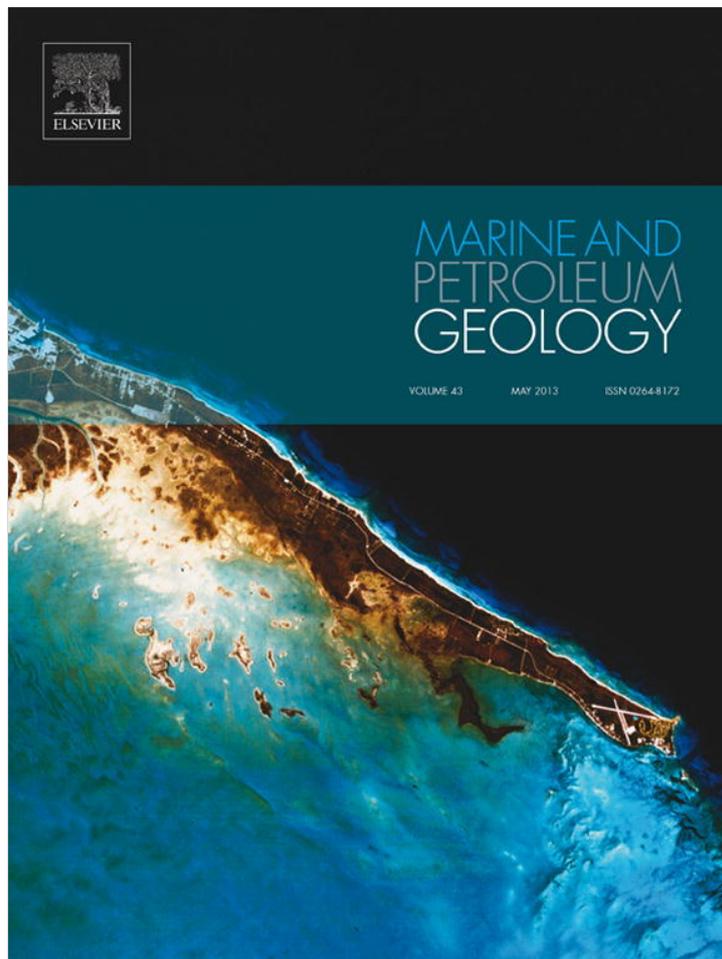


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Foraminiferal and palynological biostratigraphy and biofacies from a Santonian–Campanian submarine fan system in the Vøring Basin (offshore Norway)



Eiichi Setoyama^{a,b,*}, Wiesława Radmacher^b, Michael A. Kaminski^{a,c}, Jarosław Tyszka^b

^a Earth Sciences Department, Research Group of Reservoir Characterization, King Fahd University of Petroleum & Minerals, P.O. Box 701, Dhahran 31261, Saudi Arabia

^b ING PAN – Polish Academy of Sciences, Institute of Geological Sciences, Cracow Research Centre, BioGeoLab, ul. Senacka 1, 31-002 Kraków, Poland

^c Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, United Kingdom

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ABSTRACT

Foraminiferal assemblages from a Santonian–Campanian submarine fan system in the northwestern Vøring Basin, offshore Norway were investigated with the primary objectives to document the stratigraphic ranges of foraminiferal taxa calibrated with dinoflagellate cysts, and to interpret foraminiferal biofacies of different fan sub-environments previously proposed based on the analysis of ichnofossils. The assemblages are composed of deep-water agglutinated foraminifera (DWAF) without carbonate-cemented taxa. DWAF taxa of high biostratigraphic value are absent, but the complete agglutinated nature of the assemblages and the presence of *Gerochammina stanislawi* and *Rectogerochammina eugubina* are similar to those of the lower Campanian *Fenestrella bellii* Zone of the Norwegian Sea. More reliable dating was provided by palynology, and the age of the interval is estimated to be Santonian to Campanian.

The inner to middle fan assemblages contain small numbers of specimens, and consequently the species diversity and relative abundance of morphogroups are inconsistent. Deep infaunal forms may be more common in this sub-environment, but because the abundance is low, this observation should be treated carefully. In contrast, the abundance and diversity of the assemblages of the overbank, fringe and basin plain sub-environments are fairly high. Their morphogroup composition is also similar and comparable to each other when the assemblage size is large. The assemblage from the interval with suggested hydrothermal activity is similar to those from outside the channel sub-environment. The presence of bottom water currents, possibly in the form of a western boundary current, in the basin is suggested based on the abundant occurrence of tubular forms in the overbank, fringe, and basin plain sub-environments.

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1. Introduction

The Norwegian–Greenland Sea was a narrow epicontinental seaway during the Late Cretaceous (Fig. 1), and it existed as a strait until the break-up of the continental crust and the consequent opening of the North Atlantic Ocean around the Palaeocene–Eocene transition (Faleide et al., 2008). Prior to the break-up, the area was tectonically active in association with Late

* Corresponding author. ING PAN – Polish Academy of Sciences, Institute of Geological Sciences, Cracow Research Centre, BioGeoLab, ul. Senacka 1, 31-002 Kraków, Poland. Tel.: +48 124221910; fax: +48 124221609.

E-mail addresses: setoyama@kfupm.edu.sa, ndkrol@cyf-kr.edu.pl, ndtyszka@cyf-kr.edu.pl (E. Setoyama), kaminski@kfupm.edu.sa (M.A. Kaminski).

Cretaceous–Palaeocene rifting events, and submarine fan systems developed in the Vøring Basin in the Late Cretaceous (e.g. Kittilsen et al., 1999; Fjellanger et al., 2005).

Some studies have been published on Upper Cretaceous dinocysts from East Greenland (e.g. Kelly et al., 1998; Nøhr-Hansen, 2012) and offshore Norway (Gradstein et al., 1999; Williams et al., 2005), whereas with respect to Upper Cretaceous foraminifera from these areas Gradstein et al. (1999) is the only published work to date which established a quantitative biostratigraphy based mainly on foraminifera and dinoflagellate cysts for the whole Cretaceous of the Norwegian–Greenland seaway and reconstructed the palaeobathymetric and palaeoceanographic history of offshore mid-Norway. Recently, Knaust (2009) analysed ichnofossils in the Upper Cretaceous from well 6707/10-1 drilled in the Vøring Basin

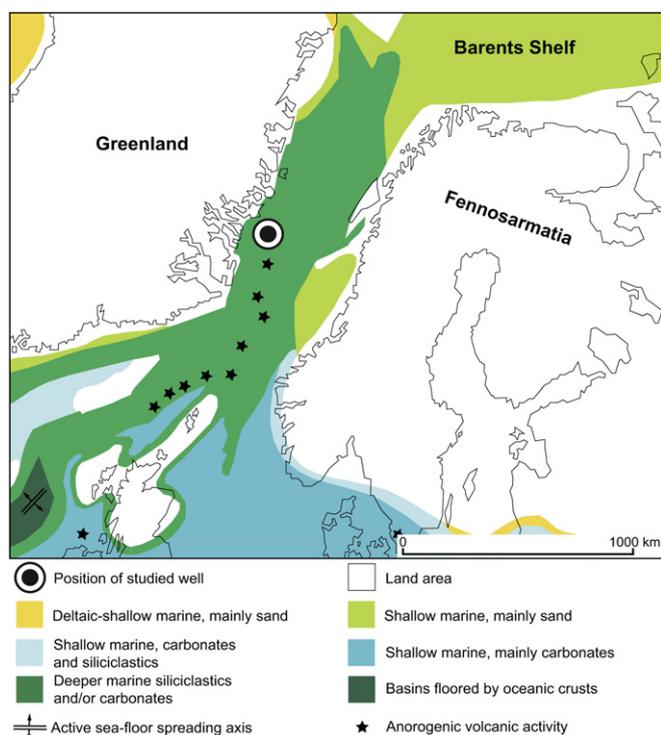


Figure 1. Palaeogeographic reconstruction of the Norwegian–Greenland Seaway and its surrounding areas for the Turonian–Campanian (modified after Ziegler, 1988).

and recognised seven ichnofabric types related to different sub-environments within a Campanian submarine fan system.

