

Biostratigraphy and paleoceanography of the Cretaceous seaway between Norway and Greenland

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Abstract

The narrow seaway between Greenland and Norway, in Cretaceous time was over 1500 km long and 300 + km wide, and partly of bathyal water depth during Aptian through Campanian. It received a large volume of fine-grained, siliciclastic sediments, with intercalated, gravity-flow sandstone wedges. As a conduit for heat transport between the low latitudes and polar region, Atlantic water masses particularly affected the eastern, Norwegian margin of this seaway. Despite its high-latitude setting, calcareous and few siliceous planktonic microfossils thus play an important role in regional stratigraphy and facies analysis, and a majority of fossil events correlate to NW European basins. The eastern margin sedimentary succession may be subdivided in several broad lithologic units: (1) Thin, multicolored, marly sediments of Hauterivian–Barremian age, with a shallow marine *Falsogaudryina/nodosariid/ostracod* assemblage; (2) Dark mudstones and minor sands, Aptian–early Cenomanian in age, with an upper bathyal, agglutinated assemblage, and monotypic *Hedbergella* floods; (3) Thick mudstone facies with thin, slope-apron turbidite sands, and an impoverished benthic/planktonic assemblage of late Cenomanian–Coniacian age, deposited in an upper bathyal, oxic/dysaerobic environment. Where Turonian sedimentation rates are low, a planktonic foraminiferal assemblage with *Whiteinella*, *Hedbergella*, *Dicarinella*, and *Marginotruncana* occurs; (4) Grayish, laminated mudstones, Santonian–Campanian in age, with local sands in the north, a low diversity, middle to upper bathyal benthic/planktonic foraminiferal assemblage, and an *Inoceramus* prisms and radiolarian/diatom flood; a Campanian agglutinated foraminiferal bloom also is known from the Atlantic oceanic realm; (5) More marly sediments of Maastrichtian age, with a low diversity planktonic/benthic foraminiferal assemblage. Using the distribution of 1755 foraminiferal and dinoflagellate microfossil events in over 30 exploration wells, a RASC (Ranking and Scaling) probabilistic zonation served as a template to build a Cretaceous zonal model with 19 assemblage and interval zones, including over 100 events. Variance analysis ranks 72 events according to reliability in correlation. Three new index taxa include *Uvigerinammina una* and *Ammonoanites globorotaliaeformis* (Albian), and *Fenestrella bellii* (Campanian). Widespread planktonic flood events occur in late Albian through early Cenomanian, early–mid Turonian, late Santonian–earliest Campanian and mid-Maastrichtian, the result of northwards shifts of warmer water masses, and disruptions in water stratification in the dysaerobic basins. An earliest Cretaceous hiatus separates Jurassic from Cretaceous strata. Ongoing block-faulting, coupled to thermal subsidence and global sealevel rise increased water depth in Aptian–Albian time from neritic to bathyal, and created sand accommodation space in dysaerobic, restricted settings. In Cenomanian–Coniacian time, sedimentation rates in the ‘central basin’ increased 10-fold, whereas paleo waterdepth did not deepen. This relatively brief

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(less than 10 m.y.) tectonic episode, resulting in deposition of deep water sands, is tentatively linked to stress re-orientation in the Rockall area. A widespread upper Maastrichtian–Danian hiatus, the result of ‘shoulder’ uplift, reflects ‘break-up’, prior to the onset of Paleogene seafloor spreading in the Norwegian Sea. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Norway; Greenland; Cretaceous seaway; quantitative foraminiferal zonation; petroleum stratigraphy

1. Introduction

This study is an attempt to better understand the Cretaceous seaway between Greenland and Norway from a paleoceanographic and paleontologic point of view. Impetus for this effort derives from data unearthed by ongoing drilling for hydrocarbons along the eastern margin of this seaway, on average buried more than 2 km deep. No detailed reconstructions exist of this seaway from presumed paleo coastline data, but Fig. 1a,b gives a schematic overview for two Cretaceous time slices, using reconstructions of the paleogeographic positions of the European and North American plates prior to opening of the Labrador Sea, regional seismic, sparse outcrop, and sparse well data. From this data, it appears that this seaway was narrow and longitudinal, over 1500 km long and 300 + km wide. Similarity between Upper Triassic–Jurassic formations on East Greenland and offshore mid-Norway also argue in favour of their relative proximity (T. Saether, pers. commun., 1997). As we will argue, this seaway was relatively shallow compared to the Cretaceous Atlantic Ocean southward, but certainly upper and temporally also middle bathyal. Depocentres in this seaway received large volumes of fine-grained siliciclastic sediments, with intercalated, gravity-flow sand wedges.

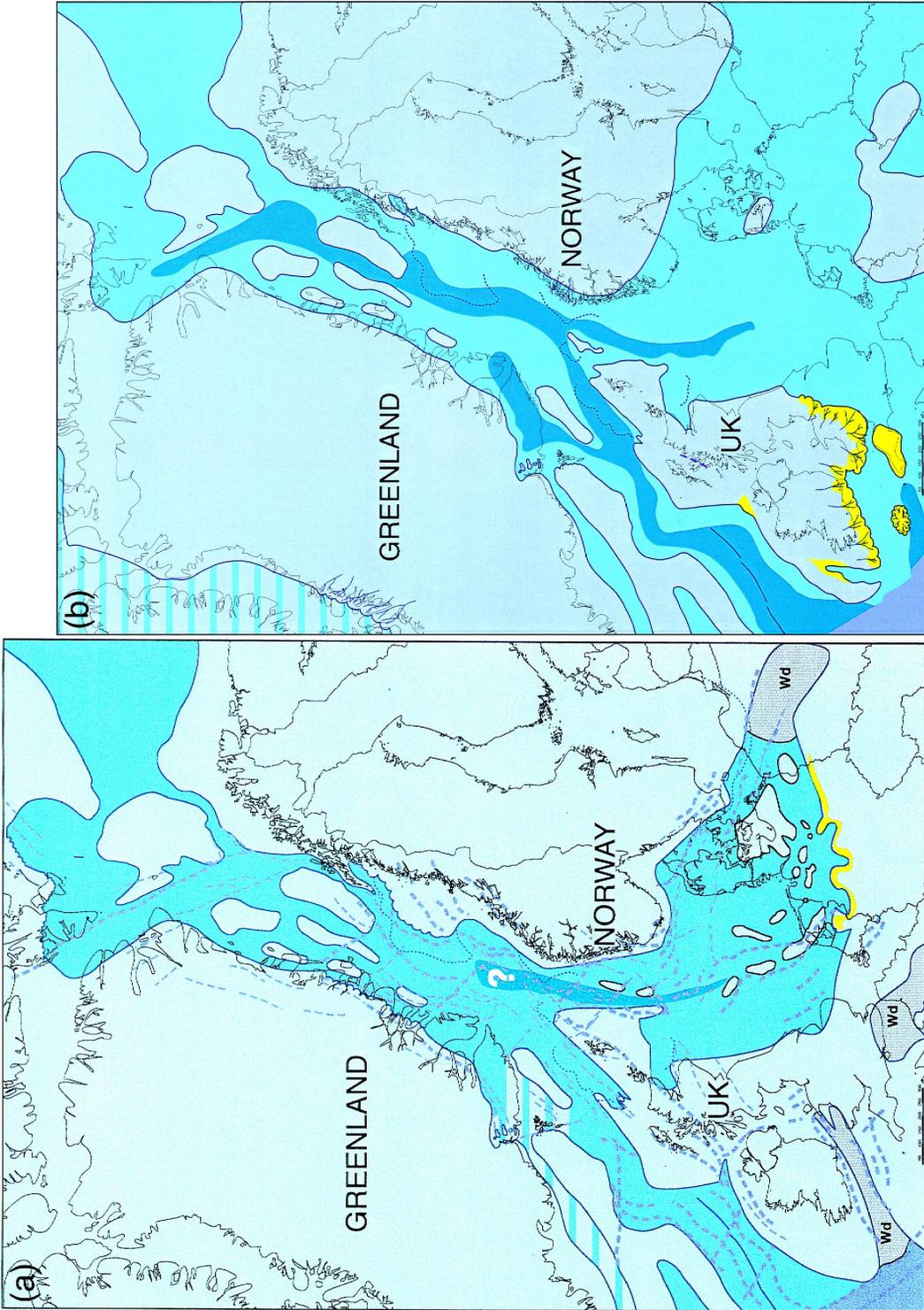
As a conduit for heat transport between the low latitudes and polar region, Atlantic watermasses particularly affected the eastern, Norwegian margin of this seaway. Despite its high-latitude setting, calcare-

ous and siliceous planktonic microfossils, thus play an important role in regional stratigraphy and facies analysis. The virtual absence of endemic fossil taxa indicates open watermass connections to the adjacent seas and ocean. Widespread planktonic flood events occur in late Albian–early Cenomanian, early to middle Turonian, late Santonian–earliest Campanian and mid-Maastrichtian. An agglutinated foraminiferal bloom occurs in Campanian time, related to a similar bloom in the Atlantic Ocean. Many Cretaceous fossil events can be correlated to the Atlantic and west Tethys regions.

Despite extensive offshore exploration for oil and gas for over two decades, there is no published documentation of the Cretaceous microfossil record in Norwegian wells. A concise and detailed documentation would be of regional benefit, and would greatly assist ongoing exploration, not only as a means to stabilize opinions, but also as a catalyst to continuous stratigraphic improvements and refinements. The Neocomian foraminiferal record in a small outcrop on Andoya, northern Norway was described by Løfaldi and Thusu (1979), while Nohr-Hansen (1993) documented Lower Cretaceous dinoflagellate stratigraphy, onshore East Greenland. Study of the mid Cretaceous foraminiferal record in some wells and outcrops is presently underway at Oslo University, and University College, London.

To better understand the microfossil record, this study documents biostratigraphic data in wells between 60° and 67°N, along the eastern margin of the

Fig. 1. (a,b) Schematic paleogeographic reconstruction of North Atlantic and Norwegian Sea in late Neocomian (a; late Hauterivian–Barremian) and in middle Cretaceous (b; approximately Cenomanian) time, showing the deep marine, bathyal passage (in dark blue) between Norway and Greenland. Purple = oceanic, abyssal (south of the Charlie Gibbs fracture zone), dark blue = middle to upper bathyal, lighter blue = marine, neritic, gray = land; Wd refers to the marginal marine Wealden facies; circum Norwegian Sea siliciclast (sand) facies is not shown. Deep marine connections into the Barents Sea are uncertain, as are various highs shown in the proto Norwegian Sea. From Barremian through Cenomanian time, transgressions progressed, and particularly since middle Albian time flooded the Bohemian Massif and other German landmasses, while land adjacent sand wedges shrank. The widespread flooding (Figs. 2 and 3), probably combined with fault tectonics enhanced graben formation offshore Norway, increasing sand accommodation space. There are no indications for deep water connections (middle to upper bathyal) in Aptian–Cenomanian time through an easterly passage via Germany towards the Polish Carpathian Trough. Ongoing transgression during Cenomanian–Turonian time removed a wide rim of Early Cretaceous siliciclasts (yellow coloured sand-prone wedges) around the NW German Basin (J. Mutterlose, pers. comm., 1998).



Norwegian seaway. Its mid-Cretaceous latitude may have been 5° or more further south (e.g., Dore, 1991), but still well in the boreal biofacies realm. We have attempted to place prominent microfossil appearances and disappearances in a paleoceanographic context, and interpret paleobathymetry and burial history. The biostratigraphy used herein derives from a combination of deterministic and probabilistic models; this combination is more reliable than a purely subjective zonation only, and brings out stratigraphically important properties of the data, not otherwise accessible.

Conventionally, biozonal schemes for petroleum exploration portray the temporal and spatial distribution of fossil events for the purpose of well correlations, using also log and seismic data. Most emphasis is on colourful displays of wells with many (not crossing) correlation lines of fossil events, presumably representing time lines. Rarely, attention is given to the broader paleogeographic and paleoceanographic setting that may clarify why fossil events actually occur, or are absent. Not uncommonly, a relative sealevel curve is strung along the fossil record in time, without actually achieving insight, unless burial histories and regional hiatuses or facies breaks also are considered. Hence, a more elaborate approach is warranted with events in the context of burial rates and regional geology. In this study we will try to link to paleoceanography, biostratigraphy and burial history.

Paleoceanography is an interdisciplinary field of study, with many aspects that need to be deciphered, including paleobiogeography, geochemistry and plate tectonics. This study is only a small attempt to achieve some paleoceanographic insight into the

Norwegian sea from a modest micropaleontological perspective. As with all first attempts to describe the regional paleontology–biostratigraphy, and place it in a paleoceanographic framework, this is a first pass at the data. The information gathered, and the interpretations will have to be continuously improved upon, and emended as temporal and geographical coverage of the Cretaceous sediments is incrementally broadened.

Below, a brief paleoceanographic and sedimentary setting is provided, followed by Stratigraphic Data and Methods (Section 3), Taxonomy (Section 4), Biostratigraphy (Section 5), Variance Analysis and Paleoceanography (Section 6), Paleobathymetry and Sequence Breaks (Section 7), and Subsidence and Sedimentation (Section 8). Appendix A is a catalogue of approximately 250 foraminiferal taxa, observed by us in the Cretaceous strata, offshore Norway, whereas Appendix B describes the three new index species. Three plates portray the three newly described index taxa, and the hedbergellid blooms. Much more work is needed to provide atlas-type coverage of the hundreds of taxa, that will stabilize taxonomy and improve subsurface stratigraphy and paleobathymetry.

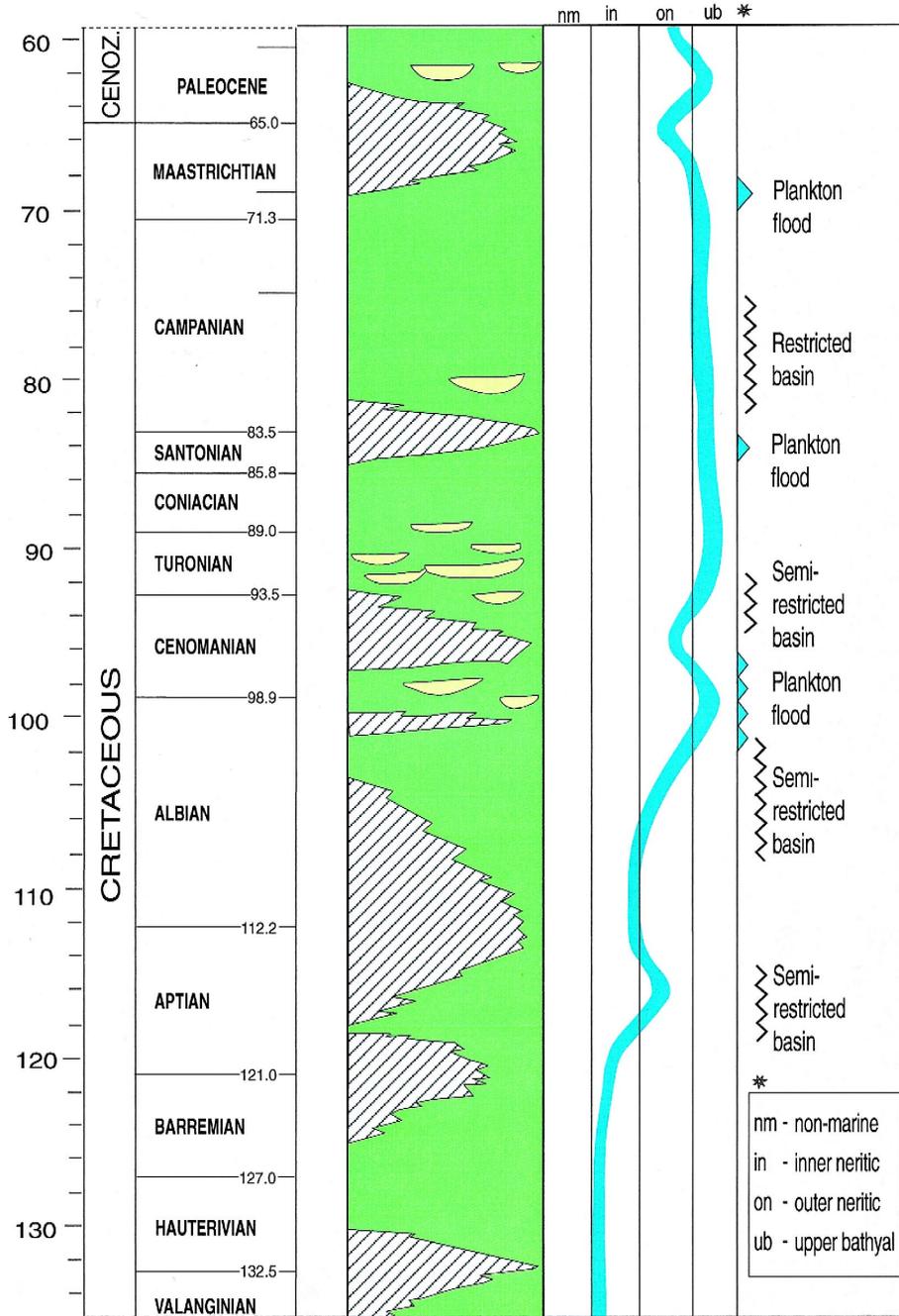
2. Cretaceous paleoceanographic and sedimentary setting

The following statement is quoted verbatim from Larson et al. (1993), as it helps to place the Cretaceous seaway in a wider paleoceanographic context.

Fig. 2. Generalized Cretaceous stratigraphic history, offshore mid Norway, showing distribution of common hiatuses (hatched diagonally) and deeper marine, gravity flow sands (in yellow). To the right of the figure is the generalized paleobathymetric trend (in blue), periods of dysaerobia (semi-restriction of watermasses) and shelly microfossil plankton flooding events. The latter are of importance in the regional stratigraphy. Both the Barremian/Aptian unconformity, and the widespread mid-Cenomanian hiatus and seismic reflector may be in common with similar features in the Mesozoic sedimentary wedge, offshore Newfoundland and Labrador. This circum-Atlantic resemblance in gross tectono-stratigraphic features points to a common cause, probably linked to plate-tectonic re-organisation. Following a universal hiatus separating shallow marine upper Jurassic from shallow marine Cretaceous (upper Hauterivian–lower Barremian), the area steadily deepened to upper bathyal paleo waterdepth in mid-Cretaceous, and middle to upper bathyal in Campanian, followed by uplift induced shallowing in Maastrichtian. Hiatuses are more widespread in upper Barremian–middle Albian than in Upper Cretaceous strata. Plankton flood events occur in upper Albian–mid Cenomanian (*Hedbergella delrioensis* and *H. planispira*), Santonian–lowermost Campanian (*Inoceramus* prisms and radiolarians) and also in lower Maastrichtian (*Globigerinelloides volutus* and *Rugoglobigerina rugosa*). Watermass restrictions are most widespread in Albian and Campanian time, when deep water agglutinated foraminifers flourished.

A paleoceanographic view clarifies the depositional history of the siliciclast strata, in the roughly south–north running gateway between the Atlantic and Arctic (Fig. 1a,b). “The mid-Cretaceous was a time

of greenhouse climates, featuring reduced temperature gradients from the equator to the poles, general absence of polar ice caps, and oceans at least 13 C warmer than the present ones. Oceans were elevated



to extremely high stands of sea levels, and were more susceptible to development of oxygen deficits, expressed in various ways. Not only were black shales more widespread, but specific ‘anoxic events’ were recorded by condensed oil-shale sequences in widely separated parts of the world, linked by global isotope anomalies. Conditions were particularly favourable for petroleum generation: more than half of our present petroleum reserves appear to have been generated during this episode, which includes Aptian time, and peaked either in the Albian, as generally believed, or in the Cenomanian. Bauxites and laterites were widespread, testifying not only to tropical climates, but also to widespread, tectonically driven uplifts and emergences.”

Although the equitable climate hypothesis in Cretaceous time is under active discussion (e.g., Sellwood et al., 1994), there is abundant evidence for global anoxic events and high sealevels. The deposition of dark shales, relatively updip, in sub-basins along the southwestern and western margins offshore Norway, clearly is related to widespread transgression along the continental margins during the high stands of mid-Cretaceous sea levels, sluggish water-mass circulation and run-off high in organics.

Fig. 1a shows a schematic paleogeographic reconstruction of NW Europe for late Neocomian time (late Hauterivian–Barremian), and Fig. 1b show a schematic one for middle Cretaceous time (approximately Cenomanian). Landmasses are in grey, the neritic seaway is light blue, the bathyal seaway is dark blue. During Barremian time, the NW German Basin, in the lower half of the sketch map of Fig. 1a, was severely restricted, with an opening towards the proto-Norwegian Sea only. Barremian sediments, offshore Norway, also are relatively restricted and thin, if at all present.

From Barremian through Cenomanian time, transgressions progressed, and particularly since middle Albian time flooded the Bohemian Massif and other German landmasses (Kemper, 1973), while land adjacent sand wedges shrank. Widespread flooding since Albian time (Figs. 2 and 3), probably combined with fault tectonics that enhanced graben formation offshore Norway, increased sand accommodation space (see Section 8). The postulated bathyal connection from the Norwegian–Greenland Seaway through the Scotland–Greenland gateway to the

mid-Cretaceous North Atlantic Ocean, south of the Charlie Gibbs fracture zone clearly stands out. It is interesting that, although mid-Cretaceous deep water agglutinated foraminiferal assemblages, offshore Norway bear similarity to flysch-type assemblages from the Carpathian Trough (see below), no ‘direct’ deep marine connection is envisaged between these regions via the NW German Basin. Biota exchange most likely took place via the North Atlantic and Tethys.

The Cretaceous sedimentary succession in the area under consideration may reach several kilometers in thickness and basinward is buried under a Cenozoic mudstone ‘blanket’ of 2–3 km. It may be subdivided in several broad units listed below; lithostratigraphic assignments follow the scheme in Daland et al. (1988).

(1) Thin, multicolored, marly sediments of late Hauterivian through early Barremian age, becoming dark coloured upwards, where the paleoenvironment changed from oxic to dysaerobic. The foraminiferal microfossil assemblage, listed in Appendix A under the heading Hauterivian–Barremian, contains common *Falsogaudryina* and nodosariids; ostracoda also are common, reflecting mostly shallow marine (neritic) conditions. The sediments belong in the Lyr Formation of the Cromer Knoll Group.

(2) Dark mudstones and minor sands, Aptian–early Cenomanian in age, with deep water agglutinated foraminifers and monotypic *Hedbergella* floods. Foraminiferal taxa present are listed under the heading Aptian–Albian in Appendix A. The sediments belong in the Lange Formation of the Cromer Knoll Group, and were laid down in an upper bathyal environment, with a dysaerobic deeper watermass (Fig. 2).

(3) Thick mudstone facies with thin, slope-apron turbidite sands, with a locally impoverished benthic assemblage deposited in an upper bathyal, oxic/dysaerobic setting, of late Cenomanian–Coniacian age (Fig. 2). The sandy sediments are assigned to the Lysing Formation of the Cromer Knoll Group. Since these sands form a disjunct set of gravity flows, not mappable as a continuous unit, the name Lysing Member would be more appropriate. Where Turonian sedimentation rates are low, a relatively rich planktonic foraminiferal assemblage may occur with *Whiteinella*, *Hedbergella*, *Dicarinella* and *Margi-*

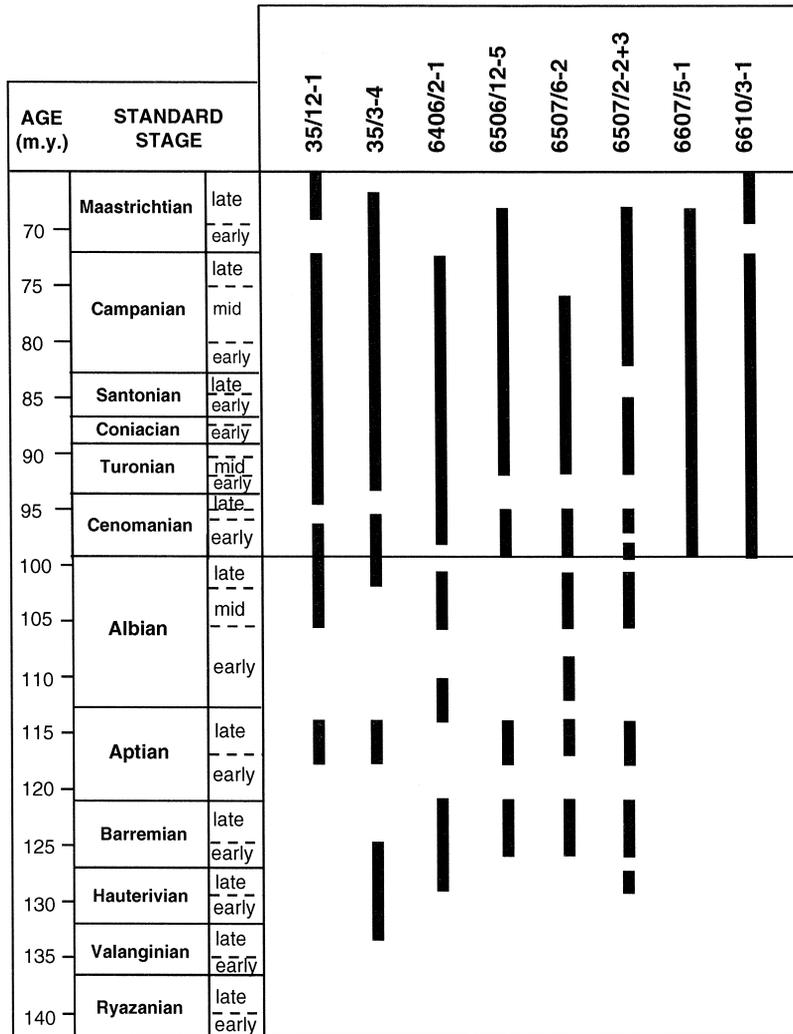


Fig. 3. Cretaceous well sections studied for foraminiferal biostratigraphy and paleobathymetry. In black-section stratigraphic section drilled; in blue-section studied in ditch-cuttings samples; in red-section studied in core samples. Note the limited stratigraphic coverage in Lower Cretaceous, when hiatuses were widespread.

notruncana (Appendix A, Cenomanian–Turonian section), yielding marly sediments.

(4) Grayish laminated, mudstones, Santonian–Campanian in age, with local sands in the distal Voering basin, offshore mid-Norway, have a mostly low diversity, middle to upper bathyal foraminiferal assemblage, an *Inoceramus* prisms peak, and a radiolarian/diatom flood (Appendix A, Coniacian–Maastrichtian section). The sediments belong in the Kvitnos to Nise Formations of the Shetland Group.

(5) Marly sediments of Maastrichtian age, with a low diversity planktonic and benthic foraminiferal assemblage. Locally, and particularly southward, the planktonics may occur in floods (Fig. 2), with monotypic *Rugoglobigerina* and *Globigerinelloides* (Appendix A, Coniacian–Maastrichtian section). The sediments are grouped in the Springar Formation of the Shetland Group.

Cretaceous lithostratigraphy of the wells to an extent depends on knowing the age of rocks, and in

that sense is not an independent descriptor. The latter is not surprising given the widespread presence of relatively monotonous mudstone facies. Although sediment units may stand out on physical well logs, biostratigraphy is an essential tool when drilling, and when attempting to correlate wells.

3. Stratigraphic data and methods

In order to arrive at an understanding of the temporal distribution of Cretaceous microfossil events, a biostratigraphic zonation was constructed, followed by variance analysis of the fossil events. During this exercise, benefit was derived from the Ranking and Scaling (RASC) method of biostratigraphy.

Principal wells that contributed to the Cretaceous zonation, offshore Norway, are from north to south: 6610/3–1, 6610/3–1R, 6607/5–2, 6607/5–1, 6607/12–1, 6507/2–1, 6507/2–2, 6507/2–3, 6507/6–2, 6507/7–1, 6507/7–2, 6506/12–5, 6406/2–1, 36/1–2, 35/3–1, 35/3–2, 35/3–4, 35/3–5, 35/12–1, 35/11–2, 35/11–5, 35/9–1, 35/9–2, 35/10–1, 34/7–21, 34/7–21a, and 30/3–1. In addition, we took into account the much condensed, but cored Lower Cretaceous interval in the 33/9–15 well, in the vicinity of the 30 and 34 block wells.

Wells are strung-out roughly in a north–south zone along the continental margin, offshore Norway, between 60° and 66°N (Brandshaug et al., 1997). On the paleogeographic map of Fig. 1b, the wells would occur in that part of the bathyal (dark blue) zone, that extends northward, just NW of the letter N of Norway, towards mid-Norway, and immediately west of its siliciclast rim. The latter encloses the Nordland Ridge, an important feature for westward sediment shedding, in the deep marine Cretaceous basin (Blystad et al., 1995; Saether et al., 1997).

Data admitted in the analysis are from released well completion reports, strongly augmented with inhouse re-analysis of original slides or re-processed ones, with emphasis on the foraminiferal fossil fraction. A majority of wells was re-studied by us in some detail, including sidewall core (swc), and core samples. Cores are largely confined to mid-Creta-

ceous sand prone intervals. The bulk of samples is from ditch cuttings, which forces use of last occurrence (LO) events, and last consistent or last common occurrence (LCO) events. The emphasis on events warrants a discussion of some of their stratigraphic peculiarities.

A paleontological record is the position of a fossil taxon in a rock sequence. The stratigraphic range of a fossil is a composite of all its records. The end-points of the range are biostratigraphic events, which includes the first occurrence (appearance in time or entry) and last occurrence (disappearance from the geologic record or exit). A biostratigraphic event is the presence of a taxon in its time context, derived from its position in a rock sequence. The fossil events are the result of the continuing evolutionary trends of Life on Earth; they differ from physical events in that they are unique, non-recurrent, and that their order is irreversible.

Often first and last occurrences of fossil taxa are relatively poorly defined records, based on few specimens in scattered samples. Particularly with time-wise scattered last occurrences, one may be suspicious that reworking has locally extended the record, reason why it is useful to distinguish between last occurrence (LO), and last common occurrence (LCO).

The shortest spacing in relative time between successive fossil events is called resolution. The greater the probability that such events follow each other in time, the greater the likelihood that correlation of the event record models isochrons. Most industrial data sets make use of sets of LO and LCO events. In an attempt to increase resolution in stratigraphy, particularly when many sidewall cores are available, efforts sometimes are made to recognize up to five events along the stratigraphic range of a fossil taxon, including last stratigraphic occurrence ('top' or LO event), last common or consistent occurrence (LCO event), last abundant occurrence (LAO event), first common or consistent occurrence (FCO event) and first occurrence (FO event). Unfortunately, such practise may not yield the desired increase in biostratigraphic resolution sought after, for reason of poor event traceability.

Event traceability is illustrated in Fig. 4, where cumulative event distribution is plotted against number of wells for the Cretaceous data set under consid-

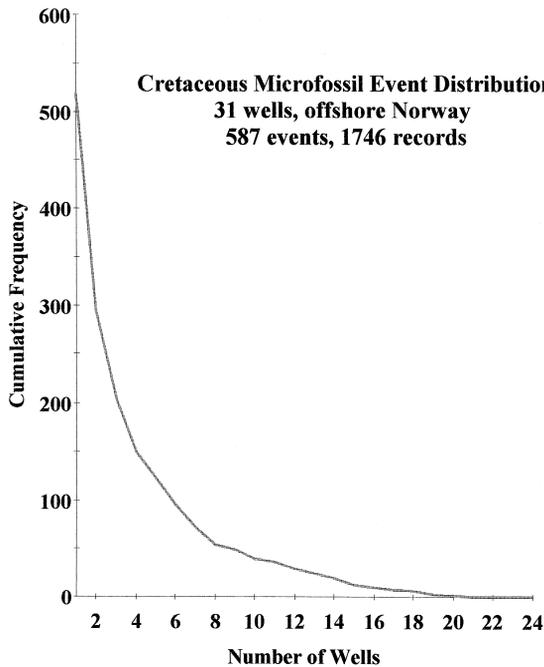


Fig. 4. Cumulative frequency of event occurrences versus number of wells for the Cretaceous, offshore Norway. There are 518 events with 1746 records in 31 wells. The events stem from dinoflagellates, foraminifers and few miscellaneous microfossils. The curve is asymptotic, showing an inverse relation between event distribution and the number of wells. None of the events occur in all wells; clearly, far fewer events occur in five or six wells than in one or two wells, and hence the cumulative frequency drops quite dramatically with a small increase in number of wells. Obviously, the majority of fossil events have poor traceability, which is true for most data sets, either from wells or from outcrops (Gradstein and Agterberg, 1998). Microfossil groups with higher local species diversity, on average have lower event traceability.

eration. The events stem from dinoflagellates, foraminifers, and several miscellaneous microfossils. The curve is asymptotic, showing an inverse relation between event distribution and the number of wells. None of the events occur in all wells; clearly, far fewer events occur in five or six wells than only in one or two wells, and hence, the cumulative frequency drops quite dramatically with a small increase in number of wells. Obviously, the majority of fossil events have poor traceability, which is true for most data sets, either from wells or from outcrops (Gradstein and Agterberg, 1998). These authors de-

duced that microfossil groups with higher local species diversity, on average have lower event traceability.

Data sets with above average traceability of events are those where one or more dedicated observers have spent above average time examining the fossil record, verifying taxonomic consistency between wells or outcrop sections, and searching for 'missing' data. In general, routine examination of wells by consultants for drilling completion reports yields only half or (much) less of the taxa and events than may be detected with a slightly more dedicated approach. Over 90% of the mentioned increase in events is due to more detailed analysis of the foraminifers, a relatively neglected microfossil group in the Cretaceous subsurface, offshore Norway.

There are other reasons than lack of detail from analysis why event traceability is relatively low. For example, lateral variations in sedimentation rate change the diversity and relative abundance of taxa in coeval samples between wells, particularly if sampling is not exhaustive, as with well cuttings or sidewall cores. It is difficult to understand why fossil events might be locally missing. Since chances of detection depend on many factors, stratigraphical, mechanical, and statistical in nature, increasing sampling and studying more than one microfossil group in detail is beneficial.

Although not always admitted or clarified, biostratigraphy relies almost as much on the absence, as on the presence of certain markers. This remark is particularly tailored to microfossils that generally are widespread and relatively abundant, and harbour stratigraphically useful events. Only if non-existence of events is recognized in many, well-sampled sections, may absences be construed as affirmative for stratigraphic interpretations. If few samples are available over long stratigraphic intervals, the chance to find long-ranging taxa considerably exceeds the chance to find short-ranging forms, unless the latter are abundant. In actual practice, so-called index fossils have a short stratigraphic range, and generally are less common, hence easily escape detection, reason why their absence should be used with caution.

Two methods that assist with the regional biostratigraphy, are multiwell event bookkeeping and probabilistic zonation and correlation. For this pur-

pose we employed the computer programs Makedat, Ranking and Scaling (RASC) and Correlation and Standard Error Calculation (CASC). Details of these methods are in a companion paper to this study (Agterberg and Gradstein, 1999; see also Gradstein et al., 1985). As a point of interest, we might mention that two other Cretaceous biostratigraphic studies, of limited scope for the Danish sector of the central North Sea, also used quantitative stratigraphic methods. A Maastrichtian dinoflagellate zonation for the Dan Field (Schioeler and Wilson, 1993), was assisted by the RASC method and Stouge (1991) employed graphic correlation to better define the biostratigraphic ranges of Upper Cretaceous calcareous foraminifers.

Traditionally, biostratigraphic zonations are executed 'by hand' through a painstaking process of (mental) stacking in relative geologic time of numerous fossil events from many different outcrop or well sections. Subtle stratigraphic order relationships are evaluated, and frequent gaps are bridged by superpositional hypothesis, where data are scarce. The human mind is good at evaluating observed and virtual superpositional data and bridging data gaps. Unless a massive amount of documentation is provided with zonations, it may be difficult to trace back zonations to the original data, and frequently the actual data are not listed in a zonal report. This lack of reproducibility in biozonation, particularly where exploration biozonations are concerned, may lead to problems with chronostratigraphic calibration and high-resolution correlations of zonal events.

Quantitative methods of biostratigraphy, like graphic zonation and correlation, or Ranking and Scaling cannot easily match the subtleties of very detailed subjective zonations, based on many, often incomplete stratigraphic sections, using much information on missing data. As mentioned above, the experienced biostratigrapher uses almost as much information on absence as on presence of data, and the former cannot be evaluated by a method. To produce a data set that is detailed and informative enough to yield quantifiable, high-resolution zonations is a considerable task. However, once such a dataset and its derived quantitative zonation is accomplished, and made available together with its raw data and data processing details, it serves as a more reliable model for correlation and chronostrati-

graphic calibration than a poorly documented, subjective zonation. True stratigraphic resolution improves if event spacing in relative time is assessed with standard deviations, that create an understanding as to the chance that two events are superpositional. In this study, a calculated zonation with error bars on most likely event positions will be used, and a subjective one, which together best explain, and predict the stratigraphic distribution of the fossil record.

4. Taxonomy

Appendix A lists over 250 benthic and planktonic foraminiferal taxa identified during this study in the wells, grouped in the four broad time slices Hauterivian–Barremian, Aptian–Albian, Cenomanian–Turonian, and Coniacian–Maastrichtian. The selection of the time slices reflect broad taxonomic changes, the result of gradual evolutionary turnover, and local changes in Cretaceous paleoenvironment.

In Appendix B, three new index taxa are discussed, i.e., *Uvigerinammima una* n. sp. and *Amoanita globorotaliaeformis* n. sp., both of the *U. una* zone, late middle to early late Albian, and *Fenestrella bellii* n. sp. of the *F. bellii* zone, early Campanian. These new taxa are important elements in the regional biozonation proposed in this study.

