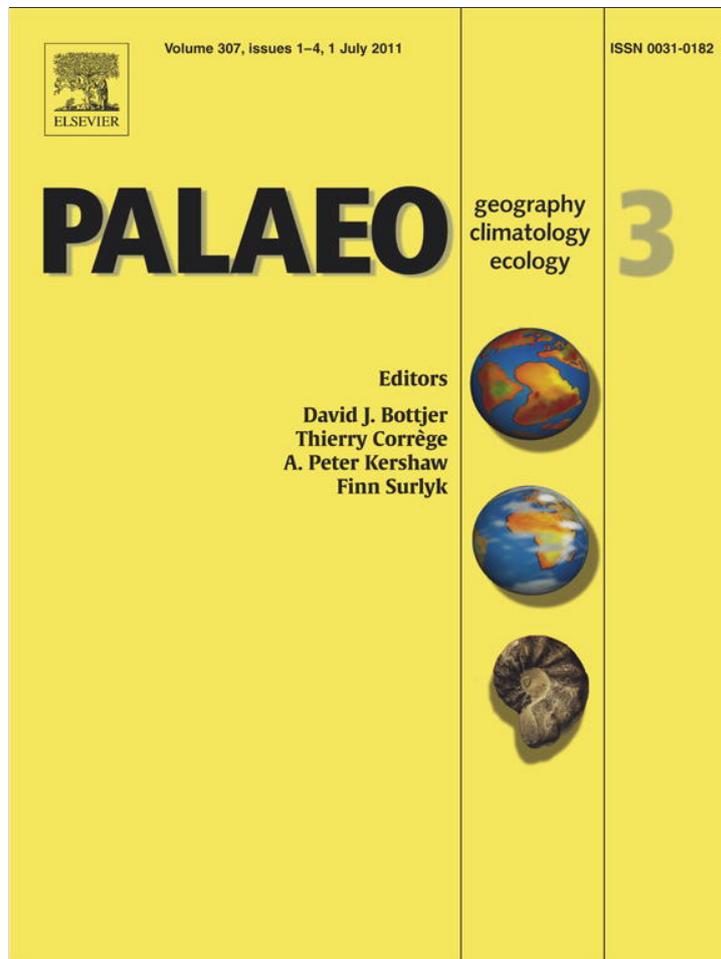


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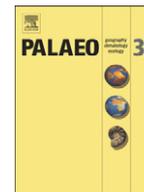
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The Late Cretaceous–Early Paleocene palaeobathymetric trends in the southwestern Barents Sea – Palaeoenvironmental implications of benthic foraminiferal assemblage analysis

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ABSTRACT

The Late Cretaceous foraminiferal assemblages from five wells drilled in the southwestern Barents Sea were analysed using morphogroup analysis in order to understand the palaeoenvironment and palaeobathymetry of the study area. Morphogroup analysis of assemblages in the Upper Cretaceous Kveite Formation suggests stable, possibly middle to lower bathyal, mesotrophic and relatively well-oxygenated environments in the Tromsø Basin during the Late Cretaceous. The depositional setting of Upper Cretaceous Kveite Formation in the tectonically more stable Hammerfest Basin was probably shallower, but still represents a deep-water environment similar to that of the Kveite Formation. A shallowing regional bathymetry in the southwestern Barents Sea is indicated by the general decreasing trend in the relative abundance of tubular forms and the species diversity of assemblages, which reflects the regional Late Cretaceous–Paleocene uplift prior to the break-up of the Greenland–Norwegian Sea. Changes in the relative abundance of morphogroups and in the main constituent in the cumulative length of tubular taxa from *Rhizammina* to *Rhabdammina* near the top of Kveite Formation agree with the possible existence of bottom water currents.

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1. Introduction

A study of Late Cretaceous palaeoenvironments of the Barents Sea has a potential importance in improving our understanding of the tectonic development and palaeoceanographic history of the surrounding region. The geological development of the Barents Shelf has been largely controlled by rifting episodes prior to the break-up of the Greenland–Norwegian Sea during the Late Cretaceous–Paleocene transition, and subsequent Cenozoic oceanic floor spreading (Faleide et al., 1984, 1993, 2008; Gabrielsen et al., 1990; Breivik et al., 1998). The exchange of marine waters and biota between the Arctic, proto-North Atlantic and Western Siberia probably took place over the Barents Sea which connected the major seas during the Late Cretaceous period of high sea levels. Benthic foraminifera are sensitive to environmental changes, and these changes can be reflected in the composition of assemblages. The distribution and abundance of

benthic foraminifera are often controlled by two generally depth-related and inversely correlated parameters, the flux of organic matter to the seafloor and oxygen concentrations of bottom and pore waters (e.g., Jorissen et al., 1995; Kaminski et al., 1995; Altenbach et al., 1999; De Rijk et al., 2000; Fontanier et al., 2002). Therefore, benthic foraminiferal assemblage structures can be used as indicators for physical and chemical properties of ambient bottom waters at the seafloor. Morphogroup analysis has been developed in an attempt to semiquantitatively evaluate palaeoenvironmental and palaeobathymetric trends reflected by foraminiferal assemblages, and this technique has been applied in both deep and shallow water settings (e.g. Corliss, 1985; Jones and Charnock, 1985; Corliss and Chen, 1988; Koutsoukos and Hart, 1990; Nagy et al., 1995, 1997, 2000; Tyszką and Kaminski, 1995; Kaminski and Gradstein, 2005; Reolid et al., 2008, 2010).

In this study, foraminiferal assemblages from the Upper Cretaceous sections of five wells drilled in the Hammerfest and Tromsø basins in the southwestern Barents Sea are analysed using morphogroup analysis in an attempt to reconstruct palaeobathymetric and palaeoenvironmental changes in the study area. The length of tubular taxa is also measured to support the interpretation of morphogroup analysis taking into account that the number of tubular fragments in samples is not only related to variable palaeoenvironments, but also the degree of mechanical breakage.

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2. Geological background

The Barents Sea was a part of a seaway between Greenland and northwestern Europe connecting the Arctic and Atlantic basins until the onset of sea floor spreading in the Greenland–Norwegian Sea around the Paleocene–Eocene transition that reached the present-day continental margin off southern Spitsbergen in the latest Eocene (Faleide et al., 2008). Prior to the spreading, the western Barents Sea was under a great influence of the Late Paleozoic and Late Jurassic–Early Cretaceous rift episodes and another rifting phase in the Late Cretaceous–Paleocene starting in the Campanian (Doré, 1991; Faleide et al., 1993; Ren et al., 2003). The eastern region, meanwhile, has been tectonically more stable since the Late Carboniferous (Gabrielsen et al., 1990; Faleide et al., 1993).

Faleide et al. (1993) divided basins in the southwestern Barents Sea into the deep Cretaceous and Early Cenozoic basins (Bjørnøya, Harstad, Tromsø and Sørvestsnaget basins) and Mesozoic basins (Hammerfest Basin and Fingerdjupet subbasin of the Bjørnøya Basin), which did not undergo the pronounced Cretaceous/Tertiary subsidence (Fig. 1). The Hammerfest Basin became separated from the Tromsø Basin during the Early Cretaceous (Gabrielsen et al., 1990), when the Bjørnøya, Harstad and Tromsø basins experienced a rapid subsidence, and the Tromsø and Sørvestsnaget basins continued to subside during the Late Cretaceous (Faleide et al., 1993). As a result of the different Cretaceous subsidence history of basins and regions, the Upper Cretaceous Nygrunnen Group varies in thickness, completeness and composition in the southwestern Barents Sea (Fig. 2). The Upper Cretaceous Kveite Formation can be over 1200 m thick in the centre of the Tromsø Basin, but thins and changes eastwards into the Kviting Formation in the Hammerfest Basin, which can be less than 50 m-thick (Worsley et al., 1988; Faleide et al., 1993). The Kveite Formation is composed of shaly claystones with thin interbeds of limestones and siltstones, and the Kviting Formation contains calcareous sandstones and limestones interbedded with mudstones (Worsley et al., 1988).

The depositional settings of Upper Cretaceous formations were interpreted as shallow to deep shelf environments by Worsley et al. (1988). Although there have been several studies on Cenozoic erosions and uplifts in the Barents Sea region (e.g. Richardsen et al., 1993; Dimakis et al., 1998), the nature of hiatus above and below the Nygrunnen Group in basinal areas is still not clear. Nagy et al. (1997) postulated the presence of periodic bottom currents as the cause of Upper Cretaceous–Paleocene hiatus based on the similarity of benthic foraminiferal fauna in the base of the Torsk Formation in the Tromsø and Hammerfest basins to the recent benthic foraminiferal assemblages found in areas affected by strong bottom currents.

3. Material and methods

3.1. Material

Foraminifera were examined in 58 picked faunal slides from five wells, including 7119/9-1 operated by Elf Petroleum Norge, and 7119/12-1, 7120/7-3, 7120/5-1 and 7121/5-1 operated by STATOIL. The first three wells were drilled in the Tromsø Basin and the other two in the Hammerfest Basin in years between 1980 and 1985 (Fig. 1). Most of the ditch cutting samples from 7119/9-1, 7119/12-1 and 7120/7-3 were collected at 10-m intervals (Fig. 3). Samples from 7120/5-1 and 7121/5-1 contain some side-wall cores and were collected at variable intervals. Washed residues were dry-sieved over a 180- μ m sieve and foraminifera were picked. In addition, the fraction smaller than 180 μ m was checked for additional taxa by Paleoservices Ltd. The picked slides were supplied by STATOIL for the purpose of this study. Unfortunately, the size of samples in wells 7120/5-1 and 7121/5-1 is much smaller than 300 specimens per sample. Because most of the samples are ditch cuttings, and sampling intervals are large, we focus on general trends rather than changes in each sample for the interpretation of data.

