphotype patterns of Norwegian Sea deep-sea benthic foraminifera and ecological implications. *Geology*, 16, 716-719.
- Dell'Agnese, D.J. & Clark, D.L. 1994. Siliceous microfossils from the warm late Cretaceous and early Cenozoic Arctic Ocean. *Journal of Paleontology*, 68, 31-47.
- Dzinoridze, R.N., Jousé, A.P., Koroleva-Golikova, G.S., Koslova, G.E., Nagaeva, G.S., Petrushevskaya, M.G. & Strelnikova, N.I. 1978. Diatom and radiolarian Cenozoic stratigraphy, Norwegian Basin. DSDP Leg 38 Initial Reports, Deep Sea Drilling Project, Supplement, 38-41, 289-427.
- Faleide, J.I., Gudlaugsson, S.T., Eldholm, O., Myhre, A.M., & Jackson, H.R. 1991. Deep seismic transects across the sheared western Barents Sea-Svalbard continental margin. *Tectonophysics*, 189, 73-89.
- Faleide, J.I., Våagnes, E., & Gudlaugsson, S.T. 1993a. Late Mesozoic - Cenozoic evolution of the southwestern Barents Sea. In: Parker, J.R. (ed.) *Petroleum Geology of northwest Europe: Proceedings of the 4th Conference*, 933-950, Geological Society, London.
- Faleide, J.I., Våagnes, E., & Gudlaugsson, S.T. 1993b. Late Mesozoic - Cenozoic evolution of the southwestern Barents Sea in a regional rift-shear tectonic setting. *Marine and Petroleum Geology*, 10, 186-214.
- Glezer, Z.I., Jousé, A.P., Makarova, I.P., Proshkina-Lavrenko, A.I. & Sheshukova-Poretskaya, V.S. 1974. *The Diatoms of the USSR Fossil and Recent*. Vol. 1. Akademii Nauk SSSR, Botanical Institute, Leningrad, 403 pp., 16 figs., 20 tabs., 93 pls. (In Russian).
- Gradstein, F.M., & Bäckström, S. 1996. Cenozoic biostratigraphy and palaeobathymetry, northern North Sea and Haltenbanken. *Norsk Geologisk Tidsskrift*, 76, 3-32.
- Gradstein, F.M., & Kaminski, M.A. 1989. Taxonomy and biostratigraphy of new and emended species of Cenozoic deep-water agglutinated foraminifera from the Labrador and North Seas. *Micropaleontology*, 35, 72-92.
- Gradstein, F.M., Kaminski, M.A., & Berggren, W.A. 1988. Cenozoic foraminiferal biostratigraphy of the central North Sea. *Abhandlungen der Geologischen Bundesanstalt*, 41, 97-108.
- Gradstein, F.M., Kaminski, M.A., Berggren, W.A., Kristiansen, I.L., & D'loro, M.A. 1994. Cenozoic biostratigraphy of the North Sea and Labrador Shelf. *Micropaleontology*, 40 (Supplement), 1-152.
- Hansen, J.M. 1977. Dinoflagellate stratigraphy and echinoid distribution in upper Maastrichtian and Danian deposits from Denmark. *Bulletin of the Geological Society of Denmark*, 26, 1-26.
- Heilmann-Clausen, C. 1985. Dinoflagellate stratigraphy of the upper Danian to Ypresian in the Viborg 1 Borehole, central Jylland. *Denmarks Geologiske Undersøelse, Series A7*, 1-69.
- Herguera, J.C., & Berger, W.H. 1991. Paleoproductivity from benthic foraminifera abundance - glacial to post-glacial change in the West-Equatorial Pacific. *Geology*, 19, 1173-1176.
- Homann, M. 1991. Die Diatomeen der Fur-Formation (Alt-tertiär) aus dem Limfjord-Gebiet, Nordjütland/Dänemark. *Geologisches Jahrbuch*, Hannover, Reihe A, 123, 285 pp., 57 pl.
- Hughes, M.J. 1981. Contribution on Oligocene and Eocene microfossils from the southern North Sea. In: Neale, J.W. & Brasier, M.D. (eds.) *Microfossils from Fos-*

- sil and Recent Shelf Seas*, 186-294, Ellis Horwood, Chichester.
- Jacqué, M. & Thouvenin, J. 1975. Lower Tertiary tuffs and volcanic activity in the North Sea. In: Woodland, A.W. (ed.) *Petroleum and the Continental Shelf of Northwest Europe*, Vol. 1: *Geology*, 455-465, Elsevier, Barking.