The taxonomy of Lower Cretaceous calcareous benthic foraminifers adopted for this study, is based to a large extent on well-known micropaleontological studies of NW Germany (Bartenstein, 1977a,b, 1978, 1981; Bartenstein and Bettenstaedt, 1962; Michael, 1966). Supplementary data include studies of the North Sea (Burnhill and Ramsay, 1981; King et al., 1989), western Siberia (Komissarenko and Belousova, 1990), the northern tethys margin (Moulade, 1961; Weidich, 1990), Atlantic Canada (Williamson and Stam, 1988), and studies based on Cretaceous DSDP Sites (Riegraf and Luterbacher, 1989). For the agglutinated benthic foraminifers, the taxonomy in this study is based on Carpathian flysch assemblages (Geroch and Nowak, 1984; Bublik, 1995; Neagu, 1965, 1972) and on more recent studies of the Cretaceous of the North Sea (King et al., 1989; Kaminski et al., 1995a,b), and of the North Atlantic (Kuhnt and Kaminski, 1990, 1997).

The taxonomy of Upper Cretaceous calcareous benthic foraminifers makes use of the study for the northern North Sea by King et al. (1989), and to a lesser extent of the southern British Isles study by Hart et al. (1989), and Czechoslovakia by Hanzlikova (1972). For planktonic foraminifers, good use was made of the atlases of Stainforth (1981) and Robaszynski et al. (1984). Agglutinated benthic foraminiferal taxonomy and stratigraphy follows studies by Geroch and Nowak (1984), Kuhnt and Kaminski (1990), Bubik (1995), Coccioni et al. (1995), and Kuhnt et al. (1998), all dealing with deep marine assemblages.

Dinoflagellate event data are included in this analysis, as far as reported for the wells. Their optimum stratigraphic distribution, relative to the foraminiferal events, is listed in the RASC optimum sequence zonation. Many of the palynological data were generated by Dr. Graham Bell, Stratlab. The dinoflagellate taxonomy benefitted from the study by Costa and Davey (in Powell (Ed.), 1992). As recently pointed out to us by P. Schioeler (pers. comm., 1998), the taxon names *Maghrebinia membraniphora* and *Apteodinium grande* used in this report, preferably should be renamed *Cyclonephelium membraniphorum* and *Apteodinium maculatum* subsps. *grande*, respectively.

A detailed search for taxonomic synonymies both in foraminifers and dinoflagellates between well reports improved taxonomic consistency. For example, *Tritaxia carinata* in some wells was reported as *T. dubia*, and *Caudammina ovuloides* as *C. ovulum*. Many haphazard records of *Hedbergella* sp. and *H. delrioensis* LO were omitted as irrelevant events; *Rugoglobigerina macrocephala* was included in *R. rugosa*. In two wells, *Endoceratium dettmaniae* was recorded well below its reasonably expected occurrence, and omitted. *Chattangiella spinosa* in some wells was renamed *C. sp. 1* (Bell, pers. comm., 1996), and *Uvigerinammina bulimoides* of some consultants is here named *Uvigerinammina una* n. sp. *Biglobigerinella multispina* was included in *Globigerinelloides volutus*. Problems exist with the taxonomy in the plexus of *Gaudryina filiformis*/*Karrerulina conversa*/*Gerochammina lenis*, and with various *Gyroidinoides* and *Gavelinella* taxa. These plexa warrant further study, using populations of specimens to describe mid-points in morphological

variation plus its spread. Similarly, population taxonomy studies of Hauterivian–Albian *Falsogaudryinella* and *Uvigerinammina* are desirable, to curtail picking of extreme morphologies as taxa, and clarifying geographic variation in morphology.

Surprisingly, well reports often paid little attention to planktonic foraminifers, that provide valuable ties to standard Cretaceous zonations. A search for planktonic foraminifers in microfossil slides in many wells yielded biostratigraphic events for *Hedbergella delrioensis*, *H. planispira*, *H. paradubia*, *H. hoelzi*, *Whiteinella* spp., *Dicarinella imbricata*, *D. hagni*, *Praeglobotruncana* spp., including *P. stephani*, and *Globotruncana*. Rare *Dicarinella concavata* and *D. carinata*, well-known indices for Coniacian–Santonian strata, but not previously recorded offshore Norway, were observed in wells of the 35 exploration blocks. In cores in well 33/9–15 we observed Aptian *Blefusciana* and middle Albian *Globigerinelloides gyroidinaeformis*, with the interval previously being dated Barremian, using dinoflagellate taxa now considered reworked in the condensed Lower Cretaceous section in this well.

5. Biostratigraphy

5.1. Introduction

The biostratigraphy of Lower and Upper Cretaceous foraminifers in NW Europe has been studied by a number of authors since the 1960s. A review of the relevant schemes developed for the NW European mudstone facies is useful in order to understand the microfossil records from the eastern side of the Norwegian Sea. Studies on rich and diversified microfossil material from both sides of the Norwegian Sea, in progress at the University of Oslo and University College London, will complement the present data compilation, and will increase insight in zonal and paleogeographic distributions.

5.2. Northwest Germany

The work from Bartenstein et al. on the benthic foraminifers of the Saxon Basin has led to the publication of a detailed biostratigraphic scheme for NW Germany (Bartenstein and Bettenstaedt, 1962), and later to a proposal for a general biostratigraphic

Table 1

Foraminiferal taxa found in the Lower Cretaceous, offshore mid Norway, that also occur in NW Germany

| Species | Range in NW Germany |
|------------------------------------|--|
| <i>Pleurostomella obtusa</i> | lower–middle Albian |
| <i>Gavelinella intermedia</i> | lower–middle Albian |
| <i>Valvulineria gracillima</i> | upper Aptian to upper Albian (max. upper Aptian) |
| <i>Gaudryina dividens</i> | upper Aptian to lower Albian (max. upper Aptian) |
| <i>Gavelinella barremiana</i> | mid Barremian to lower Aptian (max. mid Barremian) |
| <i>Reophax troyeri</i> | mid Barremian to mid Albian (max. upper Aptian–lower Albian) |
| <i>Lenticulina ouachensis</i> ssp. | upper Hauteriv. to lower Aptian (max upper–mid Barremian) |
| <i>Textularia bettenstaedti</i> | upper Hauteriv. to lower Albian (max. upper Aptian–lower Albian) |
| <i>Lenticulina eichenbergi</i> | upper Valanginian to mid Barremian (max. Hauterivian) |
| <i>Epistomina hechti</i> | Barremian |
| <i>Falsogaudryina tealbyensis</i> | Valanginian–Barremian |

zonation for the Lower Cretaceous using more cosmopolitan taxa (Bartenstein, 1978). The biostratigraphic zonation of the NW German Lower Cretaceous was based on the stratigraphic succession of 75 foraminiferal, and 12 ostracod species in middle Valanginian to lowermost Cenomanian of Saxony. The stratigraphic ranges of benthic foraminifers were calibrated to the standard ammonite zones. The zonal scheme mainly uses calcareous benthic foraminiferal species more typical of shallow marine sediments, such as *Citharina*, *Epistomina*, and ornamented *Lenticulina*. Unfortunately, neither of these genera is common in the Cretaceous Norwegian Sea. Fewer than 15 of the Northwest German index species were commonly encountered in this study. Of these, the 11 taxa occur consistently, and are used for chronostratigraphic correlation, as listed in Table 1.

5.3. Northern Tethys Margin

Weidich (1990) published a zonal scheme for the Tithonian to Cenomanian based on his studies of the Northern Calcareous Alps in Bavaria and Austria. His scheme divides the Lower Cretaceous into 10 zones, based on first occurrences or acmes of nominate zonal taxa. Weidich's zonation is based primarily on calcareous benthic foraminifers, but because his studied sections were deposited in deep water, there is a greater possibility for correlation with the Norwegian Sea region. Several of the index taxa are also found in the North Sea, which verifies Weidich's selection of taxa that are largely cosmopolitan. How-

ever, Weidich's zonal scheme was only tentatively correlated to the standard chronostratigraphy, and calibration of Weidich's samples by means of planktonic microfossils is needed to refine the age of his zones. Table 2 gives a list of stratigraphically important cosmopolitan species from Weidich's study, that also occur in the Norwegian Sea assemblages.

The biozonation of Geroch and Nowak (1984), and additions by Geroch and Koszarski (1988), provide a reference frame for cosmopolitan deep-water agglutinated foraminiferal assemblages. The Lower Cretaceous portion of their zonal scheme consists of 19 species and seven zones, and the Upper Creta-

Table 2

Foraminiferal taxa found in the Lower Cretaceous, offshore mid Norway that also occur in the Alps in Germany and Austria

| Species | Range in German Alps |
|---------------------------------------|----------------------------|
| <i>Caudammina crassa</i> | Barremian to Cenomanian |
| <i>Kalamopsis grzybowskii</i> | Barremian to Cenomanian |
| <i>Textularia bettenstaedti</i> | Berriasian to Aptian |
| <i>Plectrocurvoides</i> spp. | upper Albian |
| <i>Trochammina quinqueloba</i> | upper Albian |
| <i>Gaudryina dividens</i> | Aptian to Albian |
| <i>Spiroplectinata</i> spp. | Aptian to Albian |
| <i>Lenticulina busnardoii</i> | Berriasian to Hauterivian |
| <i>L. eichenbergi</i> | Valanginian to Barremian |
| <i>L. wisselmanni</i> | Barremian |
| <i>Valvulineria</i> spp. | upper Aptian to Albian |
| <i>Gavelinella barremiana</i> | Barremian to Aptian |
| <i>G. intermedia / berthelini</i> | Aptian to Cenomanian |
| <i>Patellina subcretacea</i> | Berriasian to lower Aptian |
| <i>Falsogaudryina (?) tealbyensis</i> | Barremian–Aptian |

ceous of 17 species and four zones. All the zones are based on the first occurrence of index taxa—so they are not equivalent to zones of the same name recognised in other areas, and are not directly applicable to wells with cavings problems. Although these zones were originally developed for the Carpathian flysch deposits, parts of the Geroch and Nowak scheme apply to other deeper marine continental margins with Cretaceous ‘flysch-type assemblages’ as far away as the NW Australian margin (Kaminski et al., 1992), and the Pacific (Riegraf and Luterbacher, 1989).

Several of the nominal index species from this zonal scheme have now been observed also in the Norwegian seaway (Appendix A; Fig. 5), including *Verneulinoides neocomiensis*, *Pseudobolivina variabilis*, *Pseudonodosinella troyeri* (= *Reophax minutus* of Geroch and Nowak), *Haplophragmoides nonioninoides*, and *Bulbobaculites problematicus*, as well as several other species from the range chart of Geroch and Nowak (1984) including *Ammobaculoides carpathicus*, *Trochammina quinqueloba*, *Trochammina abrupta*, *Thalmannamina neocomiensis*, *Caudammina crassa*, *Hippocrepina depressa*, *Kalamopsis grzybowskii*, *Gaudryina filiformis*, *Caudammina ovulum*, *Rzekina epigona*, *Tritaxia dubia* (= *T. subparisiensis*), *Marsonella crassa* and *Dorothyia oxycona*. Many of these species have not been previously reported from the North Sea, and deserve more detailed taxonomic coverage than feasible in this study.

An interesting point is that recognition, offshore Norway of many of the middle to Upper Cretaceous taxa, known well from the Polish Carpathian Trough, and partial application of its bathyal–abyssal realm zonation, does not mean a direct deep marine connection existed between the proto Norwegian Sea and the Carpathian Trough region. As may be seen on Fig. 1a,b, such a connection is not drawn in, and not likely for mid-Cretaceous time, given the string of relatively shallow marine deposits eastward into Germany. Locally in the deepest part of the NW German basin, bathyal conditions may have existed in Albian time, but such was not part of a deep passage eastward (J. Mutterlose, pers. comm., 1998). Deep marine faunal exchange most likely took place via the gateways from the proto Norwegian Sea into the North Atlantic.

5.4. Central North Sea

Foraminiferal zonal schemes for the Lower and Upper Cretaceous of the Central North Sea have been informally proposed by a number of consultants, but were not published. An exception is the biozonation developed by King et al. at Paleoservices, that was published in 1989; it links to the detailed study by Koch (1977) for the calcareous upper Cretaceous of NW Germany.

King et al. (1989) has proposed two parallel zonations for the North Sea, that subdivide the Lower Cretaceous into 12 zones and subzones, and the Upper Cretaceous in 11 zones and subzones (see Fig. 6a,b). The ‘FCS’ zonal scheme has applications in the shelf (chalk) facies of the southern sector of the North Sea, whereas the ‘FCN’ zones are based on deeper-water taxa and can be used for the bathyal shale facies in the northern and central sectors. The FCN zonation scheme is most applicable to the study area, and the zonation, offshore Norway resembles this scheme (Fig. 6a,b, and discussion below). The index taxa are normally widespread and common, which makes the scheme quite robust. However, little attention was paid to deep water agglutinated foraminifers that become more important northward. Below, we will discuss in detail similarities and differences to the northern North Sea zonation.

5.5. Cretaceous biozonation, offshore mid Norway

In this section we outline a Cretaceous biozonation for offshore mid-Norway, largely using foraminiferal taxa, and some miscellaneous microfossils. Rather than trying to create a zonation that maximizes stratigraphic resolution, and often is difficult to apply over a broad region, we prefer to outline zonal units that are easy to correlate over the offshore region. Hence, use was made of the RASC method to erect a zonation for the middle and upper part of the Cretaceous, that also helped to integrate dinoflagellate events in the biozonation. The lower Cretaceous, pre-Albian section is too fragmented (Fig. 3), and well coverage insufficient to effectively apply quantitative stratigraphic methods; that part is zoned subjectively. Below, we first will analyse

RASC results, prior to a discussion of the successive Cretaceous zones, that build on and extend the RASC results.

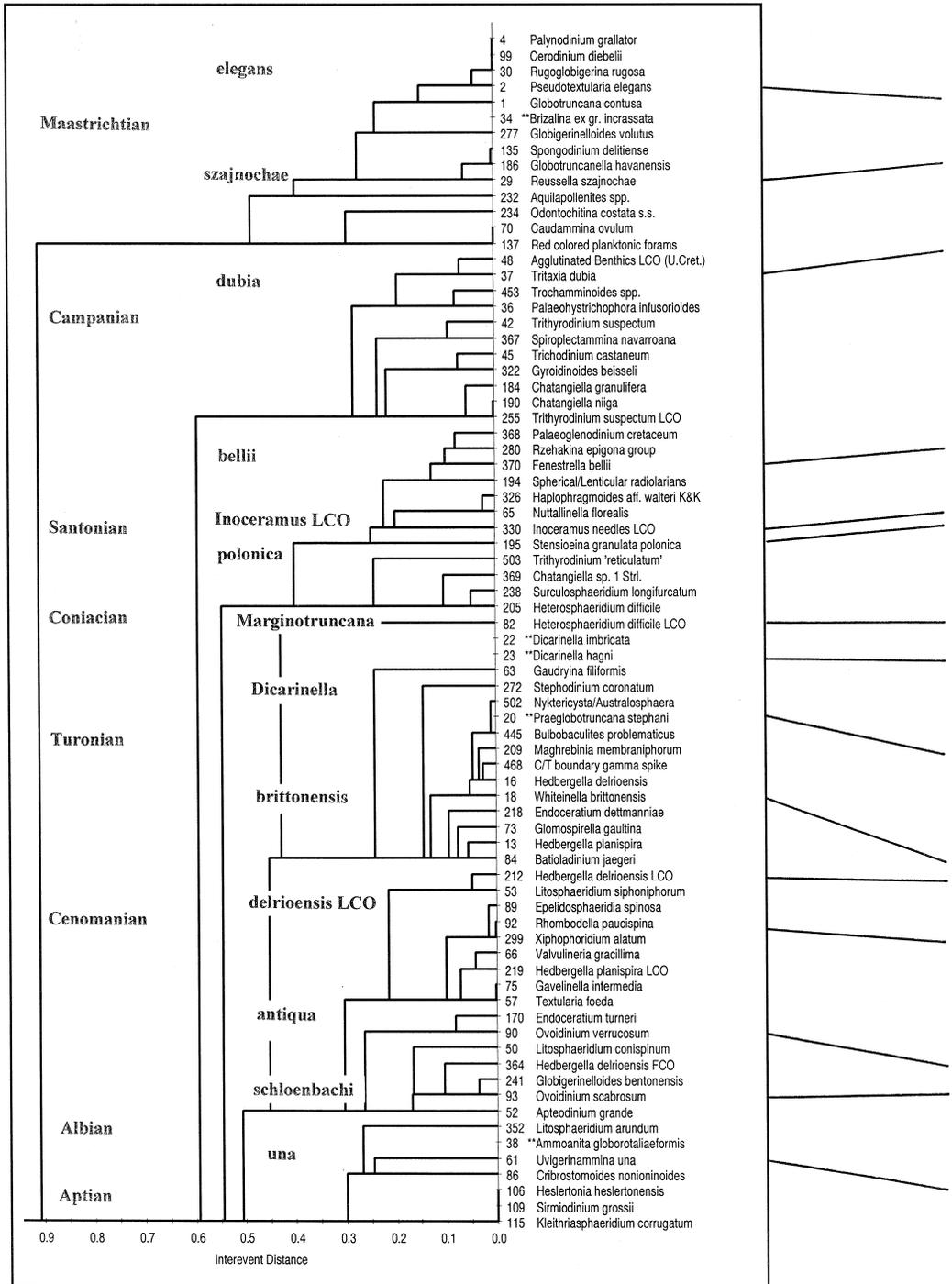
Initially, the data set for RASC comprised the multiple microfossil event record in 37 wells, mostly LO or LCO events of 550 foraminifers, some siliceous microfossils and dinoflagellates, for a total of 1873 records. After several intermediate zonations, using RASC and its normality testing functions of the event record, scores of records, five erratic events, and seven wells with very low sampling quality (partly due to turbo-drilling) were deleted from the data. For example, the following fossil event records were deleted, as being far too high, or too low stratigraphically in wells, as determined from RASC stepmodel penalty points: *Globorotalites multiseptus* in 34/7–24s, *Endoceratium dettmaniae* in 35/3–4, *Gaudryina filiformis* in 6507/6–2, *Gyrogonoides beisseli* in 34/7–22 and *Hedbergella* sp. in 6607/5–1; several LO events for dinoflagellate cyst taxa were changed into LCO events. In addition, *Rhaphidodinium fucatum*, *Heterohelix globulosa*, *Caudammina ovuloides*, *Dorothia trochoides*, *Hedbergella* sp., *Dorocysta litotes*, *Xenascus ceratoides*, *Florentinia mantelli*, *F. deanei* and *F. ferox* showed highly erratic occurrences through the wells, leading to deletion from the run data. From our own observations it is clear that *Hedbergella* sp. consistently occurs in the nominate

upper Cenomanian–lower Turonian zone, but in the original well record that is not obvious. In most cases, reasons for the erratic stratigraphic positions are not clear.

Despite filtering out (removal) of ‘bad’ data from the RASC runs, 21 cycles needed to be broken prior to zonation, where groups of three or more events had an unresolvable stratigraphic order. In our experience with datasets from a variety of regions over the world, with different microfossils, 21 event cycles is a low number. Inclusion of the 10 events that were deleted from the data set would have increased the number of cycles from 24 to 43, and the number events with of six or more stepmodel penalty points from 14 to 36; out of place (AAA events) events in the scattergrams also was higher, whereas the number of out of place events using the RASC normality test would have declined from 78 to 64, not a significant change, but possibly the result of a ‘more complete’, although not more precise optimum sequence.

As mentioned, the few wells omitted from the RASC run suffer from poor data coverage. The remaining 31 wells harbour 519 events, with 1755 records. Table 3 provides a summary of data properties and RASC results. Number of events in the optimum sequence with S.D. < ave. S.D., deals with the number of events that have a standard deviations below the average for the optimum sequence; the

Fig. 5. (Right) Optimum sequence of Cretaceous events (foraminifera, dinoflagellates, miscellaneous microfossils and one physical log marker), offshore mid Norway, using the Ranking and Scaling (RASC) method on 1753 records in 31 wells. The arrow of time is upward. The majority of events are last occurrences (LO) in relative time; LCO stands for Last Common or Last Consistent Occurrence. Each event occurs in at least six out of 31 wells, leaving 97 events. The display also shows the relative stratigraphic position of nine unique events. The optimum sequence is graphically tied to the scaled optimum sequence (= RASC zonation) to the left, largely using the nominate zone markers. (Left) Scaling in relative time of the optimum sequence of Cretaceous events shown in Fig. 5 (right). The arrow of time is upward; the interevent distances are plotted on the relative scale to the left in dendrogram display format. Each event occurs in at least seven of the 31 wells, leaving 72 events. Sixteen stratigraphically successive interval zones are recognized, middle Albian through late Maastrichtian in age. Large breaks (at events 52, 84, 205, 255 and 137) indicate transitions between natural microfossil sequences; such breaks relate to hiatuses or facies changes, some of which are known from European sequence stratigraphy (see text for more details). (1) The *una-schloenbachi* break reflects a latest Albian lithofacies change and hiatus, connected to the Octeville hiatus in NW Europe. (2) The *delrioensis* LCO–*brittonensis* break reflects the mid-Cenomanian lithofacies change and hiatus, connected to the mid-Cenomanian non-sequence and Rouen hardground of NW European sequence stratigraphy. (3) The *Marginotruncana-polonica* break, above the level of *Heterosphaeridium difficile* LCO, which represents a maximum flooding surface, may be the turn-around in the middle Coniacian tectono-eustatic phase, near the end of the Lysing sand phase. (4) The *bellii-dubia* break, is again (near or) at a maximum flooding event, this time correlated to the LCO of *T. suspectum* in the early middle Campanian, above the change from marly sediments to siliciclasts at the base of the Campanian. (5) The *dubia-szajnochae* break reflects the abrupt change from siliciclasts to marly sediment at the Campanian–Maastrichtian boundary, only noted in the southern part of the region.



| RANK | EVENT # | FOSSIL EVENT NAME |
|------|---------|-------------------------------------|
| 1 | 4 | Palyonodinium grallator |
| 2 | 99 | Cerodinium diebellii |
| 3 | 155 | Stensioeina pommerana |
| 4 | 30 | Rugoglobigerina rugosa |
| 5 | 34 | Brizalina ex gr. incrassata |
| 6 | 2 | Pseudotextularia elegans |
| 7 | 1 | Globotruncana contusa |
| 8 | 277 | Globigerinelloides volutus |
| 9 | 135 | Spongodinium delitiense |
| 10 | 186 | Globotruncanella havanensis |
| 11 | 29 | Reussella szajnochae |
| 12 | 232 | Aquilapollenites spp. |
| 13 | 379 | Karrerullina conversa |
| 14 | 234 | Odontochitina costata s.s. |
| 15 | 236 | Odontochitina costata LCO |
| 16 | 70 | Caudamina ovulum |
| 17 | 137 | Red colored planktonic forams |
| 18 | 37 | Tritaxia dubia |
| 19 | 48 | Agglutinated Benthics LCO (U.Cret.) |
| 20 | 46 | Chatangiella spp. |
| 21 | 453 | Trochaminoides spp. |
| 22 | 36 | Palaeohystrichophora infusorioides |
| 23 | 42 | Trithyrodinium suspuctum |
| 24 | 43 | Hystrirodinium pulchrum |
| 25 | 45 | Trichodinium castaneum |
| 26 | 332 | Spongodinium delitiense FO |
| 27 | 386 | Chatangiella ditissima |
| 28 | 184 | Chatangiella granulifera |
| 29 | 367 | Spiroplectamina navarroana |
| 30 | 322 | Gyroidinoides beisseli |
| 31 | 190 | Chatangiella niiga |
| 32 | 255 | Trithyrodinium suspuctum LCO |
| 33 | 368 | Palaeolenodinium cretaceum |
| 34 | 370 | Fenestrella bellii |
| 35 | 280 | Rzehakina epigona group |
| 36 | 326 | Haplophragmoides aff. walteri K&K |
| 37 | 284 | Globorotalites multiseptus |
| 38 | 194 | Spherical/Lenticular radiolarians |
| 39 | 330 | Inoceramus needles LCO |
| 40 | 195 | Stensioeina granulifera polonica |
| 41 | 65 | Nuttallinella florealis |
| 42 | 503 | Trithyrodinium 'reticulatum' |
| 43 | 369 | Chatangiella sp. 1 Strl. |
| 44 | 288 | Dinopterygium cladoides |
| 45 | 238 | Surculosphaeridium longifurcatum |
| 46 | 205 | Heterosphaeridium difficile |
| 47 | 24 | **Dicarinella concavata |
| 48 | 82 | Heterosphaeridium difficile LCO |
| 49 | 27 | Marginotruncana marginata |
| 50 | 26 | Marginotruncana coronata |
| 51 | 23 | **Dicarinella hagni |
| 52 | 22 | Dicarinella imbricata |
| 53 | 387 | Palaeohystrich. infusorioides LCO |
| 54 | 63 | Gaudryina filiformis |
| 55 | 83 | **Heterosphaeridium difficile FCO |
| 56 | 209 | Maghrebinia membraniphorum |
| 57 | 502 | Nyktericysta/Australosphaera |
| 58 | 272 | Stephodinium coronatum |
| 59 | 20 | **Praeglobotruncana stephani |
| 60 | 16 | Hedbergella delrioensis |
| 61 | 58 | Uvigerinamina jankoi |
| 62 | 445 | Bulboculites problematicus |
| 63 | 468 | C/T boundary gamma spike |
| 64 | 218 | Endoceratium detmanniae |
| 65 | 13 | Hedbergella planispira |
| 66 | 84 | Batioladinium jaegeri |
| 67 | 73 | Glomospirella gaultina |
| 68 | 18 | Whiteinella brittonensis |
| 69 | 212 | Hedbergella delrioensis LCO |
| 70 | 53 | Litosphaeridium siphoniphorum |
| 71 | 371 | Fromea sp. 2 Strl. |
| 72 | 89 | Epelidosphaeridia spinosa |
| 73 | 219 | Hedbergella planispira LCO |
| 74 | 92 | Rhombodella paucispina |
| 75 | 447 | **Textularia sp. 1 B&R81 |
| 76 | 75 | Gavelinella intermedia |
| 77 | 299 | Xiphophoridium alatum |
| 78 | 57 | Textularia foeda |
| 79 | 66 | Valvulineria gracillima |
| 80 | 342 | **Pseudotextulariella cretosa |
| 81 | 170 | Endoceratium turneri |
| 82 | 50 | Litosphaeridium conispinum |
| 83 | 526 | **Sigmollina antiqua |
| 84 | 90 | Ovoidinium verrucosum |
| 85 | 364 | Hedbergella delrioensis FCO |
| 86 | 93 | Ovoidinium scabrosum |
| 87 | 52 | Apteodinium grande |
| 88 | 60 | Falsogaudryinella alta |
| 89 | 220 | Osangularia schloenbachi |
| 90 | 241 | Globigerinelloides bentonensis |
| 91 | 353 | **Apteodinium grande LCO |
| 92 | 352 | Litosphaeridium arundum |
| 93 | 38 | **Ammonia globorotaliaeformis |
| 94 | 61 | Uvigerinamina una |
| 95 | 362 | Reopax minutus |
| 96 | 86 | Cribrostomoides nonioninoides |
| 97 | 96 | Lithodinia stoveri |
| 98 | 168 | Verneuilinoides chapmani |
| 99 | 104 | Gardodinium trabeculosum |
| 100 | 106 | Heslertonia heslertonensis |
| 101 | 103 | Dingodinium albertii/cerviculum |
| 102 | 109 | Sirmidodium grossii |
| 103 | 115 | Kleithrasphaeridium corrugatum |
| 104 | 401 | Lagena hauteriviana |
| 105 | 107 | Phoberocysta neocomica |
| 106 | 74 | Trocholina infragranulata |
| 107 | 111 | Batioladinium longicornutum |

Fig. 5 (continued).

fact that 44 out of 72 optimum sequence events have a lower than average standard deviation is good. Stratigraphic coverage is relatively good, even that, as usual, only 98 out of 519 events occur in six or more wells, and only 72 events occur in seven or more wells (Fig. 4). Cretaceous dinoflagellate cysts in particular show large taxonomic diversity, but limited traceability for many taxa.

The Cretaceous optimum sequence (Fig. 5, right) includes 98 events ('tops'), spanning Hauterivian through Maastrichtian strata. The preferred scaled optimum sequence contains 72 events; in addition, nine events noted with ** occur in fewer than seven wells but are inserted for the purpose of zonal definition and chronostratigraphic calibration. The events listed are average last occurrences (average 'top'), unless otherwise indicated; LCO stands for last common or last consistent occurrence, and FCO means first common or first consistent occurrence (in an uphole sense).

The so called 'Range' of taxa in the optimum sequence, which is a measure of the number of sequence positions an event spans (= rank positions in Fig. 5, right), is always low, except for *Fromea* sp. 2 (5 rank positions), *Dinopterygium cladoides* (6 rank positions), *Trithyrodinium reticulatum* (5 rank positions), *Gyroidina beisseli* (5 rank positions), *Chatangiella niiga* (5 rank positions), and *Chatangiella* sp. (10 rank positions). The last occurrence record for these taxa is not reliable for detailed correlations in the wells examined. The optimum sequence serves as a guide to the stratigraphic order in which events in wells are expected to occur, hence it is both predictive, and serves in high-resolution correlation, as outlined below.

Fig. 5 (left side) is the scaled optimum sequence for the Cretaceous in the 31 wells. Over a dozen stratigraphically successive RASC interval zones stand out, middle Albian through Maastrichtian in age, that guide the discussion of the 19 interval, acme and assemblage zones below. Resolution is poor in the lowermost and uppermost parts of the scaled sequence, and reflects lack of superpositional data, and condensation of 'tops' in the uppermost and lowermost Cretaceous part of wells.

The scaled optimum sequence shows major breaks between several successive zones, including between

the *una* and *schloenbachi* zones, *delrioensis* LCO and *brittonensis* zones, *Marginotruncana* and *polonica* zones, *bellii* and *dubia* zones, and particularly between *dubia* and *szajnochae* zones. The question what the meaning is of these large breaks, is best answered when we consider how RASC scaling operates. Scaling calculates the relative stratigraphic distance between successive events in the RASC optimum sequence. This relative distance is calculated from the frequency of cross-over of all possible pairs of events in the optimum sequence over all wells. Hence, large distances between successive events, corresponding to the larger RASC zonal breaks indicated above, signify strongly diminished cross-over between events that occur below and above the breaks. Reasons for these breaks thus must be thought in stratigraphic gaps, and paleoenvironmental changes that likely are connected to sequence stratigraphic changes. The reasons will be discussed in more detail below, but may be summarized as follows:

1. the *una*–*schloenbachi* break reflects a latest Albian lithofacies change and hiatus, connected to the Oteville hiatus in NW Europe.
2. the *delrioensis* LCO–*brittonensis* break reflects the mid-Cenomanian lithofacies change and hiatus, connected to the mid-Cenomanian non-sequence, and Rouen hardground.
3. the *Marginotruncana*–*polonica* break may be the turn-around in the tectono-eustatic phase of middle Coniacian, near the end of the Lysing sand deposition. The break occurs above the level of *Heterosphaeridium difficile* LCO, which represents a maximum flooding surface.
4. the *bellii*–*dubia* break occurs above the change from marly sediments to siliciclastic sediments that takes place in lowermost Campanian. The break, as the previous one, is near a maximum flooding event, i.e., the LCO of *T. suspectum* in the early middle Campanian.
5. the *dubia*–*szajnochae* break reflects the abrupt change from siliciclastic to marly sediment at the Campanian–Maastrichtian boundary, noted in the southern part of the region.

Within the major units, smaller zonal subdivisions may be recognized, using a combination of subjective judgement from individual well study, and objective subdivision from ranking and scaling analy-

sis. Hence, the final zonation takes advantage of both subjective, and more objective analysis, and integrates the two into one framework.

The zones are named after prominent foraminiferal taxa, that are easily recognized in the wells, and are relatively widespread. The zones are informal, and their description is bound to change with addition of more data, and further assessment of taxonomy. Some of the foraminiferal index taxa (*Trocholina*, *Blefusciuna*, *Globigerinelloides gyroidinaeformis*, *Hedbergella brittonensis*, *Marginotruncana coronata* and *Dicarinella concavata*) are rare due to the high-latitude setting of the study region, or poor preservation of carbonate tests in the siliceous mudstones. As mentioned earlier, integration, using the RASC method, with dinoflagellate events, improves the applicability of both types of microfossils for regional biostratigraphy.

Chronostratigraphic assignments are tentative, hampered among others by the absence, or scarcity of keeled planktonic foraminifers, like *Rotalipora*, and the majority of *Dicarinella*, *Marginotruncana*, and *Globotruncana*. Zones of short stratigraphic duration, like the *Sigmoidina antiqua* Zone, assigned to lower Cenomanian may be difficult to observe in ditch cuttings, particularly when the lithology is sandy. There is ample room for improving the resolution of the lower and upper parts of the zonation. For example in the condensed Hauterivian–Barremian, and hiatus riddled Aptian–middle Albian sections, and in the thick, carbonate devoid strata of the inner Voering Basin, assigned to Campanian. The latter represents a poorly sampled section, probably laid down on a deep marine, middle bathyal basin floor.

Stratigraphic range charts of principal taxa in the zonation are in Fig. 7a–c. The charts, like Fig. 6a and b, also show the foraminiferal zonation, established in this study, and treated in detail below. Taxon names followed by FO or FCO are events that help to define the lower level of the zones; similarly, taxon names followed by LCO or LO are events that assist with delineation of the upper level of zones.

5.5.1. *Protomarssonella kummi* zone

This zone is defined on the upper range of *Protomarssonella kummi*, prior to the acme of *Falso-*

(a)

| AGE (m.y.) | STANDARD STAGE | Offshore Norway Zonation (this study) | | | | North Sea Zonation of King et al. (1989) | | | | | | | |
|------------|----------------|---------------------------------------|----------------|---|---|---|-----------------------------------|--|--|----------------------|---------------------------------------|---|-----------------------|
| | | shale facies | marly facies | South + North | Stratigraphical Index Taxa | South | FCN | Shale facies | FCS | marly facies | | | |
| 100 | ALBIAN | late | schloenbachi | | <i>Osangularia schloenbachi</i> , <i>Falsogaudryinella alta</i> , <i>Epistomina spinulifera</i> | | 12a | <i>O. schloenbachi</i> | <i>O. schloenbachi</i> | 12 | <i>A. sabulosa</i> | <i>A. salebrosa</i> | |
| | | | ? / hiatus / ? | | | | 11 | <i>G. bentonensis</i> | <i>G. bentonensis</i> | 11 | <i>G. bentonensis</i> | <i>G. bentonensis</i> | |
| | | | una | | <i>Uvigerinammina una</i> n.sp., <i>Cribrostomoides nonioninoides</i> | | 10b | <i>Falsogaudryin. sp. 1</i> | <i>Falsogaudryinella sp. 1</i> | 10 | "Inoceramus" | <i>Inoceramus</i> flood <i>O. schloenbachi</i> | |
| | | middle | Recurvoides | | <i>Recurvoides</i> spp. LCO | | 10a | Recurvoides sp. | | 9 | <i>O. schloenbachi</i> | | |
| | | | hiatus | | | | 9 | <i>G. gyroidinaeformis</i> | "G." <i>gyroidinaeformis</i> | | | | |
| | 110 | early | | gyroidinaeformis | | " <i>Globigerinelloides</i> " <i>gyroidinaeformis</i> <i>Plectorecurvoides irregularis</i> | | | | | | | |
| | | | | chapmani | | <i>Verneulinoides chapmani</i> | | 8 | <i>Verneulinoides chapmani</i> | <i>V. chapmani</i> | 8b | <i>Reophax minutus</i> | Agglutinants dominant |
| | | late | hiatus | | | | 7 | <i>Hedbergella infracretacea</i> | <i>H. infracretacea</i> common | 8a | <i>Gaudryina dividens</i> | <i>G. dividens</i> consistent | |
| | | early | infracretacea | | <i>Hedbergella infracretacea</i> acme | | 7 | <i>Hedbergella infracretacea</i> | | 7 | <i>Hedbergella infracretacea</i> | <i>H. infracretacea</i> common | |
| | | late | intercedens | | <i>Conorotalites intercedens</i> <i>Gavelinella barremiana</i> | | 6 | <i>Gavelinella barremiana</i> | <i>G. barremiana</i> | 6b | <i>C. intercedens</i> | <i>C. intercedens</i> | |
| 120 | BARREMIAN | late | barremiana | | <i>Falsogaudryinella xenogena</i> , <i>Blefusculana</i> spp., <i>A. neocomiensis</i> | | 5 | <i>Falsogaudryinella sp. X</i> | <i>Falsogaudryinella sp. X</i> (= <i>F. xenogena</i> Kaminski et al., 1995) | 6a | <i>Gavelinella barremiana</i> | <i>G. barremiana</i> | |
| | | mid | xenogena | | <i>E. caracolla</i> , <i>E. omata</i> | | 5 | <i>Falsogaudryinella sp. X</i> | | 5 | <i>E. caracolla</i> | <i>E. caracolla</i> | |
| | early | caracolla | | | | 4 | <i>Falsogaudryinella moesiana</i> | <i>F. moesiana</i> (= <i>F. praemoesiana</i> Kaminski et al., 1995) | 4b | <i>H. aequale</i> | <i>H. aequale</i> , <i>W. antiqua</i> | | |
| 130 | HAUTERIVIAN | late | praemoesiana | | <i>Falsogaudryinella praemoesiana</i> , nodosariid/ostracod LCO <i>G. sigmaicosta</i> | | 4 | <i>Falsogaudryinella moesiana</i> | <i>P. kummi</i> | 4a | --- | <i>P. kummi</i> , <i>L. nodosa</i> consistent | |
| | | early | kummi | | <i>Protomarssonella kummi</i> , <i>Trocholina infragranulata</i> | | 3 | <i>Marssonella kummi</i> | <i>T. infragranulata</i> | 3b | <i>Marssonella kummi</i> | | |
| | late | hiatus | | <i>C. harpa</i> , <i>L. nodosa</i> , <i>C. lamplughii</i> , <i>L. ouachensis wisselmanni</i> | | 2 | <i>Trocholina infragranulata</i> | | 3a | <i>H. inconstans</i> | <i>H. inconstans</i> | | |
| 140 | RYAZANIAN | late | hiatus | | | | 1 | <i>Haplophragmoides</i> spp. | Agglutinants only | 2 | <i>Ammovertella cellensis</i> | <i>A. cellensis</i> | |
| | | early | hiatus | | | | 1 | | | 1 | --- | <i>A. cellensis</i> | |

Fig. 6. (a) Lower Cretaceous zonation, offshore mid-Norway with stratigraphical index taxa for shaly facies (more predominant northward), and for marly facies (more predominant southward). The zonation compares with the North sea zonation for shaly (north) and for marly (south) facies of King et al. (1989), with which it shows taxa and zones in common. Seemingly, stratigraphic resolution decreases northward, but this is partly a bias from a much more limited data set than available to King et al. (op. cit.) in the North Sea. The present study depends on fewer, stratigraphically more patchy wells. (b) Upper Cretaceous zonation, offshore mid-Norway, with stratigraphical index taxa for the region under study and taxa observed in its southern part only. The zonation is compared to the RASC model zonation using foraminifera and dinoflagellates (Fig. 5). The zonation compares well with the North Sea zonation for shaly facies by King et al. (1989), and is slightly more detailed in part. As expected, the chalk facies zonation of the North Sea does not compare or apply.