The objectives of this study are to describe the stratigraphic distribution of foraminifera from well 6707/10-1 drilled in the Vøring Basin calibrated with bioevents of dinoflagellate cysts, and

to interpret palaeobathymetric conditions and possible foraminiferal biofacies within a submarine fan system using morphogroup analysis of agglutinated foraminiferal assemblages. The results of the analysis are compared with the palaeoenvironmental interpretation of the same interval based on ichnofossils by Knaust (2009).

2. Geological setting

2.1. Background geology

Well 6707/10-1 was drilled on the Nyk High, located in the northwestern part of the Vøring Basin (Fig. 2). The basin started to develop as a result of thermal subsidence after the late Middle Jurassic–Early Cretaceous rifting episode, while the Nyk High was still part of a basinal area north of the Surf Lineament until the Maastrichtian when its formation initiated (Blystad et al., 1995; Brekke, 2000; Ren et al., 2003). A thick, predominantly sandy Campanian unit in well 6707/10-1 is interpreted as turbidites deposited within a submarine fan system (Kittilsen et al., 1999; Fjellanger et al., 2005; Martinsen et al., 2005; Lien, 2005), and provenance studies suggested East Greenland as the sediment source to the Campanian–Palaeocene succession in the Vøring Basin (Fonneland et al., 2004; Morton et al., 2005). A detailed ichnofabric study by Knaust (2009) distinguished seven sub-environments within the Campanian submarine fan system.

A rapid deepening of the northwest Vøring Basin in the Campanian, following much slower deepening since the Turonian, was suggested with bathymetry changing from deep neritic (150–250 m) in Turonian–Santonian time to upper bathyal (250–500 m) in the early–middle Campanian (Ren et al., 2003). These authors related the early Campanian deepening of the Vøring Basin to the initial subsidence due to extension of the lithosphere in the Late Cretaceous–Palaeocene rift episode that probably began in the middle Campanian. The area around the Nyk High was uplifted

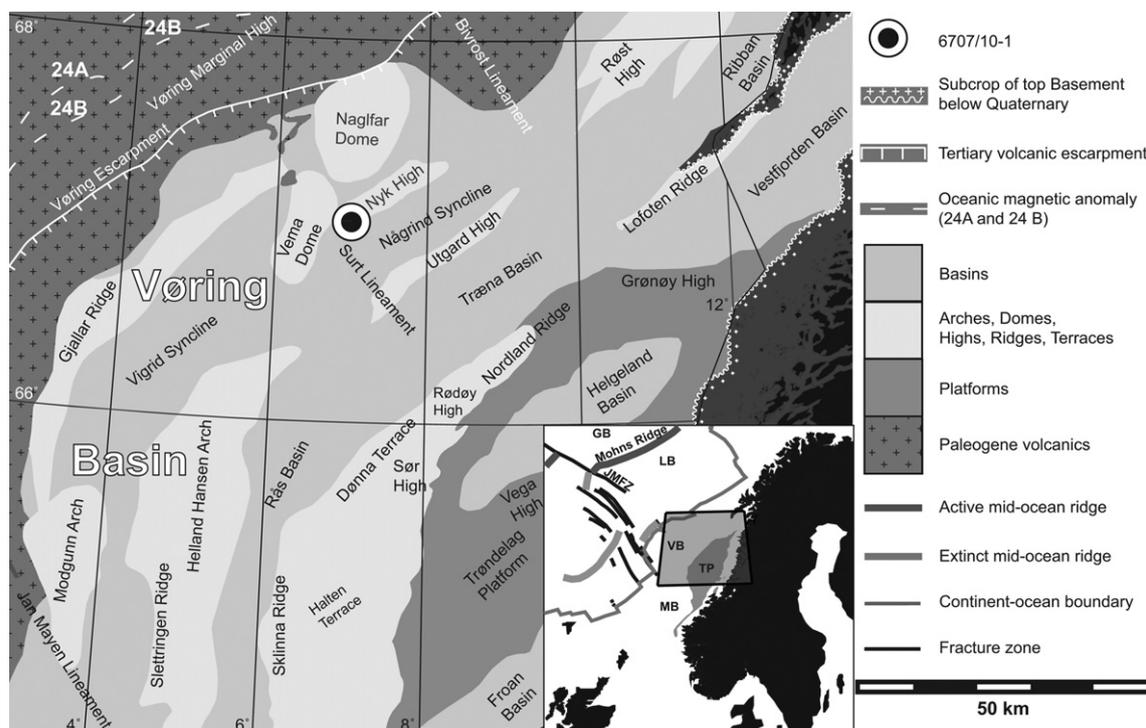


Figure 2. Study area map. GB: Greenland Basin, JMFZ: Jan Mayen Fracture Zone, MB: Møre Basin, LB: Lofoten Basin, TP: Trøndelag Platform, VB: Vøring Basin. Large map modified after Blystad et al. (1995) and small map after Mosar et al. (2002).

since the early Maastrichtian resulting in the late Maastrichtian–Early Palaeocene hiatus on intra-basinal highs (Ren et al., 2003).

2.2. Lithostratigraphy

The Upper Cretaceous unit recovered from well 6707/10-1 contains four formations of the Shetland Group (Fig. 3). The description of the three youngest formations is summarised below following Gradstein et al. (2010) and the Norwegian Interactive Offshore Stratigraphic Lexicon (NORLEX) website (http://nhm2.uio.no/norges/litho/overview_cretaceous.php). The Coniacian–upper Santonian Kvitnos Formation is composed mainly of grey and greyish green calcareous claystones, and the Tumler Member in the upper part of the formation consists of sandstones and thin mudstone interbeds. This member is equivalent to the lower part of the Delfin formation used on the Norwegian Petroleum Directorate Factpages (<http://factpages.npd.no/factpages/default.aspx>). The overlying uppermost Santonian–middle Campanian Nise Formation is grey and greyish green claystones with carbonate and sandstone interbeds, and the Spekkhogger Member, equivalent to the upper part of the Delfin formation, is composed dominantly of thick sandstones. The Springar Formation is predominantly comprised of greyish green mudstones interbedded by carbonates and sandstones, and ranges in age from the early Campanian to the late Maastrichtian. The Kvitnos Formation is considered as the post-rift sediments of the late Mid-Jurassic–earliest Cretaceous rift episode, while the Nise Formation was deposited during the transition between the post-rift period and the latest Cretaceous–Palaeocene rift episode, and the Springar Formation in the syn-rift period (Færseth and Lien, 2002; Lien, 2005). The value of total organic carbon (TOC) varies between 0.35% and 2.76% in the interval considered in this study with an exception at 3002 m (15.62%).

2.3. Previous micropalaeontological studies

The area has been intensively investigated by petroleum companies, and Gradstein et al. (1999) established a quantitative

Cretaceous biostratigraphy with 19 assemblage and interval zones based on foraminifera, dinoflagellates and diatoms from over 30 industrial wells in the area between 60°N and 66°N offshore Norway. Their findings include the dominance of agglutinated foraminifera in the upper middle–lower upper Albian and the middle–upper Campanian that is interpreted as reflecting basin-wide dysaerobic conditions caused by a lowering sea level and restricted basinal areas, and the episodic floods of planktonic foraminifera in late Albian–early Cenomanian, early–middle Turonian, late Santonian–earliest Campanian and mid-Maastrichtian times that they attributed to northwards shifts of warmer water masses and disruptions in water stratification in dysaerobic basins. These alternations of the calcareous-dominant and agglutinated-dominant assemblages are also known from the Cretaceous of the northern North Sea (King et al., 1989; van den Akker et al., 2000, 2002), and King et al. (1989) related these faunal changes to restricted and open circulation in the North Sea Basin.

