Microfossil diachronism in southern Norwegian North Sea chalks: Valhall and Hod fields

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Abstract: An integrated late Cretaceous calcareous microfossil framework for the southern Norwegian chalks is presented based on detailed study of 13 wells (many with core) and circum-North Sea outcrops, in addition to many cosmopolitan events recognized in reference sections in Tunisia, North America and Europe. Previous biozonations for the North Sea chalks: (1) lack the biostratigraphic resolution needed in production geology; (2) are largely founded on benthic foraminifera and acme events; (3) fail to recognize numerous stratigraphic discontinuities within the North Sea chalks; and (4) are poorly calibrated. Application of this new integrated framework cautions towards the use of certain acme and benthic foraminifera events as chronostratigraphic horizons both within the basin and from the basin into circum-North Sea outcrops. An additional complicating factor is palaeogeographic segregation between low and high latitudes, which intensified during the middle Campanian and became problematic within the North Sea basin itself during the late Maastrichtian. A final consideration is redeposition, which can lead to erroneous correlations between wells, but may also affect reservoir quality. Established North Sea biozonations have not recognized this primary palaeoenvironmental signal and massive redeposition across major lithostratigraphic units, which has resulted in the correlation of diachronous facies rather than isochronous horizons. This could lead to complications in operational applications, such as biosteering.

Chalks are often ideal for biostratigraphic study because the sediment itself is composed largely of microfossils and nannofossils, and was deposited in a deep-water setting. Nevertheless, the chalks of the Norwegian southern North Sea basin are far from ideal. Remobilization and redeposition have long been suspected as causes for creating porosity within these chalks. Combined with diagenetic effects that can reduce recovery and preservation within reservoir section, both the confidence and precision in biostratigraphic correlations can be seriously compromised.

Nannofossils and foraminifera have carried the bulk of operational biostratigraphic work in the North Sea chalks. Planktic foraminifera and nannofossils are important in global correlation, but their use within the North Sea basin is somewhat limited because a number of index species have Tethyan affinities. Cosmopolitan zonation schemes are further limited by their reliance on first occurrence events. North Sea biozonations have relied more on local events based on acmes and benthic foraminifera. However, both acmes and benthic foraminifera are environmentally controlled and, therefore, may be diachronous. The benthic foraminifera stratigraphic ranges were originally defined in circum-North Sea outcrop sections deposited in much shallower palaeoenvironments, whereas acme events have been established in well-to-well correlations within the basin. Their diachronism has never been tested because a high-resolution biozonation based on planktic microfossils has not been established for the North Sea chalks. In the current study, nannofossils have provided this unifying factor and have shown that many of the acme (nannofossil and foraminifera) and benthic foraminifera events are slightly to highly diachronous. In addition, palaeobiogeographic differentiation and redeposition may complicate the correlation of well sections outside the current production area in the Valhall and Hod fields, especially within the main reservoir in the Tor Formation.

Lithostratigraphy

Description of the Cenomanian–Danian Shetland Group off the north coast of Scotland (Deegan & Scull 1977) was expanded to include the formations of the Chalk Group in the southern Norwegian sector of the North Sea by Isaksen & Tonstad (1989). Isaksen & Tonstad (1989) included five formations (Fig. 1) within the Shetland Group: (1) the Cenomanian Hidra