- Jones, R.W., & Charnock, M.A. 1985. „Morphogroups“ of agglutinating foraminifera, their life positions and feeding habits and potential applicability in (paleo)ecological studies. *Revue de Paléobiologie*, 4, 311-320.
- Kaminski, M.A. 1985. Evidence for control of abyssal agglutinated foraminiferal community structure by substrate disturbance - results from the HEBBLE area. *Marine Geology*, 66, 113-131.
- Kaminski, M.A., Boersma, A., Tyszka, J., & Holbourn, A.E.L. 1995. Response of deep-water agglutinated foraminifera to dysoxic conditions in the California Borderland basins. *Grzybowski Foundation Special Publication*, 3, 131-140.
- Kaminski, M.A., Gradstein, F.M., & Berggren, W.A. 1989. Paleogene benthic foraminifer biostratigraphy and paleoecology at Site 647, southern Labrador Sea. *Proceedings of the Ocean Drilling Program, Scientific Results*, 105, 705-730.
- Karpuz, M.R., Gabrielsen, R.H., Engell-Sorensen, L., & Anundsen, K. 1991. Seismotectonic significance of the January 29, 1989 Etne Earthquake, southwest Norway. *Terra Nova*, 3, 540-549.
- King, C. 1983. *Cainozoic Micropalaeontological Biostratigraphy of the North Sea*. Institute of Geological Sciences Report 82/7, H.M.S.O., London, 40 pp., 6 pls.
- King, C. 1989. Cenozoic of the North Sea. In: Jenkins, D.G. & Murray, J.W. (eds.), *A Stratigraphical Atlas of Fossil Foraminifera*, 418-489, 2nd Edition. Ellis Horwood, Chichester.
- Knutsen, S.-M., & Vorren, T.O. 1991. Early Cenozoic sedimentation in the Hammerfest Basin. *Marine Geology*, 101, 31-48.
- Knutsen, S.-M., Skjold, L.-J., & Skott, P.H. 1992. Palaeocene and Eocene development of the Tromsø Basin - sedimentary response to rifting and early sea-floor spreading in the Barents Sea area. *Norsk Geologisk Tidsskrift*, 72, 191-207.
- Lucas-Clark, J. 1987. *Wigginsiella* n.gen., *Spongodinium*, and *Aptedinium* as members of the Aptiana-Ventriosum complex (fossil Dinophyceae). *Palynology*, 11, 155-184.
- Malm, O.A., Christensen, O.B., Furnes, H., Løvlie, R., Ruselåttén, H. & Østby, K.L. 1984. The Lower Tertiary Balder Formation: an organogenic and tuffaceous deposit in the North Sea region, 149-170. In: Spencer, A.M. et al. (eds.) *Petroleum Geology of the North European Margin*, Graham & Trotman, London.
- McNeil, D.H. 1990. Stratigraphy and paleoecology of the Eocene *Stellarima* assemblage zone (pyrite diatom steinkerns) in the Beaufort-Mackenzie Basin, Arctic Canada. *Bulletin of Canadian Petroleum Geology*, 38, 17-27.
- Mitlehner, A.G. 1994. The occurrence and preservation of diatoms in the Palaeogene of the North Sea Basin. Unpublished Ph.D. thesis, University of London, 292 pp.
- Mitlehner, A.G. 1996. Palaeoenvironments in the North Sea Basin around the Palaeocene/Eocene boundary: evidence from diatoms and other siliceous microfossils. In: Knox, R.W.O'B., Corfield, R.M., & Dunay, R.E. (eds.) *Correlation of the Early Paleogene in Northwest Europe*. Geological Society Special Publication, 101, 255-273.
- Mudge, D.C., & Bujak, J.P. 1994. Eocene stratigraphy of the North Sea Basin. *Marine and Petroleum Geology*, 11, 166-181.
- Mudge, D.C., & Bujak, J.P. 1996. An integrated stratigraphy for the Paleocene and Eocene of the North Sea. In: Knox, R.W.O'B., Corfield, R.M., & Dunay, R.E. (eds.) *Correlation of the Early Paleogene in Northwest Europe*. Geological Society Special Publication, 101, 91-113.
- Murray, J., 1895. A summary of scientific results. *Reports of the Scientific Results of the HMS Challenger*, 1608 pp. Eyre & Spottiswoode, London.