(b)

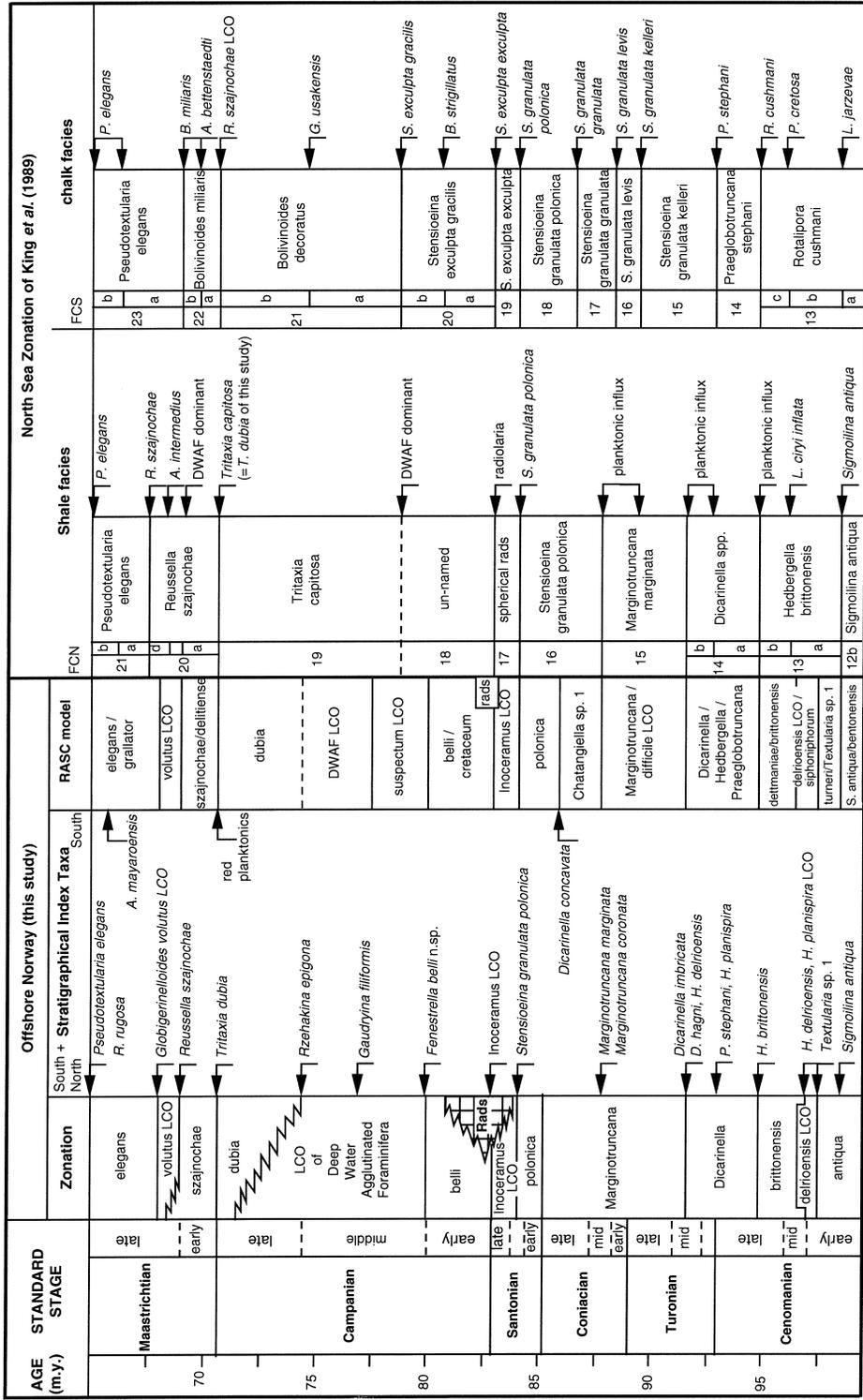


Fig. 6 (continued).

Table 3

Summary of data properties and RASC run results for the 31 wells data set discussed in this study, using Cretaceous microfossil

| Summary of data properties and RASC15 results | |
|---|------|
| Number of names (taxa) in the dictionary | 589 |
| Number of wells | 31 |
| Number of dictionary taxa in the wells | 519 |
| Number of event records in the wells | 1755 |
| Number of cycles prior to ranking | 21 |
| Number of events in the optimum sequence | 72 |
| Number of events in optimum sequence with S.D. < ave. S.D. | 44 |
| Number of events in the final scaled optimum sequence (including unique events shown with **) | 81 |
| Number of stepmodel events with more than six penalty points after scaling | 14 |
| Number of normality test events shown with * or ** | 78 |
| Number of AAAA events in scaling scattergrams | 20 |

There are 519 dictionary taxa in the wells, 72 of which occur in seven or more wells, the threshold in the scaled optimum sequence of Fig. 5. For further discussion, see text.

gaudryinella praemoesiana (Fig. 7a). The following taxa were observed in assemblages assigned to the zone:

Protomarssonella kummi LO

common to abundant nodosariids and ostracods

Falsogaudryinella praemoesiana FO (rare)

Patellina subcretacea

Trocholina infracretacea

Globospirillina neocomiana

Spirillina spp.

Lagena hauteriviana

Lenticulina aff. *subalata*

Lenticulina cf. *bunardoi* LO

Lenticulina munsteri (common)

Lenticulina heiermanni

Epistomina tenuicostata

Age: Hauterivian, probably early to mid Hauterivian.

Environment: Neritic, carbonate substrate; higher numbers of attached forms such as *Patellina subcretacea* Cushman and Alexander, *Trocholina infragranulata* Noth, *Globospirillina neocomiana* (Moulade), and *Spirillina* spp., indicate shallow neritic conditions.

Remarks: This assemblage displays high species diversity and high numbers of specimens. Preservation is good, colour is reddish.

Occurrence: Found in the 33/9–15 well (Fig. 8) between 2731.7 and 2733 m, and observed in numerous other wells in the Viking Graben. The foraminiferal assemblage at the base of the studied sec-

tion in well 33/9–15, is dominated by *Globospirillina neocomiana* and *Patellina subcretacea*. At 2731.7 m, *Falsogaudryinella praemoesiana* is still common, but in the lower sample (2733 m) it is only represented by a single specimen. Accessory species include *Lenticulina munsteri*, ammodiscids, and nodosariids. A single occurrence of a species of *Protomarssonella* that closely resembles *M. kummi* is present at 2733 m.

This type of assemblage has not been observed in the studied wells, offshore mid-Norway, where the lower part of the Lower Cretaceous interval (between the Upper Jurassic Spekk Formation and the upper Hauterivian–Barremian Lyr Formation) is represented by a hiatus.

Correlation: The assemblage probably corresponds to the *Marssonella kummi* (= FCN 3) zone of King et al. (1989) in the Viking Graben. The species *M. kummi* has been subsequently transferred to the genus *Protomarssonella* Banner and Desai (1988). This zone can be difficult to recognise, because the nominate species is often rare or absent. According to King et al. (op. cit.), either the LO of *P. kummi*, or the FO of *Falsogaudryina praemoesiana* can be used to identify the top of the zone.

The *Trocholina infragranulata* (= FCN 2) zone of King et al. (op. cit.) was not recognised in this study, because its occurrence is facies-related, and clearly diachronous. King et al. regarded it as Valanginian, corresponding to the 'basal Valhall limestone' facies of the Viking Graben. However,

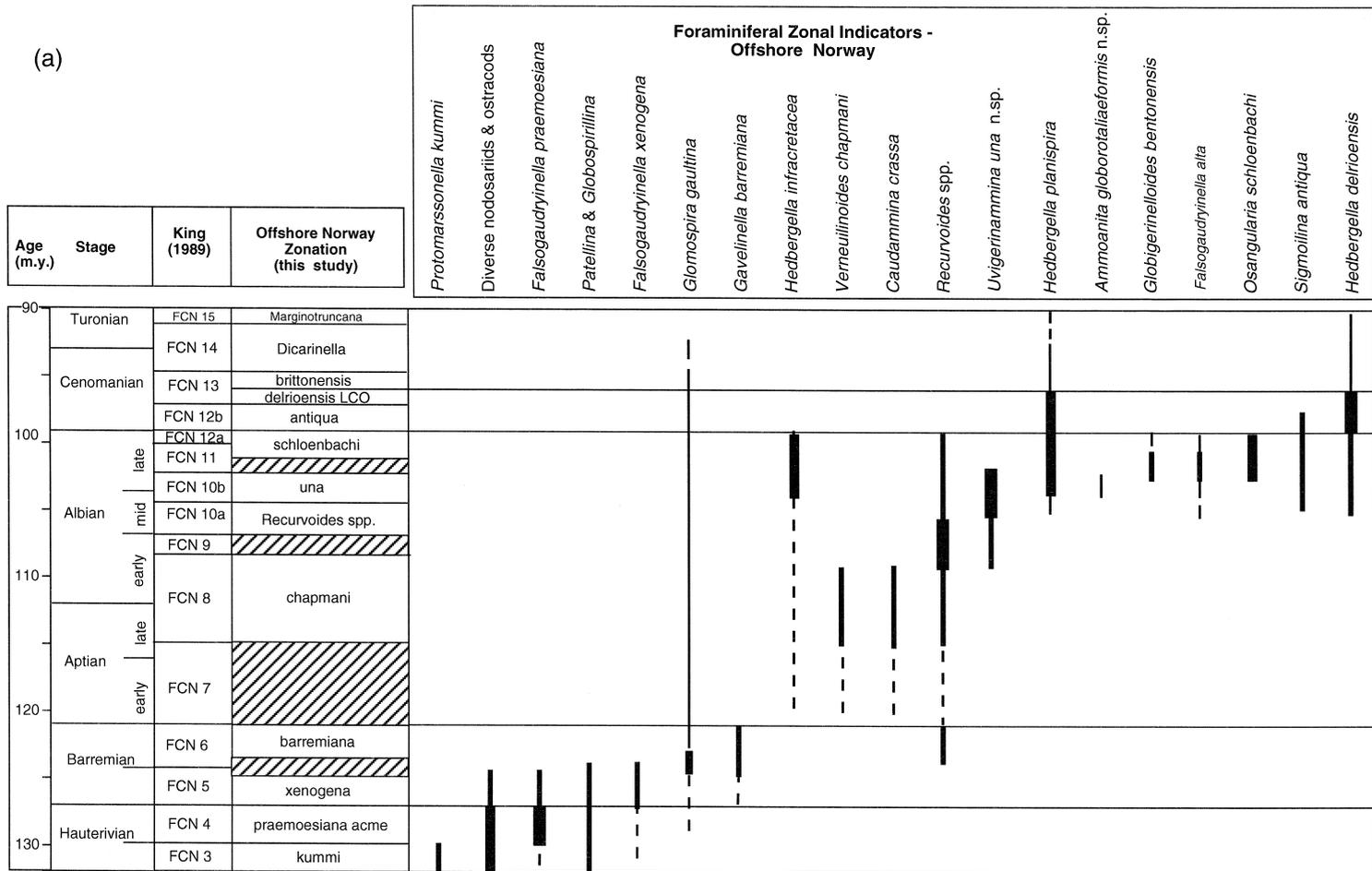


Fig. 7. (a) Stratigraphic ranges of Lower Cretaceous index taxa, offshore mid-Norway, with the foraminiferal zonation established in this study. Geochronology in a–c follows Gradstein et al. (1995). (b) Stratigraphic ranges of Upper Cretaceous planktonic foraminifera index taxa, offshore mid-Norway, with the foraminiferal zonation established in this study. (c) Stratigraphic ranges of Upper Cretaceous benthic foraminifera, and miscellaneous index taxa, offshore mid-Norway, with the foraminiferal zonation established in this study.

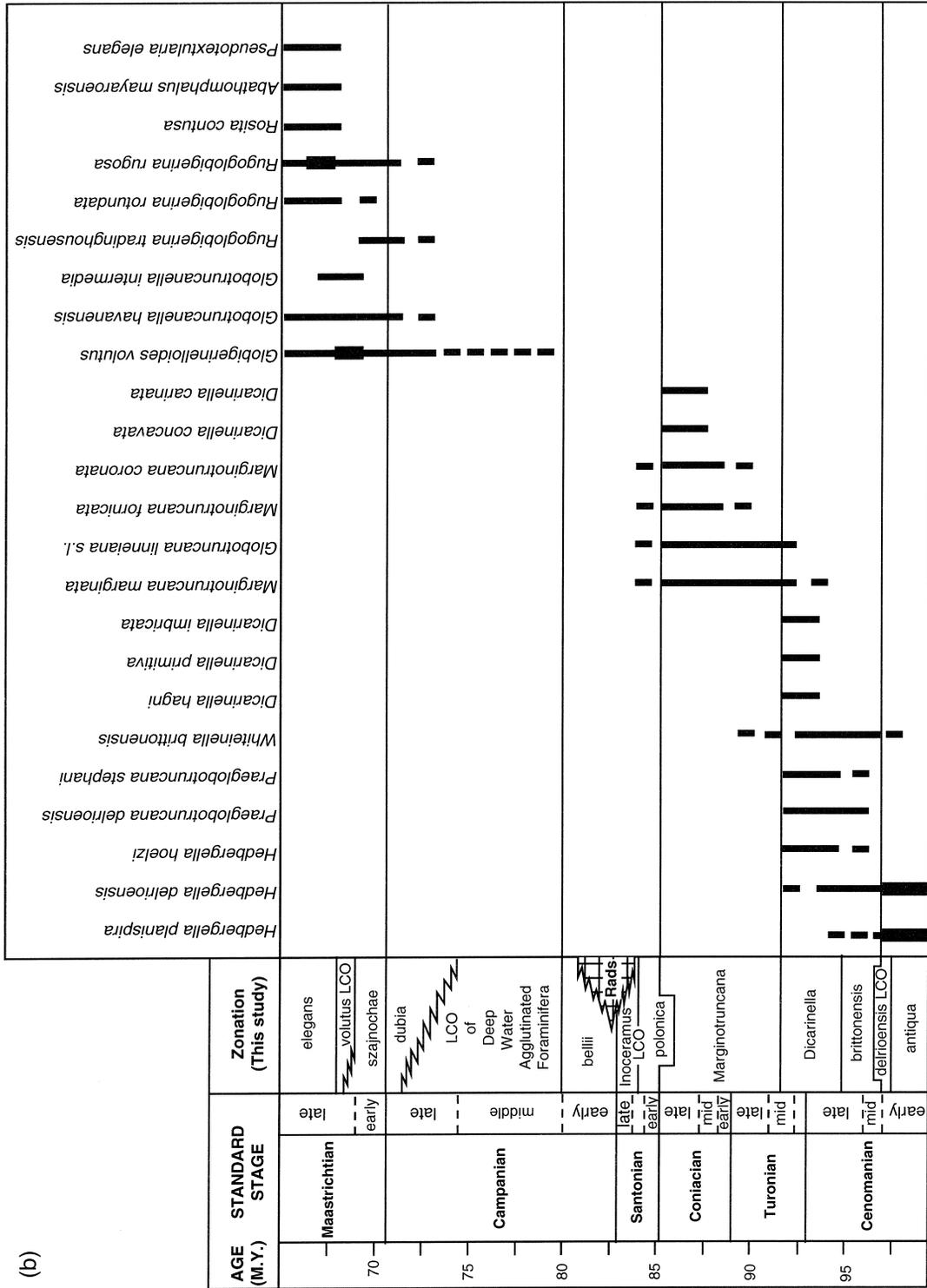


Fig. 7 (continued).

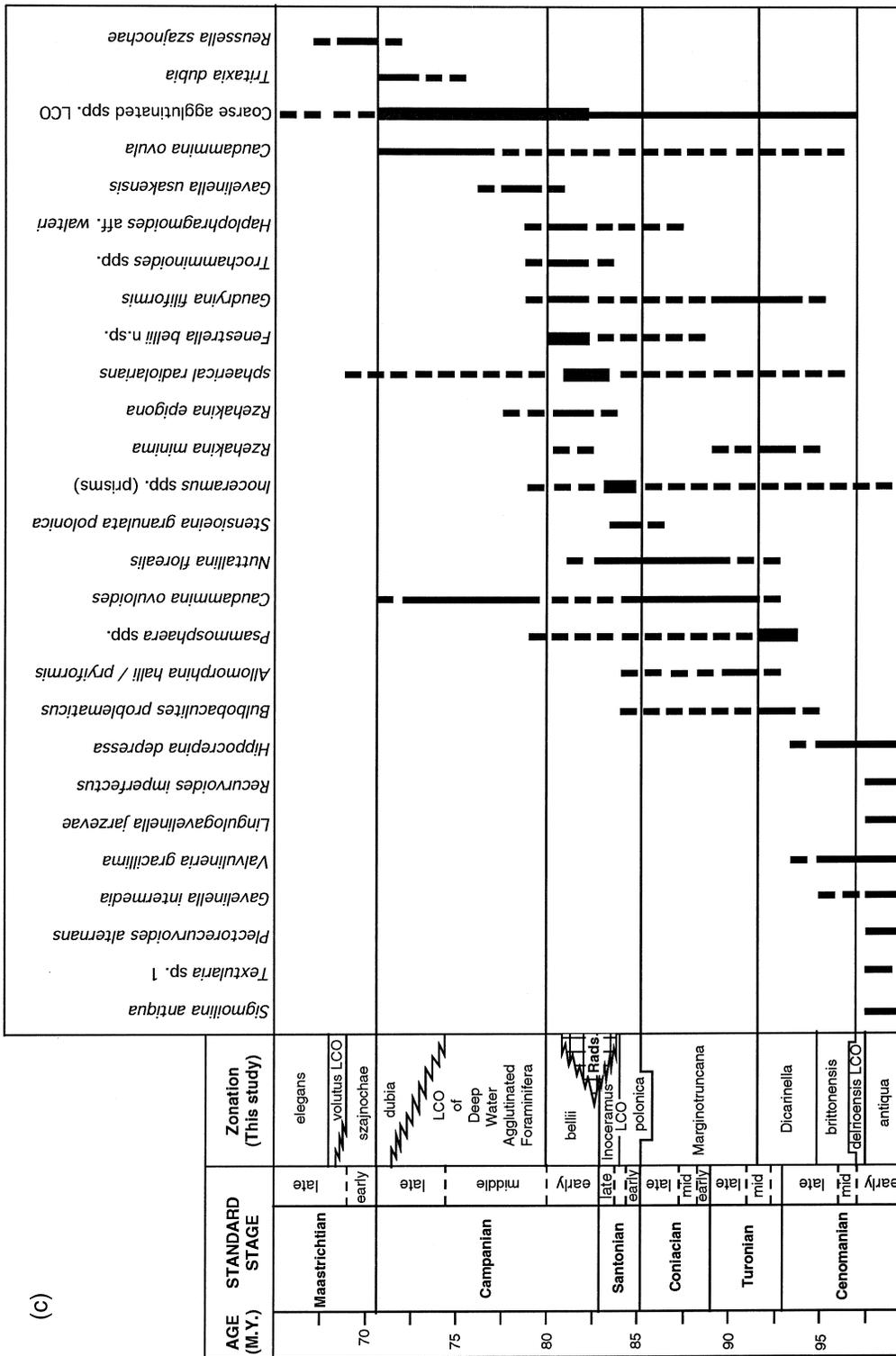


Fig. 7 (continued).

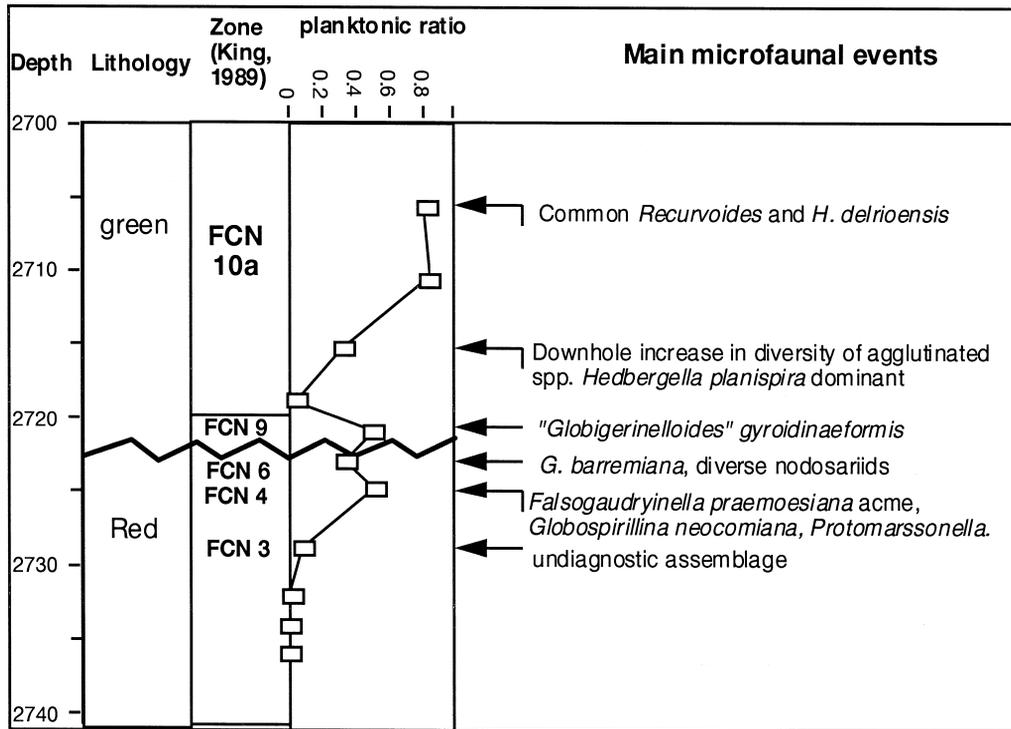


Fig. 8. Stratigraphically important events and interpreted biostratigraphy in the studied interval in well 33/9–15. Note the meters thin interval assigned to the early late Albian planktonic foraminifer *Globigerinelloides gyroidinaeformis* zone, presently the northernmost occurrence of this zone in the region. Slightly higher in this highly condensed core is the FCO of *Hedbergella planispira*, followed by the FO of *H. delrioensis* in the *Uvigerinammina una* zone, across the middle to late Albian boundary.

the species also occurs in limestones as young as Barremian in condensed facies deposited in shallower parts of the Viking Graben. Offshore mid Norway specimens were observed in the lower Barremian. Neagu (1975) also reported it from the Barremian of Romania.

5.5.2. *Falsogaudryinella praemoesiana* zone

This is a distinctive assemblage, defined on the concurrence of abundant *Falsogaudryinella praemoesiana*, abundant nodosariids and ostracods, and rare to common *Patellina* and *Globospirillina* (Fig. 7a). The zone corresponds to the base of the Lyr Formation in the study area. The following taxa were observed in the zone:

Falsogaudryinella praemoesiana LCO (abundant)
Falsogaudryinella tealbyensis (rare)
Falsogaudryinella xenogena (rare)

Recurvoides spp.

Glomospira spp. (rare)

Trocholina infracretacea (rare)

Patellina subcretacea

Globospirillina neocomiana: common to abundant nodosariids, and ostracods LCO

Lingulina semiornata LO

Lenticulina aff. *subalata*

Lenticulina cf. *busnardo* LO

Lenticulina munsteri (common)

Lenticulina heiermanni LO

Lenticulina ouachensis wisselmanni LO (rare)

Citharina harpa (rare)

Planularia crepidularis (rare)

Epistomina tenuicostata LO (rare)

Epistomina hechti

Epistomina caracolla

Conorboides lamplughii LO

Lagena haueriviana LO

Gavelinella sigmoicostata LO (rare)

small planktonics, including *Blefuscuiana* spp. (rare).

Age: Generally late Hauterivian, though locally persisting in the earliest Barremian.

Environment: Neritic; locally either shallow or deep neritic.

Remarks: The upper boundary of the zone is recognised based on the LCO of *Falsogaudryinella praemoesiana* Kaminski, Neagu and Platon. The nominate species is abundant within the zone (as much as 50% of the assemblage), but it also persists in low numbers into the overlying zone. The assemblage is characterised by high species diversity, but also high dominance. It is often dominated by the species *Falsogaudryinella praemoesiana*, but *Recurvoides* and/or *Glomospira* may also be present in large numbers. The proportion of agglutinated taxa is higher compared with the underlying zone.

Direct comparisons with the type specimens of *Falsogaudryinella moesiana* Neagu described from the middle Albian of Romania revealed that the nominate species of this acme zone in the North Sea is indeed a different species. Because it has characters that are considered to be more primitive, Kaminski et al. (1995a,b) erected the new species *Falsogaudryinella praemoesiana*.

Occurrence: This zone is readily observed in wells, offshore mid Norway. In the 33/9–15 well a single core sample collected from 2729 m contains an assemblage that is completely dominated by *Falsogaudryinella praemoesiana* and *Protomarssonella subtrochus*. Additional taxa include common ammodiscids (*Ammodiscus tenuissimus*, *Glomospira charoides*, *G. gordialis*), *Lenticulina munsteri*, and *Globospirillina neocomiana*. This level corresponds to the late Hauterivian *F. praemoesiana* acme zone (= FCN 4 of King et al., 1989). Rare planktonic foraminifers are represented by *Blefuscuiana* spp.

Because of the sample spacing in the 33/9–15 well (there is 4 m gap between samples), we cannot assume that there is a hiatus between the upper Hauterivian and upper Barremian (see below). Perhaps more detailed sampling will reveal the presence of the lower Barremian *F. xenogena* zone as well.

Correlation: This assemblage corresponds to the *Falsogaudryinella moesiana* (= FCN 4) zone of King

et al. (1989). King equated the top of this zone to the top of the Hauterivian. However, the identification of the top of this acme zone is somewhat subjective. In the Viking Graben, the maximum numbers of *Falsogaudryinella praemoesiana*, on average are found below the Monk Marl horizon, which is assigned to lower Barremian, but in some well sections, the acme of this species persists into the lowermost Barremian. The species *Falsogaudryinella praemoesiana* also occurs in the upper Hauterivian in Romania (Dambovicioara Valley).

5.5.3. *Falsogaudryinella xenogena* zone

This zone is defined on the upper part of the ranges of *Falsogaudryinella xenogena*, *F. praemoesiana*, *Patellina*, and *Globospirillina* (Fig. 7a). Assemblages assigned to this zone typically contain the following taxa:

Falsogaudryinella praemoesiana LO (rare)

Falsogaudryinella xenogena LO (rare)

Recurvoides spp.

Glomospira spp. (rare)

Textularia bettenstaedti

Ammobaculoides carpathicus LO (rare)

Trocholina infracretacea LO (rare)

Patellina subcretacea LO

Globospirillina neocomiana LO

common to abundant nodosariids and ostracods

Gavelinella barremiana FO

Lenticulina munsteri (common)

Lenticulina aff. *subalata*

Lenticulina guttata

Lenticulina saxonica LO

Saracenaria spp.

diverse unilocular species

Epistomina hechti LO

Epistomina ornata LO

Epistomina caracolla LO

Conorotalites bartensteini LO (rare)

small planktonics (*Blefuscuiana* spp.) (rare).

Age: Early Barremian.

Environment: Neritic.

Remarks: The assemblage assigned to this zone is easily distinguished from the overlying non-calcareous, agglutinated assemblages by the presence of diverse, red-stained lenticulinids and nodosariids. The nominate species, *Falsogaudryinella xenogena*

is never common, and it is found co-occurring with *F. praemoesiana*.

Occurrence: Found widespread offshore mid Norway, where it is characteristic of the reddish, calcareous sediments of the Lyr Formation.

Correlation: Corresponds to the *Falsogaudryinella* sp. X (= FCN 5) zone of King et al. (1989). The species illustrated by King et al. (op. cit.) was named *Falsogaudryinella xenogena* by Kaminski et al. (1995a,b), partly because the authors wished to preserve the letter 'X' in the name. The name also refers to the fact that it is 'foreign', (i.e., not observed in the Tethys region). In the Viking Graben, the nominate species mostly occurs in the lower to middle Barremian. It generally occurs below the Monk Marl horizon, though it is occasionally observed in or above it, partially overlapping in range with *Gavelinella barremiana*, the nominate species of the overlying zone.

In the absence of the nominate taxon, the LO of diverse, reddish lenticulinids can be used to recognize the top of the zone. Offshore mid Norway, the sediments immediately overlying the zone, are non-calcareous claystones and their benthic foraminiferal assemblages are stained green. At localities in the Viking Graben (UKCS Blocks 21 and 22) where the Barremian section is more complete, the first down-hole occurrence of diverse lenticulinids, and a peak in their relative abundance correlates to a level just below the Monk Marl (ca. 20–40 m below).

Offshore mid-Norway, the lateral equivalent of the Monk Marl horizon was not observed in the logs, possibly owing to the presence of a hiatus. This horizon represents a regional dysaerobic facies in the North Sea, and contains a distinctive, white-stained benthic foraminiferal assemblage, with common *Glomospira*. The species *Glomospira gaultina* is well represented in the Monk Marl. The significance of Lower Cretaceous *Glomospira* assemblages has been discussed by Kaminski et al. (1992).

5.5.4. *Gavelinella barremiana* zone

This zone is defined on the upper part of the range of *Gavelinella barremiana* (Fig. 7a). Assemblages assigned to this zone typically contain the following taxa:

Gavelinella barremiana LO
Glomospira spp. (common)

Recurvoides spp. (common)

small specimens of *Gyroidinoides* aff. *infracretaceus*.

Age: Barremian.

Environment: Deep neritic.

Remarks: The assemblage consisted of small-size, reddish-stained specimens. The accessory species, tentatively identified as *Gyroidinoides* aff. *infracretaceus*, differs from the typical Albian form in its much smaller size and in possessing fewer chambers.

Occurrence: The zone is rarely observed, offshore mid-Norway, due to the common presence of a hiatus, extending through part of the Aptian. A single core sample collected at 2725 m in well 33/9–15 in the northern Viking Graben, recovered a rich foraminiferal assemblage, assigned to this zone. The sample consists almost entirely of red-coloured calcareous benthic foraminifers, dominated by the Barremian index species *Gavelinella barremiana* Bettenstaedt. This species is the index taxon of the upper Barremian *G. barremiana* zone (= FCN 6 of King et al., 1989). The sample also includes diverse nodosariids, and single specimens of *Gyroidinoides* and *Ammodiscus*.

Correlation: *Gavelinella barremiana* Bettenstaedt is a cosmopolitan species, known from the upper middle Barremian to upper Barremian of the northern North Sea, and from the upper Barremian to lower Aptian of northwest Germany, and offshore Canada. This zone is equivalent to the *G. barremiana* (= FCN 6) zone of King et al. (1989).

5.5.5. *Verneulinoides chapmani* zone

This zone is defined on the upper part of the ranges of *Verneulinoides chapmani*, and *Caudammina crassa* (Fig. 7a). Assemblages assigned to this zone consist mostly of green-stained, deep-water agglutinated foraminifers. However, in some wells, some calcareous species may also be present with few specimens, especially at the base of the zone. The following taxa have been observed in assemblages assigned to the zone:

Verneulinoides chapmani LO

Caudammina crassa

Recurvoides spp. (common)

Glomospira sp. (common)

Cribrostomoides nonioninoides LCO (frequent)

Kalamopsis grzybowskii (rare)

Glomospira gaultina (rare)

Bathysiphon sp. (rare)

Rhabdammina, *Rhizammina* (few).

Age: Late Aptian–early Albian.

Environment: Outer neritic–upper bathyal.

Remarks: The taxonomic diversity is relatively high, and some deep-water taxa are present, including *Kalamopsis grzybowskii*, *Bathysiphon* sp., and *Caudammina crassa*. The relative proportion of *Glomospira gordialis* is higher in the lower part of the zone. Increased numbers of tubular agglutinated forms such as *Rhabdammina*, *Rhizammina*, and *Bathysiphon* are interpreted as indicating deposition in deeper water. Dinoflagellate events present in this zone include the LO of *Lithodinia stoveri* (Fig. 5, right).

Occurrence: Observed widespread, offshore mid Norway.

Correlation: This zone is equivalent to the *Verneuilinoides chapmani* (= FCN 8) zone of King et al. (1989). In the lower part of the zone, the ratio of *Glomospira gordialis* to *Glomospira charoides* increases considerably. This feature is often observed in the lower Albian of the Viking Graben, and probably denotes a more dysoxic environment. In the lowermost part of the zone, a few pyritized specimens of *Lenticulina*, and other calcareous benthics are occasionally observed. This is consistent with the observation by King et al. (1989), that calcareous benthic foraminifers sometimes “re-appear downsection in the lowest part of the [*V. chapmani*] zone”. King et al. (op. cit.) correlated the lowest part of zone FCN 8 with the uppermost Aptian. In all the wells studied, the base of this zone lies discontinuously upon the Barremian (mostly lower Barremian) Lyr Formation. Therefore, a regional hiatus that encompassed most of the Barremian and Aptian is present in the area. The hiatus corresponds to a change in lithology from reddish marls and limestones below, to greenish non-calcareous claystones above.

5.5.6. *Recurvoides* / *Glomospira* zone

This assemblage zone contains the following characteristic species:

Recurvoides spp. (acme)

Plectrorecurvoides irregularis

Glomospira charoides (abundant)

Glomospira gordialis

Ammodiscus spp.

Uvigerinammina una n. sp. (rare)

Cribrostomoides nonioninoides (rare)

Textularia spp. (rare)

Pseudobolivina variabilis

Gyroidinoides infracretaceus

Gavelinella intermedia.

Age: Middle Albian.

Environment: Upper bathyal.

Remarks: The assemblage is strongly dominated by *Recurvoides* spp., and *Glomospira* spp. The other agglutinated species listed above occur as single specimens. The calcareous benthic and planktonic forms are rare, and may be caved.

Occurrence: The zone is missing in many wells due to a widespread hiatus of Aptian through early middle Albian age; it occurs condensed in well 6406/2–2.

Correlation: This zone corresponds to the *Recurvoides* sp. (= FCN 10a) zone of King et al. (1989). The species *Globigerinelloides gyroidinaeformis*, the nominate taxon of the King’s underlying zone FCN 9 has not been observed, offshore mid-Norway. It is, however, known from the northern Viking Graben in well 33/9–15 (Fig. 8) at 2723 m, dated latest early Albian. The core sample collected at 2723 m in that well contains an assemblage comprised mainly of calcareous benthic species and *Hedbergella*. The dominant (and most distinctive) taxon is *Globigerinelloides gyroidinaeformis* Moullade, a species that is probably a benthic form because of its slightly streptospiral coiling, unusual for planktonics. Moreover, it is often found in assemblages where other well-known planktonic forms are absent. This distinctive species is often observed as a ‘flood’, and defines the latest early Albian *Globigerinelloides gyroidinaeformis* (FCN 9) zone in the Viking Graben (King et al., 1989). The species is also known from the Grand Banks, offshore eastern Canada, and from the Vocontian Basin, France. This stratigraphic level has not yet been found further north in the region; either the species is ecologically excluded from the area (which is unlikely, as it is common in the Viking Graben) or more likely, a hiatus is present in the offshore mid-Norway area.

5.5.7. *Uvigerinammina una* zone

This zone is defined on the upper part of the range of *Uvigerinammina una*, together with *Ammonoanites globorotaliaformis* (Figs. 5 and 7a). Assemblage assigned to this zone generally consist of diverse, green-stained deep-water agglutinated foraminifers, with few calcareous benthics present, and common to frequent planktonics, belonging to few species. The following taxa have been observed in the zone:

Uvigerinammina una n. sp. LO (common)
Falsogaudryinella alta
Textularia bettenstaedti (rare)
Haplophragmoides spp.
Reophax troyeri LO
Ammonoanites globorotaliaformis n. sp. LO
Cribostratoides nonioninoides LO
Trochammina abrupta
Gyroidinoides infracretaceus
Gavelinella intermedia
Pleurostomella barrowsi LO
Glomospira charoides
Glomospira gordialis
Hedbergella planispira FCO
Hedbergella infracretacea (common)
Hedbergella delrioensis (rare)
Globigerinelloides bentonensis (rare).

Age: Late middle to early late Albian.

Environment: Upper bathyal.