Upper Cretaceous dinocyst assemblages of the Vøring Basin have been previously analysed by Gradstein et al. (1999) and Williams et al. (2005), though the former did not include data from well 6707/10-1, and the latter analysed palynological assemblages from the same well, but with a focus on a non-acid preparation method. More detailed taxonomic and biostratigraphic studies on Upper Cretaceous dinocysts from northeast Greenland, which was located adjacent to the Vøring Basin, have been published (e.g. Kelly et al., 1998; Nøhr-Hansen, 1993, 2012), but according to these authors, the presence of the Campanian in their studied areas is questionable.

3. Materials and methods

3.1. Materials

Foraminifera were examined in 23 picked faunal slides from the interval between 2971.20 m and 4137.95 m in well 6707/10-1 provided by F.M. Gradstein. Foraminiferal specimens were extracted from core samples. Preparation methods, sample size, and sieve size following standard industrial techniques. The sampling depth of sample 17 is not given, but it is included in the study as the other samples are properly numbered in order according to depth. Samples 18 and 19 were collected at the same depth, 2991.20 m, and they are separately treated. In addition to the analysis of foraminifera, 17 palynological slides from the interval between 2410 m and 4119.50 m were analysed for dinocysts for a stratigraphic purpose. The palynological slides were prepared from ditch-cutting samples by different laboratories and provided by the Norwegian Petroleum Directorate. They were treated with standard acid digestion (HCl and HF digestion). All the palynological slides were studied under Zeiss Axioscope 50.

3.2. Foraminiferal morphogroup analysis

Morphogroup analysis has been developed in an attempt to semiquantitatively study palaeoenvironmental and palaeobathymetric changes reflected by foraminiferal assemblages (Corliss, 1985; Jones and Charnock, 1985; Corliss and Chen, 1988). This technique has been applied in both deep and shallow water settings with agglutinated and calcareous benthic foraminifera (e.g. Koutsoukos and Hart, 1990; Nagy et al., 1995, 2009; Murray et al., 2011). The morphogroup analysis is based on the idea of functional morphology, and it assumes 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; Murray

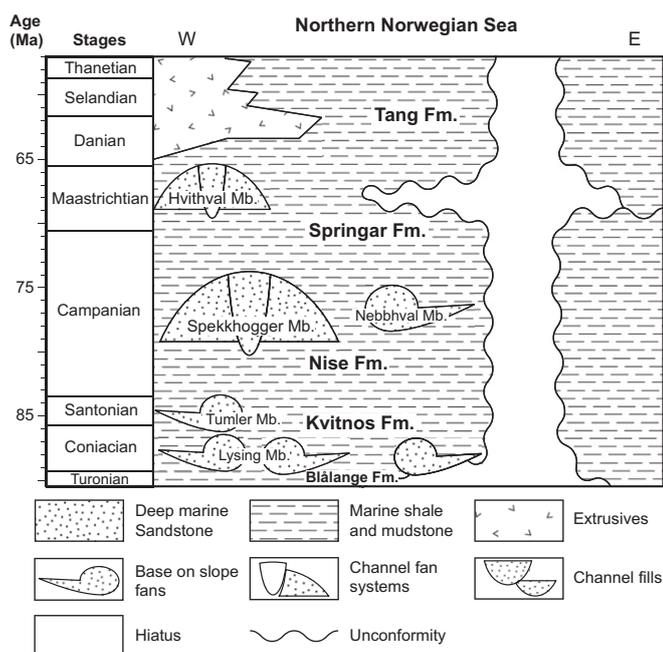


Figure 3. Lithostratigraphy for the Upper Cretaceous and Palaeocene of the northern Norwegian Sea (modified after NORLEX, 2011).

et al., 2011). Jones and Charnock (1985) devised a morphogroup scheme for agglutinated foraminifera which has been modified and applied to fossil agglutinated assemblages for palaeoecological study by subsequent authors (e.g. Båk et al., 1997; Peryt et al., 1997, 2004; van den Akker et al., 2000; Kender et al., 2009). The agglutinated foraminiferal morphogroup scheme used in this study is after Cetean et al. (2011), which is modified for the study of Upper Cretaceous deep-water agglutinated foraminiferal (DWAF) assemblages (Fig. 4).

3.3. Measurement of tubular forms

For the morphogroup analysis, each tubular fragment is counted as one specimen following previous studies (e.g. Nagy et al., 1995; Cetean et al., 2011). Additionally, the cumulative length of tubular forms was measured following Kaminski and Kuhnt (1995) in an attempt to quantify fragmented specimens. The cumulative length was plotted against the total number of tubular specimens to test whether tubular specimens in different samples were fragmented

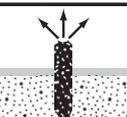
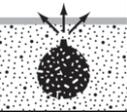
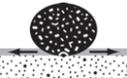
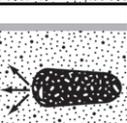
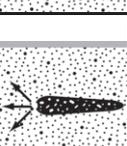
Morpho-group	Morpho-type	Test form	Life position	Feeding habit	Environment	Main genera
M1		Tubular	Erect epifauna	Suspension feeding	Tranquil bathyal and abyssal with low organic flux	<i>Arthrodendron</i> <i>Nothia</i> <i>Psammosiphonella</i> <i>Rhizammina</i> <i>Tolypammina</i>
M2	M2a 	Globular	Shallow 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>Recurvoides</i> <i>Thalmanammina</i>
		Planoconvex trochospiral				<i>Trochammina</i>
M2c 	Elongate keeled	Surficial epifauna	Active deposit feeding	Shelf to marginal marine	<i>Plectoeritidus</i> <i>Spiroplectammina</i>	
M3	M3a 	Flattened trochospiral	Surficial epifauna	Active and passive deposit feeding	Lagoonal to abyssal	not in this study
		Flattened planispiral and streptospiral				<i>Ammodiscus</i> <i>Arenoturrispirillina</i> <i>Glomospira</i> <i>Repmanina</i> <i>Rzehakina</i>
	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>Paratrochamminoides</i> <i>Praecystammina</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>
	M4b 	Elongate subcylindrical	Deep infauna	Active deposit feeding	Inner shelf to upper bathyal with increased organic matter flux	<i>Gerochammina</i> <i>Rectogerochammina</i> <i>Verneulinoides</i>
		Elongate tapered				<i>Ammobaculites</i> <i>Hormosina</i> <i>Pseudonodosinella</i> <i>Reophax</i> <i>Subreophax</i>

Figure 4. Morphogroup scheme for agglutinated foraminifera (modified after Cetean et al., 2011).

to a similar degree. The cumulative length was then standardised in sample size (100 specimens of all agglutinated foraminifera per sample) to allow a comparison of assemblages of different sizes (see Setoyama et al., 2011b).

3.4. Diversity index

In addition to species richness (the total number of species), Fisher alpha index (Fisher, 1943) was calculated as a measure of species diversity in this study. This diversity index is thought to be relatively less sensitive to variations in assemblage size (Magurran, 2004), which makes a comparison of species diversity between assemblages of variable sizes more reliable. The values of Fisher alpha index were calculated using the PAST (version 2.14) software (Hammer et al., 2001; Hammer and Harper, 2006).