In the Kveite and Kviting formations, 173 agglutinated and 15 calcareous benthic foraminiferal species are recorded (Setoyama et al.,

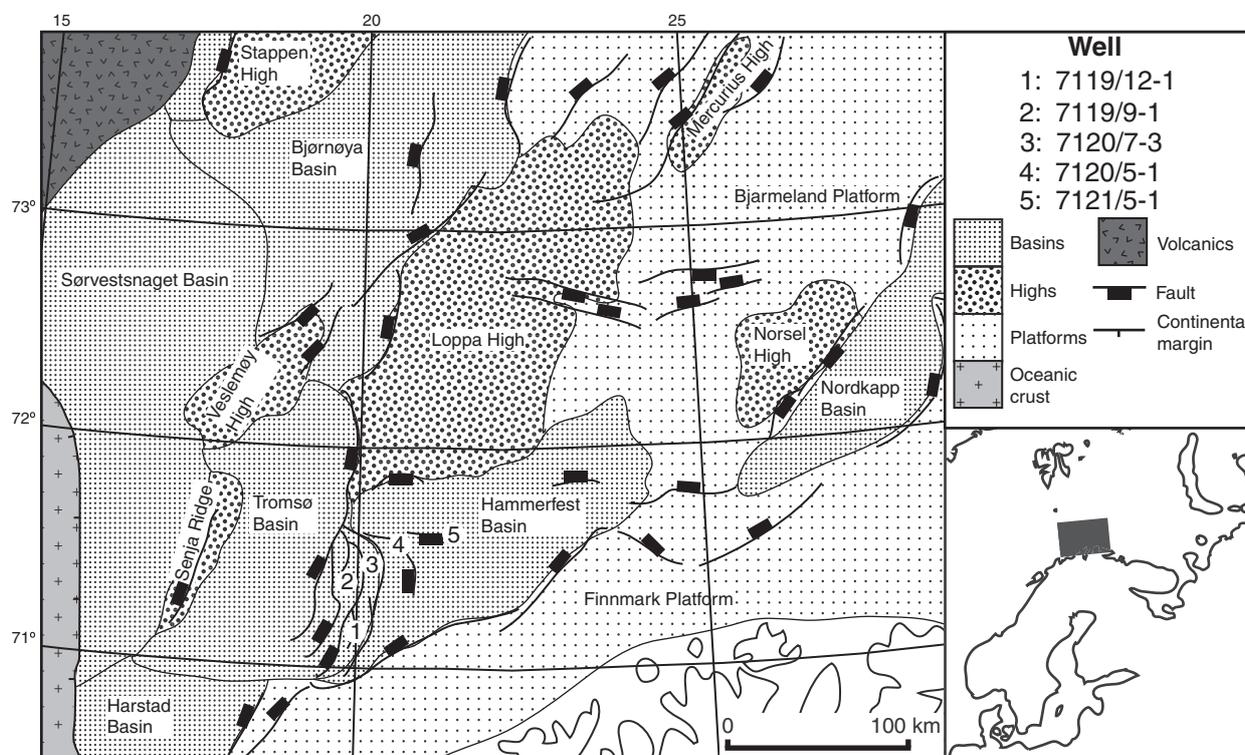


Fig. 1. Study area map with the well locations.

(Modified after NPD's FactMap; <https://npdmap1.npd.no/website/NPDGIS/viewer.htm>).

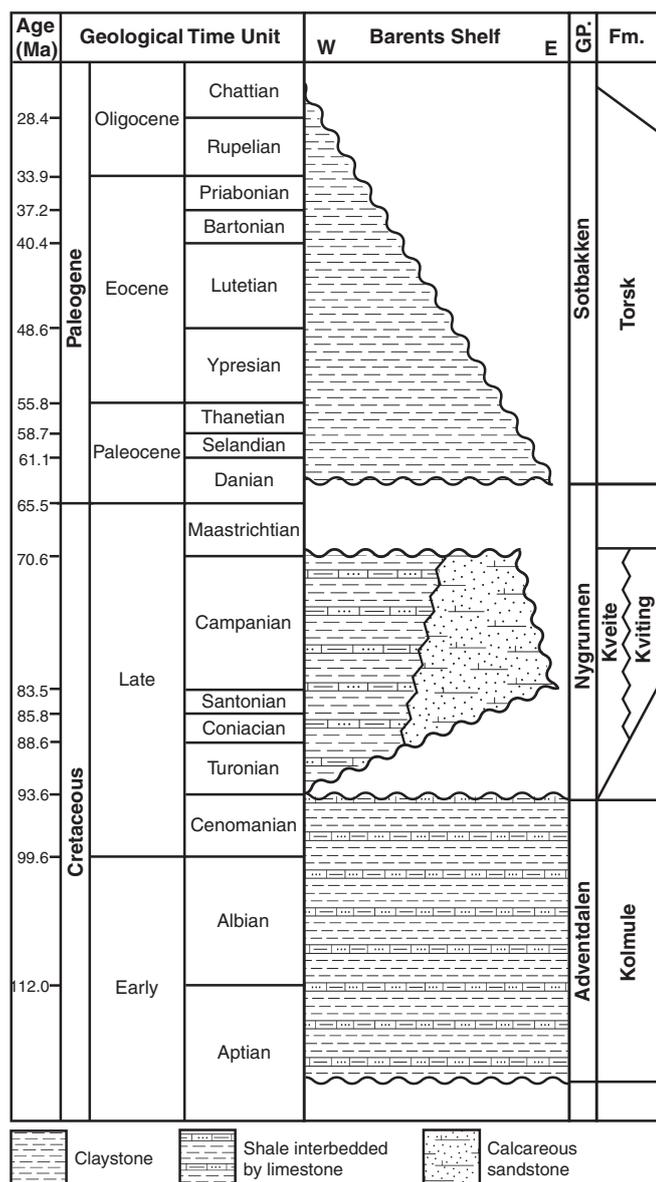


Fig. 2. Lithostratigraphy of southwestern Barents Sea. (Modified after Worsley et al., 1988; Nøttvedt et al., 1992; Nagy et al., 2004).

2011). We conclude that effects of reworking and caving of foraminiferal specimens are minimal as there are no unexpected occurrences of species known from remarkably different environments nor ages from those of the majority in samples above and below, and significant mechanical breakage of tests is rarely observed in specimens.

The data of total organic carbon content are available for the wells considered here from the NPD's Fact-pages (<http://www.npd.no/engelsk/cwi/pbl/en/index.htm>). The ranges of TOC values of the Upper Cretaceous sediments are 0.45 wt.% in 7119/9-1, 0.46–0.59 wt.% in 7119/12-1, 0.94–0.99 wt.% in 7120/7-3, 0.42–1.25 wt.% in 7120/5-1 and 0.41–0.44 wt.% in 7121/5-1. However, the TOC contents are not available for the samples analysed in this study.

3.2. Diversity and taxonomic composition

The detailed taxonomy of component taxa of foraminiferal assemblages is studied and described in Kaminski et al. (2009) and Setoyama et al. (2011). Fisher alpha diversity index as a measure of species diversity was calculated using the PAST software (version

2.03) (Hammer et al., 2001; Hammer and Harper, 2006). The species diversity is calculated only for agglutinated foraminifera because of uncertainty about the intensity of carbonate dissolution in the Upper Cretaceous of the Barents Sea (Fig. 3). The data of species occurrence and diversity is available as the supplementary content.

3.3. Foraminiferal morphogroup analysis

The main ideas behind the morphogroup analysis are that species with different test shapes have different preferred life habitats, which can be related to feeding strategies, and that changes in the relative abundance of morphogroups in assemblages reflect environmental changes through time (Corliss, 1985; Jones and Charnock, 1985). It is known that foraminifera can move vertically within and over the sediments and utilise different food sources (Alve and Bernhard, 1995; Gooday and Rathburn, 1999; Heinz et al., 2001; Fontanier et al., 2002; Nomaki et al., 2005; Suhr et al., 2008; Alve, 2010). Although test morphology is not a strict guide to their feeding strategies (Gooday et al., 2008), a number of studies on recent foraminifera show that most species show a preference for a certain trophic level (e.g. De Rijk et al., 2000; Mojtabid et al., 2010), and their preference can be attributed to their preferred infaunal or epifaunal life position and generalist or opportunistic life strategies (Jorissen et al., 1995; Altenbach et al., 1999; Fontanier et al., 2002; Nomaki et al., 2005). Since Jones and Charnock (1985) devised the morphogroup analysis, it has been refined and applied to fossil agglutinated assemblages for palaeoecological study by subsequent authors (Nagy et al., 1995, 1997, 2000; Peryt et al., 1997, 2004; van den Akker et al., 2000; Kaminski and Gradstein, 2005; Reolid et al., 2008, 2010; Cetaan et al., 2010). The morphogroup analysis of calcareous benthic assemblages is also widely applied to fossil assemblages for palaeoenvironmental studies (e.g. Sliter and Baker, 1972; Corliss, 1985; Bernhard, 1986; Corliss and Chen, 1988; Koutsoukos and Hart, 1990; Kaiho, 1994; Kaiho and Hasegawa, 1994; Tyszka, 1994). These methods are, however, not applied in this study because of the poor preservation and rare occurrence of calcareous benthic foraminifera. To study the palaeoenvironment of the southwestern Barents Sea, as in other studies, we apply morphogroup analysis to the Late Cretaceous fossil assemblages on the uniformitarian assumption that the functional morphology of foraminiferal tests and patterns seen in the recent foraminiferal assemblages along environmental gradients can be applied to fossil assemblages.

The morphogroup M1 (tubular forms) is categorised as suspension feeders (Fig. 4), though some of the recent species are known to ingest sediments as well (Gooday et al., 1992). Tubular forms are very rare in the shelf environment, but increase their abundance with depth, often reaching the maxima in the middle and lower bathyal zones, and this trend is observed at least from the Jurassic (Schröder, 1986; Nagy et al., 1995, 2000; Tyszka and Kaminski, 1995; Kaminski and Gradstein, 2005). M2 is regarded mainly as deposit feeders often found living at or just below the sediment surface. M2a (unilocular or uniserial forms with globular chambers) is, like tubular forms, very common in the bathyal and abyssal environments (Nagy et al., 1995; Gooday et al., 1997). M3 is the group of mobile or sessile epifaunal forms that are sometimes found living on elevated substrates. M3a occurs commonly in different environments from the lagoon to abyssal environments, whereas M3b and M3c are characteristic of deep-water environments (Schröder, 1986; Nagy et al., 1995). M4 (elongated multiserial forms) includes shallow and deep infaunas, regarded as deposit feeders. Both M4a (shallow infauna) and M4b (deep infauna) are commonly found in areas with increased organic flux (Nagy et al., 1995; 1997), and M4b often flourishes in dysoxic environments (Kaminski et al., 1995).