Remarks: Assemblages assigned to this zone, typically are comprised of agglutinated, and few calcareous benthic taxa, and often common to frequent planktonics, mostly *Hedbergella planispira*. The nominate taxon, *Uvigerinammina una* n. sp. apparently is a boreal species restricted to the Norwegian Sea and North Sea region. It appears not to possess calcareous cement, therefore it cannot be assigned to the genus *Falsogaudryinella*. Most likely it belongs in the genus *Uvigerinammina*, as originally reported by Burnhill and Ramsay (1981); more details are in Appendix B. It has not been found in the Albian of the Kirchrode-1 Borehole (Jaroslaw Tyszka, personal communication), or in deep-sea deposits. The acme of *Uvigerinammina una* n. sp. itself often forms a narrow zone, but it is also found in low numbers in both the overlying and underlying zones. Additionally, the LO of *Pseudonodosinella troyeri* (= *Reophax minuta* of other authors) and the

LO of *Textularia bettenstaedti* have been observed in this zone. Both events are reported to occur within the early Albian *R. minuta* zone (zone FCS 8), of King et al. in the southern North Sea. *Uvigerinammina una* n. sp. is formally described as a new taxon in Appendix B.

According to our observations, *Ammonoanites (Trochammina) globorotaliaformis* n. sp. has a tighter coil than the Paleocene *A. ingerlisae* Gradstein and Kaminski and, on average more (not fewer) chambers in the last whorl. In local well completion reports such specimens are referred to as *Trochammina globorotaliaformis*, and constitute a useful mid-upper Albian index species. This *A. globorotaliaformis* n. sp. is formally described as a new taxon in Appendix B.

Dinoflagellate events present in this zone include (Fig. 5) *Apteodinium grande* LCO, and *Lithosphaeridium arundum* LO; *Ovoidinium scabrosum* and *Endoceratium turneri* range through this zone upwards. In the zone, as far as observed in several wells, the number of planktonic foraminifers increases stratigraphically upwards, reflecting a change from more restricted marine (dysaerobic) to more oxygenated, open marine conditions. A similar change was reported by King et al. (1989) from the northern North Sea, as reflected in a change from non-calcareous to calcareous claystone (top of Sola Formation). This environmental change is further discussed in Chapter 7 on Paleobathymetry.

Occurrence: Found in a majority of the wells studied, offshore mid-Norway.

Correlation: This zone corresponds to the *Falsogaudryinella* sp. 1 (FCN 10b) zone of King et al. (1989). In the Kirchrode-1 Borehole in the Lower Saxony Basin, the change from dominant *Hedbergella planispira* (below) to *Hedbergella delrioensis* (above) is observed within the early late Albian *P. columnata* calcareous nannofossil zone, and the *Ticinella raynaudi* planktonic foraminiferal zone (Weiss, 1997). The zone probably correlates to the *inflatum* ammonite zone.

5.5.8. *Osangularia schloenbachi* zone

This zone is defined on the upper part of the stratigraphic range of *Osangularia schloenbachi*, *Sigmoilina antiqua*, *Falsogaudryinella alta*, and *Glo-*

bigerinelloides bentonensis may co-occur. (Figs. 5 and 7a). Assemblages assigned to this zone typically contain the following taxa:

Osangularia schloenbachi LO (rare to common)

Gavelinella intermedia

Gyroidinoides infracretaceus

Sigmoilina antiqua

Lenticulina muensteri

Epistomina spinulifera LO

Valvulineria gracillima (rare)

Falsogaudryinella alta LO (rare)

Clavulina gaultina

Glomospira charoides (often common)

Ammodiscus tenuissimus

Hedbergella infracretacea LO (common)

Hedbergella delrioensis FCO

Hedbergella planispira (rare)

Globigerinelloides bentonensis FO

pink coloured *Inoceramus* prisms.

Age: Late Albian.

Environment: Upper bathyal.

Remarks: This is a diverse assemblage, comprised of calcareous and agglutinated taxa, stained green. The species *Osangularia schloenbachi* occurs as an acme, and rare specimens are found in the underlying zone. The species is known from the upper Albian of Romania, Poland, Germany and France, and is probably of Tethyan origin. In addition to the nominate taxon, *Gavelinella intermedia*, *Gyroidinoides infracretaceus*, and lenticulinids are also common, as well as *Glomospira charoides*. Planktonic foraminifers are often abundant, and are strongly dominated by small specimens of *H. delrioensis*, probably the stratigraphic onset (FCO) of a regional bloom that ends in the *Hedbergella delrioensis* LCO zone, as discussed below (Fig. 11).

Dinoflagellate taxa present in the zone include *Lithosphaeridium conispinum* LO, *Ovoidinium scabrosum* LO and *Apteodinium grande* LO, marker taxa for upper Albian (Costa and Davey, 1992; E. Monteil, pers. comm., 1997).

In the RASC scaled optimum sequence of Fig. 5 (left) this zone is represented by a tight cluster of five events, and in the corresponding optimum sequence of Fig. 5 (right) by taxa at rank positions 85–90.

Occurrence: Found in several of the wells, offshore mid-Norway. Where *O. schloenbachi* is rare,

recognition of the zone may be hampered by cavings from overlying, fossiliferous strata assigned to lower Cenomanian. An uppermost Albian hiatus in some of the wells may truncate part of all of this zone, possibly related to the pronounced eustatic offlap cited by Hardenbol et al. (1993), and by Rohl and Ogg (1996) at the base of the *inflatum* zone. The hiatus is visualized by the large interfossil distance below *A. grande*, at the base of the RASC interval zone in Fig. 5 (left).

Correlation: This zone corresponds to the *Osangularia schloenbachi* (= FCN 12a) zone of King et al. (1989) (see also Crittenden, 1983, 1987). King et al. (1989) reported that the stratigraphical range of this species is diachronous from south to north, occurring in the mid-Albian in the southern sector of the North Sea, but persisting to the upper Albian in the Viking Graben. The underlying *Globigerinelloides bentonensis* (= FCN 11) zone of King et al. (1989) is not recognised in the study area owing to the rarity of this species (Fig. 10b). In the Kirchröde-1 Borehole in the Lower Saxony Basin, NW Germany, the level with abundant *Globigerinelloides bentonensis* correlates to the late Albian *E. turriseiffelii* calcareous nannofossil zone (Weiss, 1997). The zone probably correlates to the *dispar* ammonite zone (Fig. 11).

5.5.9. *Sigmoilina antiqua* zone

This zone is defined on the upper part of the stratigraphic range of *Sigmoilina antiqua* (Fig. 7b); *Textularia* sp. 1 Burnhill and Ramsay, *Pseudotextularia cretosa*, *Recurvoides imperfectus*, and *Plectorecurvoides alternans* also occur in this zone (Figs. 5 and 7a,b). Assemblages assigned to this zone typically contain the following taxa:

Sigmoilina antiqua LO

Pseudotextulariella cretosa LO

Spiroplectinata annectens LO

Arenobulimina advena

Marssonella ozawai

Textularia sp. 1 Burnhill and Ramsay (1981) LO

Textularia chapmani

Textularia foeda

Plectorecurvoides alternans LO

Recurvoides imperfectus LO

Hippocrepina depressa

Valvulineria gracillima

Hedbergella delrioensis FCO
Hedbergella planispira
Gavelinella sp. X (unpublished) LO
Gavelinella intermedia
Lingulogavelinella jarzevae
 pink coloured *Inoceramus* prisms.

Age: Early Cenomanian.

Environment: Upper bathyal.

Remarks: *Sigmoilina antiqua*, the nominate taxon is rare. Its stratigraphic range extends from the two underlying zones, *Uvigerinamina una* n. sp. zone, and *O. schloenbachi* zone, into this zone. Average LO events that co-occur in this zone are *Pseudotextulariella cretosa*, *Marsonella ozawai*, *Arenobulimina advena*, and other taxa listed above. *Gavelinella* sp. X, with its steep last chamber is probably a new form, and together with *Textularia* sp. 1 may be restricted to the northern North Sea and Norwegian Sea. When and where found with sufficient number of specimens, in offshore Norway wells, both taxa should be formally described as new taxa. The planktonic foraminifers *Hedbergella delrioensis* and *H. planispira* locally are common in this zone; *Globigerinelloides bentonensis* occurs as isolated specimens, and is only common in the immediately underlying zone.

The dinoflagellates *Ovoidinium verrucosum* and *Endoceratium turneri* on average top in this zone, and in fact form the constituent zonal cluster in the scaled optimum sequence (Fig. 5, left), which correlates to the optimum sequence (Fig. 5, right) at rank positions 80 to 84.

According to King et al. (1989), the LO events of foraminifers in this zone are indicative of lower Cenomanian strata, in agreement with the upper part of the stratigraphic range of the dinoflagellate taxon *Ovoidinium verrucosum* (see Costa and Davey, 1992).

Occurrence: Widespread offshore mid-Norway. In wells where the lithology is sandy (with gravity flows assigned to the Lange Formation), this zone may be difficult to detect. The lack of clustering of events assigned to this zone in the scaled optimum sequence (Fig. 5, left), indicates considerable 'noise',

including missing data, in the wells that penetrate this stratigraphic level. The zone may be identified in well 6507/2–3 near 3350 m, and in well 35/3–4 near 3370 m.

Correlation: This zone corresponds to the *Sigmoilina antiqua* (= FCN 12b) zone of King et al. (1989), and to the upper part of the deep marine assemblage zone with *Plectrocurvoides alternans* (Geroch and Nowak, 1984). The zone probably correlates to the lower part of the *mantelli / cantianum* ammonite zone (Fig. 11).

5.5.10. *Hedbergella delrioensis* LCO zone

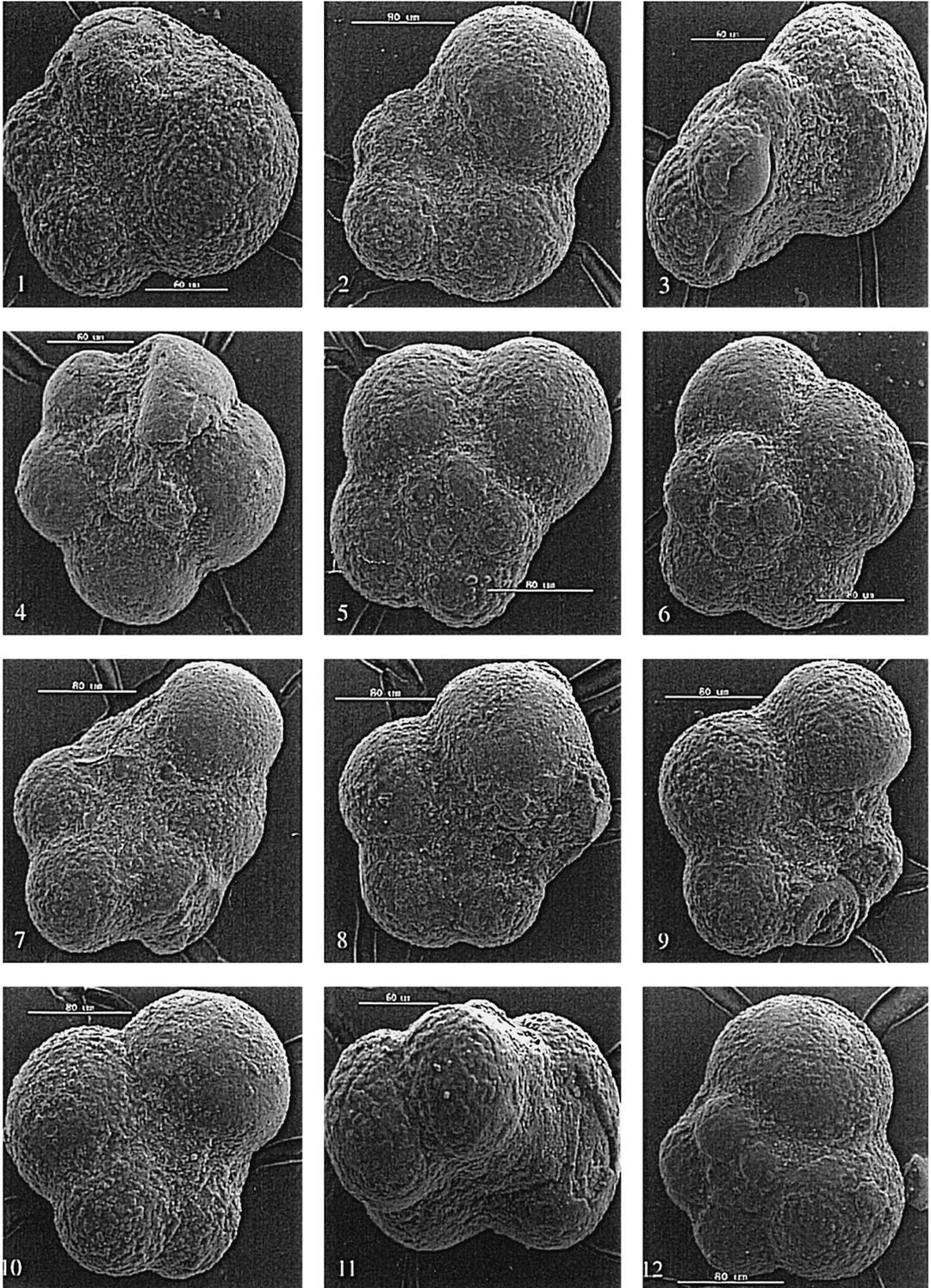
This distinctive zone is defined on the LCO of *Hedbergella delrioensis*; it may occur in floods, accompanied by the LCO of *H. planispira* (Figs. 5 and 7b). The following taxa have been observed in assemblages assigned to this zone:

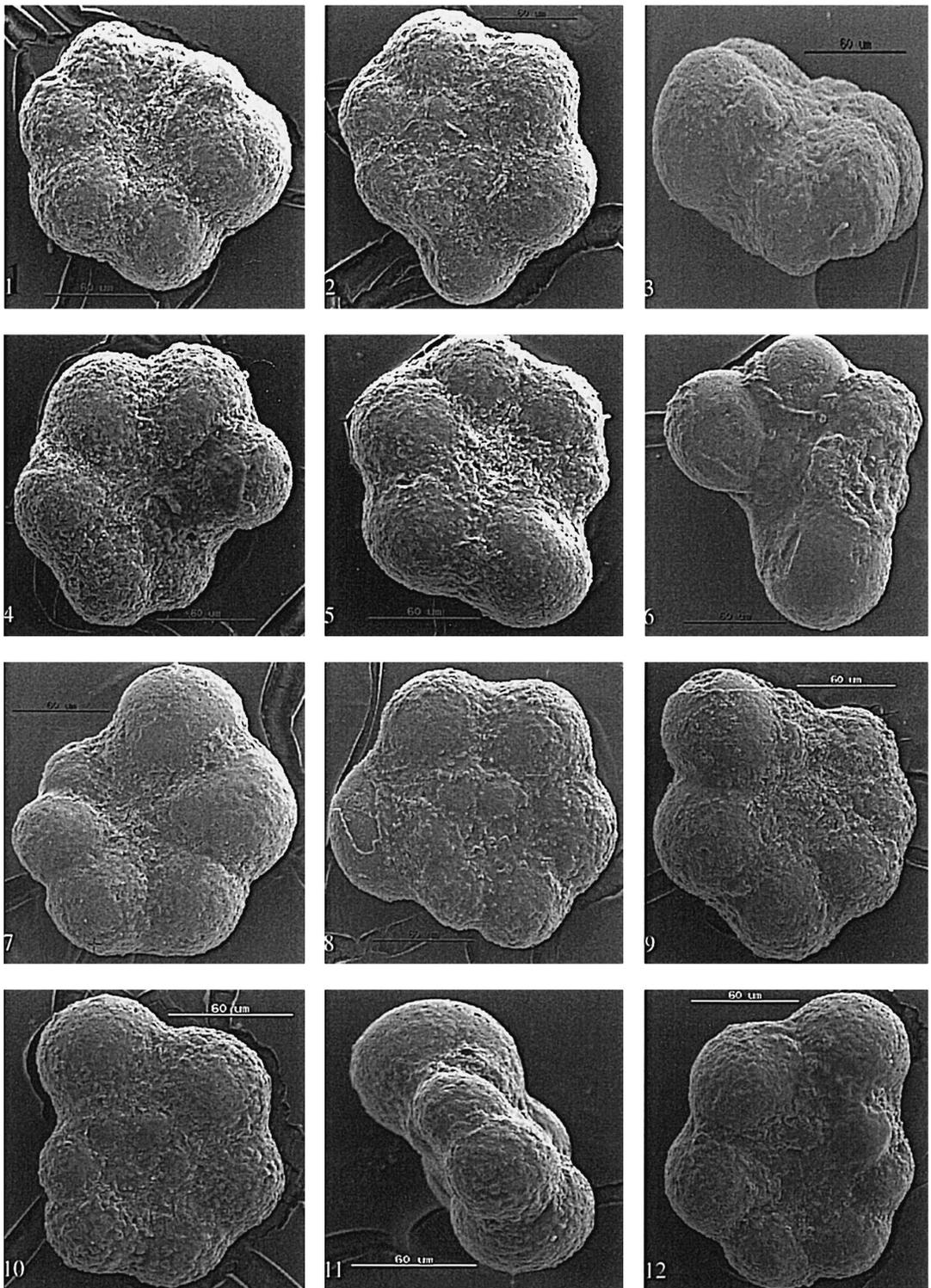
Hedbergella delrioensis LCO (common to abundant; Plate I)
Hedbergella planispira LCO (common to frequent; Plate II)
Hedbergella sigali (rare)
Whiteinella brittonensis FO (isolated occurrence, rare)
Praeglobotruncana praehelvetica FO (isolated occurrence, rare)
Gavelinella intermedia (rare)
Gavelinella cenomanica (rare)
Valvulineria gracillima (rare)
Lingulogavelinella jarzevae LO (rare)
Arenobulimina spp. (rare)
Glomospirella gaultina
Recurvoides imperfectus LO
Hippocrepina depressa LO
Plectrocurvoides spp. LO
Textularia sp. 1 LO (rare)
Textularia foeda (rare).

Age: Late early Cenomanian, probably extending into early middle Cenomanian.

Environment: Upper bathyal.

Remarks: In many wells, including 35/3–5 between 3035 and 2930 m, 6507/2–3 between 3300 and 3200 m, and 6507/6–2 near 2950 m, a distinc-





tive assemblage is observed with *Hedbergella delrioensis* LCO (last common and last consistent occurrence, as observed uphole), in association with *Gavelinella intermedia*, *G. cenomanica*, *Valvulinera gracillima*, *Lingulogavelinella jarzevae*, *Plectorecurvoides alternans*, *Recurvoides imperfectus*, *Hippocrepina depressa*, *Glomospirella gaultina*, *Ammosphaeroidina* sp. 1 (RRI), *Eggerellina mariei*, *Textularia foeda*, and *Tritaxia pyramidata*. The majority of benthic taxa assigned to this zone are rare. Among planktonics *Hedbergella planispira* LCO occurs slightly down in this zone; *H. sigali*, *Whiteinella brittonensis* and *Praeglobotruncana praelhelvetica*, occur at few localities only in this zone, and are rare; in two wells (35/3–5 and 36/1–2) single specimens of *Rotalipora* cf. *greenhornensis* were reported.

Among dinoflagellates occur (average LO) *Rhodobdella paucispina*, *Fromea* sp. 2, *Epelidosphaeridia spinosa*, *Xiphophoridium alatum* and *Litosphaeridium siphoniphorum*. The latter two taxa may extend in the overlying zone. The first (up well) occurrence of *Heterosphaeridium difficile* is in this zone (e.g., in well 6507/7–1 at 3506 m), as reported by Bell and Selnes (1997). These authors regard this event to be close to the boundary of lower and middle Cenomanian, in good agreement with stratigraphic evidence cited below.

The dinoflagellate assemblage with *E. spinosa*, *R. paucispina*, *X. alatum* and *L. siphoniphorum* overlap ranges in lower Cenomanian strata (Costa and Davey, 1992), and the benthic foraminifer *L. jarzevae* in the southern North Sea ranges upwards into the lower Cenomanian (King et al., 1989). The possible presence in this zone of the planktonic foraminifer *Rotalipora greenhornensis* would indicate an early to middle Cenomanian age. *Recurvoides imperfectus* and *Plectorecurvoides irregularis* commonly occur in the lower zones described above, and occasionally range upwards into this zone, together with *Hippocrepina depressa*. The upper range of these taxa Geroch and Nowak (1984) assigned to the *Plectorecurvoides alternans* zone, which in the Carpathians extends into the lower part of Cenomanian. Accord-

ing to Prokoph (1997) (Fig. 11), the upper part of the LCO of *H. planispira* and *H. delrioensis* in NW Germany corresponds to the *dixoni* ammonite zone of late early Cenomanian age. We adhere to this correlation for offshore Norway

From the age of the underlying and immediately overlying zones, and the evidence cited above, we assign the *Hedbergella delrioensis* LCO zone to the upper part of the lower Cenomanian, possibly extending into middle Cenomanian (see below).

Occurrence: Widespread and distinctive, offshore mid-Norway.

Correlation: The zone overlaps with the lower part of the northern North Sea zone of *H. brittonensis* (= FCN 13) of King et al. (1989) containing abundant hedbergellids, assigned broadly to the middle part of Cenomanian. Offshore mid-Norway, the top of the zone extends above the sands of the Lange Formation, and is below or in sand of the basal Lysing Formation. Since recognition of the zone is dependent on suitable, shaly lithology (the widespread gravity flow sands are not fossiliferous), the full stratigraphic extent of the zone remains to be determined. It probably incorporates a flooding horizon in the upper part of the lower Cenomanian, truncated by the mid-Cenomanian non-sequence (like the Rouen hardground of northern France), as will be discussed in Section 7.4.

5.5.11. *Whiteinella brittonensis* zone

This zone is defined on the lower part of the range of *Whiteinella brittonensis*, with rare *Hedbergella* spp., and *Praeglobotruncana* spp. (Figs. 5 and 7b). Also present may be *Gavelinella intermedia*, *Valvulinera gracillima*, and *Glomospirella gaultina*. *Dicarinella* and *Marginotruncana* taxa are not present in this zonal interval. The following taxa have been observed in assemblages assigned to this zone:

- Hedbergella delrioensis* (rare)
- Hedbergella planispira* (rare)
- Clavihedbergella simplex* LO (rare)
- Whiteinella brittonensis* FO
- Gavelinella cenomanica* LO (rare)

Gavelinella intermedia LO (rare)
Lingulogavelinella spp.
Valvulineria gracillima LO (rare)
Bulbobaculites problematicus
Glomospirella gaultina LCO
Uvigerinammia (pre-) jankoi
Ammosphaeroidina sp.
Eggerellina mariei LO.

Age: Late middle to early late Cenomanian.

Environment: Upper bathyal.

Remarks: The interval from the level of *Batioladinium jaegeri* LO upwards to *Heterosphaeridium difficile* LCO, between optimum sequence positions 68 and 47, groups relatively tightly (Fig. 5). This tight clustering in the scaled optimum sequence is the result of frequent cross-overs of the events in the wells.

A tight, lower subgroup in this interval, corresponding to rank positions 68 to 64 in the optimum sequence, is assigned to the *W. brittonensis* zone, with the events listed above, some of which are scarce, or absent in the northern part of the region under study. The depth interval in wells that might be expected to contain this zone is often impoverished in fossils due to poor sample recovery from turbine drilling, widespread watermass dysaerobia, stratigraphic hiatuses, or gravity flow sands. This zone, and the immediately overlying one may be difficult or impossible to separate.

As far as may be determined, this zone contains rare *Hedbergella delrioensis*, *H. planispira*, *Uvigerinammia (pre-) jankoi*, *Glomospirella gaultina*, *Gavelinella intermedia*, *G. cenomanica*, *Ammosphaeroidina* sp., *Eggerellina mariei*, and *Whiteinella brittonensis*. Occasional events are *Clavihedbergella simplex*, and a specimen of *Rotalipora* cf. *greenhornensis* in southern well 36/1–2 at 2660 m. The age assigned to the zone is late middle to early late Cenomanian, but more study of this interval is desirable.

Among dinoflagellates occur *Batioladinium jaegeri* LO, *Endoceratium dettmaniae* LO, *E. ludbrookii* LO *Dorocysta litotes*, and *Lithosphaeridium siphoniphorum* LO (southern wells only). These events together are assigned a late middle to early late Cenomanian age (Costa and Davey, 1992), in agreement with the age assigned to the *W. brittonensis* zone.

Occurrence: The zone is widespread, offshore Norway, but not easy to recognized, due to sandy facies.

Correlation: The *W. brittonensis* zone corresponds to the zone of the same name for the shale facies of the northern North Sea (King et al., 1989). It is possible that the upper part of the zone includes part of the unfossiliferous beds that occur as a result of widespread dysaerobia, or anoxia near the Cenomanian/Turonian boundary (see below).

5.5.12. *Dicarinella* zone

This zone is defined on the presence of *Dicarinella hagni-indica*, *D. imbricata*, or *D. primitiva* (Figs. 5 and 7b). Other key taxa that may be present include *Whiteinella inornata*, *W. paradubia*, *Praeglobotruncana stephani* LO, and *Hedbergella hoelzi* LO. The following taxa have been observed in assemblages assigned to this zone:

Dicarinella hagni indica LO
Dicarinella imbricata LO
Dicarinella primitiva LO
Gaudryina filiformis
Hedbergella delrioensis LO (isolated specimens)
H. planispira LO (isolated specimens)
Hedbergella hoelzi LO
Praeglobotruncana stephani LO
Whiteinella brittonensis LO
Whiteinella inornata
Whiteinella paradubia
Marginotruncana marginata FO
Heterohelix globulosa (rare)
Bulbobaculites problematicus LO
Stensioeina humilis LO (rare)
Lingulogavelinella spp. (rare)
Gavelinella balthica (rare)
Rzehakina spp. FO (including *R. minima*)
Caudammia ovuloides
Uvigerinammia jankoi (rare)
Psammosphaera spp. (frequent)
Allomorphina pyriformis LO
Allomorphina halli LO

C/T boundary gamma spike (more than one spike may be present)

pyritized small diatoms (frequent)

pyritized spumellarian radiolarians (rare).

Age: Latest Cenomanian–middle Turonian.

Environment: Upper bathyal.

Remarks: For the reasons, mentioned also with the immediately underlying zone, this zone maybe difficult to separate from the underlying one. Where siliciclastic sedimentation rates are high, with predominant gravity-flow sands, a typical *Psammophaera*/small pyritized diatom biofacies occurs, sprinkled with isolated *H. delrioensis*, *H. planispira* or *Dicarinella*. In few wells, particularly in the south where sand are less common, planktonic foraminifers are more diverse than in the immediately underlying or overlying zones, and include *Praeglobotruncana stephani*, *P. delrioensis*, *Dicarinella hagni indica*, *Dicarinella imbricata*, *Marginotruncana marginata* FO, *Dicarinella primitiva*, *Hedbergella hoelzi*, *H. delrioensis* (rare), *Whiteinella archeocretacea*, *W. inornata*, *W. paradubia*, and *W. brittonensis*. *Marginotruncana* is mostly rare and only represented by *M. marginata*. From the overlap of planktonic foraminiferal ranges, the zone may be assigned a late Cenomanian through early middle Turonian age (Stainforth, 1981; Robaszynski et al., 1984). *Marginotruncana marginata* and *Dicarinella* are restricted to post Cenomanian strata, and assists with constraining the age of the upper part of the zone.

It is likely that rare last occurrences in this zone of *Uvigerinammina jankoi* are in situ, since this taxon is known from the Turonian through Santonian (Geroch and Nowak, 1984).

The assignment of an event labelled Cenomanian/Turonian (C/T) boundary gamma spike (Fig. 5), reflects our hypothesis that a distinct and narrow (less than a few meters thick) gamma ray high on physical well logs, near the base of this zone, corresponds to the well-known, global oceanic, ‘anoxic’, Event-2 (Bonarelli), reported widely in latest Cenomanian through early Turonian strata. The exact reason for the spike in the wells is unclear, but it is assumed to be high thorium or uranium concentration, associated with organic rich levels. We have no reason to believe that the spike is a local feature; in few wells more than one spike occurs over a short interval in this zone. From cuttings it cannot be ascertained that the spike is actually associated with an interval barren of microfossils, but in cores in well 6507/2–3 a distinct reduction to virtually no microfossils at and below the C/T boundary gamma spike at 2972 m is observed. A peculiar, monotypic *Nyctericysta*/*Australosphaera* dinocyst assemblage

maybe more or less associated with this ‘Bonarelli’ type interval (G. Bell, pers. comm., 1996), although RASC does not link the two events closely on average (Fig. 5). A reason for the latter may be high variance in the average stratigraphic position of both events.

Considerable confusion exists over the identity of triserial to twisted biserial agglutinated benthic foraminifer specimens commonly found in the middle to upper Cretaceous of wells. Caved (?) *K. conversa* may be mislabelled as *Gaudryina filiformis*, and be difficult to distinguish from it. A detailed taxonomic study of such morphotypes in the wells is warranted.

In core sample 2885.5 m in well 6507/2–3, assigned to this zone, *Rzehakina minima* has its first stratigraphic occurrence. Such would agree with the report by Kaiho and Hasegawa (1994) that in Japan *Rzehakina* (*R. epigona*) appears in Turonian strata. *Bulbobaculites problematicus* commonly occurs in this zone, and rarely in the immediately underlying one, which agrees with broad age assignment for this taxon in (Kuhnt and Kaminski, 1990).

Among dinoflagellate cyst events *Maghrebinia membraniphorum* LO, *Palaeohystrichosphaera infusorioides* acme and LCO, *Heterosphaeridium difficile* FCO, *Stephodinium coronatum* LO, and *Spiniferites porosus* occur, associated with Turonian strata according to Costa and Davey (1992). *Dorocysta litotes* LO also may be present, but was omitted from RASC input data due to erratic stratigraphic occurrence.

The age of the *Dicarinella* zone is Turonian in its upper part, while the lower part may extend downward into Cenomanian, hence the zone is bracketed to occur across the C/T boundary. High sedimentation rates, a sandy, dysaerobic facies with occasionally much pyrite, and turbo drilling in many wells prevent satisfactory stratigraphic resolution across this interval.

Occurrence: This zone is widespread and relatively thick, offshore Norway.

Correlation: The *Dicarinella* zone corresponds to the zone of the same name in the northern North Sea, characterised by an downhole influx of abundant planktonic foraminifers, dominantly hedbergellids and *Dicarinella* spp. (King et al., 1989). Offshore Norway, this simple definition of King et al.,

op. cit.) may apply to some southern wells. The lower part of the zone contains strata coeval to the organic-rich Plenus marls, and the Blodoks shales of the North Sea and England.

5.5.13. *Marginotruncana* zone

This zone is defined on the presence of *Marginotruncana marginata*, *M. coronata*, *Globotruncana linneiana* gr., and *G. fornicata* (primitive morphotype) (Figs. 5 and 7b). The following taxa have been observed in assemblages assigned to this zone:

Marginotruncana marginata
Marginotruncana fornicata (primitive morphotype)
Marginotruncana coronata
Globotruncana linneiana gr.
Dicarinella concavata (isolated specimens)
Dicarinella carinata (isolated specimens)
Whiteinella archeocretacea
Conorbina supracretacea
Lingulogavelinella sp.
Nuttalina florealis
Globorotalites spp.
Gaudryina filiformis
Uvigerina jankoi
Haplophragmoides aff. *walteri* (sensu Kuhnt and Kaminski, 1990)
Inoceramus needles.

Age: Late Turonian–Coniacian.

Environment: Upper bathyal.

Remarks: This zone is recognized in few wells in the southern part of the study region, where it constitutes a downhole influx of *Marginotruncana*, *Globotruncana* and *Whiteinella*. An distinct influx of *Marginotruncana*, together with *Whiteinella* was for example observed in the 35/3–4 well, together with isolated specimens of *Dicarinella concavata* and *D. carinata*. The overlap of ranges of the latter two taxa is indicative of Coniacian strata (Robaszynski et al., 1984).

The zone constitutes the upper part of the high sedimentation rate interval and sandy facies of the Lysing Formation in northern wells, where globotruncaniid planktonic foraminifers are mostly absent; hence recognition of the zone there may be difficult. The large interfossil zone limit in Fig. 5 (left) at *H. difficile* LCO reflects this important

stratigraphic facies change; in the optimum sequence of Fig. 5 (right) the zone is recognized at rank positions 47–50.

The (local) relative abundance of *Marginotruncana*, together with *H. difficile* probably is the result of a condensed sedimentary sequence under open marine and relatively warm water condition. Unfortunately, the dinoflagellate cyst *Heterosphaeridium difficile* may display more than one LCO or acme, hence this event may not be unique. The acme occurrence of *H. difficile*, according to Costa and Davey (1992) suggests a Turonian age, with the taxon ranging into the Coniacian. Among dinoflagellate cyst that range through the upper part of the zone, and may extend slightly in the overlying foraminiferal *S. granulata polonica* zone, are *Chatangiella* sp. 1 Stratlab, *Trithyrodinium reticulatum*, *Surculosphaeridium longifurcatum* and *Heterosphaeridium difficile*.

Occurrence: This zone is clearly recognized in southern well 35/3–4 from 2425 to 2460 m. Where globotruncaniid foraminifers are missing, as in many northern wells, recognition of the zone may be difficult.

Correlation: A *M. marginata* zone is defined by King et al. (1989) for the northern North Sea, and was assigned a late Turonian through early Coniacian age. These authors extend the overlying *S. granulata polonica* interval zone beyond the Santonian range of the nominate taxon down into the upper Coniacian. We restrict the *S. granulata polonica* zone to the Santonian.

5.5.14. *Stensioeina polonica* zone

This distinctive zone is defined on *Stensioeina* (*granulata*) *polonica* LO (Figs. 5 and 7c). The following taxa have been observed in assemblages assigned to this zone:

Stensioeina (granulata) polonica LO
Globorotalites multiseptus
Nuttalina florealis
Gavelinella beccariiformis FO
Epistomina supracretacea
Gyroidinoides beisseli
Globotruncana marginata (rare)
Globotruncana linneiana group (rare)
Globotruncana fornicata (rare)
Heterohelix sp.

Inoceramus needles (common)

Archeoglobigerina spp.

Allomorpha sp.

Tritaxia spp.

Age: Early to middle Santonian.

Environment: Upper bathyal.

Remarks: The nominate zone marker is the key taxon in this easily recognizable zone, with the last stratigraphic occurrence of the nominate species delimiting its upper boundary. The zonal interval also contains various other calcareous taxa, listed above. Planktonic foraminifers decrease stratigraphically upwards in this zone, and are much more typical for the immediately underlying zone. Deep marine agglutinated benthics mostly are scarce, but less so offshore mid-Norway. *Uvigerinammina jankoi* only was observed in few southern wells. Lenticular radiolarians also occur. In some wells the immediately overlying *Inoceramus* LCO zone and this zone are merged (see below).

Occurrence: This zone occurs widespread, offshore Norway, and in some wells were the *Inoceramus* LCO zone merges with this zone, constitutes the first downhole carbonate rich interval, below the thick siliciclast interval assigned a Campanian age.

Correlation: This zone correlates to the *Stensioeina granulata polonica* zone of Koch (1977), of early and early middle Santonian age in NW Germany. This is the only *Stensioeina* taxon from the evolutionary plexus of *Stensioeina* that is widespread, offshore Norway, and also is observed in the Voering Basin. Elsewhere in NW Europe six or more successive *Stensioeina* zones are recognized from Turonian to Campanian age. In the North Sea, King et al. (1989) also recognizes the *polonica* zone (FCS18), but these authors extend the zone below the range of the nominate species down into the Coniacian.

5.5.15. *Inoceramus* LCO zone

This zone contains the following characteristic event (Figs. 5 and 7c):

Inoceramus LCO: This zone is recognized from a relative abundance of *Inoceramus* needles that constitute the first carbonate rich interval downhole following a thick, siliciclastic Campanian section, with pyritized diatoms, deep water agglutinated

foraminifers, and locally radiolarians. In a few wells, such as 35/3–4 this zone merges with the immediately underlying *S. granulata polonica* zone, but on average the two events are clearly superpositional (Fig. 5), possess low variances (Fig. 9), and are assigned to successive and separate zones. Spherical and lenticular radiolarians may be common in this zone, but are more so in the overlying *Fenestrella bellii* zone. In the southern part of the study area (34 and 35 blocks), the lower stratigraphic ranges of *Tritaxia dubia*, *Globotruncana bulloides* and *Whiteinella baltica* are in this zone, and *Archeoglobigerina* may also be present.

The sudden disappearance of common *Inoceramus* needles, stratigraphically upwards suggests a regional hiatus, tentatively shown in Fig. 2 to span part of upper Santonian and lowermost Campanian.

Age: Late Santonian.

Environment: Bathyal.

Occurrence: The *Inoceramus* LCO zone is widespread, offshore Norway, and easily recognizable.

Correlation: This zone correlates to part or all of the ‘radiolaria’ zone in the North Sea (King et al., 1989) that, according to these authors may have a somewhat spotty distribution northward. The latter might be the result of local dissolution of silica. The distribution of the *Inoceramus* zone north of the North Sea reflects a temporal increase of carbonate productivity during a time of limited terrigenous sedimentation.