- Rea, D.K., Zachos, J.C., Owen, R.M. & Gingerich, P.D. 1990. Global change at the Paleocene - Eocene boundary: climatic and evolutionary consequences of tectonic events. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 79, 117-128.
- Reemst, P., & Cloetingh, S. 1994. Tectonostratigraphic modelling of Cenozoic uplift and erosion in the southwestern Barents Sea. *Marine and Petroleum Geology*, 11, 478-490.
- Richardson, G., Vorren, T.O., & Tørudbakken, B.O. 1993. Post-Early Cretaceous uplift and erosion in the southern Barents Sea: a discussion based on analysis of seismic interval velocities. *Norsk Geologisk Tidsskrift*, 73, 3-20.
- Riis, F. 1992. Dating and measuring of erosion, uplift, and subsidence in Norway and the Norwegian shelf in glacial periods. *Norsk Geologisk Tidsskrift*, 72, 325-331.
- Robert, C. & Chamley, H. 1991. Development of early Eocene warm climates, as inferred from clay mineral variations in oceanic sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology* (Global and Planetary Change Section), 89, 315-331.
- Rønnevik, H.C. 1981. Geology of the Barents Sea. In: *Petroleum Geology of the Continental Shelf of North-West Europe*. 395-406.
- Rønnevik, H.C., & Jacobsen, H.P. 1984. Structures and basins in the western Barents Sea. In: Spencer, A.M. (ed.) *Petroleum Geology of the North European Margin*. 19-32, Graham & Trotman, London.
- Roufosse, M.C. 1987. The formation and evolution of sedimentary basins in the western Barents Sea. In: Brooks, J. & Glennie, K. (eds.) *Petroleum Geology of Northwest Europe*, 1149-1161, Graham & Trotman, London.
- Round, F.E., Crawford, R.M., & Mann, D.G. 1990. *The Diatoms. Biology and Morphology of the Genera*, 741 pp., Cambridge University Press.
- Schröder, T. 1992. A palynological zonation for the Paleocene of the North Sea Basin. *Journal of Micropalaeontology* 11, 113-126.
- Schroeder, C.J. 1986. Deep-water arenaceous foraminifera in the Northwest Atlantic Ocean. *Canadian Technical Report of Hydrography and Ocean Sciences*, 71, 1-191.
- Thomas, F.C. & Gradstein, F.M. 1981. Tertiary subsurface correlations using pyritised diatoms, offshore eastern Canada. In: *Current Research, Part B, Geological Survey of Canada*, 81-1B, 17-23.
- Thunell, R.C., Pride, C.J., Tappa, E. & Muller-Karger, F.E. 1994. Biogenic silica fluxes and accumulation rates in the Gulf of California. *Geology*, 22, 303-306.
- Tocher, B.A. 1987. Campanian to Maestrichtian dinoflagellate cysts from the United States Atlantic Margin, Deep Sea Drilling Site 612. *Initial Reports of the Deep Sea Drilling Project*, 95, 419-428.
- Vinken, R. (ed.) 1988. The Northwest European Tertiary Basin: Results of the International Geological Correlation Programme Project 124. *Geologisches Jahrbuch, Reihe A*, 100, 1-508.
- Walderhaug, O., 1992. Magnitude of uplift of the Stø and



- Nordmela Formations in the Hammerfest Basin - a diagenetic approach. *Norsk Geologisk Tidsskrift*, **72**, 321-323.
- Worsley, D., Johansen, R., & Kristensen, S.E. 1988. The Mesozoic and Cenozoic succession of Tromsøflaket. In: Dalland, A., Worsley, D., & Ofstad, K. (eds.) A lithostratigraphic scheme for the Mesozoic and Cenozoic succession offshore mid- and northern Norway. *NPD Bulletin*, **4**, 42-61.