All tubular specimens are found as fragments in our material. Counting each fragment as one specimen overestimates their relative abundance in assemblages. To overcome this problem, different methods are employed to semi-quantify tubular taxa. In some studies

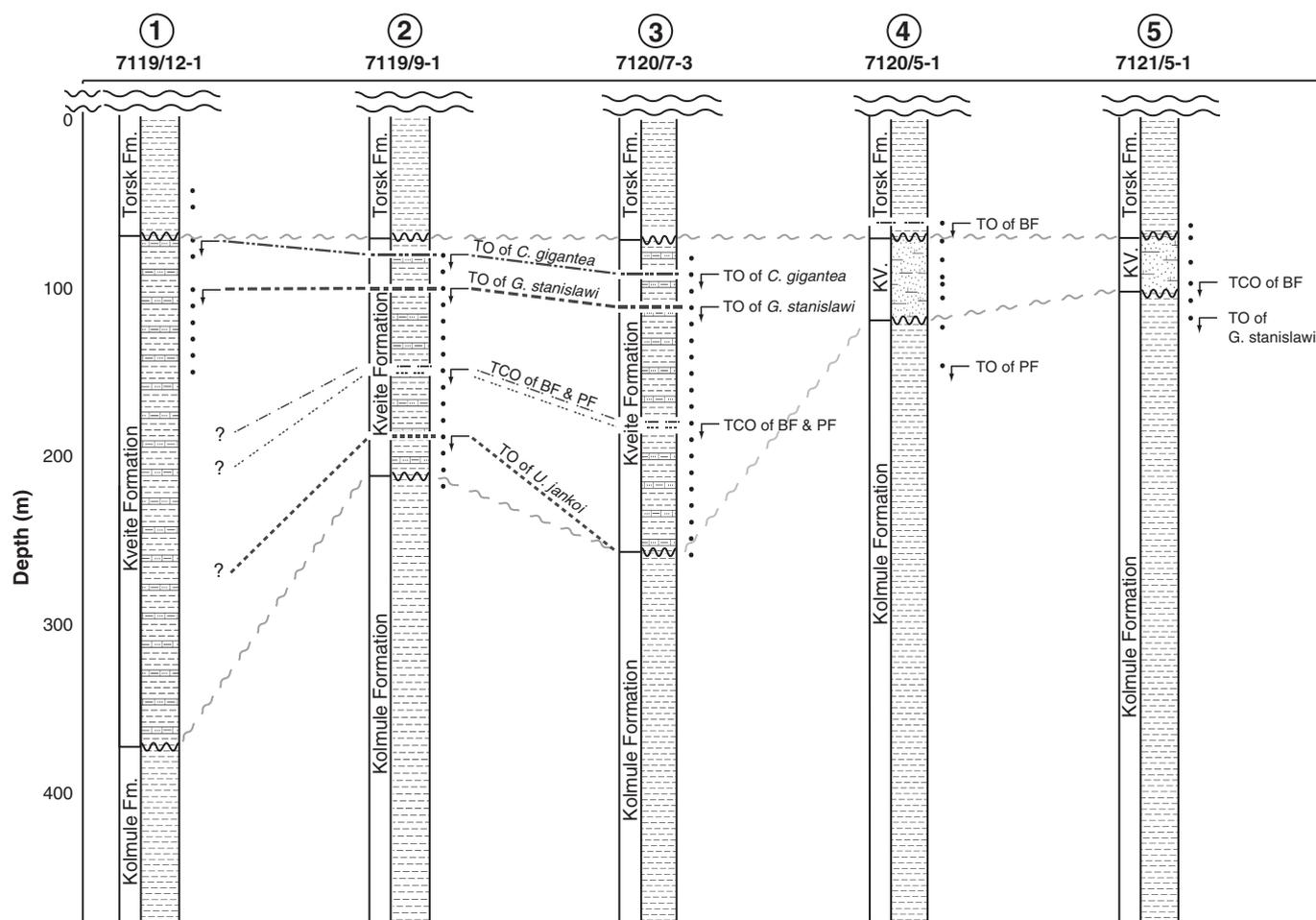


Fig. 3. Well transect with the position of samples and bioevents. KV: Kviting Formation; BF: Calcareous benthic foraminifera; PF: Planktic foraminifera; TCO: Top common occurrence; TO: Top occurrence.

on recent foraminifera, three size-standardised fragments are counted as one specimen (Kurbjewit et al., 2000; Heinz and Hemleben, 2003) or a specimen longer than 1000 μm or a fragment with the proloculus regardless of size is counted as one specimen, while smaller fragments were combined to be about 1000 μm long and counted as one specimen (Szarek et al., 2006, 2007, 2009). In this study, each fragment of tubular form is counted as one specimen to allow comparison with other studies using the morphogroup analysis (e.g. Nagy et al., 1995, 1997). Besides, we measured the length of each tubular specimen. The total cumulative length of tubular forms per sample is calculated and compared with the number of tubular specimens to examine how the two measurements of tubular specimens correlate. The cumulative length of each tubular genus is also measured to subserve the interpretation of morphogroup analysis. The cumulative length is recalculated as a tube length per 300 specimens of all the foraminiferal taxa in a sample to standardise in sample size to allow comparison of samples with different sizes because larger samples tend to contain more fragments of tubular forms and, thus, the longer cumulative length regardless of the relative abundance of tubular forms in sample.

4. Results

4.1. Foraminiferal assemblages

The Late Cretaceous assemblages of SW Barents Sea are dominated by agglutinated foraminifera and often devoid of planktic and

calcareous benthic foraminifera (Fig. 5). The agglutinated assemblages in the Kveite Formation are taxonomically similar to the highly diversified Late Cretaceous deep-water agglutinated foraminiferal assemblages of North Atlantic and Western Tethys. The presence of abundant robust tubular forms, such as *Psammosiphonella* spp., other coarsely agglutinated species including *Arthrodendron moniliformis* (Neagu), *Psammosphaera fusca* Schultze, and *Saccamina grybowskii* (Schubert), and other taxa, such as the species of *Caudamina*, *Paratrochamminoides*, *Recurvoides* and *Rzehakina*, indicates the high affinity of the Barents Sea assemblages to the flysch-type fauna found in Cretaceous and Cenozoic bathyal turbiditic environments (Gradstein and Berggren, 1981; Kuhnt et al., 1989; Kaminski and Gradstein, 2005). Furthermore, the rare occurrence of calcareous-cemented agglutinated genera, such as *Dorothia* and *Marssonella*, and calcareous benthic foraminifera and the high latitudinal position of Barents Sea during the Late Cretaceous suggest that the assemblages belong to the high-latitude slope biofacies (Kuhnt et al., 1989; Kaminski and Gradstein, 2005).

The diversity of assemblages in the Kviting Formation is lower than the Kveite Formation (Figs. 6–10). This is probably, to some extent, due to the smaller sample size in wells 7120/5-1 and 7121/5-1 and diagenesis as the preservation of specimens is more variable in the Kviting Formation. Nevertheless, some species are found in the Kviting Formation, including coarse tubular forms, *Psammosiphonella* and *Rhabdammina*, and deep-water species, such as *Bicazamina cuneata* (Krasheninnikov), *Caudamina ovula* (Grzybowski) and the species of *Gerochammina*.

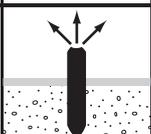
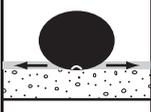
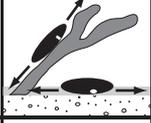
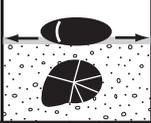
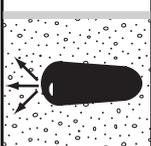
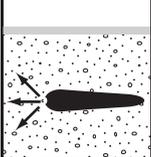
Morpho-group	Morpho-type	Test Form	Life position	Feeding habit	Environment	Main genera
M1		Tubular	Erect epifauna	Suspension feeding	Tranquil bathyal and abyssal with low organic flux	<i>Bathysiphon</i> <i>Kalamopsis</i> <i>Nothia</i> <i>Psammosiphonella</i> <i>Rhizammina</i>
M2	M2a 	Globular	Shallow infauna	Suspension feeding and/or Passive deposit feeding	Common in bathyal and abyssal	<i>Caudammina</i> <i>Hyperammina</i> <i>Placentammina</i> <i>Psammosphaera</i> <i>Saccammina</i>
	M2b 	Rounded trochospiral and streptospiral	Surficial epifauna	Active deposit feeding	Shelf to deep marine	<i>Cribrostomoides</i> <i>Recurvoides</i> <i>Thalmanammina</i>
		M2b 				
	M2c 	Elongate keeled	Surficial epifauna	Active deposit feeding	Shelf to marginal marine	<i>Plectoeratidus</i> <i>Spiroplectammina</i> <i>Spiroplectinella</i>
M3	M3a 	Flattened trochospiral	Surficial epifauna	Active and passive deposit feeding	Lagoonal to abyssal	<i>Ammonoita</i>
		M3a 				Flattened planispiral and streptospiral
	M3b 	Flattened irregular	Surficial epifauna	Suspension feeding	Upper bathyal to abyssal	<i>Ammolagena</i>
	M3c 	Flattened streptospiral	Surficial epifauna	Active and passive deposit feeding	Upper bathyal to abyssal	<i>Ammosphaeroidina</i> <i>Praecystammina</i> <i>Paratrochamminoides</i> <i>Trochamminoides</i>
M4	M4a 	Rounded planispiral	Surficial epifauna and/or shallow infauna	Active deposit feeding	Inner shelf to upper bathyal	<i>Buzasina</i> <i>Evolutinella</i> <i>Haplophragmoides</i> <i>Popovia</i> <i>Reticulophragmoides</i>
	M4b 	Elongate subcylindrical	Deep infauna	Active deposit feeding	Inner shelf to upper bathyal with increased organic matter flux	<i>Gerochammina</i> <i>Hormosina</i> <i>Karrerulina</i> <i>Praedorothia</i> <i>Protomarssonella</i> <i>Verneullinoides</i>
		M4b 				Elongate tapered

Fig. 4. Agglutinated foraminiferal morphogroups and morphotypes. (Modified after Jones and Charnock, 1985; Nagy et al., 1995, 1997; van den Akker et al., 2000; Kaminski and Gradstein, 2005; Ceteau et al., 2010).