5.5.16. *Fenestrella bellii* zone

This distinctive zone is defined on the presence of a small, pillbox diatom with an oval cross-section, and sharp periphery, named *Fenestrella bellii* n. sp. (Appendix B; Figs. 5 and 7c). It may occur in floods, accompanied by rare to common deep water agglutinated foraminifers, and rare to common spherical/lenticular radiolarians. The following taxa have been observed in assemblages assigned to this zone:

Fenestrella bellii n. sp. LO

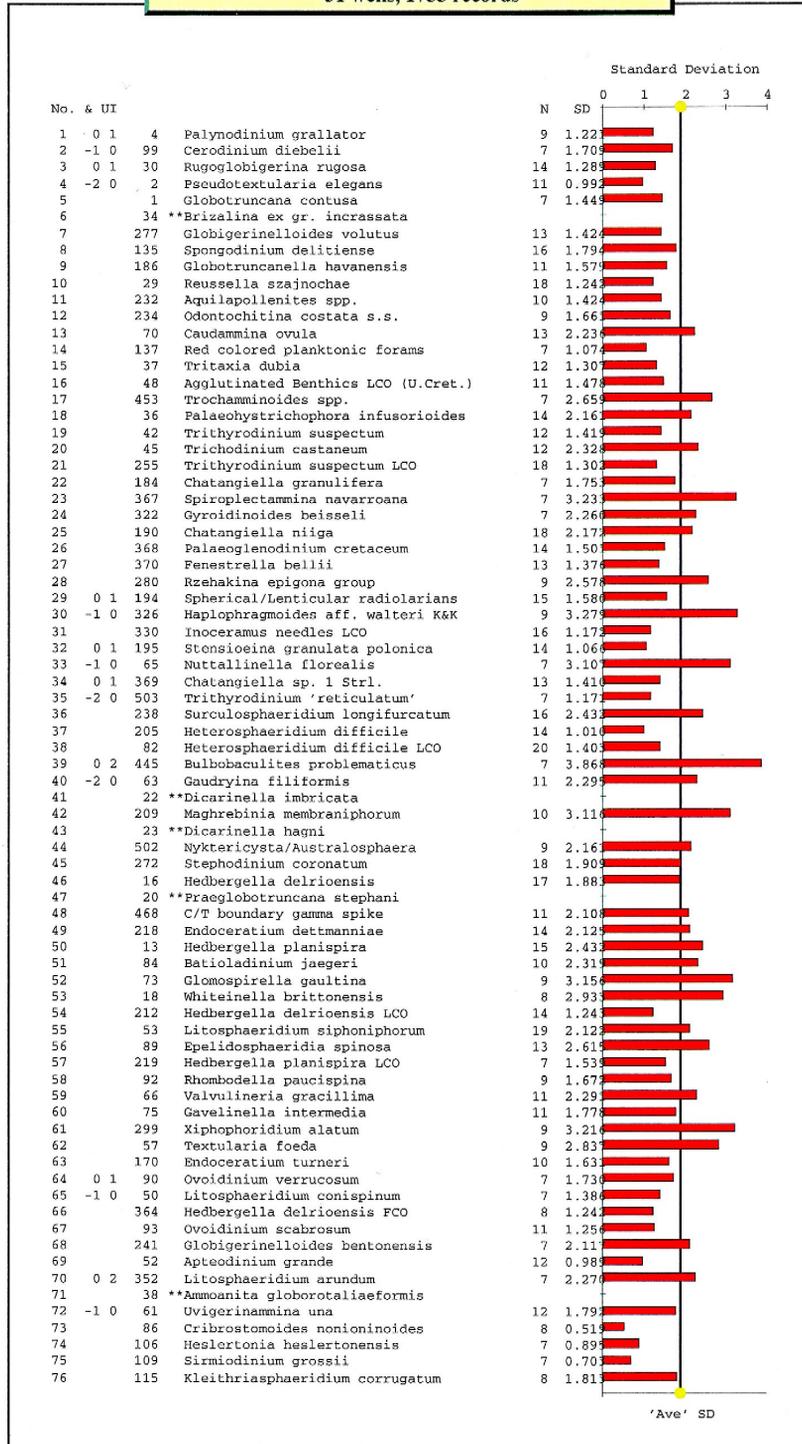
spherical/lenticular radiolarians (rare to common)

Rzehakina epigona LO

Haplophragmoides aff. *walteri* LO (sensu Kaminiski and Kuhnt, 1990) (rare)

Spiroplectammina navarroana

Cretaceous Ranked Optimum Sequence, offshore Norway
31 wells, 1755 records



Trochamminoides spp.

Deep water agglutinated foraminifers, undifferentiated.

Remarks: Above the *Inoceramus* LCO zone, an interval occurs in many wells with a small, morphologically distinctive, pyritized diatom, informally named Diatom sp. H, and here assigned to the new species *Fenestrella bellii* (see Appendix B). Spherical/lenticular radiolarians may be common, and so are coarse agglutinated benthic foraminifers with organic cemented tests. The latter include *Karrerulina conversa*, *Haplophragmoides* aff. *walteri* (sensu Kaminski and Kuhnt, 1990), *Spiroplectamina navarroana*, *Paratrochamminoides olszewska*, *P. mitratus*, *Trochamminoides subcoronatus*, and *Rzehakina epigona*, all of which may extend slightly higher in the section, above this zone. *Rzehakina epigona* has a high variance (Fig. 9), and is not a reliable correlation event; although offshore Norway it disappears on average in the *F. bellii* zone.

Various taxa of *Trochamminoides*, listed above, in the North Atlantic underwent an evolutionary radiation in the early Campanian, an ‘event’ clearly recorded offshore Norway in flysch-type, bathyal strata. In exploration reports, the distinct *Trochamminoides* taxa are commonly lumped under *Paratrochamminoides irregularis*. The appearance and local disappearance (or probably more correctly, the part of the stratigraphic range of the genus where its taxa become rare) is in Campanian strata (Fig. 5). In deeper bathyal settings, like in the Voering Basin, *Gaudryina filiformis* has its highest stratigraphic extension in this zone (cf. Geroch and Nowak, 1984), but maybe difficult to separate from *Gerochammina lenis*. On Fig. 5 (left), the *F. bellii* assemblage forms a distinct interval zone, separated with a large inter-fossil distance from the immediately overlying zone of *Tritaxia dubia* that includes the dinoflagellate *Trithyrodinium suspectum* LCO at its base.

Other dinoflagellate cyst taxa that have their average last occurrence in this zone include *Paleoglenodinium cretaceum*, while *Chatangiella niiga*, *C. granulifera*, *Xenascus ceratoides* and *Trithyrodinium suspectum* LCO on average disappear in the lowermost part of the immediately overlying zone (Fig. 5).

Age: Early Campanian.

Environment: Dysaerobic, middle to upper bathyal.

Occurrence: Widespread, offshore Norway; including the Voering Basin.

Correlation: This zone probably largely correlates to the ‘Unnamed’ zone FCN18 of King et al. (1989) with exclusively non-calcareous, agglutinated foraminifers in the northern North Sea, assigned to lower Campanian, in agreement with our superpositional zone data and the upper range of the dinoflagellate cyst *P. cretaceum* in (Costa and Davey, 1992). In the southern North Sea, in UK and in NW Germany this stratigraphic interval is probably shallower marine, and hence dominated by carbonates; it is zoned with *Stensoeina* taxa and planktonic foraminifers.

The lower Campanian *Goesella rugosa* zone of Geroch and Nowak (1984) first recognized in the Carpathian Trough, and based on the lower range of *G. rugosa*, is not recognized offshore Norway. The taxon is present in North Atlantic DSDP Sites, and in Zumaia, Spain (Kuhnt and Kaminski, 1997), but appears to be absent, offshore Norway.

The diatom, and locally radiolarian-rich interval in the Norwegian Sea wells, assigned to the *F. bellii* zone may correspond to the biosilicious event in western Tethys and North Atlantic, observed in the upper part of anomaly 34 reversed (near the Santonian–Campanian boundary). This paleoceanographic event is a faunal change at a number of localities in the Atlantic and western Tethys (Kuhnt et al., 1998) coeval with a change from well-oxygenated reddish

Fig. 9. Summary of event variance analysis results for the Cretaceous optimum sequence of Fig. 5. To the left, the optimum sequence of Cretaceous microfossil events in 31 wells, offshore mid-Norway, where each event occurs in at least seven out of 31 wells; N is the number of wells sampled to calculate the S.D. per event ($N > \text{ or } = 7$), and S.D. is the standardized deviation from the line of correlation in each well. The average standard deviation of 1.8903 is the sum of all S.D.’s, divided by the total number of events ($= 72$) in the optimum sequence. The asterisk behind events indicates an event with a S.D. that is smaller than the average S.D. From event S.D. theory it follows that events with a below average S.D. correlate the same relative stratigraphic level more faithfully from well to well than events with a higher S.D. The regional correlation application of this is discussed in the text; see also Fig. 10a–c for further details.

claystones below, to greenish, radiolarian-rich sediments above. This event has been termed Ocean Anoxic Event 3 (OAE 3), although there is no evidence for truly anoxic conditions at the seafloor. It reflects a time when surface productivity (and hence sea-floor organic flux) was comparatively high.

5.5.17. *Tritaxia dubia* zone

This zone is defined on the presence of *Tritaxia dubia* LO (Figs. 5 and 7c), widely reported under a variety of names (see below). The following taxa have been observed in assemblages assigned to this zone:

Tritaxia dubia LO
Pseudogaudryina pyramidata LO (rare)
Marsonella crassa
Trochamminoides spp. LCO
Spiroplectammina dentata (rare)
Spiroplectammina navarroana (rare)
Spiroplectammina spectabilis
Arenoturrisspirillina sp.
Caudammina ovulum
Caudammina ovuloides
Remesella varians
Glomospira spp.
 Coarse agglutinated benthic foraminifers LCO
Epistomina supracretacea
Globorotalites michelinianus
Gyroidinoides beisseli LO
Gavelinella usakensis LO
 Red coloured planktonic foraminifers including *Hedbergella*, *Rugoglobigerina*, *Marginotruncana*, *Archeoglobigerina*.

Remarks: In the southern part of the region studied, calcareous foraminifers may include abundant planktonics, as listed above, often stained red. Northward, calcareous foraminifers become rare, and the zone is more difficult to define, particularly when overlying Paleocene and Maastrichtian strata also contain coarse agglutinated foraminifers. On average though, the latter disappear stratigraphically upward together with other taxa listed above, one of the most typical which is *Tritaxia dubia*. This taxon likely is a junior synonym of *Tritaxia subparisiensis* (Grzybowski) and in reports may hide under junior synonyms like *Pseudogaudryina capitosa*, *Tritaxia tricarinata* and *T. capitosa*. Typically, several *Spiroplectammina* taxa may be present, including *S.*

spectabilis, which regionally re-appears in the upper Paleocene, and *Arenoturrisspirillina*.

The assemblage, together with the dinoflagellates listed below forms a distinctive interval zone in Fig. 5 (left), that is assigned a middle to late Campanian age, based on the upper stratigraphic range of *T. dubia* (= *T. subparisiensis*) in Geroch and Nowak (1984).

Dinoflagellates are abundantly present, and include the average last occurrences of *Trithyrodinium suspectum* LCO, *T. suspectum*, *T. castaneum*, *Chatangiella niiga*, *C. granulifera*, *C. ditissima*, *Spongodinium delitiense* FO, and *Palaeohystrichophora infusorioides*, which together belong in middle and upper Campanian (Costa and Davey, 1992). Using dinoflagellates, the LCO of *T. suspectum* and *Chatangiella niiga* LO may be used to distinguish a lower part of the *T. dubia* zone, middle Campanian (Fig. 5).

Age: Middle to late Campanian.

Environment: Upper bathyal.

Occurrence: Widespread and relatively thick, offshore Norway.

Correlation: After early Campanian, North Atlantic low diversity assemblages with *Glomospira* increase in diversity. New species belonging to the genera *Caudammina*, *Haplophragmoides*, *Paratrochamminoides*, and *Rzehakina* are observed for the first time, as are calcareous-cemented agglutinated forms belonging to the genera *Arenobulimina*, *Clavulinooides*, *Dorothia*, *Goessella*, *Marsonella*, *Remesella*, and *Spiroplectinata*. The latter assemblage change marks an Atlantic-wide drop in the level of the Carbonate Compensation depth (CCD) to a depth of below 5000 m, resulting in the deposition of the marly Crescent Peaks member of the Plantagenet Formation (Jansa et al., 1979). At this time, the distinctive ‘fysch-type’ and calcareous-cemented agglutinated taxa become common, and their overall diversity increase in the North Atlantic and also in the Norwegian Sea, reflected in the composition of the *Tritaxia dubia* zone. This faunal turnover coincides with major changes in watermass properties, owing to increased deep-water productivity from high-latitude sources, cooling and increased ventilation of deep waters, and higher upwelling rates. Active watermass communication through the Scotland–Greenland gateway (Fig. 1b), existed between

the proto Norwegian sea and the North Atlantic Ocean.

The *Tritaxia dubia* zone correlates to the *Tritaxia capitosa* zone, FCN19 of King et al. (1989), also assigned to (middle to) upper Campanian. King et al. (op. cit.) also refers to the red claystones, assigned to the upper part of the zone, that stain the foraminifers red. The claystone corresponds to the ‘Upper Red Unit’ of the Flounder Formation in Moray Firth and ‘Pink Chalk’ in the central North Sea.

5.5.18. *Reussella szajnochae* zone

This zone is defined on the LCO of *Reussella szajnochae* (Figs. 5 and 7b). Other key events include *Rugoglobigerina* spp., *Globigerinelloides volutus*, and *Globotruncanella havanensis* (Fig. 7c). The following taxa have been observed in assemblages assigned to this zone:

Reussella szajnochae LO
Caudammina ovulum
Globotruncanella havanensis
Rugoglobigerina tradinghousensis (southern area only)
Rugoglobigerina rotundata
Rugoglobigerina spp.
Globotruncana arca (south only)
Globotruncana mariei (south only)
Globotruncanella intermedia
Globigerinelloides volutus
Hedbergella spp., including *H. holmdelensis*
Bolivinoidea draco miliaris (southern area only)
 Deep water agglutinated foraminifers (more commonly found northward)
Brizalina ex. gr. *incrassata*
Anomalinoidea velascoensis
Stensioeina pommerana
Gavelinella beccariiformis.

Remarks: The zone of *Reussella szajnochae* is easily recognizable from the average LO of its distinctive, nominate species, which generally is present with few specimens only in the wells samples examined, but occurs widespread. Associated calcareous benthic taxa and planktonics are listed above. In southern wells many more taxa occur, that require study. In a few of these southern wells, isolated specimens of the nominate taxon range in the overlying zone of *Pseudotextularia elegans*. It is not clear if *R. szajnochae* is in fact reworked or extends

stratigraphically upward. A similar pattern was observed also by King et al. (1989), suggesting the taxon is in fact time transgressive southward.

In few wells, the upper part of the *R. szajnochae* zone shows a bloom of *Globigerinelloides volutus* (Fig. 7b), that may constitute a stratigraphically useful subzone, and requires study.

Organic walled microfossils that have their average last occurrence in this zone include *Odontochitina costata* and *Aquilapollenites* spp. (Fig. 5), typical for lower Maastrichtian (Costa and Davey, 1992).

Age: Probably mostly early Maastrichtian.

Environment: Deep neritic to upper bathyal.

Occurrence: Widespread, offshore Norway.

Correlation: The *R. szajnochae* zone correlates to the lower part of zone of the same name (FCN20 p.p.) in the northern North Sea (King et al., 1989). In the Carpathian belt, sediments of the same age contain *Caudammina ovulum gigantea*, a lower bathyal to abyssal taxon not observed offshore Norway. The reason for its absence is that no sediments of that larger paleo waterdepth have been sampled. The taxon is known from the North Atlantic, and the Faeroer Basin (D. van den Akker, pers. comm., 1997).

5.5.19. *Pseudotextularia elegans* zone

This distinctive zone is defined on presence of *Pseudotextularia elegans* LO (Figs. 5 and 7b); other key taxa that may be present include *Rosita contusa*, *Rugoglobigerina* spp., *Racemiguembelina varians*, and *Brizalina* ex. gr. *incrassata* (Fig. 7b). The following taxa have been observed in assemblages assigned to this zone:

Pseudotextularia elegans
Abathomphalus mayaroensis
Rosita (Globotruncana) contusa
Rugoglobigerina rugosa (includes acme)
Globigerinelloides volutus (includes acme)
Pseudoguembelina excolata
Racemiguembelina varians
Stensioeina pommerana
Brizalina ex. gr. *incrassata*
Heterohelix spp.
Hedbergella spp., including *H. monmouthensis*.

Remarks: As far as can be determined, this zone is largely missing in northern wells (together with

Danian, lower Paleocene); it may be condensed with lower Maastrichtian strata southward. Where it is present, it is rich in calcareous taxa, predominantly planktonics. The lower part of the zone harbors acmes or LCO levels of *Rugoglobigerina rugosa* and/or *Globigerinelloides volutus* which may constitute 50–90% of specimens observed. These levels may constitute a subzone. More study, particularly of cores is desirable to understand the successive records of events in this zone.

It is peculiar that *Abathomphalus mayaroensis*, where observed does not seem to occur at the top of the zone, but rather at its base or even lower. It is not clear from the data if such occurrences are due to caving, or indeed represent an older record. Dinoflagellate cysts present in the zone include *Cerodinium diebeli* and *Palynodinium grallator* LO, indicative of upper Maastrichtian (Costa and Davey, 1992).

Age: Late Maastrichtian.

Environment: Deep neritic to upper bathyal.

Occurrence: The *P. elegans* zone is largely recognized in the southern part of the area studied, offshore Norway. As may be seen from Fig. 2, a widespread Maastrichtian–Danian hiatus is present in part of the study area, particularly in its northern part, offshore mid-Norway. We postulate that this hiatus is due to shoulder uplift during ‘break-up’, prior to the onset of Paleogene seafloor spreading in the Norwegian Sea.

Correlation: The *P. elegans* zone correlates to the North Sea wide *P. elegans* zone of King et al. (1989), and the *Gavelinella danica* and *P. elegans* zones of Koch (1977) in NW Germany, correlative to the *junior* and *casimirovensis* belemnite zones (Late Maastrichtian).

6. Variance analysis and paleoceanography

Variance analysis of fossil events enhances insight in their regional occurrences. The analysis compares the relative position of fossil events in individual wells to their average position in the RASC optimum sequence, while using that average level as a stratigraphic reference. With this reference level, it is possible to trace events over all wells, and find out if they become systematically younger or

older along a geographic gradient (time transgressive behaviour). Hence, the method assists with identification of faithful stratigraphic marker events in correlation, but also points to events that are time transgressive, for example as a function of gradual paleoceanographic or paleobathymetric change.

The method proceeds as follows: Individual well sequences are compared to the (scaled) optimum sequence using curve fitting techniques to calculate a line of correlation, and obtain estimates of the spread of the events (= deviation), relative to the best fit line. For example, if an event occurs in 15 wells, a best fit line is calculated for the individual event sequence in each of the fifteen wells relative to the optimum sequence. Hence, 15 event deviations to the best fit line are known, one for each well in which the event occurs. These 15 deviations are combined in an average event variance. Or to say it in a more formal manner: The frequency distribution of events may be computed by measuring the differences between the known (observed) event positions and their line of correlation (= curve expected) values, and yields the variance and standard deviation (D’Iorio and Agterberg, 1989; Gradstein and Agterberg, 1998).

A small standard deviation indicates a good marker event in correlation, and a large standard deviation a bad one. This is because an event with small standard deviation is close to its expected position on the line (curve) of correlation in all wells. It would be possible to correlate an event with zero mean and zero standard deviation with absolute certainty between wells. On the other hand, an event with large variance occurs much lower or higher than expected in one or more wells. Graphical representation of differences between observed and expected positions at well locations, e.g., on a geographic map, may show that the large variance of an event is due to time transgressive behaviour. Thus variance analysis can be useful for tracking the time transgressive behaviour of events.

Application of RASC variance analysis to a forerunner of the present biozonation, was used by Gradstein and Agterberg (1998) to demonstrate that the lower Cenomanian Lange sands, and the middle Cenomanian to Turonian Lysing sands, offshore mid-Norway, are not seismic markers, or well log ‘sheet sands’ in a correlative sense, but showed a

more complex correlation patterns than hitherto assumed. The conclusion is in line with the sedimentological interpretation that the sands are debris flow and turbidite sands (T. Saether, pers. comm., 1996). In this study, we will again look at some fossil events associated with these sands, and also group the Cretaceous zonal events in four broad groups, using variance analysis to rate potential isochronous correlation.

6.1. *Lithosphaeridium siphoniphorum*

The optimum sequence of Fig. 9 allows differentiation between more reliable, and less reliable events for well to well correlation. To the left in Fig. 9 is the optimum sequence of Cretaceous microfossil events, where each event occurs in at least seven out of 31 wells; N is the number of wells sampled to calculate the S.D. per event ($N >$ or $= 7$), and S.D. is the standardized deviation from the line of correlation in each well. The average standard deviation of 1.8903 is the sum of all S.D.'s, divided by the total number of events ($= 72$) in the optimum sequence. An asterisk behind events indicates an event with an S.D. that is smaller than the average S.D. for an optimum sequence of events.

The first item that stands out in Fig. 9, is that Lange and Lysing reservoir sand intervals from *E. spinosa* in lower Cenomanian to *Bulbobaculites problematicus* in Turonian created higher S.D. values; this is to be expected, if we take into account increased frequency of reworking, and problems in sampling complete stratigraphic ranges where sandy intercalations occur. In this respect, it is not surprising that presumed regional marker dinoflagellates like *E. spinosa*, *L. siphoniphorum* have high S.D. values, and non-normal histograms of stratigraphic deviations (Fig. 10a); the same is true for *M. membraniphorum*. One contributing factor, other than frequently reworked tops, is that *L. siphoniphorum*, observed in 19 wells, appears to be time transgressive, ranging into younger strata southward (Fig. 10a); the same may be true for *E. spinosa*, observed in 13 wells (Fig. 10a). The single well where this time transgressive behaviour appears reversed is well 20 (35/3–4), but in this well palynology consultants, being made aware of this time transgressive 'problem', re-analysed the well and picked the events

much lower. Our original data, prior to re-analysis showed well 20 to be in line with the trend of other southern wells. This selective picking of events practise appears unwarranted, since biostratigraphers may 'know' the age before the zone, turning stratigraphy up-side down, and hampering detailed and reliable correlations.

The question is why this time transgressive behaviour of these taxa, and here answers are scarce. One possibility might be that both dinoflagellate taxa thrive in a more open marine, pelagic carbonate environment, as found in western Europe throughout Cenomanian–Turonian. According to Costa and Davey (1992) *E. spinosa* in western Europe extends well into middle Cenomanian and *L. siphoniphorum* in early Turonian. Offshore Norway, the flood of calcareous planktonic foraminifers only extends from late middle Albian into early Cenomanian (Fig. 12). Possibly, the distribution of the dinoflagellate cysts is linked to the calcareous flux and has limited the ecological niche of the two dinocysts taxa from middle Cenomanian time onward. It led to a drastic reduction in their population density, and makes detection of the upper part of their total stratigraphic range spotty. For well stratigraphy, emphasis on the last consistent stratigraphic occurrence (LCO event) of these taxa might be in order.

6.2. *Hedbergella delrioensis* LCO

The first and last common, and consistent presence of the planktonic foraminifer *Hedbergella delrioensis* (Plate I, Figs. 1–12), and the last common and consistent occurrence of *H. planispira* (Plate II, Figs. 1–12) have well below average S.D.s (Fig. 9). The local flood of specimens reflects considerable marine transgression, with slow sedimentation, and influence of Atlantic surface watermass along the eastern side of the proto Norwegian Sea. On the other hand, a perusal of samples we collected in Aptian through Albian dark shale levels in NW Germany also shows many levels with monotypic planktonic floods of *Blefuscuina*, *Blowiella*, *Globigerinelloides* and *Hedbergella*. It suggests that these simple, non-keeled planktonics thrive in relatively small bathyal, boreal basins, as long as salinity is normal (there are many ammonites in the NW Ger-

man basin), sedimentation rates low, and watermass fertility enhanced by abundant organics input, hence the dark shales. As long as the basins are connected to the Tethys and Atlantic oceans to enhance pelagic incursions, will these simple planktonics invade. Such invasions also are known from the austral Gearle shales, Aptian of NW Australia, and the mid-Cretaceous of the Western Interior, northern USA. Niches for these simple planktonics may have been less oceanic and more continental margin watermasses, possibly in response to too high salinity of open oceans (W. Hay, pers. comm, 1998) in mid-Cretaceous.

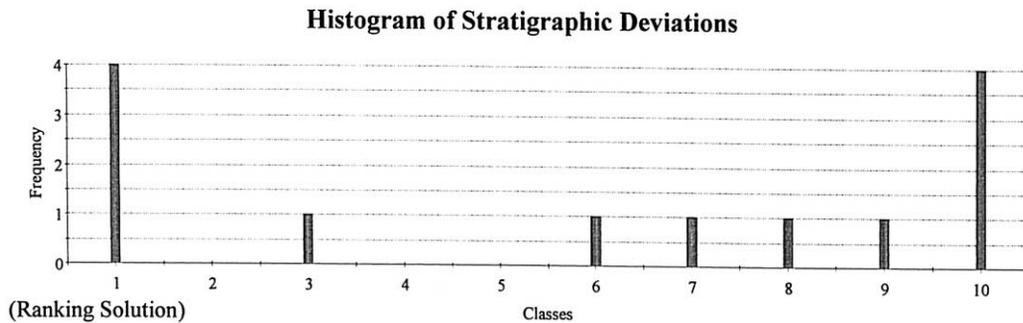
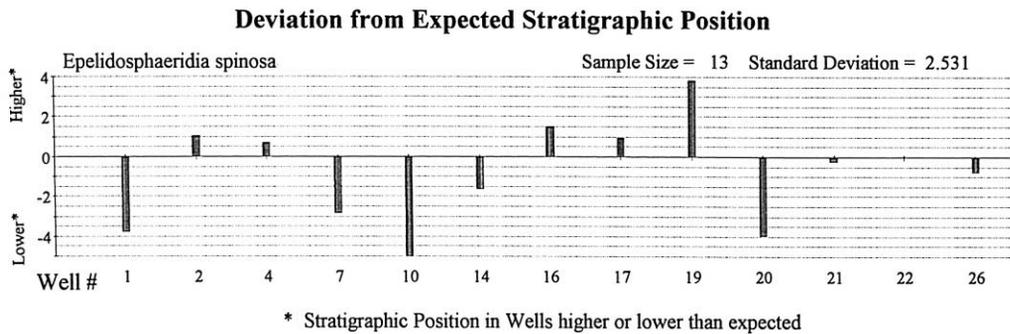
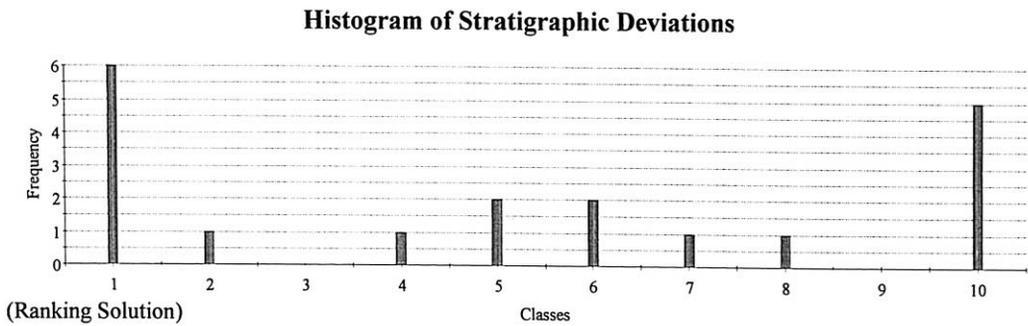
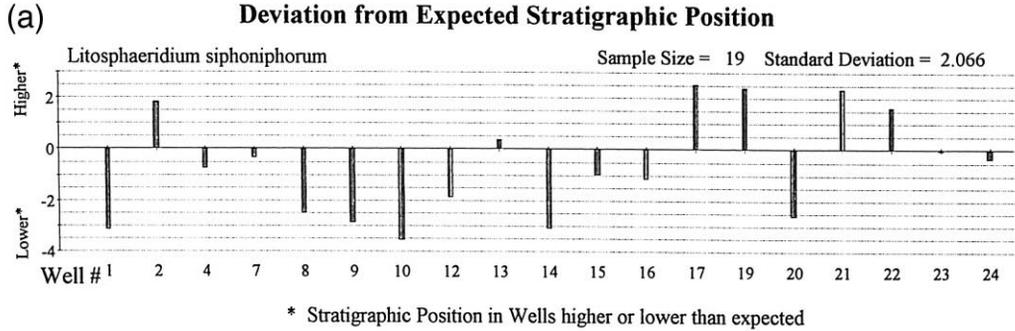
It is interesting that another simple planktonic, *Globigerinelloides gyroidinaeformis*, that from its smooth wall and slightly irregular planispiral coiling might be a benthic during part of its life cycle, in fact is common in one well, offshore Norway (Fig. 8) just below (also cored) levels where *H. planispira* and *H. delrioensis* appear. Why this taxon is not known from NW Germany is unclear; it is frequent during a brief interval (*G. gyroidinaeformis* zone, mid Albian; Fig. 6a) in the Viking Graben and also known from more Tethyan localities in France and offshore Eastern Canada. Its short stratigraphic range and wide distribution are arguments in favour of it being planktonic.

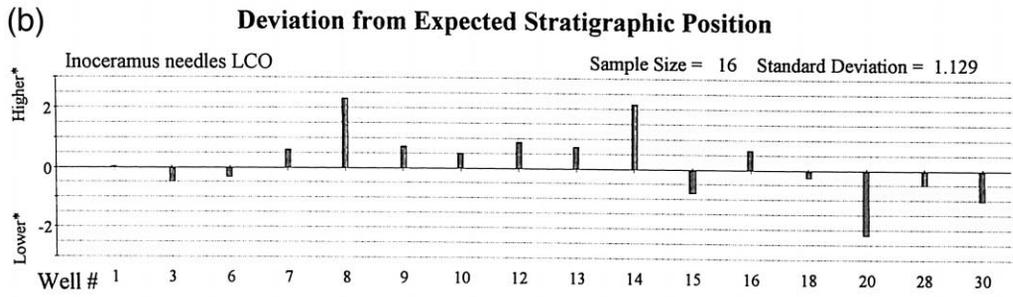
In Gradstein and Agterberg (1998), we first brought forward that *H. delrioensis* LCO, offshore mid-Norway is useful to separate more scattered Lange sands, assigned to lower Cenomanian, from more massive Lysing sands, assigned to middle Cenomanian–Turonian. The planktonic LCO event

evidently is a lull in sand sedimentation. The LCO event was observed in 14 wells, has a low S.D. of 1.118 and a normal (Gaussian) distribution of well deviations (Fig. 10c). In the 35 block area, offshore SW Norway, the *H. delrioensis* FCO event occurs closely above the top Albian as defined from the LO of *Ovoidinium scabrosum*, whereas the *H. delrioensis* LCO event marks the top of the *H. delrioensis* LCO zone (lower Cenomanian), that here also includes the LO's of *Rhombodella paucispina*, *Plectrocurvoides alternans* and *Lingulogavelinella jarzevae*. In terms of local sands, the *H. delrioensis* FCO event in the south appears abruptly above massive Albian sands, also named Agat sands, laid down under dysaerobic, bathyal conditions (see Section 7), and the LCO event occurs at the top of lower Cenomanian, above some more local lower Cenomanian sands. Hence, the stratigraphic range of common to abundant *Hedbergella delrioensis* is above Agat sands, and below Lysing sands (Fig. 14).

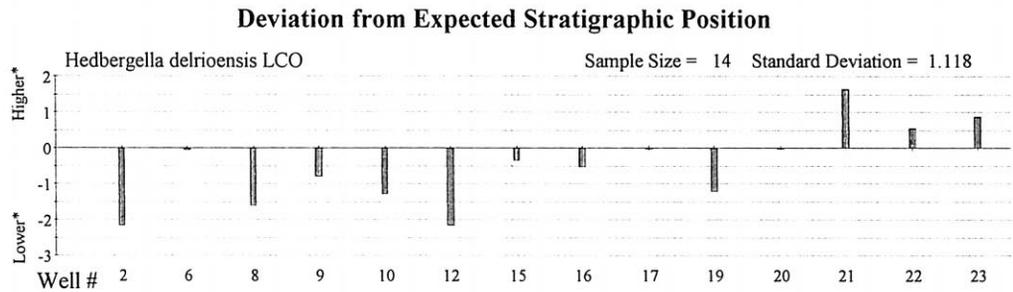
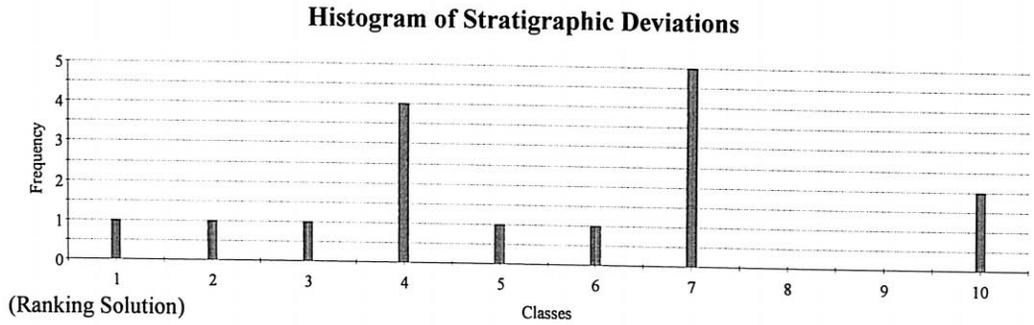
What is insightful, is to compare the planktonic ranges in UK, NW Germany and offshore Norway (Fig. 11). The boreal planktonic foraminiferal acmes, offshore mid-Norway, correlate to similar acmes in NW Germany and UK (Hart, 1993; Prokoph, 1997). Also shown are the standard ammonite and planktonic foraminiferal zonations for the interval, and the regional RASC zonation. The prominent *Globigerinelloides bentonensis* acme in NW Europe is barely recognizable further north, offshore Norway, which region is peripheral to its paleogeographic distribution. Why the hedbergellids dramatically decline abundance near the boundary of lower and middle

Fig. 10. (a) Deviations from expected stratigraphic position and histograms of stratigraphic deviations for dinoflagellate cysts events *Litosphaeridium siphoniphorum* and *Epelidosphaeridia spinosa*. These events have high S.D. values and non-normal frequency distributions which indicate low value as zonal markers. One factor, other than common reworking of these events in the often sandy Cenomanian interval that makes it difficult to pick them in wells, is that the LO's of *L. siphoniphorum* and *E. spinosa* maybe time transgressive, ranging younger southward (see text). (b) Deviation from expected stratigraphic position and histogram of stratigraphic deviations for *Hedbergella delrioensis* LCO, a calcareous planktonic LCO events that reflect oxic watermass conditions, relatively high fertility and slow sedimentation. The event, observed in 14 wells, has a low S.D. 1.118 and a tendency to a normal histogram of stratigraphic deviations. Other planktonic and some calcareous benthic events (of similar stratigraphic importance) with low standard deviations and a normal histogram are from stratigraphically younger to older, *Rugoglobigerina rugosa*, *Globigerinelloides volutus*, *Reussella szajnochae*, Red coloured planktonics, *Inoceramus* needles LCO, *Stensioeina polonica* and *Dicarinella imbricata*. (c) Deviation from expected stratigraphic position and histogram of stratigraphic deviations for agglutinated benthic foraminiferal fossil events that reflect dysaerobic watermass conditions and fine grained, low carbonate, mudstone substrate. These events are *Tritaxia dubia*, Deep water agglutinated foraminifers LCO, and *Uvigerinammina una* (not shown), with low standard deviations of 1.254, 1.358 and 1.445, respectively, and normal histograms, which indicates their value as zone markers. The Campanian deep water agglutinated foraminifer event, although easy to recognize in wells, probably is time transgressive within that stage.





* Stratigraphic Position in Wells higher or lower than expected



* Stratigraphic Position in Wells higher or lower than expected

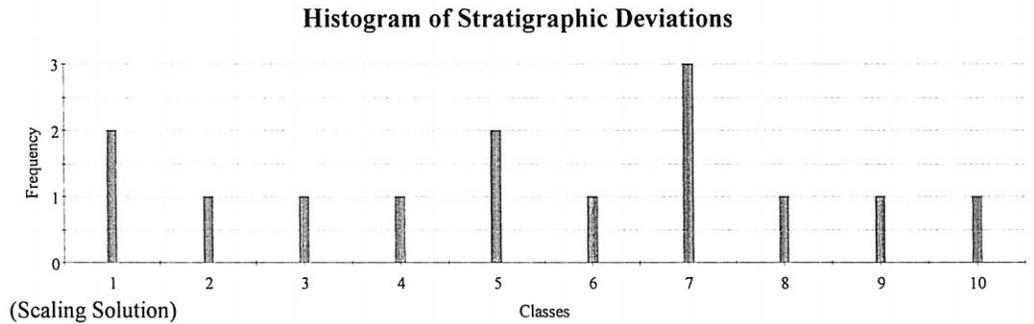


Fig. 10 (continued).