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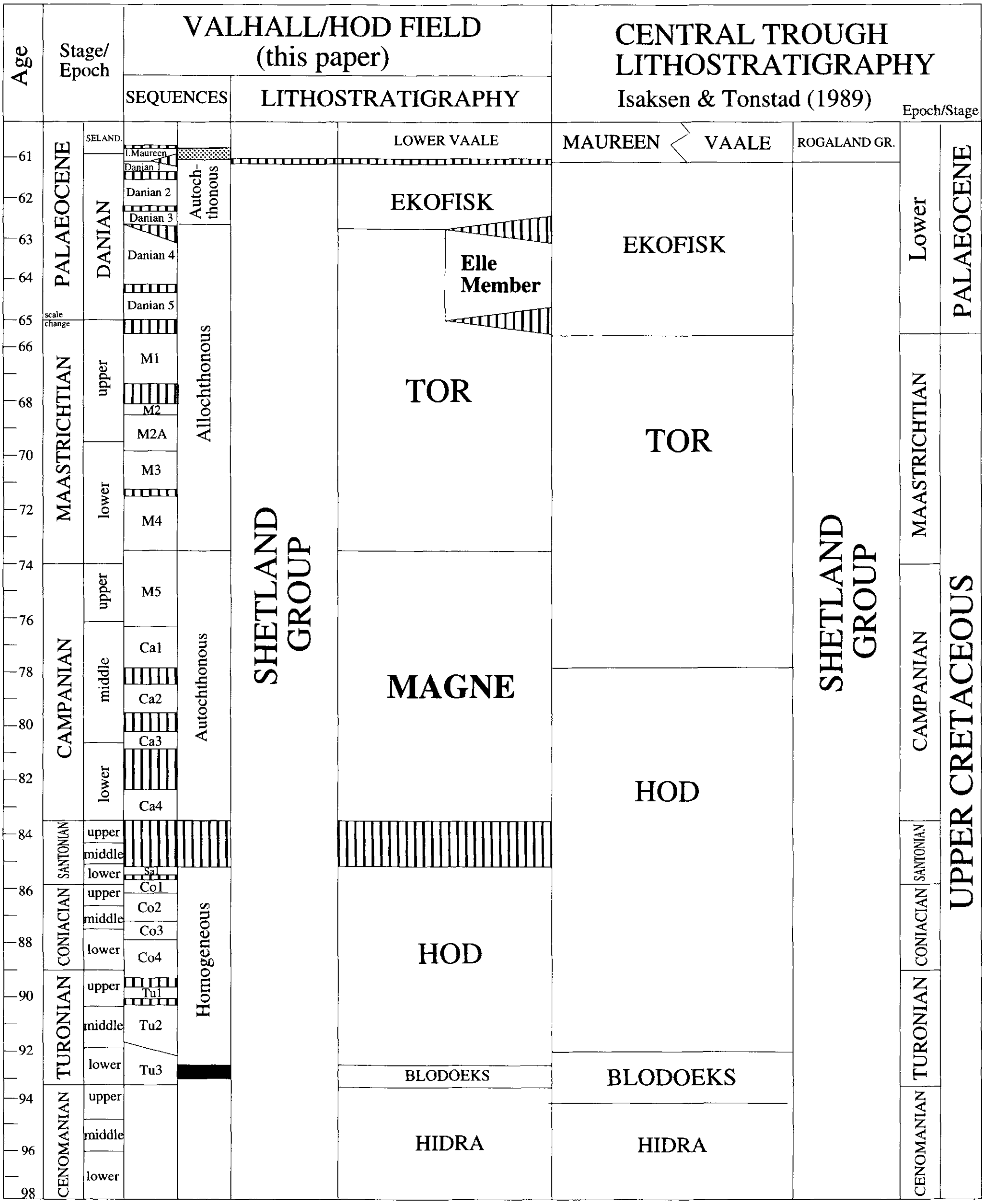

Fig. 1. Stratigraphy of the chalk, Norwegian Central Graben with new lithostratigraphic units in bold.

Formation; (2) the uppermost Cenomanian–lowermost Turonian Bloedoks Formation, which is identified by its high gamma-ray response and is considered an equivalent to the Plenus Marl in outcrop; (3) the Turonian–lower Campanian Hod Formation; (4) the upper Campanian–Maastrichtian Tor Formation; and (5) the Danian Ekofisk Formation. The current paper is focused on the post-Cenomanian Upper Cretaceous, which typically includes the Hod and Tor formations. The highly pelagic Ekofisk Formation is extremely thin within the Valhall Megaclosure and its microfossil biostratigraphy is not discussed.