The preservation of planktic and calcareous benthic foraminiferal specimens is very variable. All specimens are etched to various degrees. Planktic foraminiferal assemblages consist of only small unkeeled forms,

including *Globigerinelloides*, *Hedbergella* and *Heterohelix* (Setoyama et al., 2011), which is characteristic of high latitude areas in the Late Cretaceous until the early Maastrichtian (e.g. Premoli Silva and Sliter, 1999; Hart,

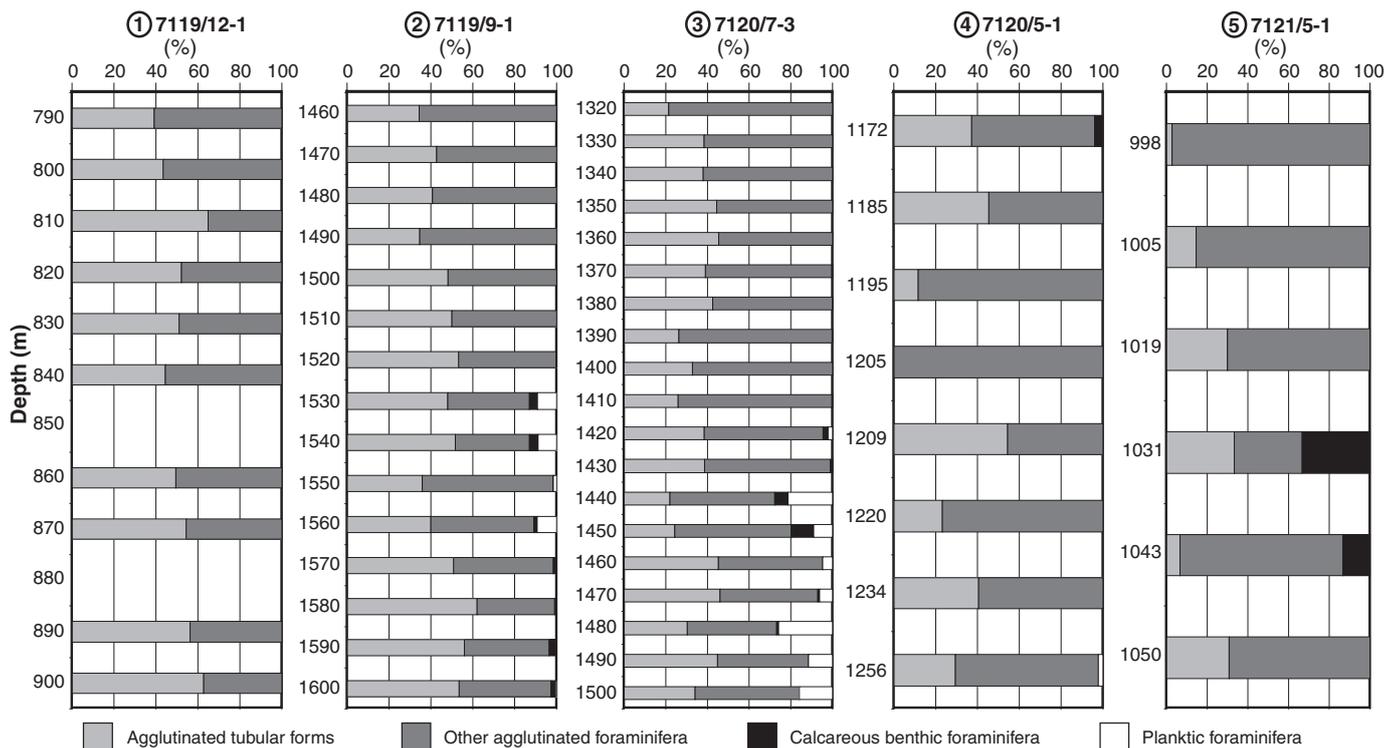


Fig. 5. Proportion of agglutinated, calcareous benthic and planktic foraminifera.

2000, 2007). Several specimens of benthic calcareous genera common in Late Cretaceous bathyal environments, *Allomorphina*, *Gavelinella* (sensu Revets, 1996, 2001), *Gyroidinoides*, *Osangularia*, *Pullenia* and *Stensioina*

(Sliter and Baker, 1972; Sliter, 1977; Olsson and Nyong, 1984; Alegret et al., 2003), are found in the Upper Cretaceous of the SW Barents Sea in some intervals (Setoyama et al., 2011).

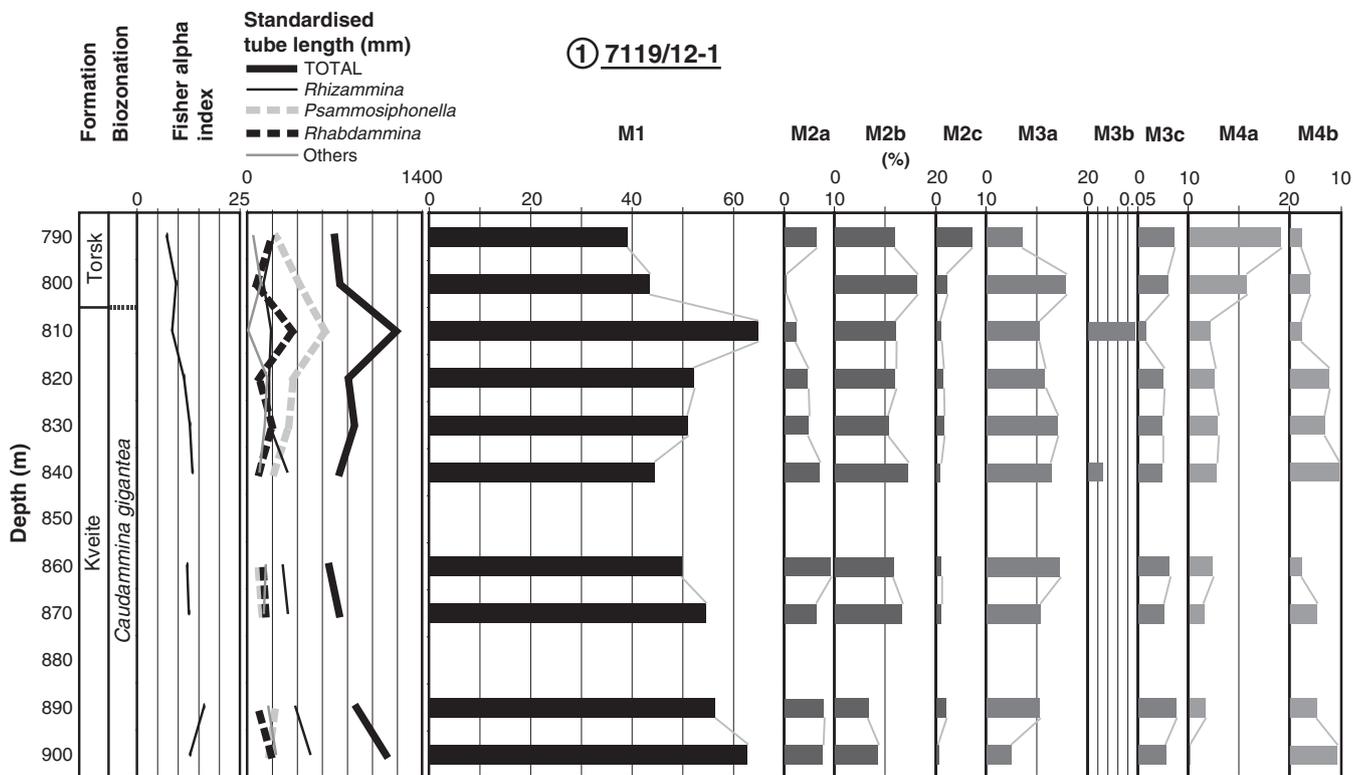


Fig. 6. Species diversity of agglutinated foraminifera, standardised tube length and proportion of morphotypes in well 7119/12-1.

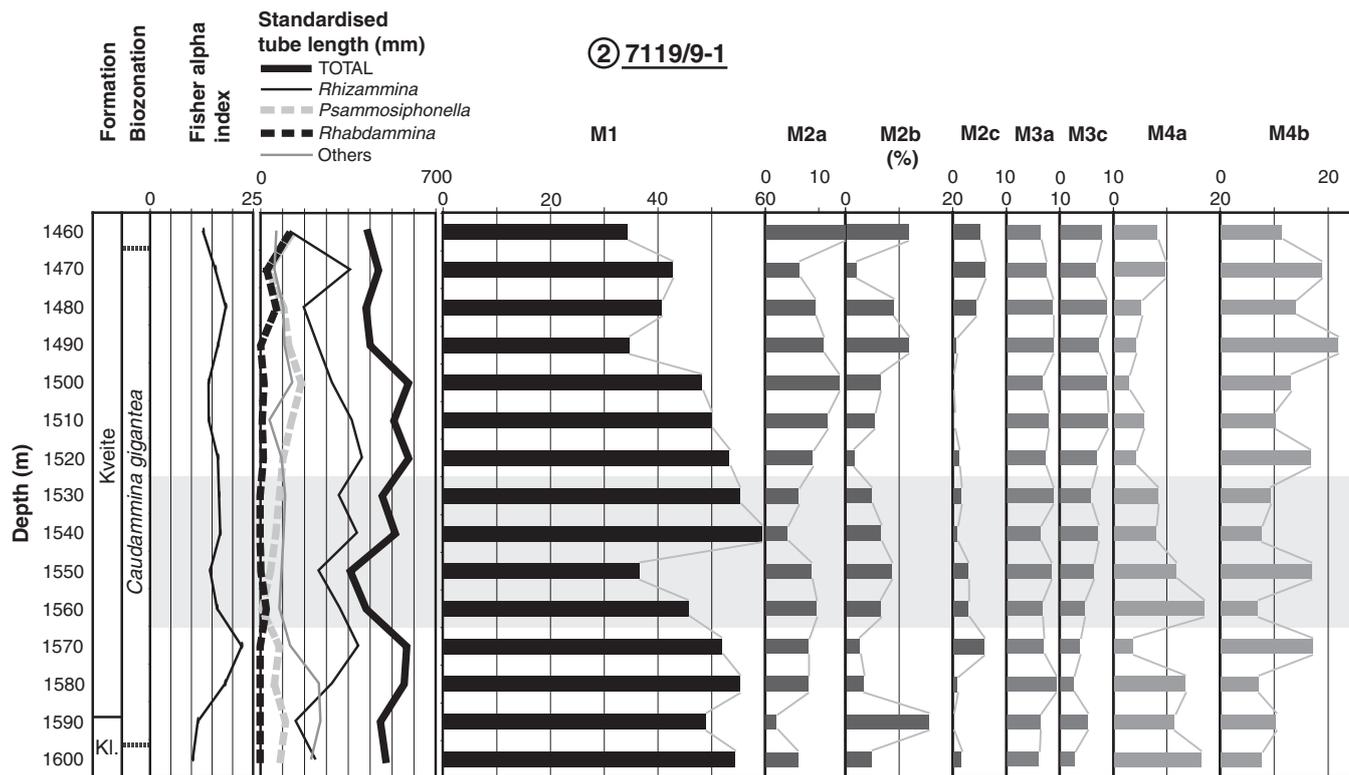


Fig. 7. Species diversity of agglutinated foraminifera, standardised tube length and proportion of morphotypes in well 7119/9-1. Shaded area: the interval with common occurrence of planktic foraminifera.