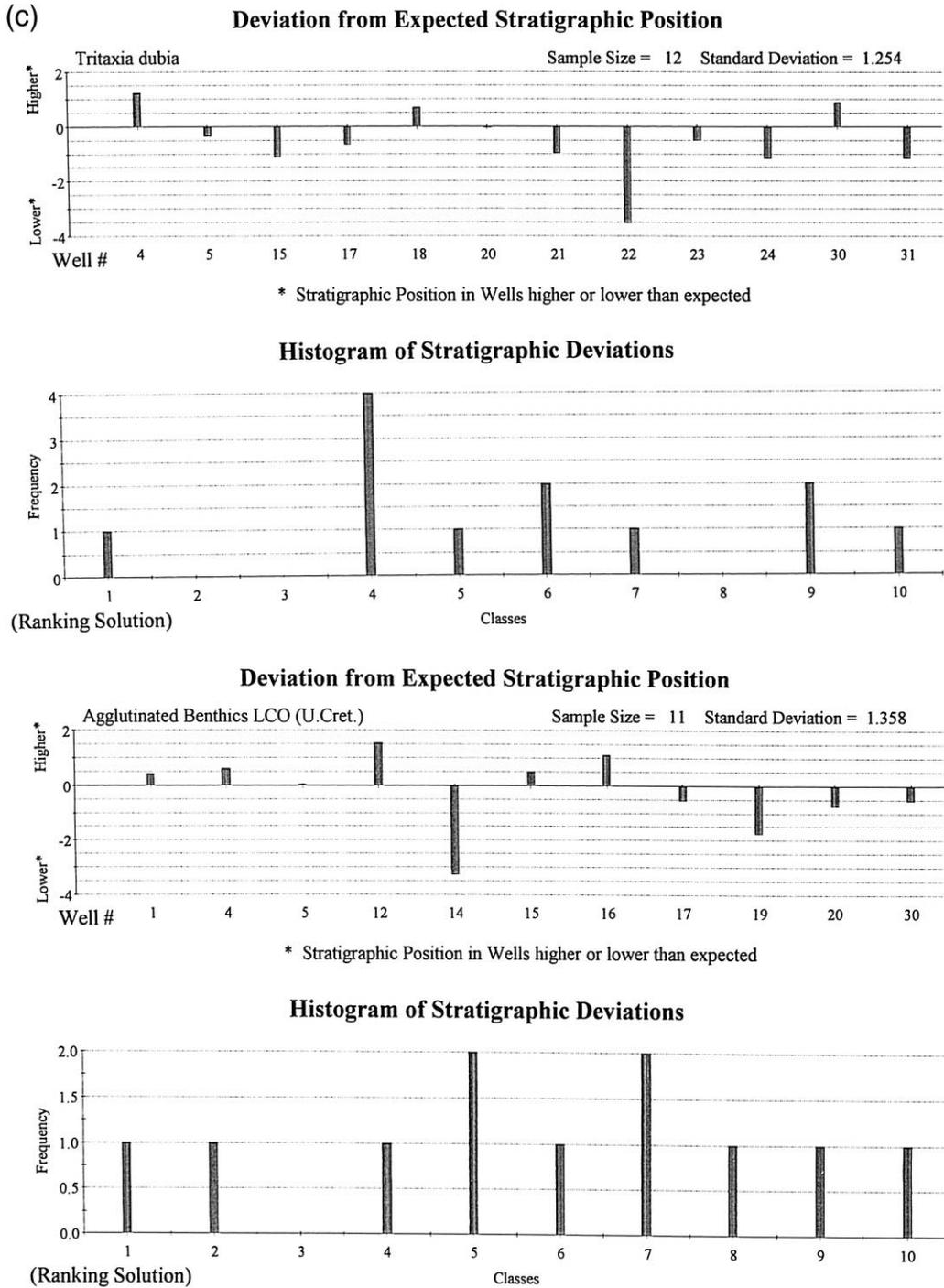


Fig. 10 (continued).

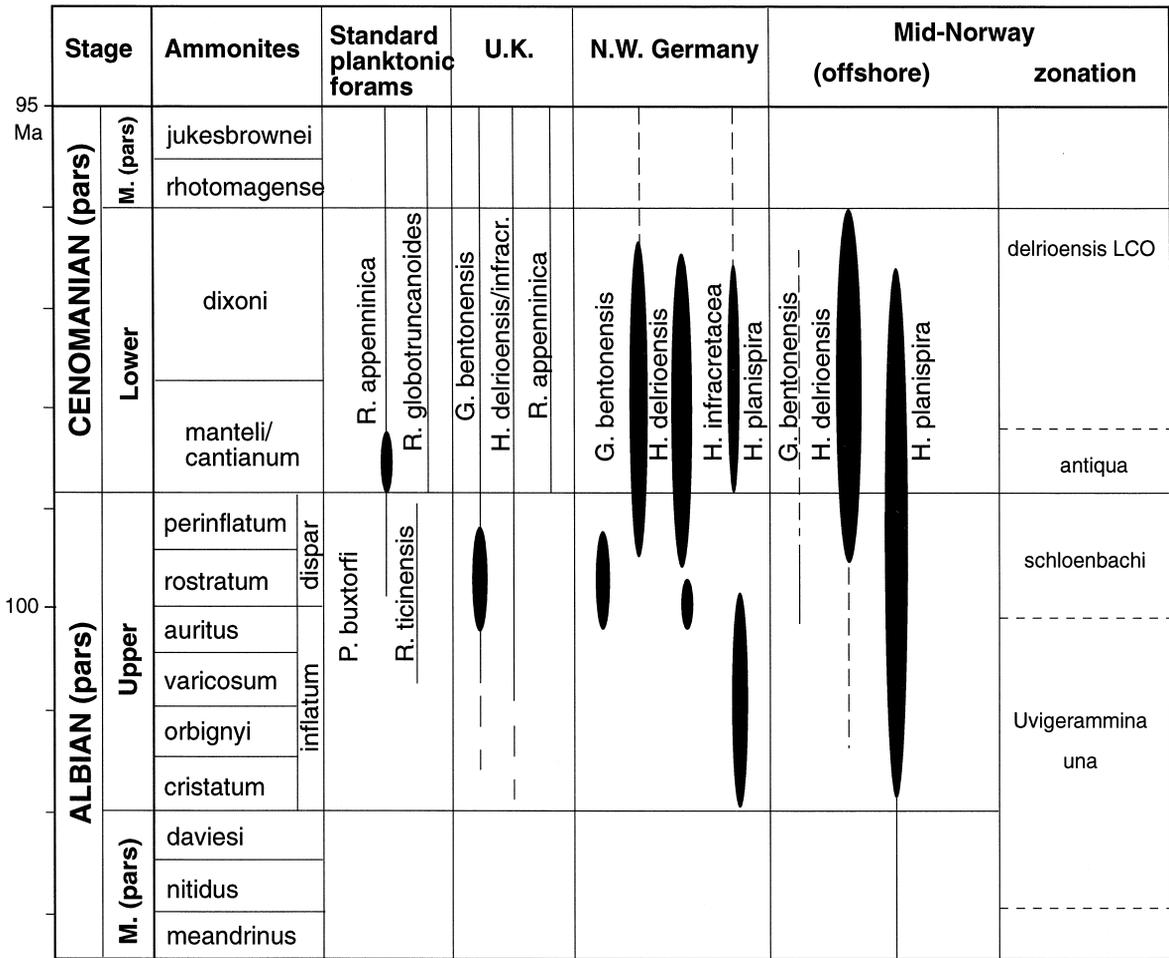


Fig. 11. Boreal planktonic foraminifera acmes, offshore mid-Norway, correlated to similar acmes in NW Germany and UK (Hart, 1993; Prokoph, 1997). Also shown are the standard ammonite and planktonic foraminifer zonation for the interval, and the regional RASC zonation. The prominent *Globigerinelloides bentonensis* acme in NW Europe is barely recognizable further north, offshore Norway, which region is peripheral to its distribution. Reasons for the acmes are discussed in the text.

Cenomanian is not certain, but several lines of evidence bear on the issue.

Firstly, in the 35 block area the abrupt reduction in hedbergellids (the *H. delrioensis* LCO event) is followed by a level with abundant brown, sideritic concretions. The latter suggests that a local hiatus or a condensed interval is present at that level, probably of early middle Cenomanian age. Although no regional sequence stratigraphic analysis is done, we postulate it is reasonable to infer that the *H. delrioensis* LCO event is indicative of the top of a transgressive or highstand sequence interval, and that

the subsequent hiatus or lag represents a rise after a sudden lowstand. Hence, we propose that this hiatus is coeval with the Rouen hardground complex in France, the mid-Cenomanian non-sequence in southern UK (Hardenbol et al., 1993), and the large hiatus at the boundary of lower and middle Cenomanian in NW Germany, e.g., in the Baddeckenstedt area (Mutterlose et al., 1997). The hiatus may be linked to a tectonic uplift and/or tilt of basin margins around the early to middle Cenomanian boundary, followed by renewed gravity-flow sand deposition, offshore mid-Norway from middle Cenomanian onward. The

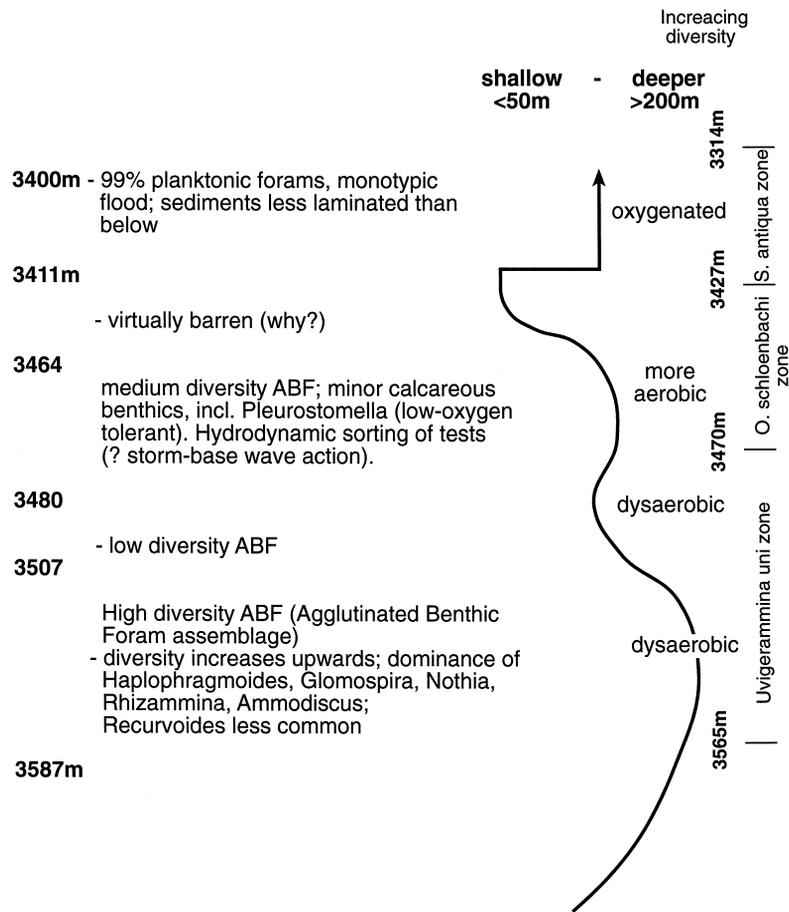


Fig. 12. Foraminiferal trends in the cored interval of Albian to earliest Cenomanian age in well 35/3–4, Agat area, offshore Norway.

sand lithology severely dilutes the planktonic record in samples, but other, not understood reasons might prevail to curtail proliferation of planktonics in middle to late Cenomanian. Detailed studies of cores may reveal global dysaerobia to play a role in the seaway, as surmised also from the C/T boundary gamma spike event in the *brittonensis* zone (see above). Not until early to middle Turonian time do rich, and more diverse planktonic assemblages re-appear, offshore Norway.

6.3. Four groups of events

Before we discuss correlation of low variance events, we like to present some thoughts on a broad classification of zonal events relative to paleo-

ceanography (Figs. 2, 5 and 11). Firstly there are calcareous planktonic LO and LCO events that reflect oxic watermass conditions, relatively high fertility and slow sedimentation. These events include *Rugoglobigerina rugosa* and *Globigerinelloides volutus*, red coloured planktonics, *Inoceramus* needles LCO, *Dicarinella imbricata*, and *Hedbergella delrioensis* LCO (Fig. 5). All of these events occur in many wells (except 'Red coloured planktonics' that is confined to eight of the southern wells, and *D. imbricata*), have low standard deviations compared to the average S.D. of 1.8903 (Fig. 9), and histograms of stratigraphic deviations that are relatively normal in shape (Fig. 10b). The same holds for the benthic foraminiferal events *Reussella szajnochae* and *Stensioeina polonica*. Hence, these commonly

observed, oxic watermass events are considered reliable zone markers.

Secondly, there are agglutinated benthic events that reflect dysaerobic watermass conditions, and fine grained, low carbonate, mudstone substrate. These events are *Tritaxia dubia*, coarse agglutinated deep water foraminifers LCO, and *Uvigerinamina una*, with low S.D.'s of 1.254, 1.358 and 1.445, respectively (Fig. 9), and normal histograms of stratigraphic deviations, which indicate their value as zone markers. The Campanian coarse agglutinated foraminifers LCO event generally is easy to recognize in wells. It may be slightly time-transgressive, but stratigraphic resolution is limited in the upper part of Campanian. As discussed earlier under the *Tritaxia dubia* zone, the coarse agglutinated assemblage reflects an Atlantic-wide drop in the level of the carbonate compensation depth. Active watermass communication through the Scotland–Greenland gateway (Fig. 1b), existed between the proto Norwegian sea and the North Atlantic Ocean.

Thirdly, there are siliceous planktonic events that reflect high watermass fertility. These events are *Fenestrella bellii* n. sp. and spherical/lenticular radiolarians, with fairly low S.D. values of 1.341 and 1.521 (Fig. 9). The histograms of stratigraphic deviations are normal, which suggests that the events are coeval over the many wells where they are observed. The radiolarian bloom event may be difficult to pick in wells, since scattered radiolarians occur also in stratigraphically younger levels that may be mistaken for this event. Differences in sedimentation rates between wells also tend to obscure the event. In the North Atlantic, greenish radiolarian-rich sediments appear near the Santonian–Campanian boundary, suggesting that it is a useful regional stratigraphic marker, offshore Norway, particularly if sediments would be cored.

A fourth category of events are dinoflagellate cysts that are extensively used for Cretaceous well stratigraphy, but are of variable stratigraphic quality. These events include *Trithyrodinium suspectum* LCO, *Heterosphaeridium difficile* LCO, *Endoceratium dettmaniae*, *Litosphaeridium siphoniphorum*, *Maghrebinia membraniphorum*, *Epelidosphaeridia spinosa*, *Ovoidinium scabrosum* and *Apteodinium grande*. The events have low S.D. values and normal frequency distributions, except for *E. dettmaniae*, *L.*

siphoniphorum, *M. membraniphorum*, and *E. spinosa*. The latter four events have high S.D. values of 2.068, 2.066, 3.024, and 2.531, respectively (Fig. 9), and skewed, and not normal histograms of stratigraphic deviations. This indicates low value as zonal markers. As discussed above, a factor, other than common reworking of these four events in the often sandy Cenomanian interval that makes it difficult to pick them in wells, is that the LO's of *L. siphoniphorum* and *E. spinosa* may be time transgressive, ranging younger southward.

6.4. Correlation

In geologic correlation it is common practise to evaluate stratigraphic resolution in terms of the number of events per stratigraphic interval. If a zonation is made up of many closely spaced events, or if wells are tied with many closely spaced parallel lines we assume high resolution in relative geologic time. This evaluation ignores the fact that stratigraphically successive individual events or tie lines might have stratigraphic uncertainties attached far in excess of the displayed stratigraphic distance between them. True resolution comes from an evaluation of stratigraphic distances between events, and an estimation of stratigraphic standard deviations on individual event positions.

Fig. 13 shows correlation in eight wells of some zonal events, with well below variance, of Albian through Maastrichtian age. The wells are arranged from north (right) to south (left). Errorbars on calculated most likely event positions in the wells show 95% confidence limit. The correlation diagram is flattened on event 16—*H. delrioensis* LO. This event occurs in the *W. brittonensis* zone, upper middle to upper Cenomanian, just below the C/T boundary gamma spike, discussed under the *W. brittonensis* zone in the previous section. Other events in the diagram include from younger to older: 29—*Reusella szajnochae*, 255—*Trithyrodinium suspectum* LCO, 370—*Fenestrella bellii* n. sp., 330—*Inoceramus* needles LCO, 82—*Heterosphaeridium difficile* LCO, 212—*Hedbergella delrioensis* LCO, 93—*Ovoidinium scabrosum*, and 61—*Uvigerinamina una* n. sp. These events have low S.D. values and normal histograms (Figs. 9 and 10); the length of the errorbars on most likely event position in Fig. 13

Cretaceous Biostratigraphic Correlations, offshore Norway
Error bars show 95% confidence limits

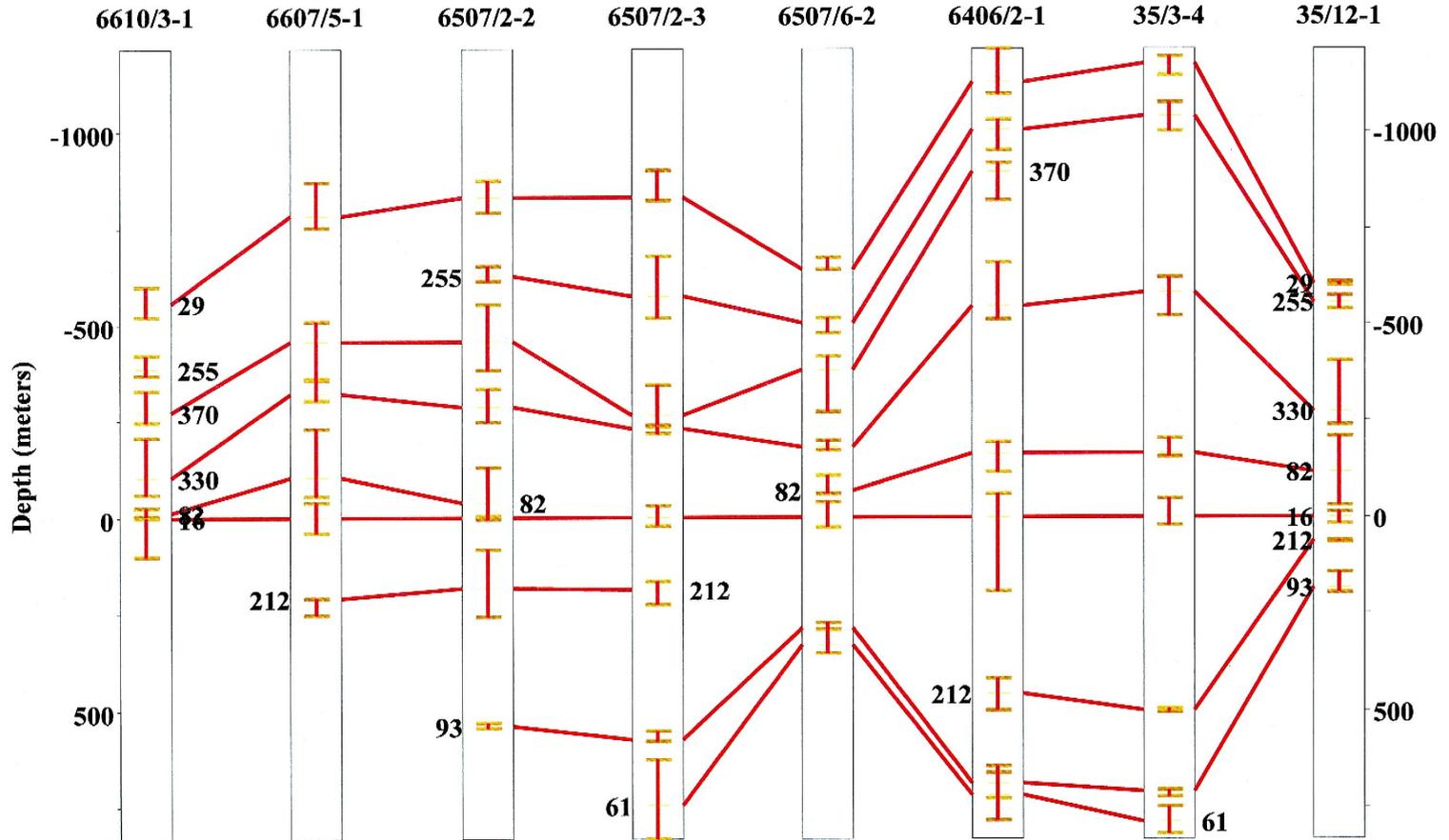


Fig. 13. Albian through Maastrichtian biostratigraphic correlations, using foraminifer and dinoflagellate events in eight wells, offshore mid-Norway. Wells are arranged from north (right) to south (left). Errorbars on most likely event positions in the wells show 95% confidence limits. The diagram is flattened on event 16, *Hedbergella delrioensis* LO. Other events include: 29—*Reussella szajnochae*, 255—*Trithyrodinium suspectum* LCO, 370—*Fenestrella bellii* n. sp., 330—*Inoceramus* needles LCO, 82—*Heterosphaeridium difficile* LCO, 212—*Hedbergella delrioensis* LCO, 93—*Ovoidinium scabrosum*, and 61—*Uvigerinamina una* n. sp. These events have low S.D. values and normal histograms (Fig. 9); the length of the errorbars on most likely event position is a function of the original stratigraphic scatter of event positions in the wells and event variances.

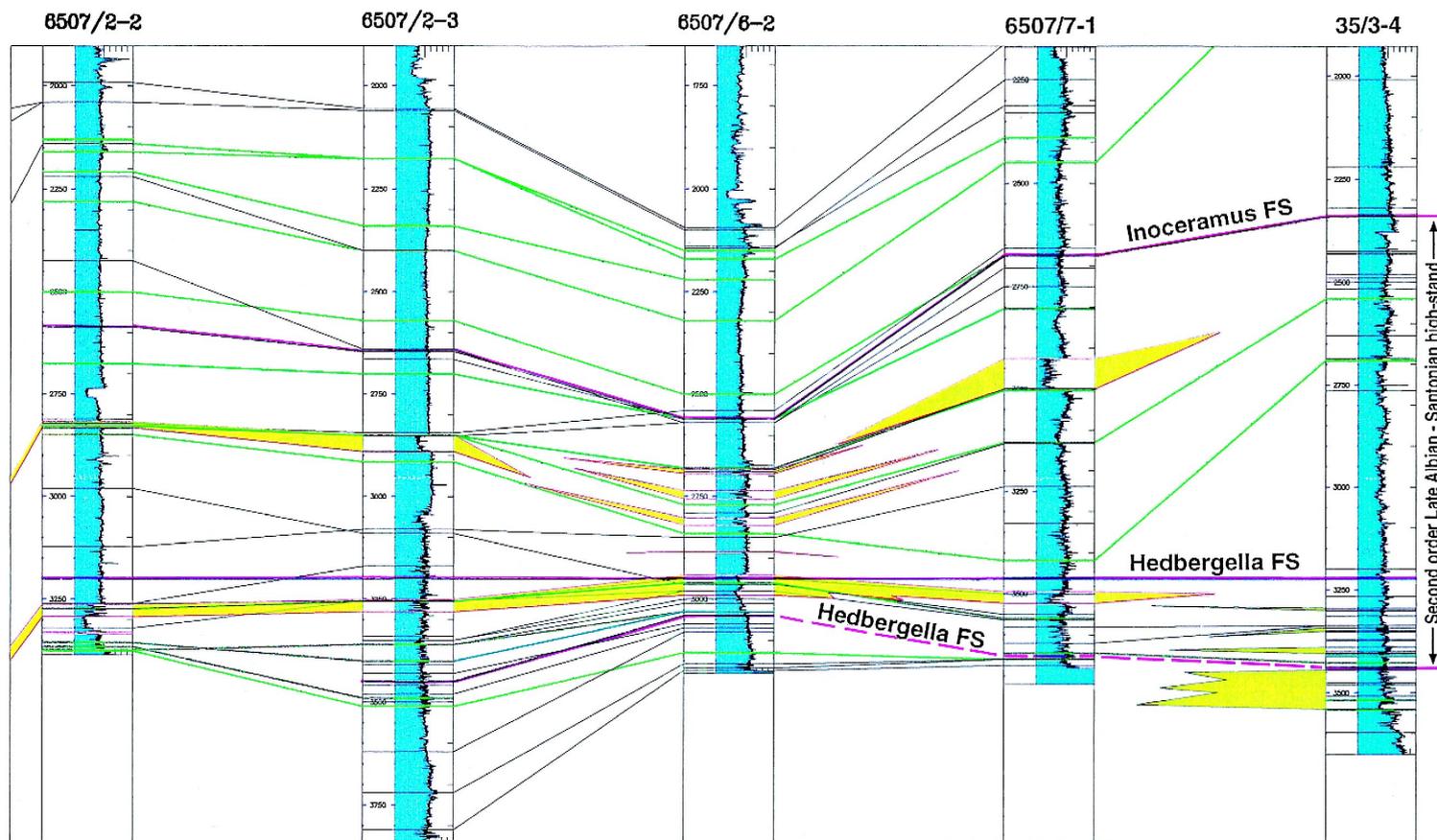


Fig. 14. Correlation of events in the optimum sequence and zonation of Figs. 5 and 6 in Albian through Santonian strata in five wells, offshore Norway. Green and red coloured correlation lines are from events that have below average stratigraphic standard deviation, and are thought to each track best the same stratigraphic levels; black lines are from events that have above average stratigraphic standard deviation (and hence are less certain in correlation, and show some cross-overs); yellow-gravity flow sands. The *Hedbergella (delrioensis)* FCO and LCO events (Lower Cenomanian), and the *Inoceramus* LCO event (Santonian) are coloured red, and are considered flooding surfaces (FS). These events represent reliable regional correlation levels, with below average S.D., that reflect considerable marine transgression, together with slow sedimentation. The sands below the *Hedbergella* FCO level are the Agat sands; the sands between the two *Hedbergella* levels, the Lange sands, and the sands above the *Hedbergella* LCO level, are Lysing sands.

is a function of the original stratigraphic scatter of event positions in the wells, and event variances.

In most cases, the error bars are relatively small, and indicate that the events are well constrained in the wells. In few cases were error bars are larger, this reflects scarcity of fossil data in the wells, with considerable scatter in that data also. Other parameters, like well logs and lithologic trends will be needed to further constrain correlations, but with the RASC program initial fossil correlations are easily and rapidly accomplished, and the simultaneous colour graphics display allows to evaluate principal correlation trends, prior to import in well log, and seismic subsurface displays.

In Fig. 14, variance data on fossil events are used to create a different, but effective type of correlation plot. Here variance analysis data are utilized to correlate the Cretaceous turbiditic sands in five wells, offshore mid and southwestern Norway. These sands are difficult to track on seismic, and regionally have a complex architecture. The stratigraphic interval displayed in the figure covers upper middle Albian through lower Campanian. Initially, correlation of all zonal events as observed in the wells produced a diagram (not shown) with many reasonably concordant correlation lines, but also a number of lines that crossed each other, suggesting uncertainty in local point correlations. It would be possible to calculate most likely event positions from a crossplot between zonation and well data, as achieved in Fig. 13. Correlation of such interpolated event positions produces parallel tie lines between wells. The problem with such a procedure is that considerable geologic information must be taken into account to avoid 'nonsense' correlations across hiatuses and unconformities not readily seen from event data only. Also, events are not ranked as 'good and bad' trackers of the same stratigraphic level, unless additional information is taken into account, like event variance, shown in Fig. 13 as error bars.

A simpler and more direct manner of proceeding with event correlation between the wells is to tie the wells together with the observed rather than interpolated depth of the fossil events, and indicate with a colour which events have below average S.D. values. In Fig. 14, these low S.D. events are coloured green and red, whereas events with above average S.D. values are in black. Gravity flow sand are in yellow.

Log traces are gamma ray, and sonic/neutron density. The first and last common to abundant occurrences of the planktonic foraminifer *H. delrioensis* (FCO and LCO events), and *Inoceramus* LCO also have well below average S.D., and are coloured red on Fig. 14. The red events reflect considerable marine transgression, together with slow sedimentation. In Fig. 13, the *Hedbergella* LCO event is 212, and the *Inoceramus* LCO event 330.

It may be readily observed in Fig. 14 that sand correlations are relatively complex, but are tracked by green and red markers. None of the green and red markers cross-over, although some black ones do (as expected). At the outset of this exercise geologists had stratigraphically lined up the sands between wells much more than appears likely from the microfossil correlation data. Hence, prospectivity may have degraded but the correlation trends are more in line of what is expected with turbiditic sands. It is beyond this study to enlarge on the geologic implications of these findings, but the point may be made that correlation of low S.D. events from RASC analysis enhances insight in well to well correlation, in search of stratigraphic traps.

7. Paleobathymetry and sequence breaks

In this section, we will outline principal trends in lower and middle Cretaceous paleobathymetry, its underlying reasons, and microfossil criteria utilized to assign paleo waterdepth in exploration wells. Details of upper Cretaceous paleobathymetry await more core data, including information from the Voering Basin, where massive Campanian gravity flow sands indicate 'central' depocentres in the seaway between Norway and Greenland.

7.1. Lyr formation, upper Hauterivian–lower Barremian

One of the most outstanding features of the Lower Cretaceous microfossil record, offshore southwest and mid Norway is the abrupt appearance of diversified foraminiferal assemblages that characterise the reddish, calcareous sediments of the Lyr Formation, assigned to the *Protomarsonella kummi*, *Falso-*

gaudryinella praemoesiana and *F. xenogena* zones, upper Hauterivian through lower Barremian. The Lyr sediments follow upon an extensive hiatus separating middle or late Jurassic from early Cretaceous strata (Figs. 2 and 3), during which (hiatus) period we postulate much land existed between Greenland and Norway.

Multicoloured microfossil assemblages assigned to the zones cited above and the Lyr Formation are known from Andoya as mentioned earlier, and have now also been observed by us on Eastern Greenland. The assemblages are generally fairly rich in calcareous benthics like lenticulinids and other nodosariids, spirillinids, *Patellina*, calcareous cemented agglutinated forms like *Falsogaudryinella* and textulariids. *Epistomina* and *Trocholina* are mostly rare, while smooth ostracods are common, and so are macrofossil fragments. A more complete microfossil listing is in Appendix A.

This type of microfossil assemblage is typical for relatively shallow marine, neritic and photic zone conditions, with oxic watermass. Dominant forms like *Falsogaudryinella* and *Lenticulina* possess in-faunal morphologies that in modern oceans are dominant on the outer part of the neritic zone, passing into upper bathyal. Few endemic taxa have been observed. Water circulation must have been largely anti-estuarine, allowing flushing of fresh-water input, and keeping oxygenation high. Hence, the sediments of the Lyr Formation represent a major circum Norwegian Sea transgression in Hauterivian to Barremian time, with marine connections opening to both the Atlantic via the Scotland–Greenland gateways, and via the Viking Graben into NW Germany (Fig. 1a).

In few northern sites, it was observed that the typical calcareous and oxic Lyr Formation assemblages in Barremian time change into an almost monotypic assemblage with *Spirulina*, some ammodiscids, and common pyrite. Hence, we postulate that the open marine, oxic conditions locally may have locally changed to become enclosed, lagoonal with abundant organics input limiting oxygenation of bottom waters.

In one updip well site, 36/1–1, in the southwestern portion of the study region, the benthic foraminiferal assemblage correlative to Lyr Formation assemblages northward, consists largely of *Epis-*

tomina caracolla, of shallow marine and oxic watermass character. This well was not included in the RASC zonation due to the presence of many stratigraphic gaps, and poor fossil recovery.

7.2. Aptian–Albian shales and sands

Stratigraphically upwards in lower Cretaceous well sections, in strata assigned to Aptian and Albian, the microfossil assemblage changes dramatically from below. It includes well-known deep-water agglutinated taxa like *Caudammina crassa*, *Kalamopsis grzybowski*, *Cribostomoides nonioninoides*, *Recurvoides* spp., *Plectorecurvoides* spp., and rare *Pseudobolivina*. The assemblages also contains a fair proportion of tubular, deep water agglutinated taxa such as *Rhabdammina*, *Rhizammina*, and *Bathysiphon*. There is little doubt that such assemblages, known as they are from the Carpathian Trough, other flysch basins and oceanic environments, are indicative of bathyal conditions. Sediments are dark shales with minor amounts of carbonate, and gravity flow sands during Albian time, in the southern part of the region.

Lower Cretaceous planktonic foraminifers are generally rare, but locally and temporally occur in floods in Albian time (and also in Aptian time southward, probably because of fewer hiatuses there), discussed in the previous chapter. The upper part of middle and upper Albian locally also harbour calcareous benthic taxa with *Osangularia*, *Gavelinella*, *Pleurostomella*, *Epistomina* and *Gyroidina*. Again, the occurrence of these taxa fits in the interpretation that we are dealing with bathyal assemblages.

The question is what caused the change from neritic to bathyal conditions, in mid-Cretaceous (Fig. 1a,b). Hauterivian to Aptian sediments are mostly thin, at maximum hundred meter or so thick, probably reflecting slow, thermal subsidence, following Jurassic graben formation between Greenland and Norway, and further compaction of massive underlying Jurassic strata. It is possible that the limited sedimentation, in a slowly subsiding basin, might have sufficed to increase paleo waterdepth, as observed. Mid-Cretaceous block-faulting is thought to have played an important role (see below; Guy, 1992), but another factor contributing to the increase

in sediment accommodation space, was the rise in eustatically controlled sealevel in early through middle Cretaceous time. Estimates vary, but an increase in paleo waterdepth in excess of 250 m may have been the result from global sea-level rise (W. Hay, pers. commun., 1996). Hence, even if the sediment basins between Greenland and Norway were tectonically passive, and without much sediment input, paleo waterdepth would have increased from neritic to upper bathyal. With minor sediment input as observed, ongoing thermal subsidence, and the compaction of underlying Jurassic strata, upper bathyal paleo waterdepths in Aptian to Albian time are in line with what we postulate independently from the microfossil assemblage.

An interesting feature in the Albian bathyal setting is the dramatic change from dysaerobic to oxic basin, clearly observed in several southern wells, e.g., in the 35 block area (Agat). There, Albian reservoir sand deposits were mapped by J. Nystuen (pers. comm., 1995) as mass-flow deposits, including turbidites, from several easterly point sources. The paleo waterdepth may be interpreted from the foraminiferal assemblages in the core samples of dark shales interbedded with the sands in wells 35/3–2 and 35/3–4. Fig. 12 summarizes the foraminiferal trend in the more proximal well 35/3–4, during middle to late Albian, and earliest Cenomanian time.

The foraminiferal assemblage in dark, and often laminated shales between the mass-flow sands, are dominated by agglutinating benthic foraminifers, resembling flysch-type fauna. Over 30 taxa are recognized, and the assemblage is diverse in genera and species, with many tubular taxa, like *Rhabdammina*, *Rhizammina* and *Bathysiphon*, and varying proportions of *Haplophragmoides*, *Cribrostomoides*, *Glomospira*, *Ammodiscus*, *Recurvoides*, *Psammospaera*, *Reophax*, *Plectorecurvoides*, *Falsogaudryina*, *Caudammina*, *Saccamina*, *Dorothia*, *Trochamminoides* and *Lituotuba*.

In Fig. 12, it may be seen that from 3587 to 3507 m, upper middle to lower upper Albian, the agglutinated benthic foraminiferal assemblage is of high diversity, with a diversity that increases upwards. It differs from the agglutinated assemblages in the Polish Carpathians, that fewer *Plectorecurvoides* and *Pseudobolivina* are present. There are no calcareous

benthic taxa, and the assemblage is interpreted as reflecting dysaerobic conditions in a restricted basin. The basin is open marine, but the lower water column is restricted, and beyond the influence of storm wave base. An bathyal, slope setting is likely, the upper depth limit probably being upper bathyal as generally interpreted for flysch-type assemblages (Gradstein and Berggren, 1981).

From 3507 to 3480 m, the agglutinated foraminiferal assemblage decreases in diversity, and from 3480 to 3473 m (upper Albian), minor calcareous benthics appear, including rare *Pleurostomella*, tolerant to dysaerobic conditions. Also at 3473 m hydrodynamic sorting of the assemblage is observed, with either largely tubular, or largely discoidal foraminiferal tests. This trend from 3507 m upward is interpreted as a decrease in waterdepth, decrease in watermass restriction, and shallowing to wave-base level.

It is not clear why from 3464 through 3411 m, across the Albian–Cenomanian boundary, shale samples are barren of shelly microfossils; pyritisation does not seem to be an active cause of shell destruction in this well site. Above 3411 m to the top of the cored interval at 3400 m, lowermost Cenomanian, the microfossil assemblage in the dark shales is 99% planktonic foraminifers, consisting of *Hedbergella delrioensis*, with rare *H. planispira*. Dark shales are less laminated than below, and we conclude that the youngest shale sediment was laid down in an oxygenated, open marine basin setting that might be deep neritic at maximum wave base level.

As discussed earlier, such monotypic planktonics flood also are reported from NW Germany, southern North Sea and UK, representing the same transgressive, maximum flooding interval when watermass conditions in the basins changed from dysaerobic to oxic.

In the 35/3–2 well, seismically basinward of 35/3–4, the middle to late Albian reservoir sands and interbedded shales also have a rich and diversified ABF assemblage. From 35/3–4 to 35/3–2 calcareous benthics all but disappear, diversity of ABF increases, their test size decreases, and an increase takes place in the frequency of *Falsogaudryinella*, *Recurvoides*, *Reophax*, *Plectorecurvoides*, *Gaudryina* and *Saccamina*. There is no obvious hydrodynamic sorting in the samples studied

from 35/3–2. The change in test size from larger in 35/3–4 to smaller in 35/3–2, in conjunction with a higher diversity is interpreted as reflecting more optimal conditions for the flysch-type assemblage, as found in lower energy, deeper marine, more distal conditions. This agrees with the more distal basin setting from seismic interpretation (B. Torudbakken, pers. comm., 1995).

The conclusion from the paleoecologic interpretation is that the Agat reservoir sands in 35/3–4 were laid down in an upper bathyal, dysaerobic environment, that slightly shallowed upward, and became better oxygenated across the Albian–Cenomanian boundary interval.

7.3. Lysing formation, upper Cenomanian–Turonian

A poorly understood assemblage of agglutinated foraminifers occurs in Cenomanian, and particularly in Turonian sand-prone mudstone strata, offshore mid Norway, north of the Agat area discussed above. The interval includes gravity flow sands assigned to the *brittonensis* and *Dicarinella* zones and part of the *Marginotruncana* zones, middle-late Cenomanian and Turonian or slightly younger. The unit may be over 1000 m thick, and is relatively poor in microfossils. Sparse planktonic foraminifers indicate normal salinity, (fairly) open marine conditions; the poor benthic assemblage with few calcareous taxa (*Dentalina*, *Gyroidinoides*, *Pleurostomella*), and few coarse agglutinated ones like *Bathysiphon*, *Psammosphaera*, *Trochammina* and *Ammodiscus* might reflect restricted bottom conditions in a bathyal setting, with some hydrodynamic sorting of test shapes, during sediment transport in deeper water. Small pillbox diatoms are common and pyritized, pyritized radiolarians occur rarely, but testify to normal marine salinity, and bathyal conditions. A high sedimentation rate (see Section 8), under restricted bottom conditions, together with some sorting, and diagenetic loss of taxa due to dissolution, probably combined to yield the ‘impoverished’ microfossil assemblage. The reason for a barren interval with the C/T boundary gamma spike, was touched upon under the *Dicarinella* zone.