In a broad sense, we recognize four major depositional regimes in the chalks overlying the Bloedoks Formation within the Valhall and Hod fields, including 23 lower-order units defined by stratigraphic discontinuities (Fig. 1). These four major depositional regimes include: (1) the Turonian-lower Santonian Hod Formation characterized by high pelagic depositional rates over the entire area; (2) Campanian–lowermost Maastrichtian deep-water, autochthonous deposition off-structure with structural crests mantled by submarine hardgrounds, herein informally termed the Magne Formation; (3) the Maastrichtian–lower Danian Tor Formation, characterized by its low gamma-ray signature and largely allochthonous lithologies; and (4) the middle–upper Danian Ekofisk Formation, which forms a thin pelagic drape (1–10 m) over the area. Of particular importance within the Valhall Megaclosure is the recognition of lower Danian section characterized by a low gamma-ray response (Tor Formation) and massive upper Maastrichtian redeposition, previously unrecognized and informally referred herein to the Elle Member of the Tor Formation (Fig. 1). The formal descriptions of the Magne Formation and the Elle Member of the Tor Formation await determination of their lateral extent.

Methodology and biostratigraphy

The current results are based on the study of 13 wells in the Valhall Megaclosure (Valhall–Hod fields) and a reference well for the Ekofisk Formation in the Tor Field (Fig. 2). The wells were selected for their available core material, being more densely sampled in the main reservoir interval of the Tor Formation. In addition, regional trends in event diachronism are partially based upon analysis of a number of wells to the north of the main study area (Block 2/5 and northern Block 2/8).

Graphic correlation methodology (Shaw 1964; Mann & Lane 1989) was used to develop a new biostratigraphical model for the Turonian–Maastrichtian chalks of the Valhall and Hod fields. Critical to this model were the global Amoco Composite Standard Database and its localization through examination of circum-North Sea outcrops and core material. Circum-North Sea outcrops examined for the current study include: (1) the Coniacian–Turonian boundary interval of the Culver Cliff section, Isle of Wight, UK; (2) the middle Coniacian–middle Campanian portion of the Whitecliff section, Isle of Wight, UK; and (3) an upper Campanian–Maastrichtian composite section in the type area of the Maastrichtian in the Netherlands. For the Turonian, core material from two wells in the Valhall Field, including a reference well for the Hod Formation (Isaksen & Tonstad 1989), served as reference material.

Planktic foraminifera are very rare and sporadic in surrounding outcrop sections, thus making them unsuitable for outcrop-to-basin correlations. Our analyses of outcrop sections confirmed the accuracy and great utility of the established benthic foraminiferal zonation in outcrop (Hart *et al.* 1989). However, the majority of benthic indices used in the North Sea basin zonation of King *et al.* (1989) proved ineffective in basin-to-outcrop correlations either because they were absent or extremely rare and sporadic in occurrence in the basin (e.g. *Bolivinoides decoratus*, *Gavelinella usakensis*, *Stensioina granulata levis*) or they were highly diachronous between the basin and the shallower-water outcrop sections (e.g. *Tritaxia capitosa*, *Stensioina exsculpta exsculpta*). This necessitated the construction of an entirely new microfossil zonation for the basin, against which the calcareous nannofossils were used to calibrate between the outcrop and basinal succession.

The integrated calcareous microfossil biostratigraphy for the Turonian–Maastrichtian of the Valhall Megaclosure (Fig. 3) stresses the use of first and last appearance data points of planktonic organisms, many of which can be used for correlations outside the North Sea basin and northwestern Europe. The nannofossil and microfossil biozonations for the Turonian–Maastrichtian chalks of the southern Norwegian sector are described separately in the Appendices; no formal description of an integrated biozonation is attempted. Real (palaeoenvironments and palaeogeography) and apparent (redeposition) diachronism encountered in the chalks of the Valhall and Hod fields are discussed in the following three sections.