4. Results

4.1. Foraminiferal assemblages

The foraminiferal assemblages from the studied interval are completely devoid of calcareous foraminifera. No casts or broken pieces of calcareous benthic or planktonic foraminifera are recorded. Similarly, carbonate-cemented agglutinated foraminifera are absent in the assemblages. Flattened specimens are very frequent, and glauconite and pyrite infillings are very rare (see Fig. 5). Typical Upper Cretaceous taxa of the “flysch-type” fauna (sensu Gradstein and Berggren, 1981; Kaminski and Gradstein, 2005) constitute the assemblages, including species of *Arthrodendron*, *Caudammina*, *Gerochammina*, *Nothia*, *Psammosiphonella* and *Subreophax* (see Figs. 5 and 6).

Assuming that all the core samples are of the same size, the number of specimens and the value of species diversity are very variable (Fig. 7). The number of specimens varies between 1 in sample 32 and 418 in sample 23. The value of Fisher alpha index is between 0 in sample 32 and 13.51 in sample 25. Relatively high numbers of specimens and diversity are recorded for six samples from the interval between 3093.02 m and 3016.05 m, interpreted to represent the overbank settings and the sub-environment with a hydrothermal vent by Knaust (2009). In contrast, the number of specimens per assemblage is low in samples from sections interpreted as the inner to middle fan with amalgamated channels represented by massive sands and the middle to outer fan with lobate sheets by Knaust (2009), except for sample 16 (Fig. 7).

4.2. Biostratigraphy

The interval considered in this study is regarded as of Santonian–Campanian age by previous studies (Ren et al., 2003; Fjellanger et al., 2005; Knaust, 2009). Important index species of DWAF for this time period, such as *Caudammina gigantea* and *Uvigerinammina jankoi*, are, however, not recorded (Fig. 6). The taxonomic composition and the completely agglutinated nature of the foraminiferal assemblages are similar to those of the lower Campanian diatom *Fenestrella bellii* Zone of Gradstein et al. (1999) assuming that forms identified as *Karrerulina conversa* and *Gaudryina filiformis* in their study are *Gerochammina stanislawi* and *Gerochammina lenis*. The assemblages differ from the middle–upper Campanian *Tritaxia dubia* Zone of Gradstein et al. (1999) by the absence of the nominal species and carbonate-cemented agglutinated taxa, though the absence of these carbonate-cemented taxa can be related to their ecological preferences and/or early diagenesis dissolution.

In contrast to agglutinated foraminifera, several stratigraphically useful bioevents were identified among the dinoflagellate cysts

(Fig. 6). Several of these events can be correlated with those in the southwestern Barents Sea (Radmacher, personal observation), the North Sea (Costa and Davey, 1992), West Greenland (Nøhr-Hansen, 1996; Dam et al., 2000), East Greenland (Nøhr-Hansen, 2012) and the Scotian Margin (Fensome et al., 2009).

The presence of *Heterosphaeridium* cf. *H. difficile* together with *Dinopterygium alatum* recorded at a depth of 4119.50 m suggests that the interval below is not younger than the early Santonian. The LO of *Heterosphaeridium* cf. *H. difficile* has been recorded in the Santonian of the Scotian Margin (Fensome et al., 2009) and the lower Santonian of West Greenland (Nøhr-Hansen, 1996). The species has also been reported from the same time interval in the Scotian Margin (Fensome et al., 2008) and in the North Sea (Costa and Davey, 1992). The LO of *D. alatum* was recorded in the (?) lowermost Santonian in West Greenland (Nøhr-Hansen, 1996, 2012), as well as in the lowermost Santonian of the North Sea by Costa and Davey (1992). Additionally, the first occurrence (FO) of *Raphidodinium fucatum*, at 4119.50 m in this study, was recorded from the upper Coniacian by Costa and Davey (1992) and from the middle Turonian (Nøhr-Hansen, 2012) suggesting that the interval below 4119.50 m is not younger than the early Santonian and not older than the middle Turonian.

The LOs of *Trithyrodinium suspectum* and *R. fucatum* are recorded at 2967.46 m. The LO of *R. fucatum* suggests a late Campanian age, according to the NORLEX biozonation for the Norwegian Sea (<http://nhm2.uio.no/norlex/>), and the LO of *T. suspectum* suggests a late Campanian age according to Williams et al. (2004). The LOs of species, such as *Odontochitina* spp. and *Trichodinium castanea*, the common occurrence of *Spongodinium delitiense* and the abundant occurrence of *Heterosphaeridium* sp. at 2967.20 m suggest an age not younger than late Campanian. The LO of *Desmocysta plekta* (at the same depth of 2967.20 m) also suggests a late Campanian age (Radmacher, personal observations) and confirms the late Campanian age estimate for this depth (Fig. 6). Additionally, the dinocyst assemblage recorded at a depth of 2969.18 m including *Odontochitina operculata* and *Palaeohystrichophora infusorioides* together with *T. castanea* and *Laciniadinium arcticum*, suggest a late Campanian age.

4.3. Quantification of foraminiferal tubular forms

The contribution by different tubular forms varies from one sample to another (Fig. 7). The number of tubular specimens (M1) and their cumulative length are compared to assess whether fragmentation of M1 specimens occurred at similar degrees and if a comparison of the relative abundance of M1 is reasonable in this study. The correlation between the total number of M1 specimens and the cumulative length of M1 specimens ($R^2 = 0.924$) is not as high as for the Upper Cretaceous assemblages of the SW Barents Sea ($R^2 = 0.949$) (Setoyama et al., 2011b) (Fig. 8). Sample 25 is clearly an outlier with a longer average tube length and the median for the length of specimens and a larger standard deviation. When it is removed from the data set, the correlation improves ($R^2 = 0.959$). In this sample, *Psammosiphonella* is the main constituent (Fig. 7). *Psammosiphonella* has a thick-walled test in comparison to other tubular forms, such as *Rhizammina* and *Tolypammina*, and this may be the cause of a large deviation of the sample from others as thick-walled tests would be more resistant to mechanical breakage, and consequently broken tubular pieces would be longer. Although general trends in the relative abundance and the standardised tube length of M1 through the interval are generally similar, some assemblages are so small that the relative abundance and the length of M1 are either extremely overestimated or underestimated (Fig. 7). For example, the peak of the standardised tube length and the complete domination of the