Of interest is that several levels in wells, poor in microfossils, give the impression being sorted hydrodynamically, with a prevalence of spherical, tubular

or disk-shaped forms, including *Psammosphaera*, *Bathysiphon*, *Ammodiscus*, and sideritic and pyritic concretions that maybe tiny burrows. The environment of deposition probably was largely dysaerobic, semi-restricted, and of high energy due to turbidite scouring, and on average unfavourable to a diversified benthic life. A bathyal setting is most likely, in agreement with the fairly common presence of tubular agglutinated taxa, like *Bathysiphon*. In discussion with W. Kuhnt and T. Sæther (pers. comm., 1996), the possibility was raised that such a benthic foraminiferal assemblage might represent overbank deposits at bathyal depth, to the side of a mass-flow sand conduit. Where sands were sampled, presumably in these conduits, no foraminiferal assemblage was recovered, also not shallow marine taxa that could be considered transported down slope.

Another scenario is that the common *Psammosphaera* component, found as dominant form in many Lysing samples in the region, was an early seafloor colonizer after a mass-mortality event, reflecting a disturbed environment, due to repeated sand scour in a ‘fan sand delta’. A low oxygen watermass impinging on the slope would keep benthic diversity low, further threatened by repeated erosional events from sand scour. Such an environment would favour *Psammosphaera* as an opportunistic, early seafloor settler, in a bathyal environment.

7.4. Middle and upper Cretaceous breaks in the fossil record

As mentioned earlier, the scaled optimum sequence of Fig. 5 (left) shows major breaks between several successive zones, including between the *una* and *schloenbachi* zones, *delrioensis* LCO and *brittonensis* zones, *Marginotruncana* and *polonica* zones, *bellii* and *dubia* zones, and particularly between *dubia* and *szajnochae* zones. In trying to answer what the meaning is of these large breaks in the RASC scaling solution, it is useful to consider how RASC scaling of relative interevent distances operates. The relative distance between events in the optimum sequence is calculated from the frequency of cross-over of all possible direct and indirect pairs of events in the optimum sequence. Hence, large distances between successive events in the scaled optimum sequence reflect strongly diminished re-

gional cross-over between the majority of events below and above the breaks. Reasons for these regional breaks must be thought in stratigraphic gaps and paleoenvironmental changes, related to sequence stratigraphic breaks, and will be discussed below.

The *una-schloenbachi* break reflects a latest Albian lithofacies change, and hiatus. An uppermost Albian hiatus, assigned in some of the wells, may truncate part or all of this zone, possibly related to the pronounced eustatic offlap cited by Hardenbol et al. (1993; in press), and by Rohl and Ogg (1996), at the base of the Tethyan *Mortoniceras inflatum* zone. The hiatus is visualized by the large interfossil distance below *A. grande*, at the base of the RASC interval zone in Fig. 5 (left). In boreal NW Europe this level frequently is a disconformity, separating upper Albian deposits (not uppermost) of the *Stolcskaia dispar* ammonite zone from the lowermost Cenomanian transgressive deposits of the lower *N. carcitanense* ammonite subzone. The combined sequence boundary and transgressive surface is known as the Octeville transgressive surface in Normandy (Hardenbol et al., in press).

The *delrioensis* LCO–*brittonensis* break reflects the mid-Cenomanian lithofacies change, and hiatus. The hiatus is visualized by the large interfossil distance in Fig. 5 (left) below *Batioladinium jaegeri*, at the base of the *brittonensis* interval zone. The top of the zone extends above the sands of the Lange Formation, offshore mid-Norway, and is below or in sand of the basal Lysing Formation. Since recognition of the zone is dependent on suitable, shaly lithology (the widespread gravity flow sands not being fossiliferous), the full stratigraphic extent of the hiatus remains to be determined. The break probably incorporates a maximum flooding horizon with *Hedbergella delrioensis* LCO near the turn-around position in the eustatic sealevel cycle, in late early Cenomanian. This level is then truncated by the mid-Cenomanian non-sequence, like the Rouen hardground of northern France (Hardenbol et al., 1993; in press).

The considerable *Marginotruncana-polonica* break at the level of *H. difficile* may reflect the lowstand between two major tectono-eustatic cycles in middle Coniacian (Hardenbol et al., in press). There is no doubt that above the break, at the end of Lysing sand deposition time, the section is generally

more condensed and more marly. Again, just as below the previous break, there is a LCO event just below this RASC zonal break, in this case the widespread *Heterosphaeridium difficile* LCO event, which may represent maximum transgressive flooding, prior to the turn-around point in the eustatic sealevel cycle.

The significance of the *bellii-dubia* break in the RASC zonation is not obvious to us, but it may be significant that again a widely recognized LCO event, this time of *Trithyrodinium suspectum* is (near or) at the RASC zonal break. Hence, a maximum flooding horizon occurs likely at this level in the lower part of the Campanian; it approximates the transition from the early Campanian biosiliceous assemblage to the coarse agglutinated deep water foraminifer assemblage in the North Atlantic and Tethys, discussed earlier (see *Fenestrella bellii* and *Tritaxia dubia* zones).

The *dubia-szajnochae* break reflects the abrupt change from siliciclasts to marly sediment at the Campanian–Maastrichtian boundary, only noted in the southern part of the region.

In detail, individual well sedimentology and stratigraphy may show more complexity than outlined here, but such will need local well log, lithology and possibly seismic input, and is beyond the scope of this study that represents a first pass at the data.

8. Subsidence and sand sedimentation

Although speculative, we postulate that the widespread Barremian–Aptian disconformity (Fig. 2) may be linked to Atlantic rift-onset unconformities, e.g., recognized offshore eastern Canada, north of the Figueiro Fracture zone and Newfoundland Seamounts, prior to oceanisation just after M0 time (Jansa and Wade, 1975). As argued above, ongoing block-faulting, coupled to weak thermal subsidence, and first order global sea level rise, increased water depth in Aptian–Albian time from neritic to upper bathyal, and created sedimentary clastics accommodation space, in a dysaerobic, restricted setting. Just above the Albian–Cenomanian boundary, watermass conditions in the SW part of the study region (e.g., Agat region) changed from dysaerobic to normal

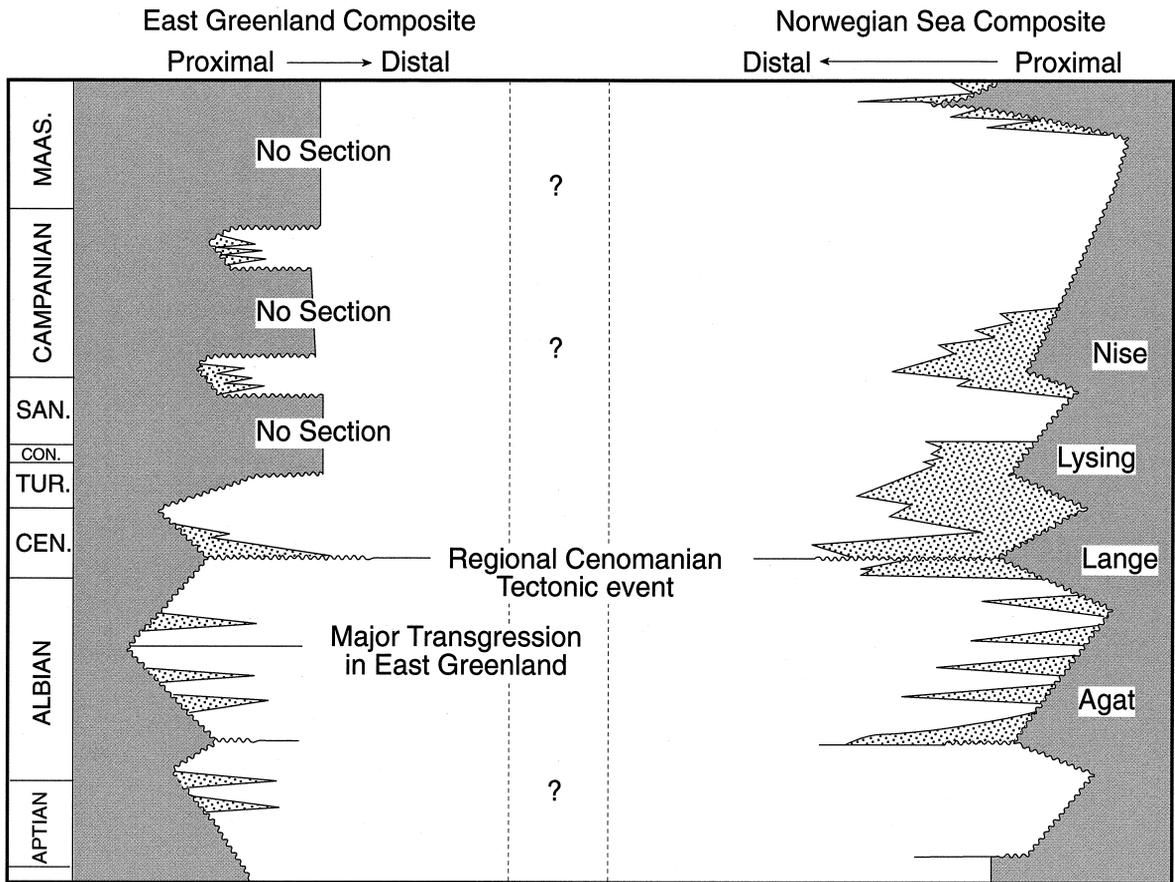


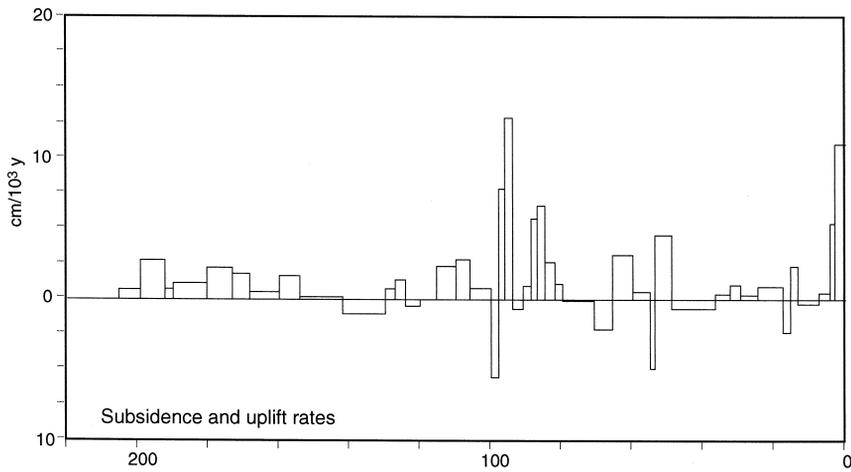
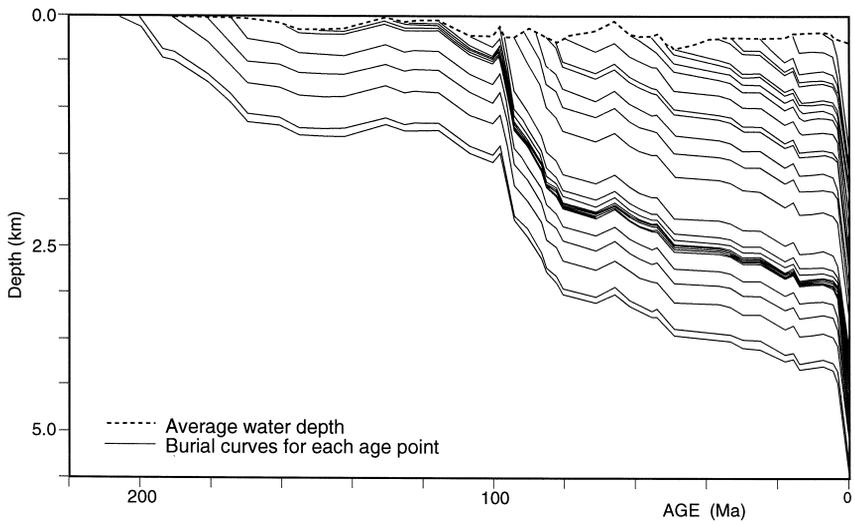
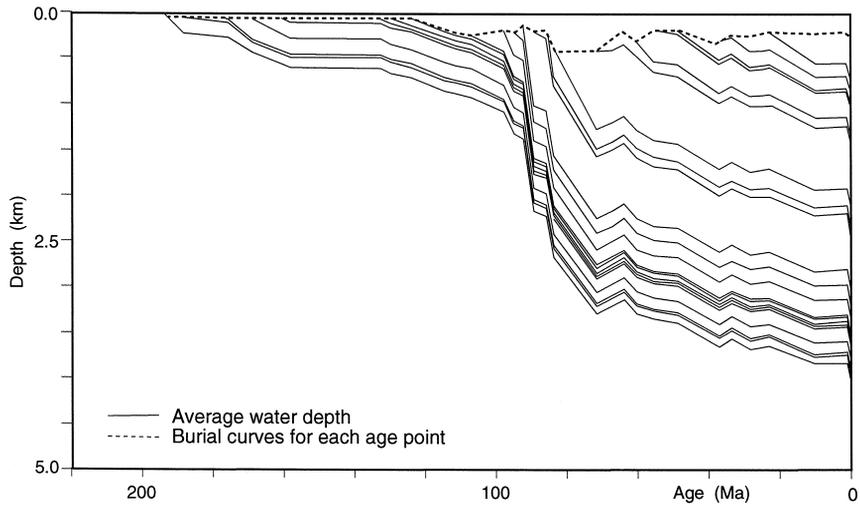
Fig. 15. Schematic illustration of Cretaceous chronostratigraphy and gravity flow sand pulses in the seaway between Norway and Greenland; slightly modified after Dore et al. (1997). For details, see text.

oxygenated marine (Fig. 12), the cause of which must lie in more widespread palaeoceanographic and tectonic changes, as discussed earlier.

The Cenomanian–Turonian sand facies genetically are grouped as gravity flows, which operated

on a westward prograding, slope to basin apron (Saether et al., 1997). As we have discussed earlier, turbidity currents are not uncommon, and agree with an upper bathyal, flysch-type agglutinated foraminiferal assemblage that is locally hydrodynamically

Fig. 16. Airy compensated tectonic subsidence and uplift plot for well 6406/2–2 (bargraph in lower part of figure), and the decompacted burial curves for 6406/2–2, and well 35/3–4 (respectively middle and upper part of this figure). The two wells are several hundred km apart. Four successive stages of tectonic subsidence and subsequent sedimentation clearly stand out. The first stage operated from 200 to 160 Ma, Jurassic, and may be conventionally described as an early to middle Jurassic rifting event followed by thermal relaxation and some sediment loading. The second tectonic stage operated in middle Cretaceous, 100–80 Ma, and may have been enhanced by subsequent sediment loading. The third tectonic stage was active around 60 Ma, related to the opening of the Norwegian sea, while the fourth tectonic stage operated in the late Neogene, and may be ongoing today. Comparable subsidence and burial patterns are also seen in many other wells throughout the region under study, between 60° and 67° N. The combination of a brief hiatus plus shallowing in the uppermost Albian appears as a rapid uplift, which might be expected regionally, just prior to Lower Cenomanian sand deposition. A tenfold increase in subsidence and sedimentation took place in Cenomanian through Coniacian time, during about 15 m.y., creating considerable deep marine sand deposition potential.



sorted. In Fig. 15, which is slightly modified after Dore et al. (1997), these authors have tried to summarize the spatial and chronostratigraphic distribution of conjugate sand units, off east Greenland and off western Norway. The figure, albeit sketchy, clearly shows the Albian–middle Campanian distribution of reservoir sand targets in exploration, offshore Norway.

The question if local block faulting generated local or widespread uplift for sand erosion, and simultaneously increased accommodation space in the basins to deposit the sands, is an interesting one that may be looked upon in a geodynamic context. Take for example the airy compensated tectonic subsidence and uplift plot for well 6406/2–2 (lower part of Fig. 16), and the decompacted burial curves for that well, and for well 35/3–4, in the upper part of Fig. 16, southwestern (Agat) area. The two wells are several hundred km apart. Four successive stages of tectonic subsidence and subsequent sedimentation stand out clearly. The first one operated from 200 to 160 Ma, Jurassic, and may be conventionally described as a Early to Middle Jurassic rifting event followed by thermal relaxation, and sediment loading of basement. The second tectonic stage operated in mid-Cretaceous, 100–80 Ma, and may have been enhanced by subsequent sediment loading, the third one around 60 Ma is related to the opening of the Norwegian sea, while the fourth one operated in the late Neogene and may be ongoing today. From the literature it is not known if detailed geodynamic modelling has been performed on the second and fourth tectonic episodes.

What may be surmised from the mid-Cretaceous tectonics? After a modest increase of burial rate in the Albian, Cenomanian–Turonian time sedimentation rates increased 10-fold, but paleo waterdepth did not deepen noticeably, as shown in decompacted burial curves. Enough sediment ‘rushed forward to fill the hole’, at least in the study area, but more distal parts of the seaway may have subsided to middle bathyal paleo waterdepths.

The combination of a brief hiatus plus shallowing in the uppermost Albian, appears in the models of Fig. 16 as a rapid uplift, which can be expected regionally, just prior to lower Cenomanian sand deposition in a (suddenly) rapidly subsiding basin. This is in line with shallowing observed in the uppermost

Albian in the 35/3–4 well discussed earlier. Subsidence modelling of the observed mid-Cretaceous burial trends with local airy isostatic compensation (lower part of Fig. 16), leaves no doubt the mid-Cretaceous trend is tectonic. The tenfold increase in subsidence and sedimentation raised sand deposition potential. Reasons for this dramatic increase in sediment accommodation potential, offshore Norway are not well understood, but tentatively are linked to basinal extension and basin margin uplifts during mid-Cretaceous plate-tectonic re-organisation. For example, one scenario links such uplifts and surge in sedimentation are due to an ‘intra-Cenomanian’ tectonic event. This event could be related to the fact that in mid-Cretaceous time, a significant change in stretch was modelled in the Rockal area from SW–NE to SE–NW. Prior to Cenomanian, conjugate Grand Banks/Iberia (south of the Charlie Gibbs fracture zone) underwent transition to drifting, whereas north of this fracture zone, between Labrador/Greenland and between Greenland/NW Europe, this drifting is post-Cenomanian in age.

This relatively brief (less than 20 m.y.) tectonic episode, known widespread offshore Norway, and not only in the two wells shown makes the mid-Cretaceous attractive in the search for stratigraphic traps. It is striking that the stratigraphic distribution of the Norwegian deep marine sand targets in Fig. 15, from Albian through middle Campanian, almost exactly coincide with the 105 through 75 Ma, Albian through middle Campanian high burial rate in the mid-Norway well of Fig. 16. Although it is quite possible that on a local scale sequence stratigraphic episodes played a role in the sand distribution (cf. Dore et al., 1997), the overall control on the sand deposition potential is related to the still enigmatic mid-Cretaceous tectonic phase.

A widespread upper Maastrichtian–Danian hiatus, accompanied by some uplift (Figs. 2 and 15), reflects ‘break-up’, prior to the onset of Paleogene seafloor spreading in the Norwegian Sea. This plate tectonic driven opening changed the Cretaceous epicontinental, bathyal seaway into an abyssal oceanic basin.

9. Conclusions

The narrow seaway between Greenland and Norway, in Cretaceous time was over 1500 km long and

300 + km wide, and partly of bathyal water depth during Aptian through Campanian. It received a large volume of fine-grained siliciclastic sediments, with intercalated, gravity-flow sandstone wedges. As a conduit for heat transport between the low latitudes and polar region, Atlantic watermasses particularly affected the eastern, Norwegian margin of this seaway. Despite its high-latitude setting, calcareous and few siliceous planktonic microfossils thus play an important role in regional stratigraphy and facies analysis, and a majority of fossil events correlate to NW European basins. Cosmopolitan, agglutinated deep water foraminifers also are widespread, and assist with the biozonation. An agglutinated foraminiferal bloom occurs in Campanian time, related to a similar bloom in the Atlantic Ocean. Many Cretaceous fossil events can be correlated to the Atlantic and west Tethys regions. Three new microfossil taxa include *Uvigerinammina una*, *Ammoanita globorotaliaeformis*, and *Fenestrella bellii*.

The eastern margin sedimentary succession may be subdivided in several broad lithologic units; (1) Thin, multicoloured, marly sediments of Hauterivian–Barremian age, with a shallow marine *Falsogaudryinella*/nodosariid/ostracod assemblage; (2) Dark mudstones and minor sands, Aptian–early Cenomanian in age, with an upper bathyal, agglutinated assemblage, and monotypic *Hedbergella* floods; (3) Thick mudstone facies with thin, slope-apron turbidite sands, and an impoverished benthic/planktonic assemblage of late Cenomanian–Coniacian age, deposited in an upper bathyal, oxic/dysaerobic environment. Where Turonian sedimentation rates are low, a planktonic foraminiferal assemblage with *Whiteinella*, *Hedbergella*, *Dicarinella*, and *Marginotruncana* occurs; (4) Grayish, laminated mudstones, Santonian–Campanian in age, with local sands in the north, a low diversity, middle to upper bathyal benthic/planktonic foraminiferal assemblage, and an *Inoceramus* prisms and radiolarian/diatom flood; a Campanian agglutinated foraminiferal bloom also is known from the Atlantic oceanic realm; (5) More marly sediments of Maastrichtian age, with a low diversity planktonic/benthic foraminiferal assemblage.

Using the distribution of 1755 foraminiferal and dinoflagellate microfossil events in over 30 exploration wells, a RASC (Ranking and Scaling) zona-

tion served as a template to build a Cretaceous zonal model with 19 assemblage and interval zones. The zones are:

Protomarsonella kummi zone, early to middle Hauterivian;

Falsogaudryinella praemoesiana zone, late Hauterivian–earliest Barremian;

Falsogaudryinella xenogena zone, early Barremian;

Gavelinella barremiana zone, Barremian;

Verneuilinoides chapmani zone, late Aptian–early Albian;

Recurvovoides / *Glomospira* zone, middle Albian;

Uvigerinammina una zone, late middle to early late Albian;

Osangularia schloenbachi zone, late Albian;

Sigmoilina antiqua zone, early Cenomanian;

Hedbergella delrioensis LCO zone, late early Cenomanian–early middle Cenomanian;

Whiteinella brittonensis zone, late middle to early late Cenomanian;

Dicarinella zone, latest Cenomanian–middle Turonian;

Marginotruncana zone, late Turonian–Coniacian;

Stensioeina polonica zone, early to middle Santonian;

Inoceramus LCO zone, late Santonian;

Fenestrella bellii zone, early Campanian;

Tritaxia dubia zone, middle to late Campanian;

Reussella szajnochae zone, early Maastrichtian;

Pseudotextularia elegans zone, late Maastrichtian.

Planktonic flood events occur in late Albian through early Cenomanian, early–mid Turonian, late Santonian–earliest Campanian and mid-Maastrichtian, the result of northwards shifts of warmer water masses, and disruptions in water stratification in the dysaerobic basins.

The combination of deterministic and probabilistic biostratigraphic models enhances reproducibility of the results, and brings out stratigraphically important properties of the data, not otherwise accessible, including estimates from variance analysis on the reliability of correlation for 72 of the zonal events. Using variance analysis, four groups of events stand out.

Firstly, there are calcareous planktonic LO and LCO events that reflect oxic watermass conditions, relatively high fertility and slow sedimentation. These

events include *Rugoglobigerina rugosa* and *Globigerinelloides volutus*, red coloured planktonics, *Inoceramus* needles LCO, *Dicarinella imbricata*, and *Hedbergella delrioensis* LCO. All of these events occur in many wells (except ‘Red coloured planktonics’ that is confined to eight of the southern wells, and *D. imbricata*), have low standard deviations in correlation, and histograms of stratigraphic deviations that are relatively normal in shape. The same holds for the benthic foraminiferal events *Reussella szajnochae* and *Stensioeina polonica*. Hence, these commonly observed, oxic watermass events are considered reliable zone markers.

Secondly, there are agglutinated benthic events that reflect dysaerobic watermass conditions, and fine grained, low carbonate, mudstone substrate. These events are *Tritaxia dubia*, Coarse Agglutinated (Deep Water) Foraminifers LCO, and *Uvigerinammina una*, with low standard deviations, and histograms of stratigraphic deviations, which indicate their value as zone markers. The Campanian Coarse Agglutinated LCO event generally is easy to recognize in wells. It may be slightly time-transgressive, but stratigraphic resolution is limited in the upper part of Campanian.

Thirdly, there are siliceous planktonic events that reflect high watermass fertility. These events are *Fenestrella bellii* n. sp. and spherical/lenticular radiolarians, with fairly low standard deviations. The histograms of stratigraphic deviations are normal, which suggests that the events are coeval over the many wells where they are observed. The radiolarian bloom event may be difficult to recognize in wells, since scattered radiolarians occur also in stratigraphically younger levels that may be mistaken for this event. Differences in sedimentation rates between wells also tend to obscure the event. In the North Atlantic, greenish radiolarian-rich sediments appear

near the Santonian–Campanian boundary, suggesting that it is a useful regional stratigraphic marker, offshore Norway, particularly if sediments would be cored.

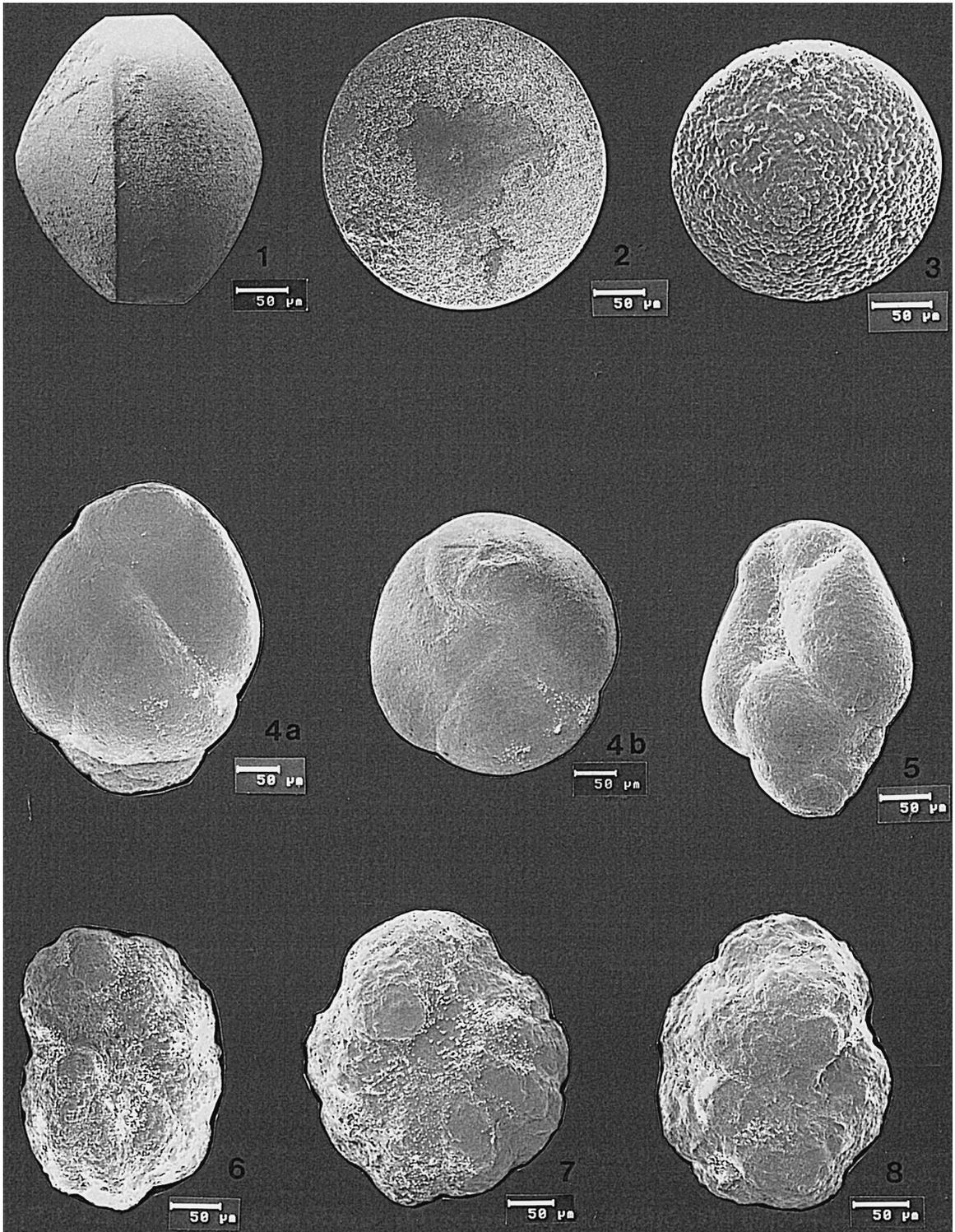
A fourth category of events are dinoflagellate cysts that are extensively used for mid-Cretaceous well stratigraphy, but are of variable stratigraphic quality. These events include *Trithyrodinium suspectum* LCO, *Heterosphaeridium difficile* LCO, *Endoceratium dettmaniae*, *Litosphaeridium siphoniphorum*, *M. membraniphorum*, *Epelidosphaeridia spinosa*, *Ovoidinium scabrosum* and *Apteodinium grande*. The events have low S.D. values and normal frequency distributions, except for *E. dettmaniae*, *L. siphoniphorum*, *M. membraniphorum*, and *E. spinosa*. The latter four events have high S.D. values, and not normal histograms of stratigraphic deviations, indicative of low value as zonal markers. A factor, other than common reworking of these four events in the often sandy Cenomanian interval that makes it difficult to pick them in wells, is that the LO's of *L. siphoniphorum* and *E. spinosa* maybe time transgressive, ranging younger southward.

The quantitative zonation (= scaled optimum sequence) shows major breaks between several successive zones, including between the *una* and *schloenbachi* zones, including between the *una* and *schloenbachi* zones, *delrioensis* LCO and *brittonensis* zones, *Marginotruncana* and *polonica* zones, *bellii* and *dubia* zones, and particularly between *dubia* and *szajnochae* zones. We postulate the following reasons for the stratigraphic breaks between zones.

(1) The *una*–*schloenbachi* break reflects a latest Albian lithofacies change and hiatus, connected to the Oteville hiatus in NW Europe.

(2) The *delrioensis* LCO–*brittonensis* break reflects the mid-Cenomanian lithofacies change and hiatus, connected to the mid-Cenomanian non-sequence, and Rouen hardground.

Plate III. *Fenestrella bellii* Gradstein and Kaminski, n.sp. Figs. 1–3, well 6507/6–2, *Fenestrella bellii* zone, cts. 2320 m, offshore mid-Norway; holotype in Fig. 1. Specimens were pyritized during burial. *Uvigerinammina una* Gradstein and Kaminski, n.sp. Fig. 4a,b (holotype), *Uvigerinammina una* zone, well 6507/6–2 at cts. 3110 m, offshore mid-Norway. The specimen in Fig. 5 is from cts. 3040 m in the same well. *Ammoanita (Trochammina) globorotaliaeformis* Gradstein and Kaminski, n.sp. Figs. 6–8 (same specimen, holotype) *Uvigerinammina una* zone, well 6507/6–2 at cts. 3110 m, offshore mid-Norway.



(3) The *Marginotruncana–polonica* break, above the level of *Heterosphaeridium difficile* LCO, which represents a maximum flooding surface, may be the turn-around in the middle Coniacian tectono-eustatic phase, near the end of the Lysing sand deposition phase.

(3) The *bellii–dubia* break, significantly is again (near or) at a maximum flooding event, this time correlated to the LCO of *T. suspectum* in the early middle Campanian, above the change from marly sediments to siliciclastic sediments at the base of the Campanian.

(4) The *dubia–szajnochae* break reflects the abrupt change from siliciclastic to marly sediment at the Campanian–Maastrichtian boundary, noted in the southern part of the region.

A widespread earliest Cretaceous hiatus separates Jurassic from Cretaceous strata. Ongoing block-faulting, coupled to thermal subsidence and global sealevel rise increased water depth in Aptian–Albian time from neritic to bathyal, and created sand accommodation space in dysaerobic, restricted settings. In Cenomanian–Coniacian time, sedimentation rates in the ‘central basin’ increased 10-fold, whereas paleo waterdepth did not deepen. This relatively brief (less than 10 Ma) tectonic episode, resulting in deposition of deep water sands, is tentatively linked to stress re-orientation in the Rockall area. A widespread upper Maastrichtian–Danian hiatus, the result of ‘shoulder’ uplift, reflects ‘break-up’, prior to the onset of Paleogene seafloor spreading in the Norwegian Sea. This plate tectonic driven opening changed the Cretaceous epicontinental, bathyal seaway into an abyssal oceanic basin.