Diachronism: palaeoenvironments

Underlying the integrated calcareous microfossil biozonation scheme is the temporal framework provided by composite standard methodology. The resulting biostratigraphic model has defined 18 stratigraphic packages (Fig. 1) delineated by biostratigraphic discontinuities for the Hod–Tor formations within the Valhall Megaclosure. The diachronism of acme and benthic foraminifera events relative to these established schemes and the chronostratigraphic framework are discussed in the following two subsections.

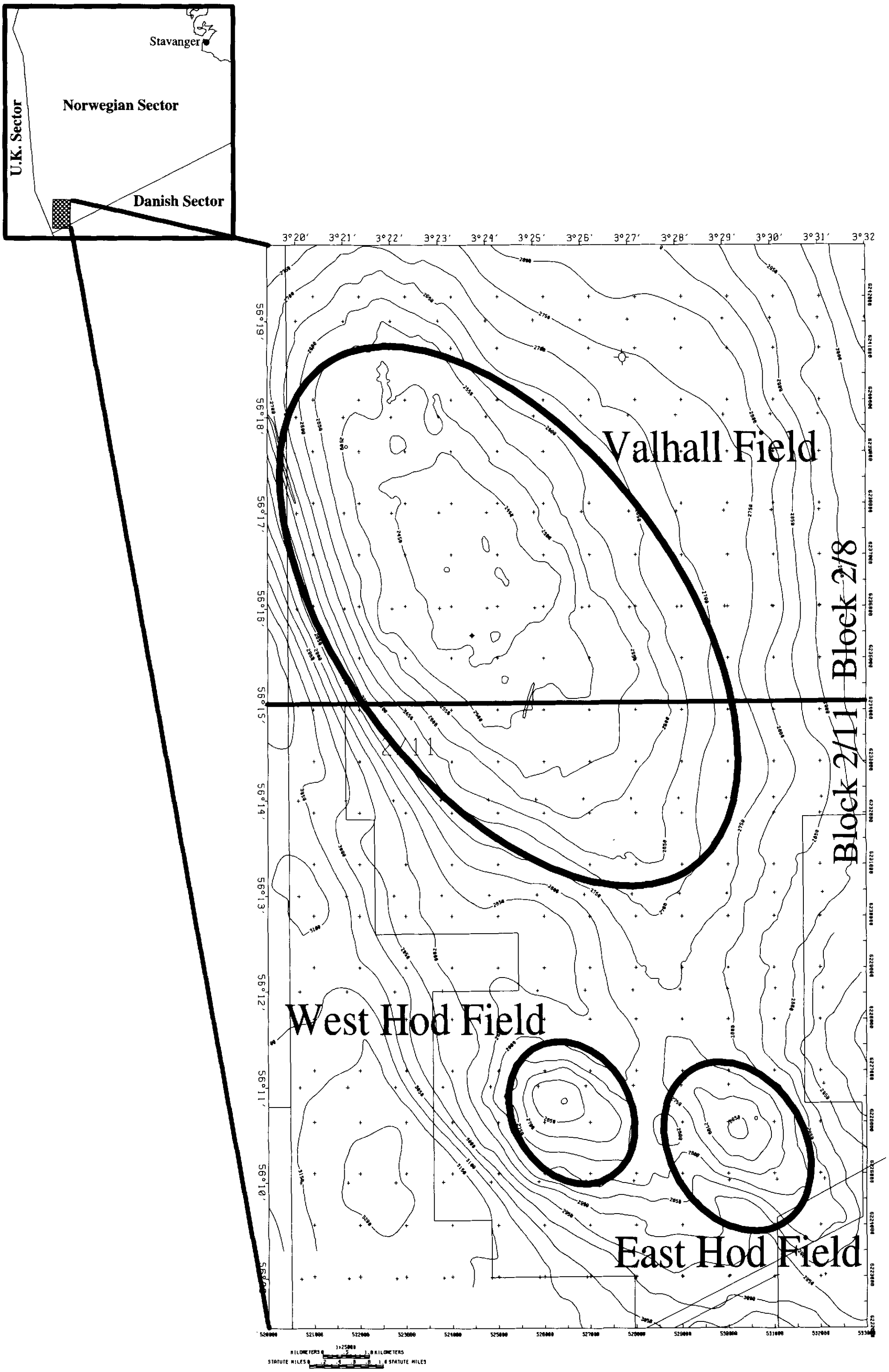

Fig. 2. Location map of fields with top chalk contours.