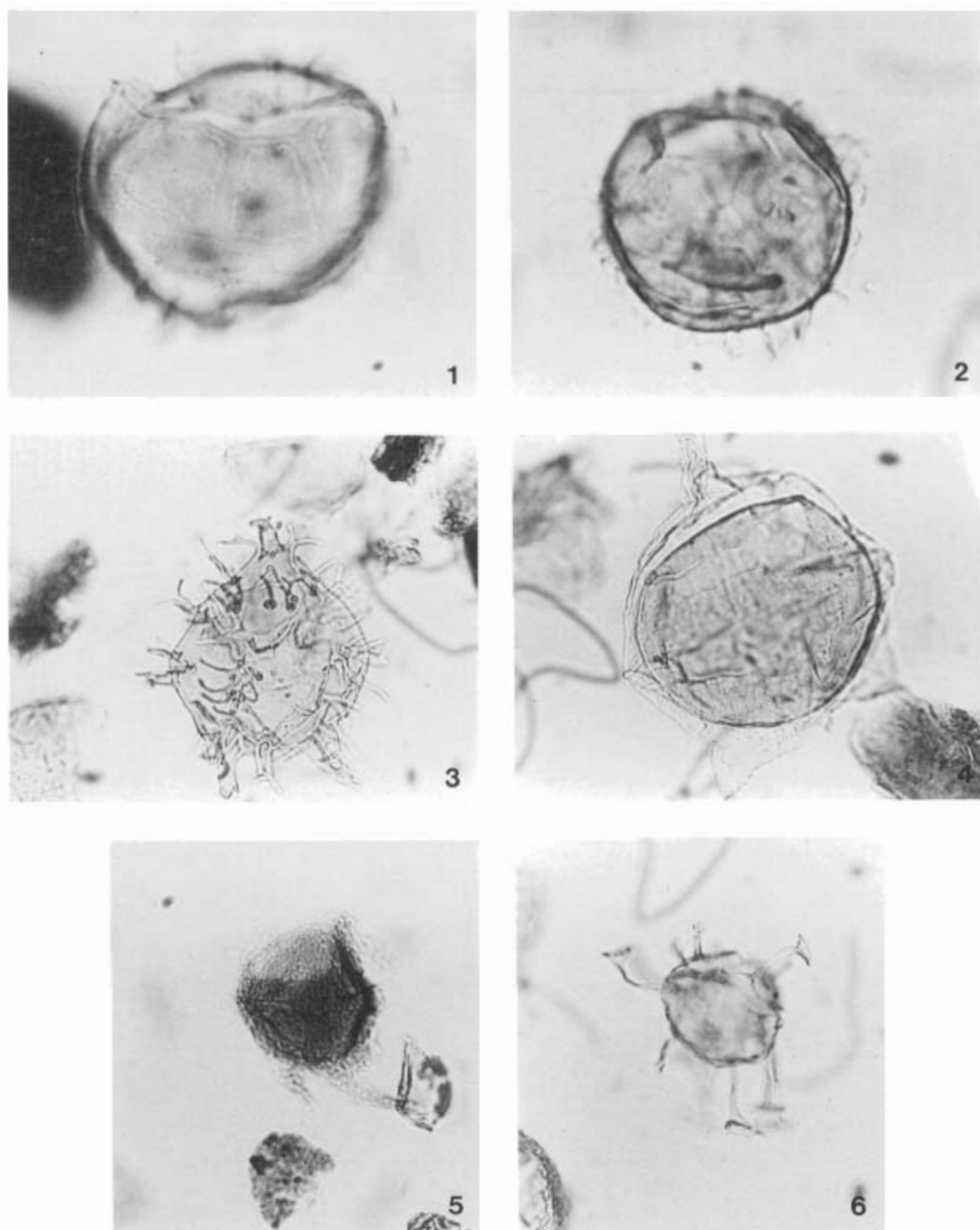
**Table 1 (cont.).** Palynomorph distribution in samples from Well 7119/9-1. Depth in metres.

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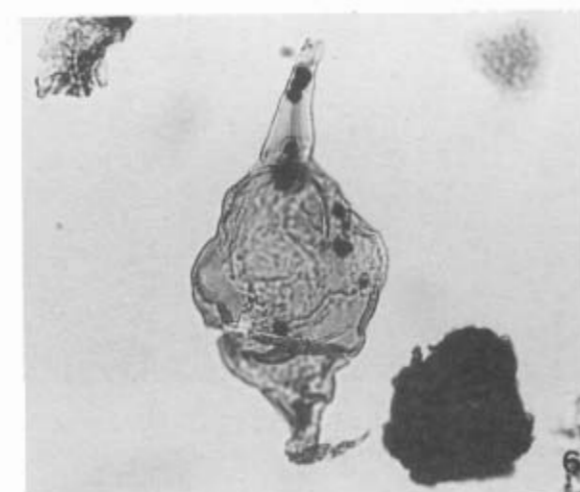
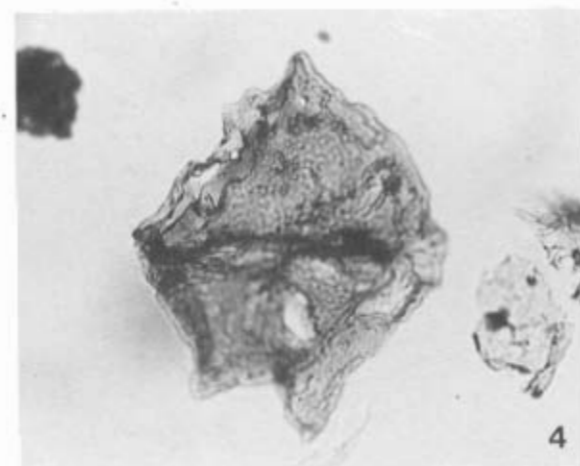
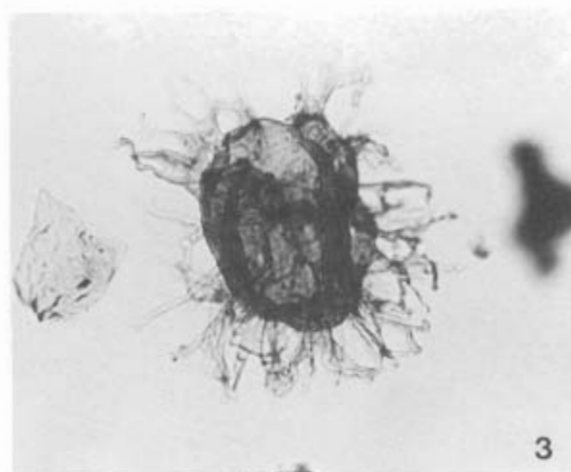
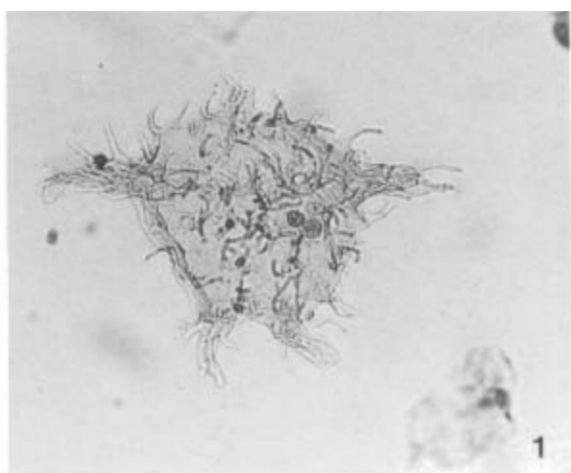


**Table 2 (continued).** Benthic foraminiferal distribution in samples from Well 7119/9-1. Depth in metres.

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**Plate 1.** Stratigraphically important palynomorphs from the western Barents Sea. 1,2. *Alisocysta* sp. 2 Heilmann-Clausen, 1985, x1000. 3. *Apectodinium quinquelatum* (Williams & Downie) Costa & Downie, 1979, x500. 4. *Deflandrea oebisfeldensis* Alberti, 1959b, x500. 5. *Deflandrea denticulata* Alberti, 1959b, x500. 6. *Hystrichosphaeridium tubiferum* (Ehrenberg) Deflandre emend. Davey & Williams, 1966b, x500.



**Plate 2.** Stratigraphically important palynomorphs from the western Barents Sea. 1. *Apectodinium augustum* (Harland) Lentin & Williams, 1981, x300. 2. *Alisocysta margarita* (Harland) Harland, 1979a, x1000. 3. *Areoligera* cf. *senonensis* Lejeune-Carpenter, 1938, x500. 4. *Palaeoperidinium pyrophorum* (Ehrenberg) Sarjeant, 1967b, x500. 5. *Cerodinium striatum* (Drugg) Lentin & Williams, 1987, x500. 6. *Palaeocystodinium bulliforme* Ioannides, 1986, x250.