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Appendix A

Catalogue of approximately 250 foraminiferal taxa, and some miscellaneous forms, observed by us in the Cretaceous, offshore mid Norway. The taxa have been grouped in four broad time slices that reflect broad evolutionary turnover, and biofacies development, offshore Norway. Relative abundance: /—rare, x—common, o—frequent, oo—abundant.

| Agglutinated Benthics | Rare = / Common = x | Frequent = o Abundant = oo | Calcareous Benthics | Rare = / Common = x | Frequent = o Abundant = oo |
|---|------------------------|-------------------------------|-----------------------------------|------------------------|-------------------------------|
| HAUTERIVIAN–BARREMIAN | | | | | |
| <i>Rhizammina</i> sp. | / | | <i>Globospirillina neocomiana</i> | x | o |
| <i>Saccammina compressa</i> | / | | <i>Spirillina</i> spp. | x | |
| <i>Ammodiscus</i> spp. | x | o | <i>Patellina subcretacea</i> | x | |
| <i>Reophax</i> spp. | x | | <i>Trocholina infracretacea</i> | / | |
| <i>Pseudonodosinella troyeri</i> | x | | <i>Lagena hauteriviana</i> | x | |
| <i>Glomospira charoides</i> / <i>gordialis</i> | x | o | <i>Lingulina semiornata</i> | / | |

| Agglutinated Benthics | Rare = / Common = x | Frequent = o Abundant = oo | Calcareous Benthics | Rare = / Common = x | Frequent = o Abundant = oo |
|---|------------------------|-------------------------------|-----------------------------------|------------------------|-------------------------------|
| HAUTERIVIAN–BARREMIAN | | | | | |
| <i>Glomospirella gaultina</i> | x | | <i>Pseudonodosaria</i> sp. | / | |
| <i>Haplophragmium aequale</i> | x | | <i>Citharina harpa</i> | / | |
| <i>Bulbobaculites</i> sp. | x | | <i>Saracenaria</i> spp. | / | |
| <i>Ammobaculoides carpathicus</i> | / | | <i>Lenticulina munsteri</i> | | oo |
| <i>Haplophragmoides</i> sp. | x | o | <i>L. aff. subalata</i> | / | |
| <i>Cribrostomoides nonioninoides</i> | x | | <i>L. heiermanni</i> | / | |
| <i>Recurvoides</i> spp. | x | | <i>L. guttata</i> | / | |
| <i>Protomarsonella kummi</i> | x | | <i>L. ouachensis wisselmanni</i> | / | |
| <i>Trochammina</i> spp. | x | | <i>I. aff. nodosa</i> | / | |
| <i>Textularia bettenstaedti</i> | x | | <i>L. saxonica</i> | / | |
| <i>Falsogaudryina xenogena</i> | x | o | <i>L. cf. busnardoii</i> | / | |
| <i>F. praemoesiana</i> | x | | <i>Planularia crepidularis</i> | / | |
| <i>F. tealbyensis</i> | / | | <i>Marginulina bettenstaedti</i> | / | |
| <i>Verneuiliinoides neocomiensis</i> | x | | <i>Gavelinella sigmoicostata</i> | / | |
| | | | <i>Gavelinella barremiana</i> | x | |
| | | | <i>Conorboides lamplughi</i> | / | |
| | | | <i>Epistomina tenuicostata</i> | / | |
| | | | <i>E. hechti</i> | / | |
| | | | <i>E. ornata</i> | / | |
| | | | <i>E. chapmani</i> | / | |
| | | | <i>E. caracolla</i> | x | |
| | | | <i>Conorotalites bartensteini</i> | / | |
| Miscellaneous | | | | | |
| Small planktonic foraminifera (= Blefuscuiana) | x | | | | |
| Ostracoda (mostly smooth) | x | o | | | |
| APTIAN–ALBIAN | | | | | |
| <i>Rhizammina</i> sp. | x | o | <i>Lenticulina</i> spp. (smooth) | x | |
| <i>Rhabdammina</i> spp. | x | o | <i>Pleurostomella barroisi</i> | / | |
| <i>Kalamopsis grzybowskii</i> | / | | <i>Gavelinella intermedia</i> | x | |
| <i>Hippocrepina depressa</i> | / | | <i>Gavelinella</i> sp. | x | |
| <i>Psammosphaera</i> spp. | x | o | <i>Osangularia schloenbachi</i> | x | |
| <i>Ammodiscus</i> spp. | x | o | <i>Epistomina spinulifera</i> gr. | / | |
| <i>Caudammina crassa</i> | / | | <i>Gyroidinoides</i> | x | |
| | | | <i>infracretaceus</i> | | |
| <i>Reophax</i> spp. | x | o | <i>G. sp.</i> | / | |
| <i>Pseudonodosinella troyeri</i> | / | | <i>Polymorphinidae</i> | / | |
| <i>Glomospira charoides</i> / <i>gordialis</i> | x | oo | <i>Dentalina</i> sp. | / | |
| <i>Glomospirella gaultina</i> | x | o | <i>Sigmoilina antiqua</i> | x | |
| <i>Cribrostomoides nonioninoides</i> | x | | <i>Valvulineria gracillima</i> | x | |
| <i>Haplophragmoides</i> spp. | x | o | <i>Eponides</i> sp. | / | |
| <i>H. kirki</i> | / | | | | |
| <i>H. minor</i> | x | | | | |
| <i>H. concavus</i> | x | | | | |
| <i>Ammosphaeroidina</i> sp. | / | | | | |
| <i>Ammoanita globorotaliaeformis</i> n.sp. | x | o | Planktonic Foraminifera | | |
| <i>Trochammina</i> sp. | / | | <i>Hedbergella infracretacea</i> | | o |
| <i>T. abrupta</i> | / | | <i>Hedbergella planispira</i> | | oo |
| <i>T. quinqueloba</i> | / | | <i>H. delrioensis</i> | x | o |
| | | | <i>Globigerinelloides</i> | x | |
| | | | <i>bentonensis</i> | | |

| Agglutinated Benthics | Rare = / | Frequent = o | Calcareous Benthics | Rare = / | Frequent = o |
|---|------------|---------------|----------------------------------|------------|---------------|
| | Common = x | Abundant = oo | | Common = x | Abundant = oo |
| APTIAN–ALBIAN | | | | | |
| <i>Recurvoides</i> spp. | x | o | | | |
| <i>Plectorecurvoides irregularis</i> | / | | | | |
| <i>P. alternans</i> | / | | | | |
| <i>Thalmanammina neocomiensis</i> | / | | | | |
| <i>Pseudobolivina variabilis</i> | / | | | | |
| <i>Uvigerinammina una</i> n.sp. | x | o | | | |
| | | | Miscellaneous | | |
| | | | pyritized radiolarians | / | |
| | | | <i>Inoceramus</i> needles | x | |
| | | | (pink, white) | | |
| <i>Falsogaudryinella alta</i> | x | o | | | |
| <i>Textularia foeda</i> | / | | | | |
| <i>T. bettenstaedti</i> | / | | | | |
| <i>Gaudryina filiformis</i> | / | | | | |
| <i>Verneuilinoides chapmani</i> | x | | | | |
| <i>Arenobulimina</i> sp. | / | | | | |
| <i>Clavulina gaultina</i> | / | | | | |
| CENOMANIAN–TURONIAN | | | | | |
| <i>Rhizammina</i> sp. | x | o | <i>Allomorphina pyriformis</i> | x | |
| <i>Rhabdammina</i> spp. | x | oo | <i>A. halli</i> | / | |
| <i>Psammosphaera</i> spp. | x | oo | <i>Pleurostomella obtusa</i> | / | |
| <i>Ammodiscus tenuissimus</i> | x | oo | <i>Lenticulina</i> spp. (smooth) | / | |
| <i>Reophax</i> spp. | x | o | <i>Gavelinella intermedia</i> | x | |
| <i>Caudammina ovulum</i> | / | | <i>G. sp. X</i> (unpublished) | x | |
| <i>C. ovuloides</i> | / | | <i>G. sp.</i> | / | |
| <i>Glomospira charoides</i> / <i>gordialis</i> | x | o | <i>Gavelinopsis cenomanica</i> | / | |
| <i>Glomospirella gaultina</i> | x | | <i>Lingulogavelinella</i> | / | |
| | | | <i>jarzevae</i> | / | |
| <i>Bulbobaculites problematicus</i> | / | | <i>Globorotalites</i> spp. | / | |
| <i>Arenoturrspirillina</i> sp. | / | | <i>Gyrooidinoides nitida</i> | x | |
| <i>Haplophragmoides</i> spp. | x | o | <i>Valvulineria gracillima</i> | x | |
| <i>Recurvoides imperfectus</i> | / | | <i>Stensioeina humilis</i> | / | |
| <i>Trochammina</i> spp. | x | o | | | |
| <i>Rzehakina</i> spp. | / | | | | |
| (including <i>R. minima</i>) | | | | | |
| <i>Psamminopelta</i> sp. | / | | Planktonic Foraminifera | | |
| <i>Plectorecurvoides alternans</i> | / | | <i>Globigerinelloides</i> | x | |
| | | | <i>bentonensis</i> | | |
| <i>Thalmanammina neocomiensis</i> | / | | <i>Hedbergella delrioensis</i> | x | oo |
| <i>Pseudobolivina</i> sp. | / | | <i>H. planispira</i> | x | o |
| <i>Uvigerinammina (pre-) jankoi</i> | / | | <i>H. paradubia</i> | x | |
| <i>Gerochammina</i> spp. | x | | <i>H. hoelzi</i> | x | |
| <i>Gaudryina filiformis</i> | x | | <i>H. sigali</i> | / | |
| <i>Eggerinella mariei</i> | / | | <i>Clavihedbergella simplex</i> | / | |
| <i>Ammosphaeroidina</i> sp. | / | | <i>Whiteinella brittonensis</i> | x | |
| <i>Dorothia</i> spp. | x | | <i>W. inornata</i> | / | |
| <i>Textularia foeda</i> | / | | <i>Praeglobotruncana</i> | x | |
| | | | <i>stephani</i> | | |
| <i>T. sp. 1 B and B81</i> | / | | <i>P. delrioensis</i> | x | |

| Agglutinated Benthics | Rare = / | | Frequent = o | | Calcareous Benthics | Rare = / | | Frequent = o | |
|--|------------|---------------|--------------|---------------|---|------------|---------------|--------------|--|
| | Common = x | Abundant = oo | Common = x | Abundant = oo | | Common = x | Abundant = oo | | |
| CENOMANIAN–TURONIAN | | | | | | | | | |
| <i>T. chapmani</i> | / | | | | <i>P. praehelvetica</i> | / | | | |
| <i>T. pyramidata</i> | / | | | | <i>Dicarinella hagni indica</i> | x | | | |
| <i>Pseudotextularia cretosa</i> | / | | | | <i>D. inbricata</i> | x | | | |
| <i>Marsonella ozawai</i> + spp. | / | | | | <i>D. primitiva</i> | x | | | |
| <i>Spiroplectamina</i> cf. <i>carinata</i> | / | | | | <i>Marginotruncana marginata</i> | x | | o | |
| <i>Arenobulimina advena</i> | / | | | | <i>Globotruncana linneiana</i> gr. | / | | | |
| | | | | | <i>Heterohelix globulosa</i> | / | | | |
| CONIACIAN–MAASTRICHTIAN | | | | | | | | | |
| <i>Rhizammina</i> sp. | x | | o | | <i>Eponides beisseli</i> | x | | | |
| <i>Rhabdammina</i> spp. | x | | oo | | <i>Gavelinella</i> sp. | / | | | |
| <i>Psammospaera</i> spp. | x | | oo | | <i>Pullenia</i> sp. | x | | | |
| <i>Ammodiscus</i> spp. | x | | oo | | <i>Gavelinella usakensis</i> | / | | | |
| <i>A. bornemanni</i> | / | | | | <i>G. beccariiiformis</i> | x | | | |
| <i>Reophax</i> spp. | x | | o | | <i>Conorbina supracretacea</i> | x | | | |
| <i>Caudamina ovulum</i> | x | | | | <i>Nuttalina florealis</i> | x | | | |
| <i>C. ovuloides</i> | / | | | | <i>Globorotalites multiseptus</i> | x | | | |
| <i>Glomospira charoides</i> / <i>gordialis</i> | x | | o | | <i>G. micheliniana</i> | / | | | |
| <i>Rzehakina</i> spp. (including <i>minima</i>) | / | | | | <i>Stensioeina granulata polonica</i> | / | | | |
| <i>Psammionopelta bowsheri</i> | / | | | | <i>S. pommerana</i> | / | | | |
| <i>Haplophragmoides</i> spp. | x | | o | | <i>Brizalina</i> ex. gr. <i>incrassata</i> | x | | | |
| <i>H. walteri excavatus</i> | x | | | | <i>Reussella szajnochae</i> | x | | | |
| <i>H. aff. walteri</i> sensu Kuhnt and Kaminski | x | | | | | | | | |
| <i>Recurvoides</i> sp. | / | | | | Planktonic Foraminifera | | | | |
| <i>Trochammina</i> spp. | x | | o | | <i>Globotruncana arca</i> | / | | | |
| <i>Paratrochamminoides olszewska</i> | x | | | | <i>G. linneiana</i> gr. | x | | | |
| <i>P. mitratus</i> | x | | | | <i>G. fornicata</i> | x | | | |
| <i>Trochamminoides subcoronatus</i> | x | | | | <i>G. bulloides</i> | x | | | |
| <i>T. spp.</i> | x | | | | <i>G. mariei</i> | / | | | |
| <i>Spiroplectamina dentata</i> | / | | | | <i>Rosita</i> (<i>Globotruncana</i>) <i>contusa</i> | / | | | |
| <i>S. navarroana</i> | / | | | | <i>Rugoglobigerina rugosa</i> | x | | oo | |
| <i>Gaudryina filiformis</i> | x | | o | | <i>R. rotundata</i> | / | | | |
| <i>Karrerulina conversa</i> | x | | | | <i>G. volutus</i> | x | | oo | |
| <i>Gerochammina</i> spp. | x | | | | <i>Dicarinella concavata</i> | / | | | |
| <i>Remesella varians</i> | / | | | | <i>D. carinata</i> | / | | | |
| <i>Marsonella crassa</i> | / | | | | <i>Abathomphalus mayaroensis</i> | x | | | |
| <i>Tritaxia dubia</i> | / | | | | <i>Globotruncanella intermedia</i> | / | | | |
| | | | | | <i>G. havanensis</i> | x | | | |

| Agglutinated Benthics | Rare = / | Frequent = o | Calcareous Benthics | Rare = / | Frequent = o |
|-----------------------|------------|---------------|---------------------|------------|---------------|
| | Common = x | Abundant = oo | | Common = x | Abundant = oo |

CONIACIAN–
MAASTRICHTIAN

Miscellaneous

Fenestrella bellii n.sp.

lenticular/spherical radiolarians

oo

oo

Pseudoguembelina excolata /

Racemiguembelina varians /

Whiteinella archeocretacea x

Appendix B

Genus: *Uvigerinammina*.

Species: *Uvigerinammina una* Gradstein and Kaminski, new species.

Illustrations: Plate III, Fig. 4a,b, Fig. 5.

Synonymy: 1981—*Uvigerinammina* sp. 1 Burnhill and Ramsay.

Derivation of name: Latinisation of the original open nomenclature name *Uvigerinammina* sp. 1 Burnhill and Ramsay, 1981.

Diagnosis: Test rounded triserial, rapidly expanding in width, with last whorl occupying most of test.

Holotype: Housed in the Micropaleontology Collection of the British Museum of Natural History, London.

Material, localities and horizons: The type level is the interval of 3040–3130 m in greenish mudstones in well 6507/6–2, offshore mid Norway. The species is known from the *Uvigerinammina una* zone, late middle Albian to early late Albian. Auxiliary material is in the UK North Sea well 21/1A–10 at 2765 m, assigned by Burnhill and Ramsay (1981) to upper Albian.

Additional occurrences of this new taxon, offshore Norway are in wells 6507/2–1 at 3580 m, 6507/2–3 at 3450 m, 6506/12–5 at 3727.50 m, 6406/2–2 at 4260 m, 6406/2–3 at 4578 m, 6506/12–4 at 3784 m; 35/3–2 at 3639.10 m, 35/3–4 at 3542.10 m, 35/12–1 at 2310 m, 35/11–2 at 2712 m, and 34/7–21 A at 2852 m.

Description: Test triserially coiled, with three whorls, the last one of which occupies most of the test and widens rapidly; the greatest width of the semicircular test is halfway up the last whorl. Sutures slightly depressed. Test smooth, shiny, fine grained agglutinated with organic cement. Aperture a elongate opening, bordered by a rim, at the top of last chamber.

Dimensions: Specimens range between 150 and 300 micrometer in size.

Remarks: The nominate taxon, *Uvigerinammina una*, apparently is a boreal species restricted to the Norwegian and North Sea regions. It appears not to possess calcareous cement, therefore it cannot be assigned to the genus *Falsogaudryinella*. Most likely it belongs in the genus *Uvigerinammina*, as originally reported by Burnhill and Ramsay (1981). It has not been found in the Albian of the Kirchrode-1 Borehole, NW Germany (Jaroslaw Tyszk, personal communication), or in deep-sea deposits. The acme of *Uvigerinammina una* itself often forms a narrow zone, but the species also is found in low numbers in both the immediately overlying and immediately underlying zones.

The species differs from co-occurring *Uvigerinammina alta* in its much wider test; *U. alta* is relatively long and slender.

Genus: *Ammoanita*.

Species: *Ammoanita globorotaliaeformis* Gradstein and Kaminski new species.

Illustrations: Plate III, Figs. 6–8.

Derivation of name: Based on resemblance of the *Ammoanita* specimens to a high conical, many chambered planktonic foraminifer of the genus *Globorotalia*.

Diagnosis: Planoconical, high spired with nine or more chambers in last whorl; chambers strongly overlap; sutures swing backward.

Holotype: Housed in the Micropaleontology Collection of the British Museum of Natural History, London. The holotype is registered in slide PF 66923.

Material, localities and horizons: The type level is the interval of 3040–3140 m in greenish mudstones in well 6507/6–2, offshore mid Norway.

This interval belongs in the *Uvigerinamina una* zone, late middle Albian to early late Albian. The species appears to be restricted to this zone. Additional occurrences of this new taxon, offshore Norway are in wells 6507/2–3 at 3450 m, 6406/2–2 at 4280 m, 35/3–5 at 3476 m, and 34/7–21A at 2852.22 m.

Description: Test trochospirally coiled, with two to four whorls; spiral side flat; umbilical side highly convex, with no or only a narrow umbilical depression; periphery acute. Outline circular to slightly lobate. Chambers are numerous, increasing rapidly in height, nine or more in the last whorl; last chamber may tower over previous ones. Sutures limbate, and can be slightly depressed or smooth; on the umbilical side the sutures are curved backward; on the spiral side the sutures are tangentially situated. Wall agglutinated, silicified. Aperture extraumbilical, poorly visible, a slit at the base of the final chamber.

Dimensions: Specimens range between 125 and 300 micrometer in diameter.

Remarks: We place this species in the genus *Ammoanita* Seiglie and Baker, rather than in *Trochammina* because of its angular chambers and acute periphery. According to our observations *Ammoanita globorotaliaeformis* has a tighter coil than the Paleocene *A. ingerlisae* Gradstein and Kaminski, with chambers increasing more rapidly in height, and more chambers in the last whorl. In local well completion reports such specimens are referred to as *Trochammina globorotaliaeformis*, and constitute a useful mid–upper Albian index.

Charnock and Jones (1990) mention occasional specimens of their *Trochammina subvesicularis* in Albian mudstones, offshore mid Norway, which probably belong in the new taxon *Ammoanita globorotaliaeformis*.

Trochammina abrupta Geroch of the middle Cretaceous Verovice Beds of Poland is less planoconvex, has more radial sutures, far fewer and wider chambers and a wider spire than *A. globorotaliaeformis*.

T. subvesicularis Hanzlikova, of the Albian of Czechoslovakia has fewer chambers in the last whorl and is more strongly planoconvex, with a lobate periphery. Its chambers increase more rapidly in height than *A. globorotaliaeformis* (see Gradstein and Kaminski, 1997).

During final stages of this study, we became aware of a study by Tairov (1961), in which the author described and illustrated several conical taxa of *Trochammina* from the Cretaceous of Adzerbaydzhan. Taxa include *T. planuliformis* and *T. globorotaliforma*. It is not clear at this stage if any types are preserved, and/or available for study.

Genus: *Fenestrella*.

Species: *Fenestrella bellii* Gradstein and Kaminski, new species.

Illustrations: Plate III, Figs. 1–3.

Synonymies: Unpublished well completion reports for the offshore Norway area report this taxon either as *Diatom* sp. H. Stratlab, or as *Diatom* sp. 17 Robertson Research.

Derivation of name: Named after Dr. Graham Bell, Stratlab, Norway in recognition of his detailed well research with stratigraphic palynology, offshore Norway.

Diagnosis: A small and pyritized diatom test that is disk shaped with sharp periphery.

Holotype: Housed in the Micropaleontology Collection of the Department of Botany of the British Museum of Natural History, London. The holotype is registered in slide BM 100179.

Material, localities and horizons: The type level is in mudstones at 2320 m in well 6507/6–2. Additional types are from 2330 m in well 34/7–7, also offshore Norway. The type level is the *Fenestrella bellii* zone, lower Campanian. Additional occurrences of this taxon, widespread and common offshore Norway are in wells 6610/3–1 at 2245 m, 6607/5–2 at 4134 m, 6607/5–1 at 3172 m, 6507/2–2 at 2220 m, 6507/2–3 at 2400 m, 6507/7–1 at 2330 m, 6507/7–2 at 2091 m, 6506/12–4 at 2449 m, 6406/2–1 at 2700 m, and 34/7–24 s at 2630 m.

Description: Test small, always pyritized (due to depth of burial below the stability level of siliceous tests) and shiny. The tests are disk shaped, with a circular equatorial outline, a rather sharp periphery, and a low conical side view, giving rise to the distinctive oval or low-conical cross-section when viewed perpendicular to the equatorial plane. Some specimens show a small dimple in the cone.

Dimensions: Specimens range between 80 and 150 micrometer in diameter.

Remarks: This species also occurs stratigraphically in lower zones than the *F. bellii* zone. Its total stratigraphic range has not been determined, but it may range down from the *F. bellii* zone into the *Marginotruncana* zone. The last occurrence and last common occurrence are stratigraphically distinct and key indicators for the *F. bellii* zone, assigned to lower Campanian.

References

- Agterberg, F.P., Gradstein, F.M., 1999. The RASC method for ranking and scaling of biostratigraphic events. *Earth-Sci. Rev.* 46, 1–25.
- Banner, F.T., Desai, D., 1988. A review and revision of the Jurassic–Early Cretaceous Globigerinina, with especial reference to the Aptian assemblages of Speeton (North Yorkshire England). *Journal of Micropalaeontology* 7 (2), 143–185.
- Bartenstein, H., 1977. *Falsogaudryinella* n.g., Foraminifera in the Lower Cretaceous. *N. Jahrb. Geol. Paleontol. Abh.* 385–401.
- Bartenstein, H., 1977b. Stratigraphic parallelisation of the lower Cretaceous in the northern hemisphere: zonation with benthonic foraminifera. *Newsletters on Stratigraphy* 14 (2), 110–117.
- Bartenstein, H., 1978. Phylogenetic sequences of Lower Cretaceous benthic foraminifera and their use in biostratigraphy. *Geologie en Mijnbouw* 57 (1), 19–24.
- Bartenstein, H., 1981. Additional observations on *Textularia bettenstaedti* Bartenstein and Oertli 1977 and *Falsogaudryinella* Bartenstein 1977 (Foraminifera). *N. Jb. Geol. Paleont. Abh.* 161 (2), 309–323.
- Bartenstein, H., Bettenstaedt, F., 1962. Marine Unterkreide, Boreal and Tethys. In: Simon, W., Bartenstein, H. (Eds.): *Leitfossilien der Mikropaläontologie*. Gebrüder Borntraeger, Berlin, 225–298.
- Bell, G., Selnes, H., 1997. The first appearance datum (FAD) of *Heterosphaeridium difficile* (Manum and Cookson), dinoflagellata, in clastic deposits offshore Norway. *J. Micropalaeontology* 16, 30.
- Blystad, P., Brekke, H., Faereth, R.B., Larsen, B.T., Skogseid, J., Torudbakken, B., 1995. Structural elements of the Norwegian continental shelf: Part II. The Norwegian Sea Region. *Norw. Petr. Dir.-Bull.* 8.
- Brandshaug, P., Stensoey, A.B., Runestad, S.K., 1997. Borehole list, Exploration. *Norw. Petr. Dir., Rept.* YA-747.
- Bubik, M., 1995. Cretaceous to Paleocene agglutinated foraminifera of the Bile Karpaty unit, West Carpathians, Czech Republic. In: Kaminski, M.A., et al. (Eds.), *Proc. Fourth International Workshop on Agglutinated Foraminifera*, Krakow, Poland, 1993. *Grzybowski Found. Spec. Publ.* 3, pp. 71–116.
- Burnhill, T.J., Ramsay, W.V., 1981. Mid-Cretaceous Paleontology and Stratigraphy, Central North Sea. In: *Petroleum Geology of the Northwest European Continental Shelf*. Institute of Petroleum, London, pp. 245–254.
- Charnock, M.A., Jones, R.W., 1990. Agglutinated foraminifera from the Palaeogene of the North Sea. In: Hemleben et al., (Eds.), *Paleoecology, Biostratigraphy, Paleocyanography and Taxonomy of Agglutinated Foraminifera*, Nato ASI Series, C. 327, Kluwer Academy Publ., pp. 139–244.
- Coccioni, R., Galeotti, S., Gravili, M., 1995. Latest Albian–earliest Turonian deep-water agglutinated foraminifera in the Bottacione section (Gubbio, Italy)—biostratigraphic and palaeoecologic implications. *Rev. Espanola Paleont.*, 135–152.
- Costa, L.I., Davey, R.J., 1992. Dinoflagellate Cysts of the Cretaceous System. In: Powell, A.J. (Ed.), *A Stratigraphic Index of Dinoflagellate Cysts*. Chapman & Hall, London.
- Crittenden, S., 1983. *Osangularia schloenbachi* (Reuss, 1863): an index foraminiferid species from the Middle Albian to Late Aptian of the southern North Sea. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlung* 167, 40–64.
- Crittenden, S., 1987. The Albian transgression in the southern North Sea Basin. *J. Petrol. Geol.* 10 (4), 395–414.
- Dalland, A., Worsley, D., Ofstad, K., 1988. A lithostratigraphic scheme for the Mesozoic and Cenozoic succession, offshore mid-and northern Norway. *Norw. Petr. Dir., Bull.* 4.
- D’Iorio, M.A., Agterberg, F.P., 1989. Marker event identification technique and correlation of Cenozoic biozones on the Labrador Shelf and Grand Banks. *Bull. Can. Petr. Geol.* 37, 346–357.
- Dore, A.G., 1991. The structural foundation and evolution of Mesozoic seaway between Europe and the Arctic. *Paleogeography, Palaeoclimatology and Palaeoecology* 87, 441–492.
- Dore, A.G., Lundin, E.R., Birkeland, O., Elisassen, P.E., Jensen, L.N., 1997. The NE Atlantic margin: implications of Late Mesozoic and Cenozoic events for hydrocarbon prospectivity. *Petroleum Geology* 3, 117–131.
- Geroch, S., Nowak, W., 1984. Proposal of zonation for the late Tithonian–late Eocene, based upon arenaceous foraminifera from the outer Carpathians, Poland. In: Oertli, H.J. (Ed.), *Benthos ’83, 2nd International Symposium on Benthic Foraminifera* (Pau, April 1983), pp. 225–239.
- Geroch, S., Koszarski, L., 1988. Agglutinated foraminiferal stratigraphy of the Silesian flysch trough. *Abh. Geol. Bundesanstalt*, 73–79.
- Gradstein, F.M., Berggren, W.A., 1981. Flysch-type agglutinated foraminifera and the Maastrichtian to Paleogene history of the Labrador and North Sea. *Marine Micropal.* 6, 211–268.
- Gradstein, F.M., Kaminski, M.A., 1997. New species of Paleocene deep-water agglutinated foraminifera from the North Sea and Norwegian Sea. *Ann. Soc. Geol. Poloniae* 67, 217–229.
- Gradstein, F.M., Agterberg, F.P., 1998. Uncertainty in Stratigraphic Correlation In Gradstein, F., Sandvik, O., Milton, D. (Eds.), *Sequence Stratigraphy—Concepts and Applications*. Elsevier.
- Gradstein, F.M., Agterberg, F.P., Brower, J.C., Schwarzacher, W., 1985. *Quantitative Stratigraphy*. Unesco and Reidel Publ.
- Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., Huang, Z., 1995. A Triassic, Jurassic and Cretaceous time scale. *Soc. Sedimentary Geology, Spec. Publ.* 54, 95–126.

- Guy, M., 1992. Facies analysis of the Kopervik sand interval, Kilda Field, Block 16/26, UK North Sea. From Hardman, R.F.P. (Ed.), 1992, Exploration Britain: Geological insights for the next decade. Geol. Soc. Spec. Publ. 67, pp. 187–220.
- Hanzlikova, E., 1972. Carpathian Upper Cretaceous Foraminifera of Moravia. Turonian-Maastrichtian. Ustr. ust. geol. 39.
- Hardenbol, J., Caron, M., Amedro, F., Dupuis, C., Robaszynski, F., 1993. The Cenomanian–Turonian boundary in central Tunisia in the context of a sequence stratigraphic interpretation. Cretaceous Research 14, 449–454.
- Hardenbol, J., Thierry, J., Farley, M.B., Jaquin, T., Graciansky, P., Vail, P., in press. Mesozoic and Cenozoic Sequence Chronostratigraphic Framework of European Basins. Soc. for Sedimentary Geology, Spec. Publ. 60.
- Hart, M., 1993. Cretaceous foraminiferal events. In: Hailwood, E.A., Kidd, R.B. (Eds.), High Resolution Stratigraphy. Geol. Soc. Spec. Publ. 70, pp. 227–240.
- Hart, M.B., Bailey, H.W., Crittenden, S., Fletcher, B.N., Price, R., Swiecicki, A., 1989. Cretaceous. In: Stratigraphical Atlas of Fossil Foraminifera, 2nd edn., E. Horwood Ltd., pp. 273–372.
- Jansa, L., Wade, J., 1975. Geology of the continental margin, off Nova Scotia and Newfoundland. Geol. Survey Canada Paper 74–30 (2), 51–105.
- Jansa, L., Enos, P., Tucholke, B.E., Gradstein, F.M., Sheridan, R.E. (1979) Mesozoic–Cenozoic sedimentary formations of the North American Basin, western North Atlantic. In: Talwani, M., Hay, W., Ryan, W.B.F. (Eds.), Deep Drilling Results in the Atlantic Ocean: Continental margins and paleo-environment, American Geoph. Union, Maurice Ewing Series 3, 1–57.
- Kaiho, K., Hasegawa, T., 1994. End-Cenomanian benthic foraminiferal extinctions and oceanic dysoxic events in the northern Pacific Ocean. Paleogeography, Paleoclimatology, Paleocology 111, 29–43.
- Kaminski, M.A., Gradstein, F., Geroch, S. (1992). Uppermost Jurassic to Lower Cretaceous deep-water benthic foraminiferal assemblages from Site 765 on the Argo Abyssal Plain. In: Gradstein, F., Ludden, J.N., et al. (Ed.) Proceedings of the Ocean Drilling Program, Scientific Results, 123: College Station, TX, Ocean Drilling Program, 239–269.
- Kaminski, M.A., Boersma, A., Tyszka, J., Holbourn, A.E.L. (1995). Response of deep-water agglutinated foraminifera to dysoxic conditions in the California Borderland Basins. In: Kaminski, M.A., et al. (Eds.), Proceedings of the Fourth International Workshop on Agglutinated Foraminifera Grzybowski Foundation Special Publication 3, 131–140.
- Kaminski, M.A., Neagu, T., Platon, E. (1995). A revision of *Falsogaudryinella* from the Lower Cretaceous of the North Sea and Romania, and its relationship to *Uvigerinammina*. In: Kaminski, M.A., et al. (Eds.), Proceedings of the Fourth International Workshop on Agglutinated Foraminifera, Grzybowski Foundation Special Publication 3, 145–157.
- Kemper, E. (1973). The Aptian and Albian stages in northwest Germany. In: The Boreal Lower Cretaceous, R. Casey, P.F. Rawson (Eds.), 345–361.
- King, C., Bailey, H.W., Burton, C.A., King, A.D., 1989. Cretaceous of the North Sea. In: Stratigraphical Atlas of Fossil Foraminifera, 2nd edn., E. Horwood, 373–417.
- Komissarenko, V.K., Belousova, S.P., 1990. Atlas molluskoy I foraminifer morskikh otlozhenii verney Jury I Neokoma Zapadno-Sibirskoy neftegazonosnoy oblasti. Vol. 2 Sibirskiy nauchnoissledovatel'skii inst. geologii, geofiziki, I minerealnogo syrya. 358 p.
- Kuhnt, W., Kaminski, M.A., 1990. Upper Cretaceous deep-water agglutinated benthic foraminiferal assemblages from the western Mediterranean and adjacent areas. In: Wiedmann, J. (Ed.). Cretaceous of the Western Tethys. Proceedings of the 3rd International Cretaceous Symposium, Tübingen, 91–120.
- Kuhnt, W., Kaminski, M.A., 1997. Cenomanian to lower Eocene deep water agglutinated foraminifera from the Zumaya section, northern Spain. Annales Societatis Geologorum Poloniae 67, 257–270.
- Kuhnt, W., Kaminski, M.A., Moullade, M., 1998. Late Cretaceous deep water agglutinated foraminiferal assemblages from the North Atlantic and its marginal seas. Geologische Rundschau 78, 1121–1140.
- Larson, R.L., Fischer, A.G., Erba, E., Premoli Silva, I. (Eds.), 1993. APTICORE–ALBICORE: Workshop report on global events and rhythms of the mid-Cretaceous, 4–9 October 1992, Perugia, Italy, pp. 1–56.
- Løfaldi, M., Thusu, B., 1979. Micropalaeontological studies of the Upper Jurassic and Lower Cretaceous of Andoya, northern Norway. Palaeontology 22 (2), 413–425.
- Michael, E., 1966. Die Evolution der Gavelinelliden (Foram.) in der NW-deutschen Unterkreide. Senck. Leth. 47 (5/6), 411–459.
- Moullade, M., 1961. Contribution à l'étude géologique et micropaléontologique des Baronnies (Drôme): Nyons no. 3 au 20.000^{ème}. Thèse Doctorat 3^{ème} Cycle, Université de Paris, 1–100, pls. 1–17.
- Mutterlose, J., Wippich, M., Geisen, M. (Eds.), 1997. Cretaceous depositional environments of NW Germany. Bochumer Geol. Geotechn. Arb. (46), pp. 1–133.
- Neagu, T., 1965. Albian foraminifera of the Rumanian Plain. Micropaleontology 11 (1), 1–38.
- Neagu, T., 1972. The Eo-Cretaceous foraminiferal fauna from the area between the Ialomitza and Prahova valleys (eastern Carpathians). Rev. Esp. Micropaleont. 4 (2), 181–224.
- Neagu, T., 1975. Monographie de la faune des Foraminifères éocétacés du couloir de Dimboviciora, de Codlea et des Monts (Persani), (Couches de Carhaga). Mémoires de l'Institut de Géologie et Géophysique 25, 1–141.
- Nohr-Hansen, H., 1993. Dinoflagellate cyst stratigraphy of the Barremian to Albian, Lower Cretaceous, North–East Greenland. Bull. Grönl. Geol. Unders. 166.
- Prokoph, A., 1997. Palaeoenvironment and stratigraphy of Late Albian - Early Cenomanian planktonic foraminifera from NE-Germany. Freiburger Forschungsheft C 468, 259–271.
- Riegraf, W., Luterbacher, H., 1989. Benthonische Foraminiferen aus der Unterkreide des 'Deep Sea Drilling Project' (Leg 1–79). Geologische Rundschau 78 (3), 1063–1120.
- Robaszynski, F., Caron, M., Gonzalez Donoso, J.M., Wonders,

- A.H. (Eds.), 1984. Atlas of Late Cretaceous Globotruncanids. *Rev. Micropaleontologie*, 26 (3–4).
- Rohl, U., Ogg, J., 1996. Aptian–Albian sea level history from guyots in the western Pacific. *Paleoceanography* 11, 595–624.
- Saether, T., Nystuen, J.P., Gradstein, F.M., Olaussen, S., 1997. Cretaceous basin development and sedimentology between Norway and East Greenland. *Symp.-Sedimentary Events and Hydrocarbon Systems, CSPG-SEPM Joint Convention, Calgary, 1997. Abstract volume*, 244.
- Schioeler, P., Wilson, G.J., 1993. Maastrichtian dinoflagellate zonation in the Dan Field, Danish North Sea. *Rev. Palaeobotany and Palynology* 78, 321–351.
- Sellwood, B.W., Price, G.D., Valdes, P.J., 1994. Cooler estimates of Cretaceous temperatures. *Nature* 370, 453–455.
- Stainforth, R.M., 1981. Catalog of Cretaceous Planktonic Foraminifera. Esso Production Research, Report 36EX.81.
- Stouge, S., 1991. Graphic correlation of the wells MA-1, M-8X, M-9X and M-10X of the Dan Field (Chalk group), danish Central Trough. *Geol. Survey of Denmark Report* 7-1990.
- Tairov, Ch.H., 1961. Foraminifera from the Aptian and Albian formations of the southwestern Caucasus, and their stratigraphic significance. *Azerbaidzanskoye Gosudarstvennoye Izdatelstvo (Baku)*, 1–188.
- Weidich, K.F., 1990. Die kalkalpine Unterkreide und ihre Foraminiferenfauna. *Zitteliana*, 17, *Abhandlungen der Bayerischen Staatssammlung für Paläontologie und historische Geologie*, 1–312.
- Weiss, W., 1997. Late Albian immigrations of planktonic foraminifera into the Boreal sea: Results from the Kirchrode-1 Borehole. *Newsletters on Stratigraphy* 35 (1), 1–27.
- Williamson, M., Stam, B., 1988. Jurassic/Cretaceous Epistominidae from Canada and Europe. *Micropaleontology* 34 (2), 136–158.

Erratum

Erratum to: Biostratigraphy and paleoceanography of the
Cretaceous seaway between Norway and Greenland
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In the original article a previous version of Plate 3 has been printed. The correct version is given here. The publisher apologizes for any inconvenience caused.

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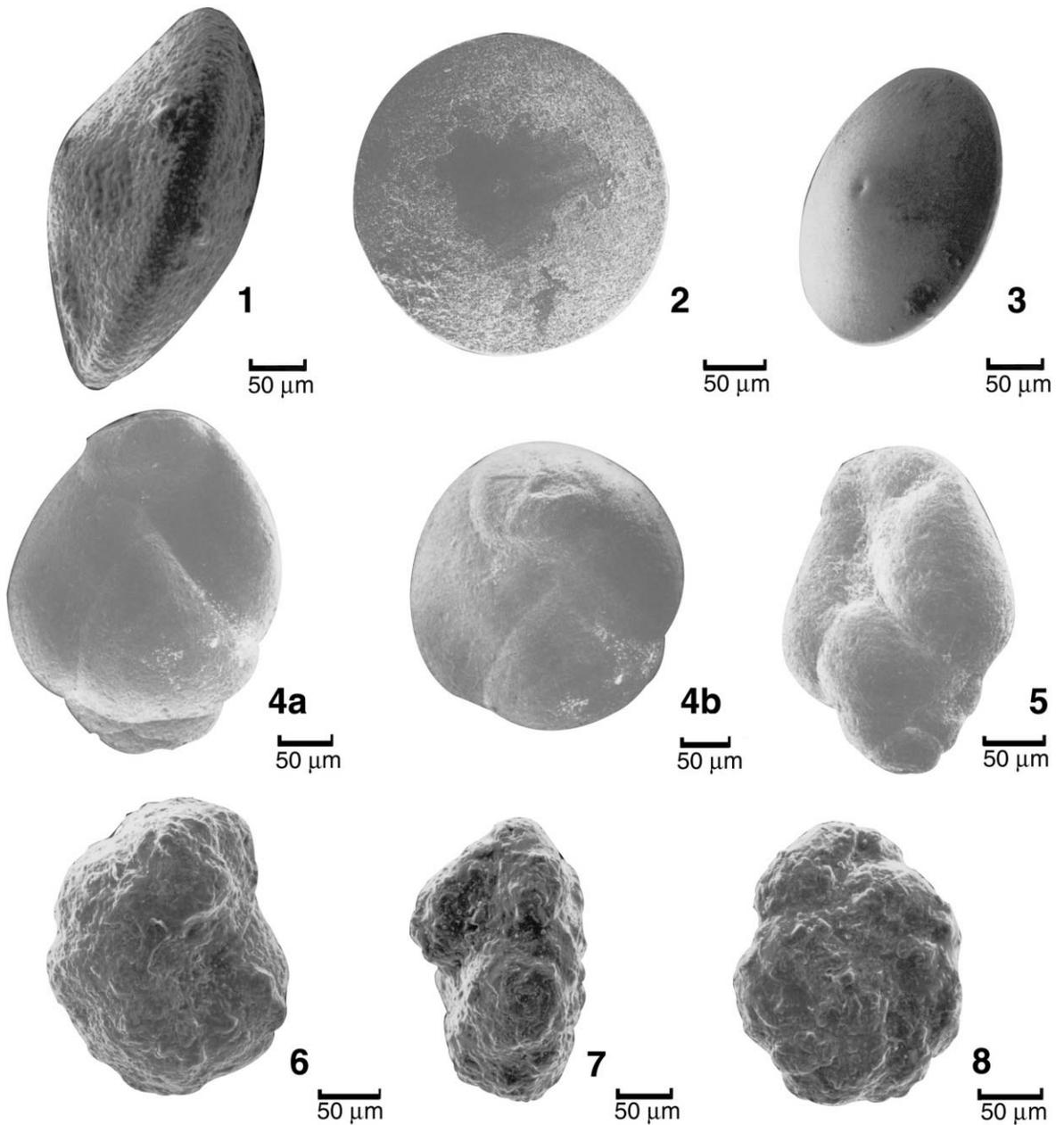


Plate 3. *Fenestrella bellii* Gradstein and Kaminski, n.sp. Figs. 1–3, well 6507/6-2, *Fenestrella bellii* zone, cts. 2320 m, offshore mid-Norway; holotype in Fig. 1. Specimens were pyritized during burial. *Uvigerinammina una* Gradstein and Kaminski, n.sp. Fig. 4a,b (holotype), *Uvigerinammina una* zone, well 6507/6-2 at cts. 3110 m, offshore mid-Norway. The specimen in Fig. 5 is from cts. 3040 m in the same well. *Ammoanita (Trochammina) globorotaliaeformis* Gradstein and Kaminski, n.sp. Figs. 6–8 (same specimen, holotype) *Uvigerinammina una* zone, well 6507/6-2 at cts. 3110 m, offshore mid-Norway.