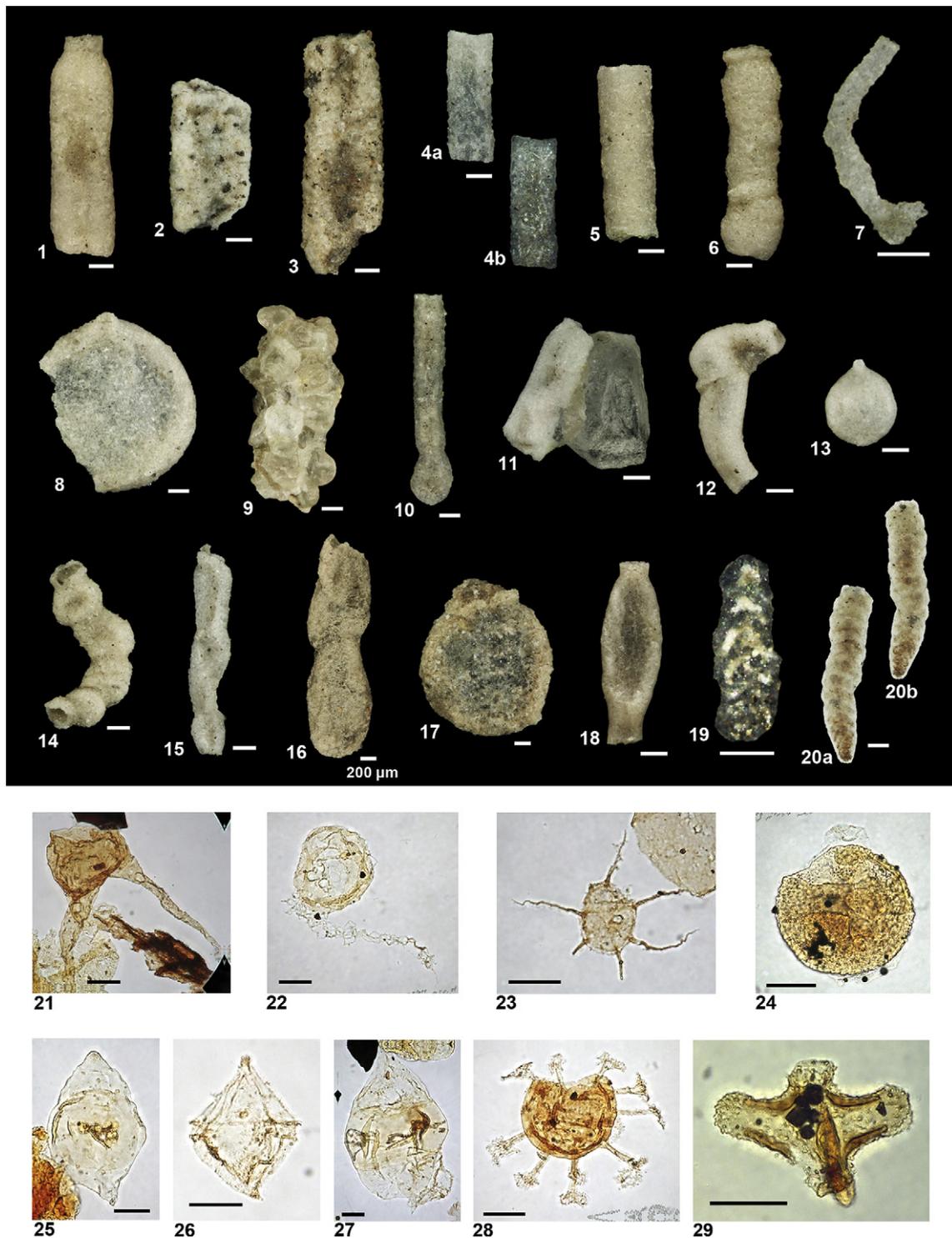


Figure 5. Photographs of selected foraminiferal and dinoflagellate cyst species from well 6707/10-1. All scale bars are 100 µm for foraminifera and 20 µm for dinocysts and a pollen, except for number 16. 1. *Bathysiphon nodosariaformis*, 3016.50 m. 2. *Nothia excelsa*, 3126.99 m. 3. *Nothia* sp. 1, 3093.02 m. 4. *Nothia* sp. 2, 3021.75 m. a) dry, b) in immersion. 5. *Psammosiphonella cylindrica*, 3059.20 m. 6. *Psammosiphonella discreta*, 3,059.20 m. 7. *Rhizammina* spp., 2974.70 m. 8. *Placentammina placenta*, 3022.20 m. 9. *Hyperammina rugosa*, 3141.50 m. 10. *Saccorhiza* sp. 1, 3021.75 m. 11. *Tolypammina* sp. 1, 3141.50 m. 12. *Tolypammina* sp. 1, 3141.50 m. 13. *Caudammina ovula*, 3022.20 m. 14. *Subreophax scalaris*, 3059.20 m. 15. *Subreophax longicameratus*, 3141.50 m. 16. *Arthrodendron diffusum*, 3059.20 m. 17. *Arthrodendron grandis*, 3022.20 m. 18. *Kalamopsis grzybowskii*, 3016.05 m. 19. *Plectoeratidus subarcticus*, 2971.82 m. 20. *Rectogerochammina eugubina*, 3016.50 m. a) and b) in immersion. 21. *Odontochitina operculata*, 2969.18 m. 22. *Desmocysta plekta*, 2969.18 m. 23. *Raphidodinium fucatum*, 2969.18 m. 24. *Trithyrodinium suspectum*, 2967.46 m. 25. *Isabelidinium microarmum*, 2969.18 m. 26. *Laciniadinium arcticum*, 2969.18 m. 27. *Chatangiella ditissima*, 2969.18 m. 28. *Oligosphaeridium pulcherrimum*, 3059.96 m. 29. *Aquilapollenites* sp., 2989.30 m.

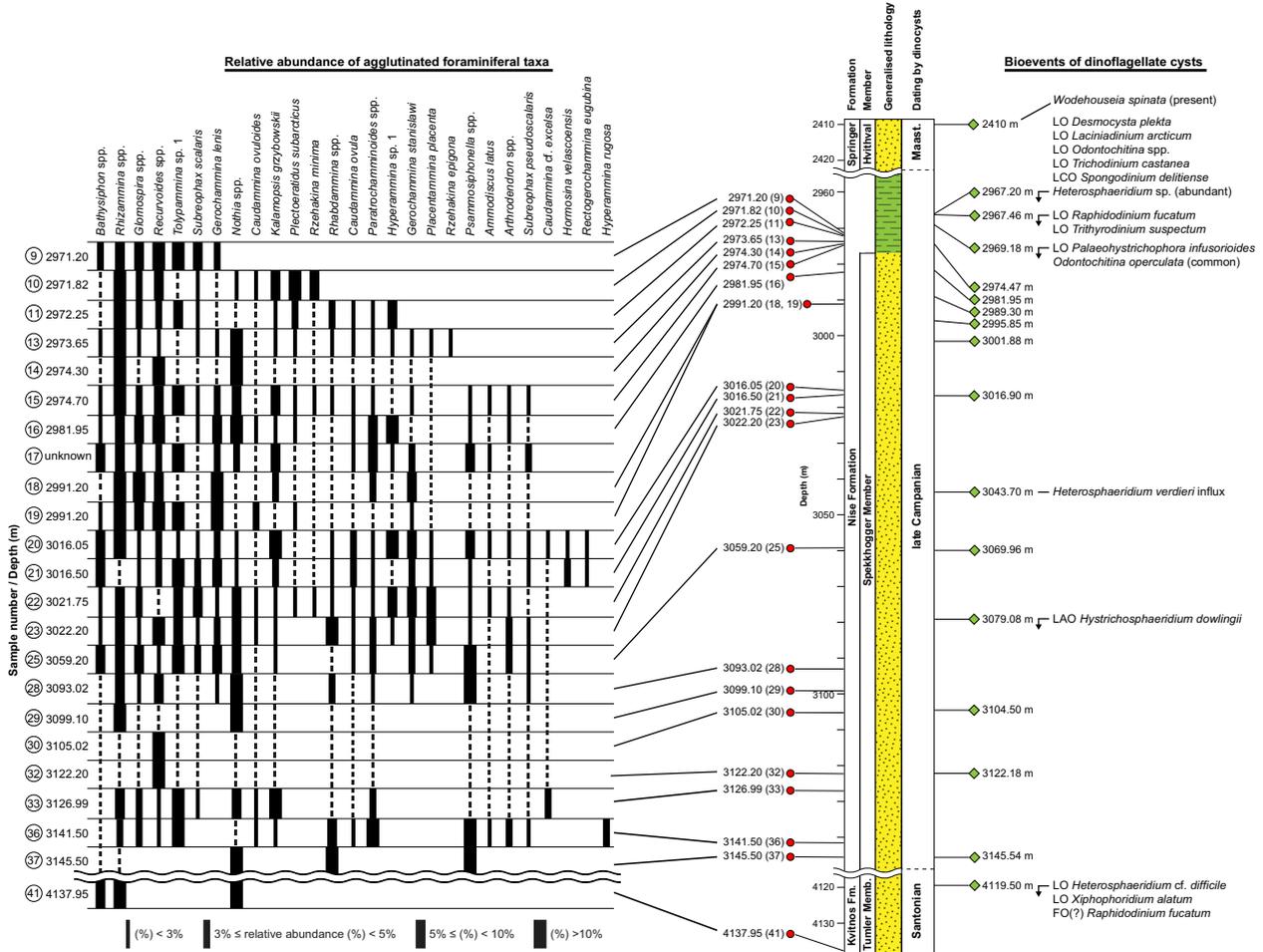


Figure 6. Relative abundance of selected agglutinated foraminifera taxa and dinocyst bioevents.