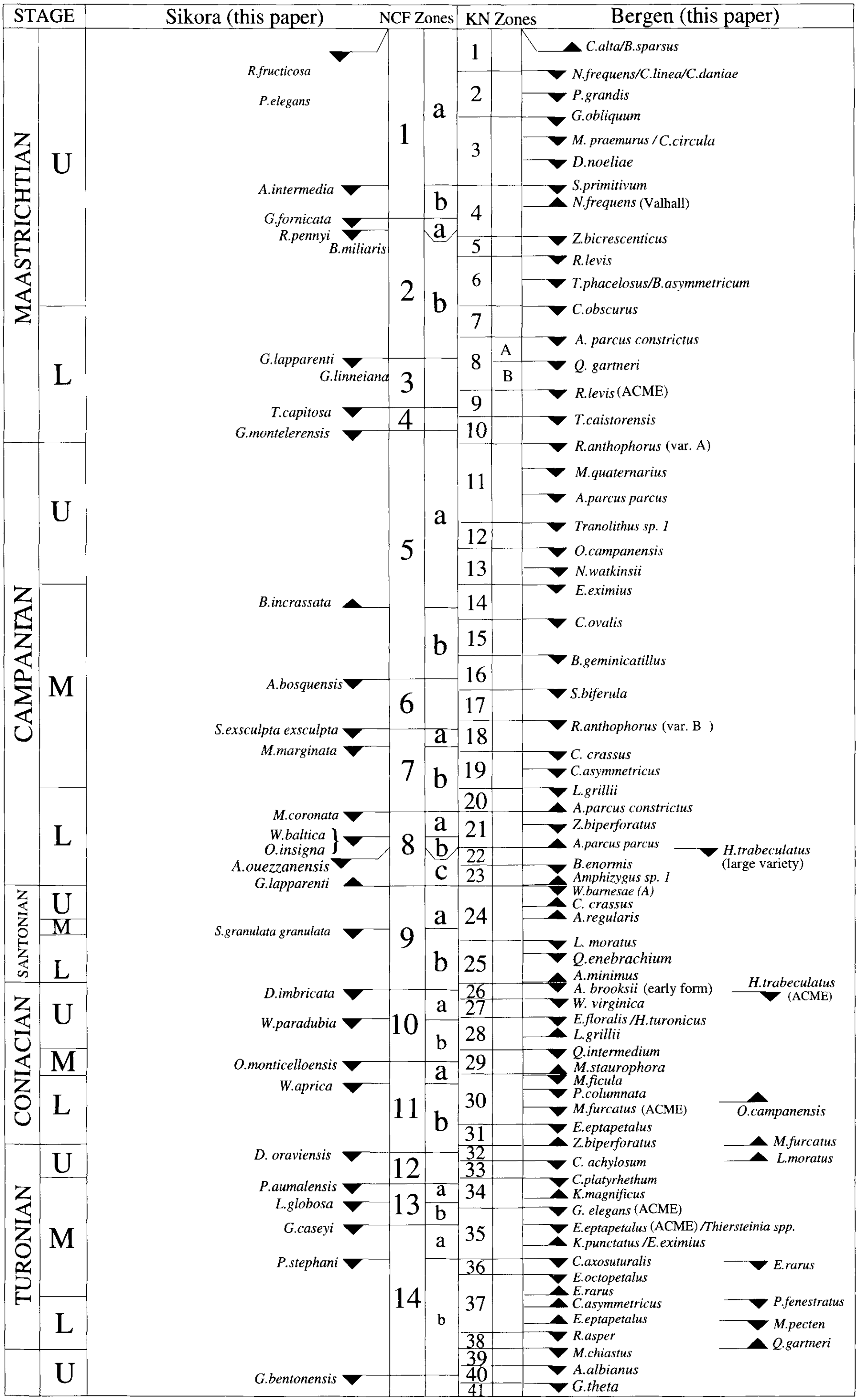

Fig. 3. Integrated calcareous microfossil biozonation for the southern Norwegian North Sea.