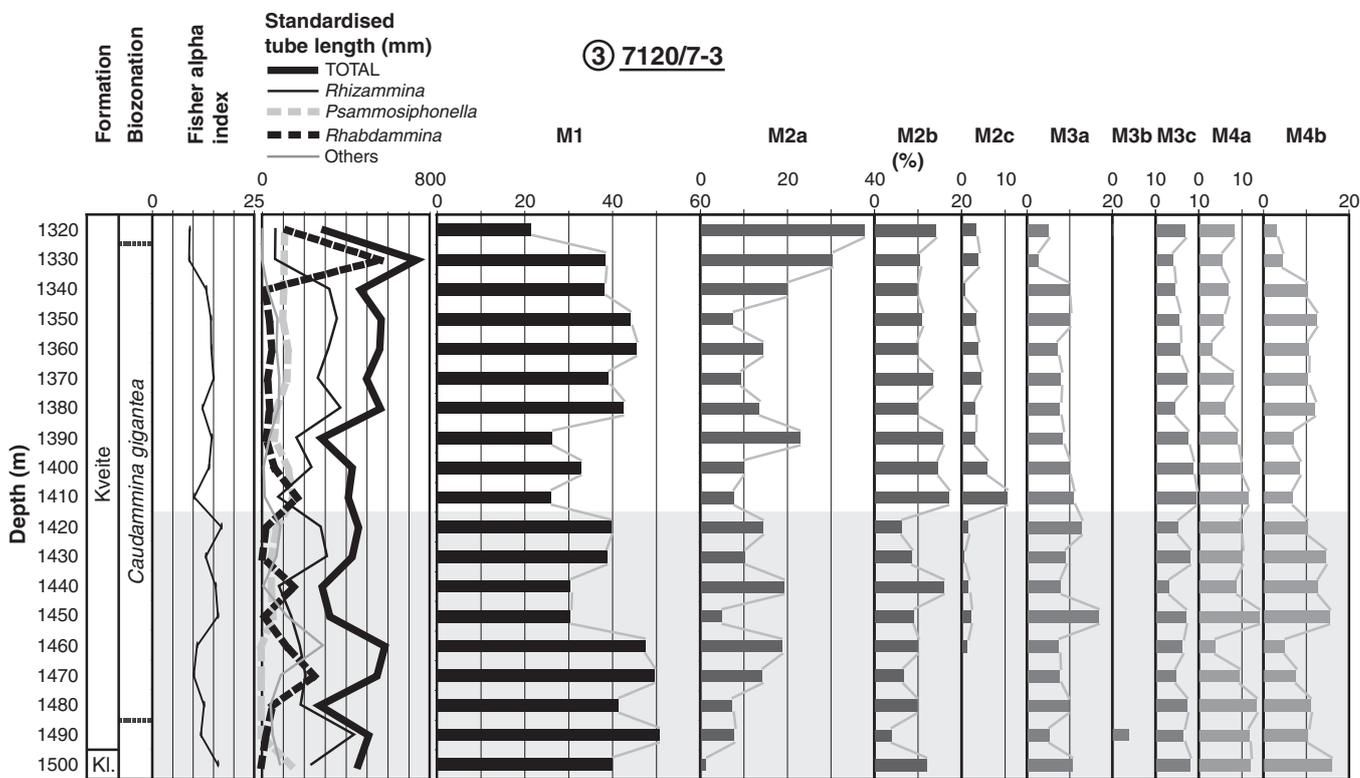


Fig. 8. Species diversity of agglutinated foraminifera, standardised tube length and proportion of morphotypes in well 7120/7-3. Shaded area: the interval with common occurrence of planktic foraminifera.

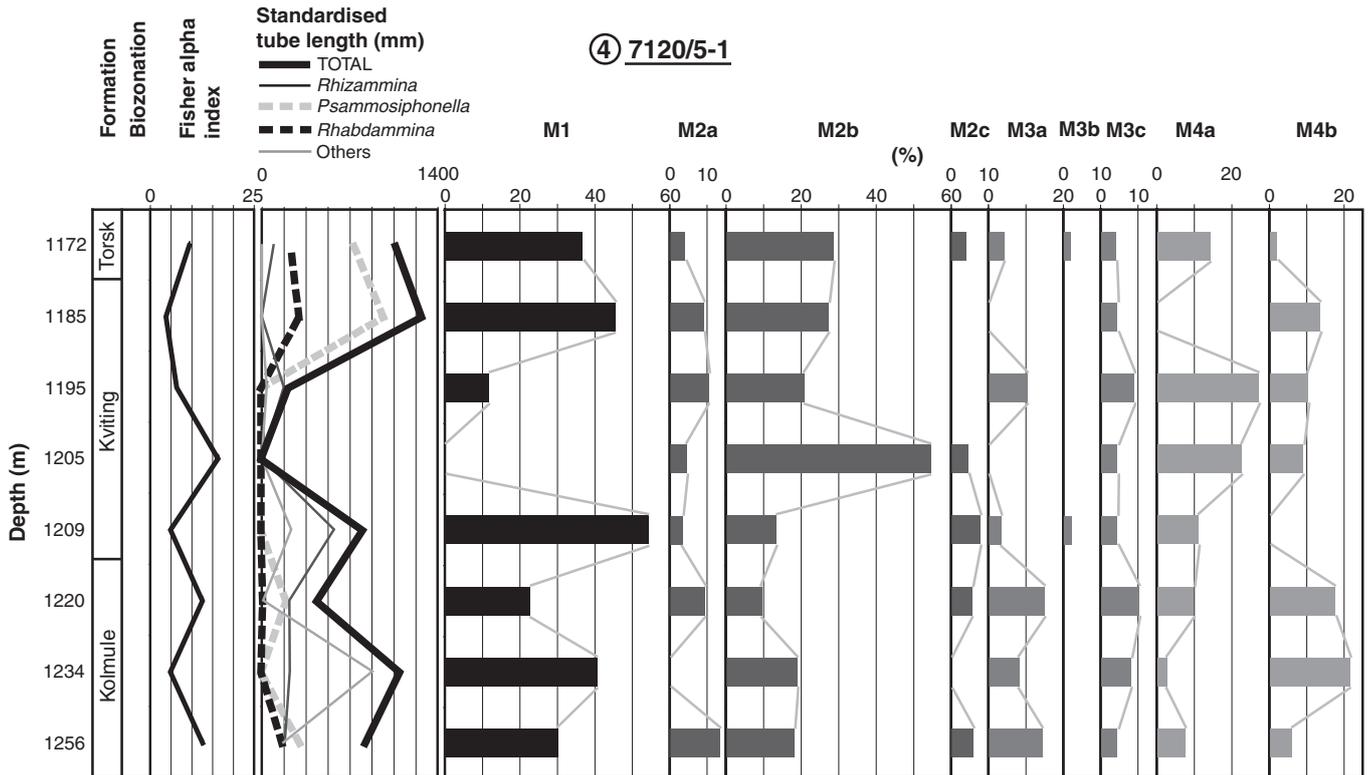


Fig. 9. Species diversity of agglutinated foraminifera, standardised tube length and proportion of morphotypes in well 7120/5-1.

4.2. Correlation of the wells

The biostratigraphy of the Upper Cretaceous of the SW Barents Sea is based on agglutinated foraminiferal taxa, as biostratigraphically

useful planktic and calcareous benthic taxa are not recorded. The *Caudammina gigantea* Zone and the *Uvigerinammina jankoi* Zone are established in the study area (Setoyama et al., 2011) (Fig. 3). For this palaeobathymetric study, the top occurrence of *Gerochammina*

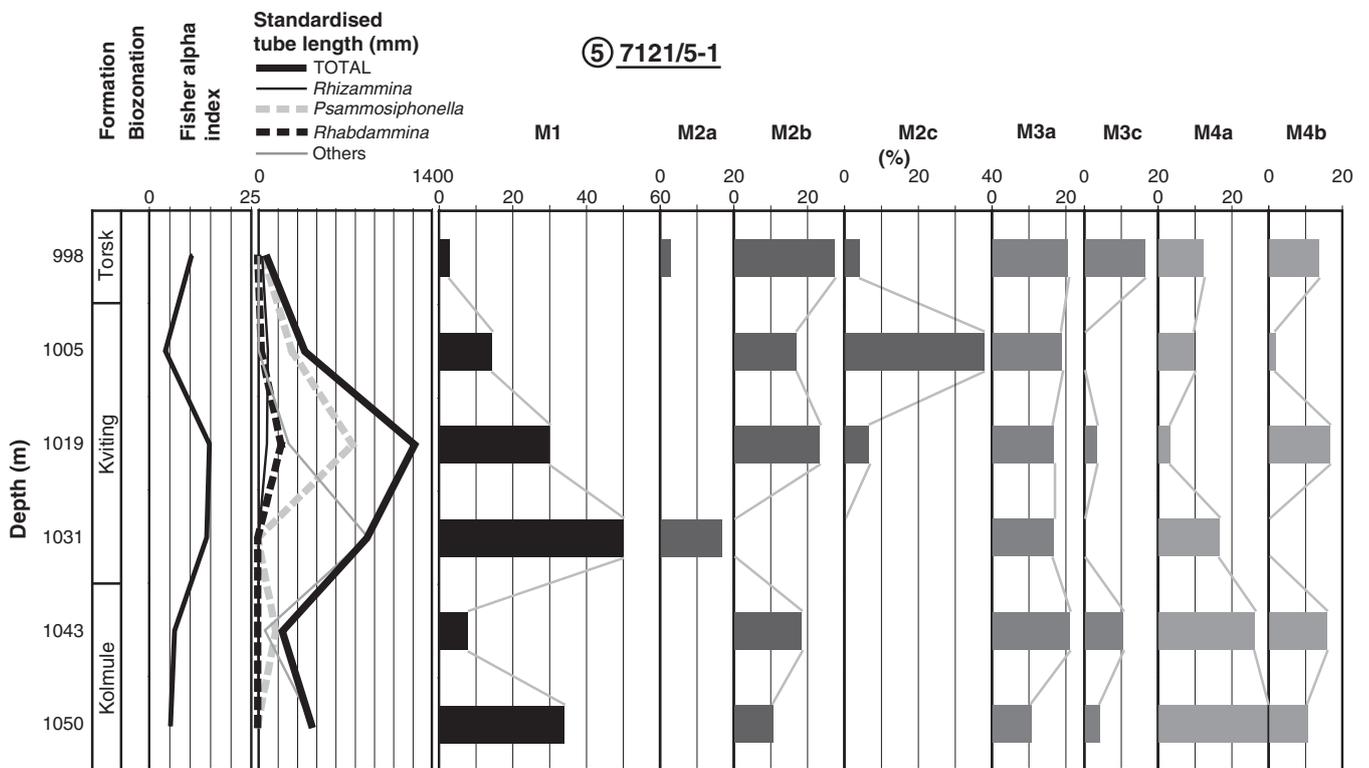


Fig. 10. Species diversity of agglutinated foraminifera, standardised tube length and proportion of morphotypes in well 7121/5-1.

stanislawi Neagu is also used to correlate changes in the composition of assemblages in the wells (Fig. 3). The last occurrence of *G. stanislawi* is diachronous in different basins. It is recorded in the lower Turonian in the Eastern Carpathians, Romania (Neagu, 1990), and in the Santonian of the Contessa Highway section, Italy (Kaminski et al., 2010b). Therefore, age is not assigned to the top occurrence of *G. stanislawi* in the SW Barents Sea. Nevertheless, the top occurrence of *G. stanislawi* is recorded below the top occurrence of *C. gigantea* (Geroch), and this bioevent is probably isochronous within the Tromsø Basin.