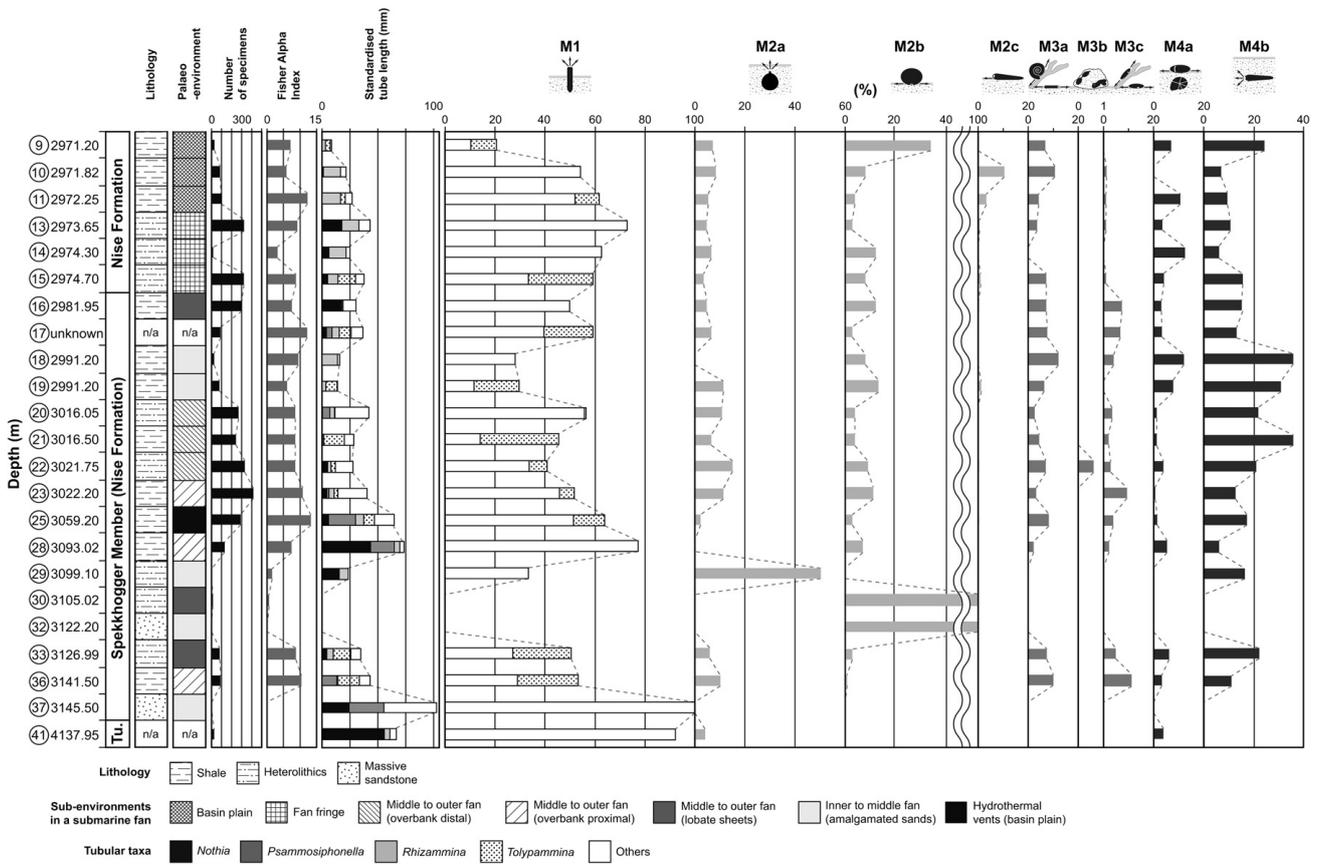


Figure 7. Lithology, sub-environments in a submarine fan system, diversity measures, standardised tube length and morphogroups (lithology and sub-environment interpretation from Knaust, 2009). Tu: Tumler; n/a: not available.

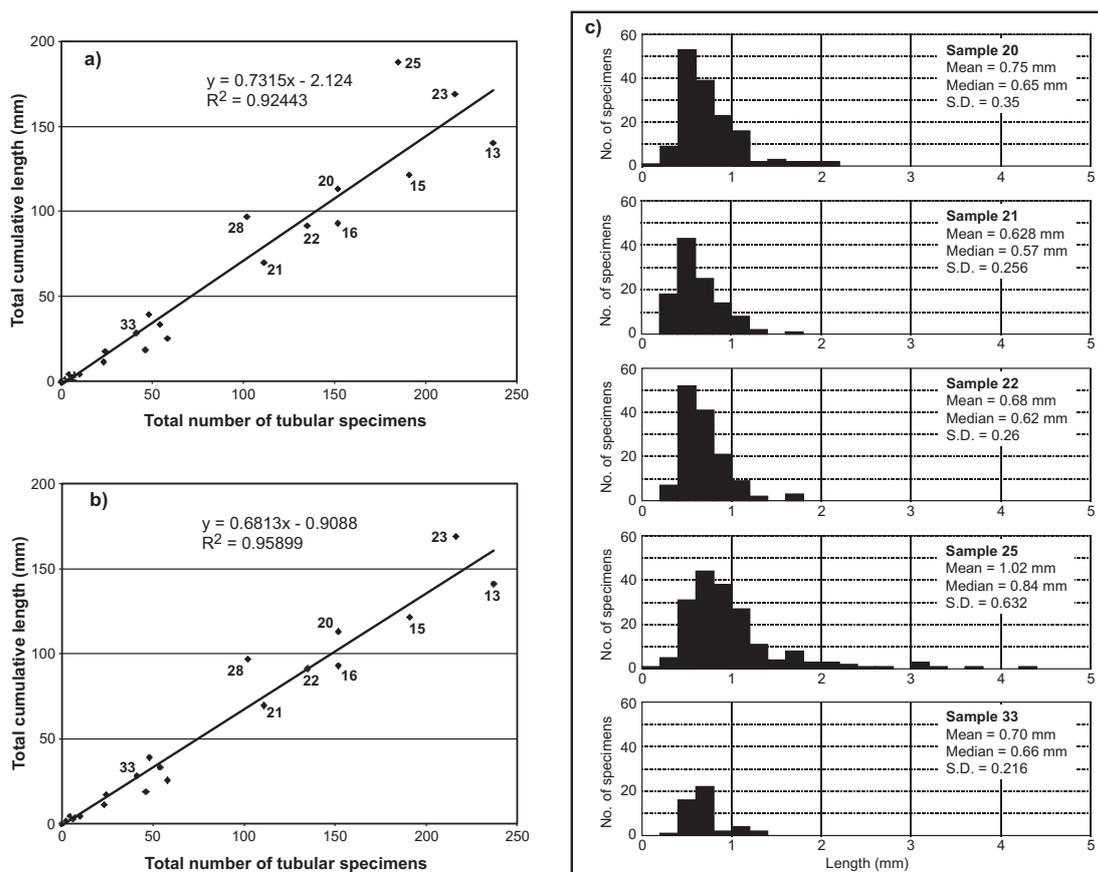


Figure 8. Comparison of the total number and the total cumulative length of tubular specimens. a) with all the samples, b) without Sample 25, c) frequency of specimens of different length. Numbers assigned to dots are the sample numbers. S.D.: standard deviation.

assemblage by M1 in sample 37 are due to the small sample size of the assemblage which contains only four relatively long specimens of *Nothia*, *Psammosiphonella* and *Rhabdammina*.