Acme events

Calcareous nannofossils. Local nannofossil acmes events are used rather extensively in North Sea biozonations, especially within the Hod Formation (Mortimer 1987) and the Ekofisk Formation (Varol 1989). Their quick determination makes them practical in operational work, but several factors caution towards their rigorous application, especially in production geology.

Five nannofossil acme events (Fig. 4) are used in routine operation work in the Turonian–lower Campanian. The most obvious problem with these events is their calibration, as all five have conveniently marked stage and substage boundaries (Fig. 4). Their definition in terms of abundance can also be difficult in actual application, specifically the three Coniacian–Turonian events (Fig. 4). In the Valhall Megaclosure these three taxa often do not reach their defined abundances (common) or are extremely rare and sporadic in a number of well sections. More often, these acmes are expressed as shifts to higher abundances (single specimens to rare, rare to few) or from sporadic to consistent occurrences. All three taxa also present taxonomic questions. *Helicolithus valhallensis* is invalid as it has never been formally described. Thus, this acme could represent either one or both valid species, *Helicolithus compactus* and *Helicolithus turonicus* (Fig. 4). The *Helicolithus trabeculatus* acme could represent a number of *Helicolithus* species with diagonal cross-structures. Herein, forms greater than 7.2 μm in length are ascribed to this acme. The early Turonian acme of *Lithastrinus* (Mortimer 1987) is confusing because the genus did not appear until the late Turonian. Within the Valhall Megaclosure, this event is better recognized by the highest consistent occurrence of *Eprolithus eptapetalus*.

The diachronism of these local events has never been suspected because they occur in consistent order between well sections (Fig. 4) and operational resolution within the Hod and Magne formations is low. This low resolution is surprising as this interval is characterized by high abundances, good preservation and the general absence of redeposition. The *Eprolithus* acme (*Lithastrinus* of Mortimer 1987) appears isochronous, although it could not be recognized in off-structure wells (Fig. 4). Conversely, the *Helicolithus trabeculatus* acme occurs within the upper Coniacian section in the Hod Field and in off-structure wells (not the terminal Coniacian), and has no utility on-structure in the Valhall Field (probably due to truncation). The most problematic late Cretaceous acme event is that of *Helicolithus turonicus/compactus* (*Helicolithus valhallensis* of Mortimer 1987). It has been used to define the terminal Turonian, yet occurs in lower–middle Coniacian sections in all but two wells examined for this study. Two acmes in *Watznaueria barnesae* have been used to date the tops of the lower Campanian and lower Santonian (Mortimer 1987). A general abundance decrease of this species from the Santonian–Maastrichtian occurs in the southern Norwegian North Sea chalks, until the species disappears immediately below the top of the Cretaceous. The shift down-section to common *Watznaueria barnesae* at the top of the lower Campanian has utility in the basin because it is associated with an intra-Campanian unconformity off-structure and in the Hod Field (Fig. 4), but could not be precisely determined in the more complete section onshore at Whitecliff Bay. The top of abundant *Watznaueria barnesae* is associated with the Santonian–Campanian boundary in the Whitecliff section, but so far has no utility in the basin because upper Santonian section has not been detected. Caution is exercised towards using these events because of massive deposition that can occur near the base of the Magne megasequence (Fig. 4).