The continuous occurrence of calcareous benthic and planktic foraminifera is recorded only in the lower part of the Kveite (7119/9-1 and 7120/7-3) and Kviting (7121/5-1) formations (Fig. 3). The reason for the absence of calcareous taxa in the samples from well 7119/12-1 is likely that the interval studied here is only the upper part of the Kveite Formation and it did not sample the interval with calcareous foraminifera.

The uppermost Cretaceous–Lower Paleocene hiatus is probably extended stratigraphically further down in well 7119/12-1 than in wells 7119/9-1 and 7120/7-3 as the top occurrence of *C. gigantea* is recorded at the hiatus and the top of the biozone seems to be missing in well 7119/12-1.

4.3. Foraminiferal morphogroup analysis

All the morphogroups are present throughout the intervals in the Kveite Formation in the Tromsø Basin (Figs. 6–8). M1 (tubular forms) consistently dominates the assemblages, and it often comprises more than 60% of the assemblages together with M2 (surficial epifauna and shallow infauna) and M3 (epifauna living occasionally on elevated substrates). There is the consistent occurrence of M4a (shallow infauna) and M4b (deep infauna), but both at low levels. Fewer M4b and more M2b (multichambered, streptospiral or trochospiral epifauna) are recorded in well 7119/12-1 than in wells 7119/9-1 and 7120/7-3. In the latter two, the higher proportion of M4b is accompanied by more M2a and M4a than in well 7119/12-1. The highest values of relative abundance of M1 in the Kveite Formation are found below the top common occurrence of planktic foraminifera.

In the Kviting Formation, all the morphogroups are present in the sequences studied (Figs. 9–10). M1 is common in most of the samples, and the others are more variable comparing to the Kveite Formation. In well 7121/5-1, there is a decreasing trend in the relative abundance of M1 towards the top of the Kveite Formation. However, these results have to be treated with caution as all the samples from the Kviting Formation contain much less than 300 specimens.

4.4. Quantification of tubular forms

The total cumulative length and the total number of tubular specimens correlate very well in our material as indicated by high correlation coefficient ($R^2 = 0.95$) (Fig. 11). This demonstrates that, at least in this study, fragmentation of tubular forms happened at similar intensity during fossilisation and washing processes in all samples so that the number of tubular fragments represents the total cumulative length of tubes in samples, and probably does not exceedingly overestimate the abundance of tubular forms in fossil assemblages. The overall trend in changes in the proportion of M1 (tubular forms) is similar to that of the standardised tube length (Figs. 6–10).

In well 7119/9-1, the general trend in changes in the proportion of M1 and the standardised tube length is similar (Fig. 7). Both measures of tubular forms decrease towards the top of the Kveite Formation with a slight increase at the top of the *Caudammina gigantea* Zone. *Rhizammina* contributes most to the standardised length. There is a high similarity between the general trends in the standardised length and the relative abundance of M1 in well 7120/7-3, except at 1330 m where the top occurrence of *C. gigantea* is recorded (Fig. 8). This

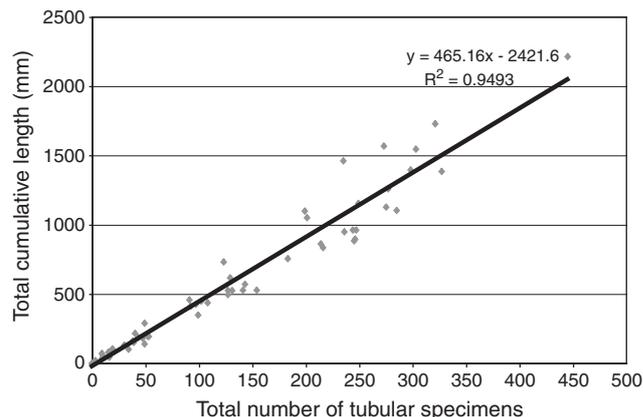


Fig. 11. Comparison of total number of tubular specimens and total cumulative length of tubular forms.

disagreement is caused by the change of the longest constituent from *Rhizammina* to *Rhabdammina* in the tube length because *Rhabdammina* is much more robust than *Rhizammina* and their fragments are longer on average. Nonetheless, there is a general decreasing trend both in the standardised tube length and the proportion of M1 towards the top of the Kveite Formation. The variation in the standardised length correlates well with the proportion of M1 in well 7119/12-1 (Fig. 6). The differences from the other two wells in the Tromsø Basin are that the main constituent to the standardised tube length is *Psammosiphonella* and both the tube length and the proportion of M1 increase towards the Late Cretaceous–Early Paleocene hiatus. This increase in both measures of tubular forms might be representing the part of increase below the top occurrence of *C. gigantea* in wells 7119/9-1 and 7120/7-3 as the latest Cretaceous–Early Paleocene hiatus in well 7119/12-1 is probably more extensive than the others.

The proportion of M1 and the standardised tube length correlate well in wells 7120/5-1 and 7121/5-1. Both measures increase towards the top of the Kviting Formation in well 7120/5-1, and decrease in well 7121/5-1.

5. Discussion

5.1. Palaeoenvironments of the Late Cretaceous southwestern Barents Sea

Although the structure of benthic foraminiferal assemblages is controlled by multiple environmental factors, the organic carbon flux to the sea floor is the predominant environmental parameter controlling the composition of assemblages, and the oxygen concentration becomes limiting when it reaches a critical level for a species (Jorissen et al., 1995; Altenbach et al., 1999; van der Zwaan et al., 1999; De Rijk et al., 2000; Wollenburg and Kuhnt, 2000; Murray, 2001; Szarek et al., 2007, 2009; Mojtahid et al., 2010). As shown in the TROX model (Jorissen et al., 1995), in an oligotrophic environment with well oxygenated bottom water, assemblages would be comprised of epifaunal forms with rare deep infaunal forms due to the deprivation of food deep in sediments because food would be exploited by epifaunal and shallow infaunal forms before becoming available for deep infauna. In a eutrophic environment with limited oxygen, deep infaunal forms, many of which are adapted to dysoxic conditions, would dominate assemblages, for epifaunal and shallow infaunal forms suffer from the low oxygen level. Assemblages in a mesotrophic, well-oxygenated environment would be characterised by a mixture of forms occupying different habitats and employing different feeding strategies since both organic matter and oxygen levels are high enough to support all the epifaunal, shallow and deep

infaunal forms. Various studies show that these patterns in the model can be observed in recent benthic foraminiferal assemblages (Jorissen et al., 1995; Kaminski et al., 1995; Gooday and Rathburn, 1999; Heinz et al., 2001; Fontanier et al., 2005).

The morphogroup analysis shows the presence of all morphogroups through the intervals studied (Figs. 6–10). M1 (tubular forms) dominates the assemblages throughout the Upper Cretaceous sections, whereas the relative abundance of M4 (shallow and deep infauna) and the other morphogroups remain relatively low and never dominate the assemblages in the Kveite Formation (Figs. 6–8). Tubular forms are abundant in tranquil lower bathyal to abyssal environments (e.g. Brouwer, 1965 Olszewska, 1984; Schröder, 1986), and they are rare or absent in severely oxygen-depleted (Kaminski et al., 1995) and oligotrophic areas (Gooday et al., 2000). In contrast, deep infaunal taxa (M4b) flourish and dominate assemblages in eutrophic and/or dysoxic conditions (Kaminski et al., 1995). *Haplophragmoides* (M4a), along with *Recurvoides* (M2b), is also well adapted to environments with high organic flux (Tyszka et al., 2010). The morphogroup analysis of Late Cretaceous foraminiferal assemblages suggests that the bottom water environments in the Barents Sea basins were mesotrophic and relatively well-oxygenated. The slightly higher values of TOC recorded in well 7120/7-3 than the others are reflected in the somewhat increased proportion of infaunal forms (M4). The consistently low proportion of M4 and the absence of flux of opportunistic taxa suggest that the environment was stable at least at the resolution of this study. No flux of opportunistic taxa could be interpreted as reflecting low seasonality in the level of organic carbon flux during the time interval studied here (see Tyszka, 2009). However, because of the large size of sieve (180 µm) used, the generally small size of opportunistic taxa and the low sampling density of this study, we cannot conclude on this point.