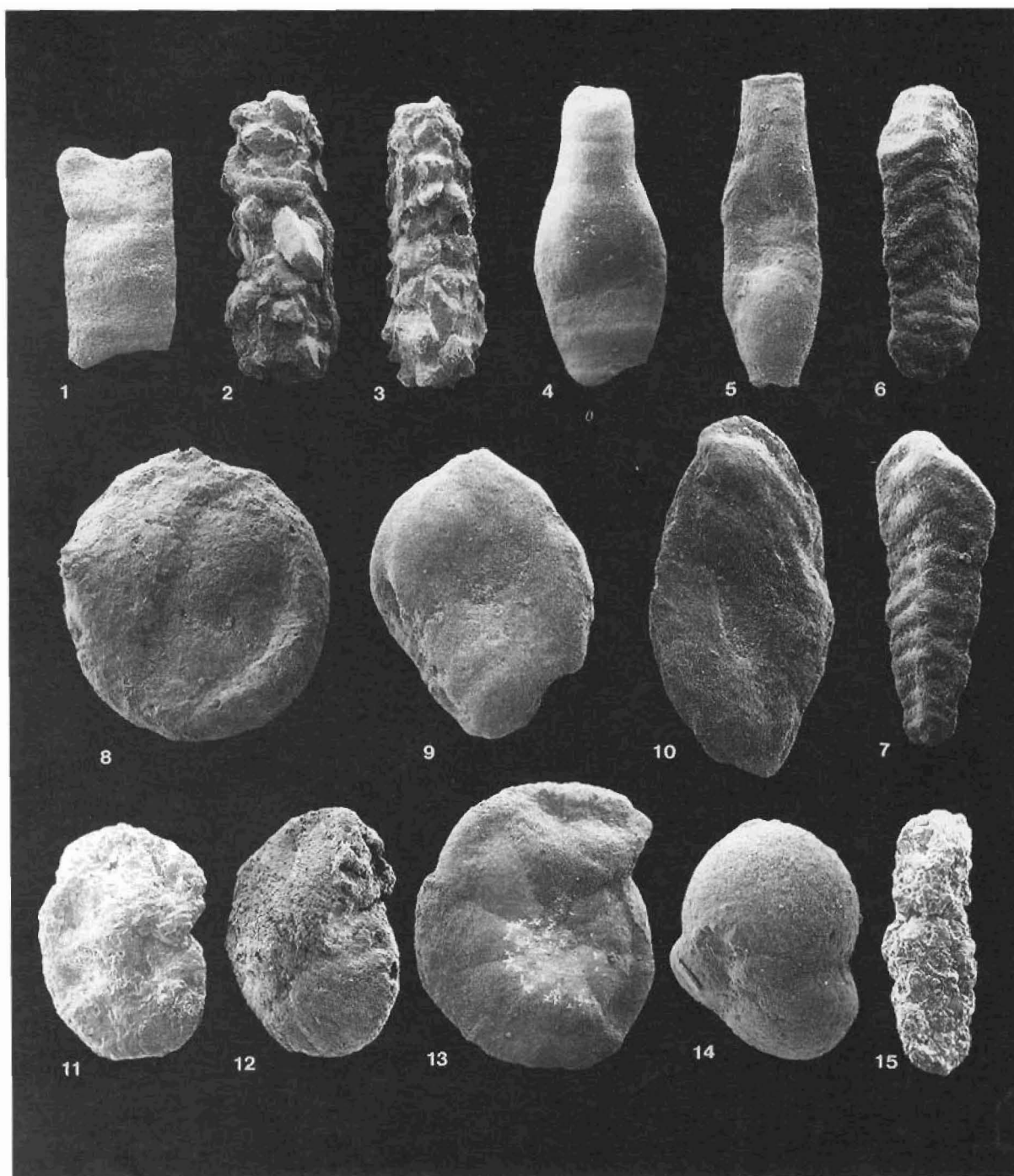


Plate 3. Stratigraphically important benthic foraminifera from Well 7119/1. 1. *Nothia robusta* (Grzybowski), x37. 2. *Hyperammina rugosa* Verdenius & Van Hinte, 1320m, x28. 3. *Hyperammina rugosa*, x45. 4. *Caudammina excelsa* (Dylazanka), 1350m, x33. 5. *Kalamopsis grzybowskii* (Dylazanka), 1349, x140. 6. *Spiroplectammina spectabilis* (Grzybowski) megalosphaeric, 1370m, x80. 7. *Spiroplectammina spectabilis* microspaeric, 1370m, x80. 8. *Saccamina placenta* (Grzybowski), 1320m, x78. 9. *Rzehakina epigona* (Rzehak), 1380m, x70. 10. *Rzehakina minima* Cushman & Renz, 1330m, x145. 11. *Haplophragmoides excavatus* Cushman, x93. 12. *Reticulophragmium annectens* (Grzybowski), x90. 13. *Reticulophragmium paupera* (Chapman), 1380m, x45. 14. *Prucystammina* sp., 1380m, x160. 15. *Karrerulina* sp., x115.