Causal mechanisms for these acme events are speculative, although decreasing temperatures from post-Cenomanian time (Jenkyns *et al.* 1994) may be the overriding factor. In the Southern Ocean, decreased abundances of *Watznaueria barnesae* during the late Campanian–Maastrichtian were associated with increased endemism of austral taxa and have been explained by cooling (Watkins *et al.* 1995). A general progressive decline in the abundance of *Watznaueria barnesae* from Campanian–Maastrichtian occurs within the Valhall Megaclosure. *Eprolithus* and *Helicolithus* may also be temperature-dependent. Both genera appeared during a period of rising sea level (late early–late Aptian), when the strong Tethyan-boreal provinciality that had existed since the Tithonian began to breakdown. Thus, abundance decreases and extinctions within these genera in the North Sea basin during the Turonian–early Campanian could be associated with overall late Cretaceous cooling. Another factor could be fertility. An acme event of short duration, such as the early Coniacian acme of *Marthasterites furcatus*, would be better explained by changes in surface-water fertility.

Planktic foraminifera. North Sea contractor biozonations utilize various foraminifera abundance events, mainly those of planktic taxa. Such

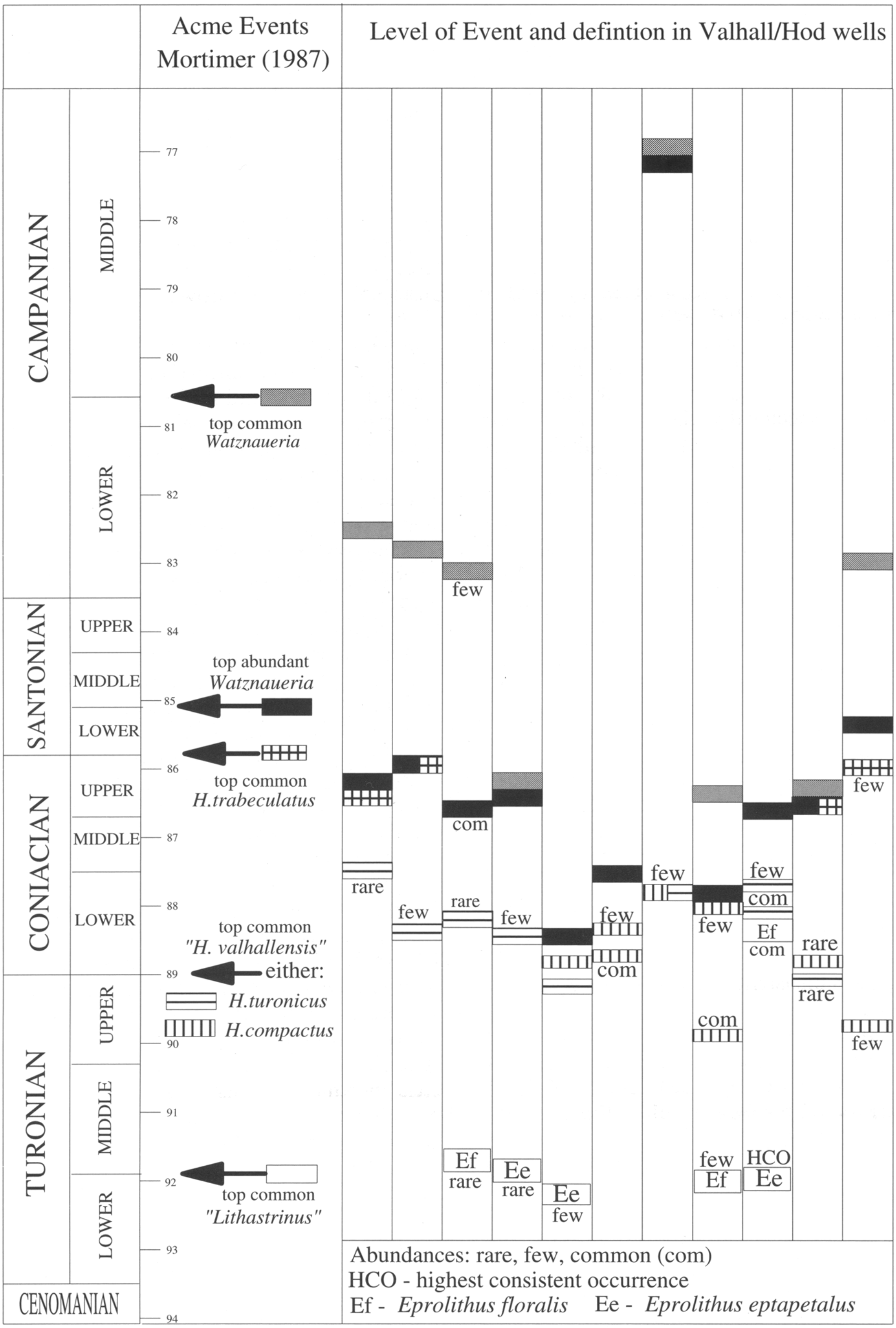

Fig. 4. Chronostratigraphy of Valhall Megaclosure wells and diachronism of Turonian–Campanian nannofossil acmes.

influxes are also noted as subsidiary zonal criteria by King *et al.* (1989). The most commonly used abundance events involve the planktic foraminifer *Rugoglobigerina rugosa* in the Maastrichtian Tor Formation, and multiple influxes of *Marginotruncana marginata* primarily in the Coniacian portion of the Hod Formation. Such events can be extremely useful in directing a well bit during horizontal drilling. However, abundance events are less useful in regional correlation within the chalk for two reasons: (1) palaeoenvironmental control; and (2) sorting in allochthonous chalks.

Marginotruncana marginata is extremely abundant in the upper Turonian–Coniacian portion of the Hod Formation. Two distinct pelagic microfossil assemblages are recovered from the Hod Formation, indicative of two oceanographic water masses (Sikora *et al.