Rhabdammina contributes most to the standardised tube length in well 7119/12-1, whereas *Rhizammina* is the longest constituent in wells 7119/9-1 and 7120/7-3 (Figs. 6–8). The relative proportion of M1 is similar in the three wells, and the higher TOC values are recorded in well 7120/7-3 that is reflected in the slightly elevated proportion of M4. Therefore, it is unlikely that there was a higher organic flux to the sea floor in the area of well 7119/12-1 which could be a cause of the abundant occurrence of *Rhabdammina* (see Kaminski and Kuhnt, 1995). The difference in the longest constituent, therefore, might indicate a stronger bottom water current in well 7119/12-1 because *Rhizammina*, delicate tubular forms, are common in tranquil deep-water environments, and would be at risk in areas regularly affected by strong currents, and a fauna in such areas would be dominated by robust tubular forms and opportunistic epifaunal and infaunal forms, which can reproduce fast and can deal with unstable substrates (Kaminski, 1985; Kaminski and Schröder, 1987; Jones, 1988; Fontanier et al., 2008). Furthermore, lateral currents at the sea floor also re-suspend particulate organic carbon, which once settled on the sea floor, making it available to suspension feeders and allow large, robust tubular forms to inhabit areas with rather low trophic levels. There are the increased relative contribution of *Rhabdammina* and/or *Psammosiphonella* in wells 7119/9-1 and 7119/12-1, and the higher proportion of M2 and M4a in the three wells in the Tromsø Basin around the top of the *Caudammina gigantea* Zone. This supports the possible existence of bottom water currents that might have intensified and caused the latest Cretaceous–Early Paleocene hiatus in deep basinal areas of the Tromsø Basin (Nagy et al., 1997). Although the hiatus could also have been caused by subaerial exposure as our rough estimate of uplift and subsidence rates being between 0.11 mm/yr (1000 m/Maastrichtian (70.6 Ma)–Danian (61.1 Ma) and 0.56 mm/yr (4000 m/late Maastrichtian (69.1 Ma)–early Danian (62 Ma)), the presence of similar bathyal foraminiferal assemblages above (Nagy et al., 1997) and below (this study) the hiatus favours bottom water currents as the cause. Such regional hiatuses caused by bottom water currents are reported from shallower settings within

the chalk facies of the Danish Basin (see Lykke-Andersen and Surlyk, 2004; Esmerode and Surlyk, 2009). Although our interpretation favours the submarine erosion scenario (Nagy et al., 1997), it does not contradict with the regional subaerial exposure of the surrounding areas due to the regional uplift caused by the latest Cretaceous–Paleogene intercontinental compressional tectonics (see Lyberis and Manby, 1993).

5.2. Palaeobathymetric implications

5.2.1. Assemblages and morphogroup analysis

There are several methods for the estimation of palaeobathymetry based on foraminiferal assemblages, for example, the P/B ratios (Murray, 1976), the improved P/B ratios (van der Zwaan et al., 1990; Van Hinsbergen et al., 2005), and the two-step procedure based on the presence/absence data devised by Hohenegger (2005). These methods are, however, like any other methods based on fossil assemblages, not entirely free from problems, such as vagaries of fossilisation, the lack of living representatives of ancient taxa and regional variation in depth distribution. Besides, methods that require data on calcareous foraminifera are not applicable to assemblages of the “flysch type” or “high latitude slope DWAF” biofacies which are dominated by agglutinated foraminifera and often devoid of calcareous forms either due to ecological or diagenetic causes (Gradstein and Berggren, 1981; Kuhnt et al., 1989; Kaminski and Gradstein, 2005). The Late Cretaceous assemblages of the Barents Sea are dominated by agglutinated forms, and calcareous specimens are rare and show signs of dissolution, and consequently the methods mentioned above are not applicable.

The species diversity of benthic foraminiferal assemblages usually increases with greater water depth as a result of decreasing organic carbon flux to the sea floor (Lutze and Colbourn, 1984; Schröder-Adams et al., 2008; Szarek et al., 2009), and thus foraminiferal assemblages of deep-sea environments are generally highly diversified (Murray, 2006). The SW Barents Sea assemblages of both Upper Cretaceous formations show high diversity, and the values of Fisher alpha index are comparable to those of Late Cretaceous bathyal assemblages in other North Atlantic–Tethyan regions (Figs. 6–10).

The high proportion of tubular forms (Figs. 6–8), together with the occurrence of various species of flysch-type fauna, also indicates a bathyal setting as the depositional environments of the Kveite Formation of the study area. Firstly, agglutinated foraminifera are rarely the major components of foraminiferal assemblages in shelf environments, except for marginal marine environments (Wall, 1976; Schröder-Adams, 2006; Sabbatini et al., 2007; Haig and McCartney, 2010; Pruitt et al., 2010), and usually become more important constituents in slope environments (Sliter and Baker, 1972; Olsson and Nyong, 1984; Birkenmajer and Gasiński, 1992; Schröder-Adams et al., 2008; Szarek et al., 2009). Besides, many of the characteristic flysch-type taxa, such as *Caudammina* spp., *Gerochammina* spp. and *Rzehakina* spp., are reported only from deep-water environments (e.g. Kaminski et al., 1988; Kaminski and Gradstein, 2005; Cetean, 2009). Secondly, the high proportion of tubular forms is characteristic of bathyal to abyssal environments showing its acme in the middle to lower bathyal zones in the modern North Atlantic (Jones and Charnock, 1985; Schröder, 1986; Kaminski and Gradstein, 2005). A similar pattern in the relative abundance of tubular forms along a depth transect is observed in the Paleogene Barents Sea (Nagy et al., 2000) (Fig. 12). Furthermore, tubular forms are rare or absent in the shelf environment, and this is probably because epifaunal suspension feeders are generally more adapted to environments with low organic flux (Nagy et al., 1997), and the organic carbon flux usually decreases with increasing water depth. The common occurrence of *Recurvoides* and *Thalmanammina* (M2b) also indicates a bathyal environment for the Late Cretaceous SW Barents Sea basins. Streptospiral multichambered forms are not frequent in inner and

middle shelf environments, but they show the increased abundance in outer shelf and bathyal settings in the Paleogene of SW Barents Sea (Nagy et al., 2000) (Fig. 12), and *Recurvoides* is confined to deep basinal areas in the Paleogene of the North Sea and Labrador Sea (Gradstein et al., 1994).

There is a general decreasing trend in the relative abundance of M1 and the standardised tube length in wells 7119/9-1 and 7120/7-3 and in species diversity in the three wells in the Tromsø Basin towards the top of the Kveite Formation (Figs. 6–8). As mentioned above, the abundance of tubular forms and the diversity of assemblages increase with depth in the recent Atlantic and the Paleogene of the SW Barents Sea. Therefore, the decreasing trend in both parameters may indicate a shallowing regional bathymetry close to the end of the Cretaceous in the SW Barents Sea, which might be related to the Late Cretaceous–Paleocene rifting and the subsequent uplift of the Svalbard and adjacent areas (Birkenmajer, 1972; Harland, 1997). The absence of this trend in well 7119/12-1 is probably due to the more extensive latest Cretaceous–Early Paleocene hiatus in this well as indicated by the top occurrence of *Caudammina gigantea* at the hiatus (Fig. 3).

Worsley (2006) suggested that, in the Hammerfest Basin, the calcareous and sandy Kviting Formation was deposited intermittently only at times of transgression in deep to shallow shelf environments. Although the samples from the Kviting Formation are small, they contain coarse tubular forms, such as *Psammosiphonella* and *Rhabdammina*, and deep-water forms, such as *Ammosphaeroidina pseudopauciloculata* (Mjatluk), *Caudammina ovula* and *Gerochammina* spp. Furthermore, the species diversity of assemblages is relatively high (Figs. 9–10). These faunal parameters suggest that the Kviting

Formation was probably deposited in a deep-water environment, possibly a slope setting. The occurrence of deep-water taxa also indicates that the intermittent deposition of Kviting Formation in the Hammerfest Basin took place in a deep-water environment and might have been caused by bottom currents. This is in accordance with the possible existence of periodic bottom water currents in the Tromsø Basin in late Maastrichtian–Early Paleocene times (Nagy et al., 1997) when the basin shows a shallowing trend and the surrounding region might have been uplifted and emerged.

5.2.2. Species as a palaeobathymetric indicator in the SW Barents Sea

The occurrence of *Caudammina gigantea* is thought to be related to the bathymetry of an area and/or the carbonate saturation level of bottom waters (Kuhnt et al., 1998) as this species is characteristic of areas with carbonate-poor substrates and low terrigenous detrital input (Kuhnt et al., 1992). Its upper depth limit is estimated as the lower bathyal zone in the Atlantic (Kuhnt et al., 1998) and the middle to upper bathyal in the western Tethys (Bak, 2000; Cetean et al., 2010). *C. gigantea* is not recorded in the Upper Cretaceous of offshore mid-Norway (Gradstein et al., 1999) and very rare or absent in the Foula Sub-basin (van den Akker et al., 2000, 2002), though *C. ovula* is present in these sites. The palaeobathymetry of offshore mid-Norway sites are estimated to be the upper bathyal or shallower (Gradstein et al., 1999), and the lower bathyal depositional environment was inferred for the Foula Sub-basin (van den Akker et al., 2000). Therefore, the simple deduction based on the frequent and sometimes abundant occurrence of *C. gigantea* in the Kveite Formation in the Tromsø Basin is that the depositional environment of the Upper Cretaceous formation was deeper than the upper bathyal offshore mid-Norway sites and at least as