4.4. Foraminiferal morphogroups

All the morphogroups (M1–M4) are present in the assemblages, except for some samples which contain less than 30 specimens (Fig. 7). The exceptionally high abundance of M1 in samples 37 and 41, of M2a in sample 29 and of M2b in samples 9, 30 and 32 are most likely related to the small number of specimens in the assemblages. Apart from some of the samples mentioned above and samples 18 and 19, M1 (tubular forms) is the dominant component of the assemblages. M2 (epifauna/shallow infauna) is usually a minor component of assemblages, and the slightly elevated abundance of M2a in samples 22 and 23 is related to the increased occurrence of *Placentamina placenta* and *Saccamina grzybowskii*. M3 (epifauna) is sometimes a common component of the assemblages and its abundance varies between 0 and 21%. M3b (sessile forms), represented by *Ammolagena contorta* in this well, is recorded in sample 22. The genus *Tolypamma*, an attached form by its taxonomic definition, is included in M1 in this study as most of fragmented specimens are found as free forms. If *Tolypamma* is shifted from M1 to M3b, M3b becomes the dominant group in samples 33 and 36, and M4b (deep infauna) is the dominant morphotype in samples 21. M4 (infauna) is present in most of the samples, and dominates the assemblages in samples 18 and 19. M4b (elongate forms) is more abundant than M4a (lituolids) with exceptions in samples 11 and 14, and the species of *Gerochammina* are the main component of M4b in this study.

5. Discussion

5.1. Palaeoenvironments

Results of quantitative analyses of the foraminiferal assemblages and the palaeoenvironmental interpretation of the same interval based on the ichnofabric analysis by Knaust (2009) (Fig. 9) are compared here. The foraminiferal assemblages in the sandy amalgamated channels of the inner to middle fan are generally less abundant. The diversity and the relative abundance of morphogroups vary among this assemblage, and they may contain more M4b (deep infauna) (samples 18 and 19 in Fig. 7) than those of other submarine fan environments as reported for the channel-axis assemblage of Jones et al. (2005). The number of specimens in these assemblages are, however, too small to conclude on this point for certain. The foraminiferal assemblages from the overbank samples are more consistent in terms of the number of species and the value of Fisher alpha index, but not clearly different from the fringe and basin plain assemblages. The assemblage composition of proximal and overbank environments are similar, but the latter may contain more M4b (deep infauna). The composition of the lobate sand sheet assemblages is similar to the overbank when the assemblages are large. The highest diversity expressed by Fisher alpha index is recorded in sample 25, which is within the interval with possible hydrothermal vent activity suggested by Knaust (2009). Recent and fossil foraminiferal assemblages in an area under the influence of a hydrothermal vent are usually dominated by agglutinated foraminifera and less diversified and contain either less or distinctly more individuals compared to surrounding areas with normal marine conditions (Nienstedt and Arnold, 1988; Jonasson et al.,

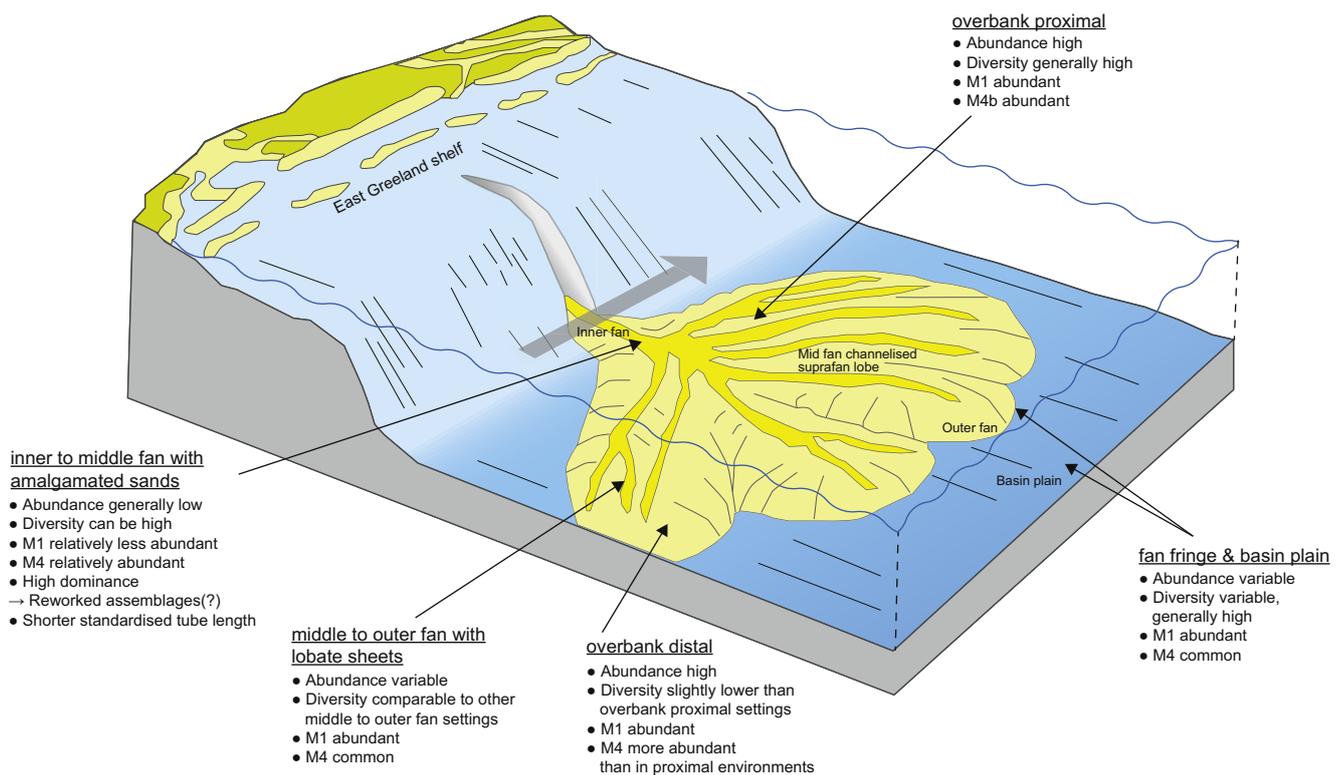


Figure 9. Foraminiferal biofacies in sub-environments of a Campanian submarine fan system suggested by Knaust (2009). The arrow indicates the presence of bottom water currents possibly in a form of a western boundary current. The block model is modified after Reading and Richards (1994) and Knaust (2009).

1995; Panieri et al., 2005; Tysza et al., 2010). However, the abundance and the composition of assemblages in such areas are also considerably variable due to highly localised environmental conditions (Jonasson et al., 1995; Panieri et al., 2005). The component taxa, their abundance and the diversity of the foraminiferal assemblage in sample 25 do not remarkably differ from the overbank, fringe, and basin floor samples (Fig. 7), and the complete absence of calcareous foraminifera is consistent in all the samples considered in this study. If there had been hydrothermal activity in the area, the foraminiferal assemblage might have been established either in a patch with local conditions very close to normal marine or during a time period when the vent activity was temporarily ceased. It is also possible that the foraminiferal assemblage is older than the vent activity.