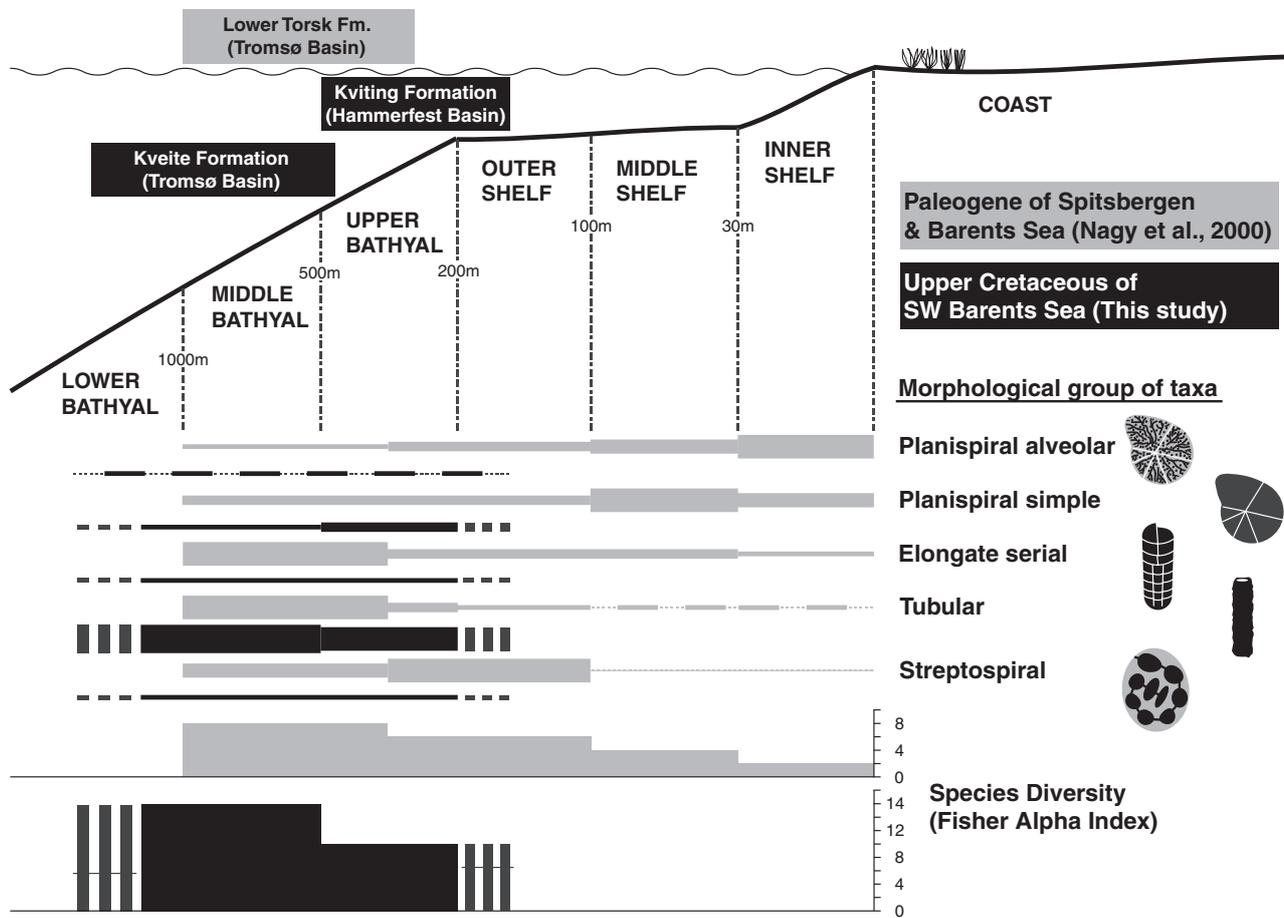


Fig. 12. Conceptual model comparing different groups of agglutinated foraminifera in the Paleogene and Late Cretaceous assemblages along the depth transect in the SW Barents Sea.

deep as the lower bathyal Foula Sub-basin. However, although the assemblages from the Barents Sea, offshore mid-Norway and Foula Sub-basin recover very similar agglutinated assemblages with taxa characteristic of the flysch-type fauna, the Barents Sea sediments contain more impoverished calcareous assemblages. The Barents Sea assemblages do not show any sign of restricted, dysoxic nor eutrophic bottom water environments so that the localised shoaling of the foraminiferal lysocline within the basins, for example, due to enhanced upwelling of corrosive deep waters and an increased organic carbon flux as hypothesised for the South Atlantic along the Rio Grande Rise–Walvis Ridge system during the latest Cretaceous by Sliter (1977) and Kucera et al. (1997), is not likely. The calcium compensation depth (CCD) shallows at higher latitudes (Berger and Winterer, 1974), and the proportion of calcareous foraminifera in assemblages in the Shetland Group, the Late Cretaceous bathyal facies, decreases northwards in the North Sea and becomes close to zero further north in the Faeroes Basin and Norwegian Sea (King et al., 1989). Therefore, the shoaling of the CCD in higher latitudes during the Late Cretaceous period of supposedly equable climate is likely and could have had an effect on the upper depth limit of *C. gigantea*, allowing this species to occur in shallower environments in such regions. Thus, although the common occurrence of *C. gigantea* supports the results of morphogroup analysis of Late Cretaceous assemblages in the SW Barents Sea (middle to lower bathyal environments), the species alone should not be used as a reliable depth indicator in high latitude regions.

The Late Cretaceous calcareous benthic species are often used as palaeobathymetric indicators. Species of *Allomorphina*, *Gavelinella*, *Gyroidinoides*, *Osangularia*, *Pullenia* and *Stensioina*, are common in the bathyal environments of the Central and South Atlantic and Tethys (Sliter and Baker, 1972; Sliter, 1977; Olsson and Nyong, 1984; Alegret et al., 2003) and recorded in the Upper Cretaceous of SW Barents Sea. The distribution of calcareous benthic foraminifera shows latitudinal changes in the South Atlantic in the late Maastrichtian, and the latitudinal transition is related to organic flux and/or oxygenation levels (Widmark, 2000). A similar latitudinal change in the distribution of calcareous benthic foraminifera might have existed in the proto-North Atlantic for the same reasons and/or others, such as the shallowing CCD, and could have allowed deep-water forms to invade shallower environments than their preferred habitats in the Central Atlantic and Tethys.

We do not know the depth of foraminiferal lysocline nor the position of CCD in high latitude areas in the Late Cretaceous. Nevertheless, we assume that the Kveite and Kviting formations in the southwestern Barents Sea were deposited near the foraminiferal lysocline based on the rare occurrence of calcareous-cemented agglutinated and calcareous taxa, and the etched tests of calcareous benthic and planktic specimens. Postmortem loss of calcareous specimens is probably small because the planktic foraminiferal assemblages are composed of very small unkeeled forms which are more prone to dissolution than large planktic and calcareous benthic foraminifera (Malmgren, 1987; Nguyen et al., 2009). Supposing that the estimation of palaeobathymetry based on the morphogroup analysis (middle to lower bathyal zones) is correct, and that calcareous specimens are more or less in situ, the foraminiferal lysocline was probably situated at a shallower depth in the Barents Sea than in the South Atlantic (ca. 3 km) (Kucera et al., 1997) during latest Cretaceous times.

5.3. Comparison with the Paleocene of SW Barents Sea

The Paleocene foraminiferal assemblages from the base of Torsk Formation are interpreted as reflecting middle to upper bathyal environments (Nagy et al., 1997, 2000) (Fig. 12). The diversity of Paleocene assemblages (Fisher alpha index: 8 on average) is similar to that of the Kviting Formation (ca. 8.5) and lower than in the Kveite Formation (ca. 14). The difference in diversity between the Upper Cretaceous and Paleocene strata could be related to the K/Pg extinc-

tion event, but benthic foraminifera did not suffer as much as many other marine invertebrates (Tappan and Loeblich, 1988; Kaminski et al., 2010a). Thus, the diversity change seen across the hiatus is likely to reflect changes in environments. The lower part of Torsk Formation contains abundant tubular forms (ca. 23% of assemblages on average) (Nagy et al., 2000), and this proportion is similar in the Kviting Formation (ca. 29%) and higher in the Kveite Formation (ca. 45%). The proportion of elongated serial forms (M4, infauna) is much higher in the Torsk Formation (ca. 35% on average) (Nagy et al., 2000) than in the Kveite (ca. 18%) and Kviting (ca. 20%) formations. Furthermore, the relative abundance of streptospiral forms is also higher in the Torsk Formation (ca. 30% on average) than in the Kveite (ca. 13%) and Kviting (ca. 16%) formations. These may indicate a similar bathymetric setting of the Torsk Formation to the Kviting Formation, but with higher organic carbon flux to the sea floor, and a deeper depositional setting for the Kveite Formation.

The rare occurrence of planispiral alveolar forms in the deep-water Upper Cretaceous strata is conceivable as the first known occurrence of *Reticulophragmium* and *Reticulophragmoides* outside the Barents Sea is in the Paleocene, and *Popovia* in the Maastrichtian (Kaminski et al., 2008). These planispiral alveolar forms are known in both shallow- and deep-water environments in the early Paleocene, but become more diverse and somewhat more common in deep-water environments from the late Paleogene (Gradstein and Kaminski, 1989; Kaminski et al., 1989; Charnock and Jones, 1990; Schröder-Adams and McNeil, 1994; McNeil, 1997; Nagy et al., 2000; Filipescu and Kaminski, 2008).

The similar deep-water environments indicated for the Upper Cretaceous formations and the Lower Paleocene formation across the hiatus in the SW Barents Sea imply that it is not likely that the region was subaerially exposed and submerged again during the Cretaceous–Paleocene transition. Being close to the land areas during the Late Cretaceous, the northern coast of the Scandinavia and the Loppa High (Faleide et al., 1993), sediment starvation is also unlikely to be a cause of the hiatus. The changes in the Late Cretaceous foraminiferal assemblages mentioned above support the possible presence of bottom currents in the latest Cretaceous and early Paleocene times in the SW Barents Sea which is possibly a cause of the hiatus as suggested by Nagy et al. (1997) based on the foraminiferal assemblages from the bottom of the Torsk Formation.

6. Conclusions

- 1) The morphogroup analysis of Late Cretaceous assemblages in the Kveite Formation shows that all the morphogroups were present throughout the studied intervals (Figs. 6–10). Neither epifaunal nor infaunal forms dominate the assemblages and show sudden changes in their relative abundance. Comparison of the results from the morphogroup analysis with the observation of recent and fossil foraminiferal assemblages and the TROX model leads to the conclusion that the benthic environments in the southwestern Barents Sea were mesotrophic, relatively well-oxygenated and stable at the resolution of this study during the Late Cretaceous.
- 2) The high proportion of tubular forms (M1) and common occurrence of mostly elongated, infaunal forms (M4) and streptospiral forms (M2b) in the assemblages dominated by the deep-water agglutinated foraminifera (DWAF) suggest that the Kveite Formation was most probably deposited in a bathyal environment, possibly middle to lower bathyal, which is much deeper than a shelf environment suggested by Worsley et al. (1988). The results of morphogroup analysis of assemblages from the Kviting Formation have to be treated with caution because of small sample size. However, the relatively high diversity of assemblages and the occurrence of robust tubular forms and deep-water species indicate the Kviting Formation was also deposited in relatively deep-water conditions.

- 3) There is a general decreasing trend in the relative abundance of tubular forms in wells 7119/9-1 and 7120/7-3 accompanied by decreasing species diversity towards the top of the Kveite Formation in the three wells in the Tromsø Basin. This suggests a shallowing regional bathymetry in the SW Barents Sea towards the end of the Cretaceous, which might be related to the Late Cretaceous–Paleocene rifting phase prior to the subsequent regional uplift and the break-up of the Greenland–Norwegian Sea.
- 4) The increased contribution of *Rhabdammina* and *Psammosiphonella* to the standardised tube length in wells 7119/9-1 and 7119/12-1 and the increased proportion of shallow infauna (M2 and M4a) in the three wells in the Tromsø Basin around the top of the *Caudammina gigantea* Zone agree with the proposition of Nagy et al. (1997) that bottom water currents might have existed, which intensified and caused the latest Cretaceous–Paleocene hiatus in the SW Barents Sea. There are no signs of subaerial emergence of the Tromsø and Hammerfest basins during the latest Cretaceous–Paleocene transition.

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