5.2. Palaeocurrents and palaeobathymetry

Abundant occurrences of fragments of tubular taxa are reported from recent ocean slopes or deeper settings with bottom water currents which carry and/or resuspend organic matter making them available for suspension feeding epifauna (e.g. Kaminski, 1985; Jones and Charnock, 1989; Kuhnt and Collins, 1995; Schönfeld, 1997). M1 (tubular forms) is commonly present in most samples in this study, including the basin plain and overbank sub-environments of Knaust (2009), which were probably not under the influence of currents thorough channels within a submarine fan system. The abundant occurrence of tubular forms outside the channel sub-environment, thus, may indicate the presence of gentle bottom water currents in the basin possibly in the form of a western boundary current.

A bathyal environment can be inferred from the abundant occurrence of tubular forms (see Jones and Charnock, 1985; Murray et al., 2011) as well as the dominant deep-water agglutinated

foraminifera in the assemblages, and this agrees with the middle–upper bathyal palaeobathymetric estimation by Gradstein et al. (1999) and Ren et al. (2003). It is difficult to estimate the palaeobathymetry at the subzone level with the assemblages of well 6707/10-1 because no foraminiferal taxa useful for more specific palaeobathymetric estimation were recorded. The absence of *C. gigantea* might suggest the palaeobathymetry of the site to have been shallower than lower–middle bathyal (Kuhnt et al., 1998; Gradstein et al., 1999) as the known geographic limit of this species is further north in the SW Barents Sea (Setoyama et al., 2011a). The value of the Fisher alpha index is lower for the studied assemblages of well 6707/10-1 than for more or less contemporaneous assemblages of the SW Barents Sea. While turbiditic conditions within a submarine fan system may account for this reduced diversity in the NW Vøring Basin as the fauna may have not reached the highest possible diversity for similar environments with more stable substrates (see Hess et al., 2005), it may also reflect a shallower palaeobathymetry of the area because the foraminiferal assemblages from basinal plain and fan fringe palaeoenvironments suggested by Knaust (2009) are still less diversified where assemblages are usually more diversified than in a channel-axis or off-axis environment (Jones et al., 2005). In addition, the composition of the assemblages with all the morphogroups and a fair abundance of M4b (deep infauna), except for those associated with amalgamated channels and lobate sheets, indicates stable conditions, at least for the time when the assemblages were established (see Jorissen et al., 1994; Hess et al., 2005; Hess and Jorissen, 2009).

5.3. Oxygenation

Campanian deep-water faunas dominated by agglutinated foraminifera have been reported from the Viking Graben (King et al., 1989), the Foula Sub-Basin (van den Akker et al., 2000, 2002) and

offshore Norway (Gradstein et al., 1999) in the northern high-latitude areas. The dominance of agglutinated foraminifera was related to restricted water circulation in semi-enclosed basins, resultant poor oxygenation and low pH environments at the sea floor by King et al. (1989) and Gradstein et al. (1999), whereas van den Akker et al. (2000) concluded that the bottom water was well oxygenated, and dysaerobic bottom water conditions were unlikely in the Foula Sub-Basin based on the low abundance of M4 (infauna). The foraminiferal assemblages of well 6707/10-1 contain all the morphogroups, except for those associated with sandy deposits of amalgamated channels and lobate sheets, and M4b (deep infauna) is common, but not dominant when the assemblages are large. These features are similar to that of modern agglutinated assemblages in oxygenated deep sea settings (Jones and Charnock, 1985; Murray et al., 2011). A comparison of the morphogroup composition of the assemblages with the TROX (TROphic conditions and OXYgen concentration) model (Jorissen et al., 1995) and other ecological models (Kaminski et al., 1995; Kuhnt et al., 1996; Van der Zwaan et al., 1999) also suggests a relatively well oxygenated environment with a moderate flux of organic carbon which is also in accordance with the values of TOC. There is no domination by particular species that are known to be tolerant to low oxygen conditions, although it is still possible that all DWAF taxa found in the assemblages are tolerant to consistent dysoxia depending on its degree. Nevertheless, it is likely that bottom water oxygen concentration was not particularly low, and the flux of organic carbon was moderate in the NW Vøring Basin during the Santonian–Campanian.

Some calcareous benthic foraminifera are known to be tolerant to consistent low oxygen conditions in the recent (Bernhard, 1986; Kaiho, 1999; Gooday et al., 2000; Szarek et al., 2007) and in Cretaceous times (Koutsoukos and Hart, 1990; Widmark and Speijer, 1997; Gebhardt et al., 2010), and live in areas below the calcium carbonate compensation depth (CCD) (Cornelius and Gooday, 2004). As discussed above, it is not likely that oxygen was limited in bottom water or organic flux to the sea floor was neither low nor very high. It can be assumed that this area was probably above the regional CCD in Santonian–Campanian times because some calcareous foraminifera were recorded from deeper environments in the SW Barents Sea (Setoyama et al., 2011a) and in other boreholes offshore Norway (Gradstein et al., 1999). The original foraminiferal assemblages were probably dominated by agglutinated taxa that are characteristic of fossil assemblages associated with turbiditic conditions (Gradstein and Berggren, 1981) and in the Late Cretaceous deep-water environments in the northern high latitudes (see Kuhnt et al., 1989). Additionally, the early diagenetic dissolution of relatively rare calcareous taxa may have led to their complete loss from foraminiferal assemblages of well 6707/10-1.

6. Conclusions

- The agglutinated nature of the assemblages, the presence of *G. stanislawi* and *Rectogerochammina eugubina* and the absence of *T. dubia* are similar to those of the lower Campanian *F. bellii* Zone of Gradstein et al. (1999). Because the foraminiferal assemblages lack species of high biostratigraphic value including the carbonate-cemented *T. dubia*, the age of the top of the interval studied could not be determined. The LOs of dinoflagellate cysts, such as *Odontochitina* spp., *T. suspectum*, *R. fucatum*, *D. alatum* and *Heteresphaeridium* cf. *H. difficile*, gave a better stratigraphic age estimate suggesting an early Santonian to late Campanian age for the studied interval.
- A comparison of foraminiferal assemblages and the results of ichnofabric analysis by Knaust (2009) shows that the inner to middle fan assemblages of amalgamated channels are

generally poor and may contain more infaunal forms, as suggested by Jones et al. (2005) for the channel-axis assemblages, but with small numbers of specimens this observation cannot be confirmed for certain. The foraminiferal assemblages of the overbank, fringe and basin plain environments generally contain fairly high numbers of specimens, and the diversity of the assemblages is comparable to each other. The morphogroup analysis of the assemblages shows similar results for these assemblages where the assemblage size is large. The foraminiferal assemblage from the interval with suggested hydrothermal vent activity (Sample 25) has the highest diversity, and its taxonomic composition is very similar to the other assemblages indicating the assemblage was possibly established in a patch with a normal marine environment or when the vent activity was temporally ceased if the vent had existed at all.

- The abundant occurrence of tubular forms and DWAF taxa supports the middle–upper bathyal palaeobathymetric estimation by Gradstein et al. (1999) and Ren et al. (2003). The lower value of Fisher alpha index of the assemblages of overbank, fringe, and basin plain environments than that of more or less contemporaneous foraminiferal fauna of the SW Barents Sea may indicate a shallower upper bathyal setting. The presence of all the morphogroups in the assemblages and a moderate abundance of M4 (infauna) suggest a mesotrophic environment with bottom water oxygen level which was not too low to inhibit diversity.
- The abundant occurrence of suspension feeding tubular forms outside the channel sub-environment may imply that gentle bottom currents were present in the basin, possibly in the form of a western boundary current.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.marpetgeo.2012.12.007>.

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