* 1999): (1) a deeper-water assemblage dominated by keeled planktic species (such as *M. marginata*) and diverse radiolarians, and most frequently found off-structure; and (2) a shallower-water pelagic assemblage dominated by non-keeled planktic species (mainly *Whiteinella* spp.) and low-diversity radiolarians, which was prevalent along the Valhall–Hod anticline. Nevertheless, there are multiple layers across the Valhall–Hod anticline which contain the deeper-water assemblage, probably indicative of discreet flooding events. Thus, *M. marginata* is generally common from the top of the Hod Formation and continuing down-section in off-structure wells, whereas it may not be common on-structure until lower in the section. Consequently, the first downhole occurrence of abundant *M. marginata* in crestal and off-structure wells is unlikely to be an isochronous datum. Correlation of on-structure wells based upon *M. marginata* events is also hazardous, as crestal Valhall was erosionally truncated during uplift in the latest Coniacian and Santonian. The amount of truncation on top of the Hod Formation varies from the central crestal area to the upper flank. Correlation across the crest based upon *M. marginata* abundance events may therefore result in the correlation of an older flooding deposit from a more deeply truncated central crestal site with a younger flooding event from a less truncated flank section. The first downhole occurrence of common *M. marginata* relative to the chronostratigraphic framework (Fig. 5) demonstrates the very diachronous nature of this event.

Rugoglobigerina rugosa is a species of wide environmental tolerances, and is one of the most common planktic species recovered from the Tor Formation. However, the central crestal area of the Valhall anticline was marked by very shallow-water environments throughout much of the Maastrichtian and, except for discreet flooding events, planktic foraminifera were absent (Sikora *et al.* 1999). Off-structure, the Tor Formation is often characterized by thick, stacked sequences of distal mudflows and turbidites containing well-sorted, tiny foraminifera of the genera *Globigerinelloides* and *Heterohelix*. *R. rugosa* is a relatively large planktic foraminifer and has been sorted out of these deposits. However, occasional coarser-grained debris flows reach these localities transporting larger bioclasts into the basin, including common *R. rugosa*. Thus, the first downhole occurrence of common or abundant *R. rugosa* in different wells may mark a discreet flooding event over the central crestal zone, a typical pelagic assemblage on the structure flank or a debris flow deposit in the basin. It would be pure coincidence if these various manifestations of the *R. rugosa* abundance 'event' represented the same stratigraphic level, and the regional chronostratigraphy indicates considerable diachronism for the event (Fig. 5). In off-structure wells, this diachronism is small. This was a time marked by widespread movement of coarse-grained debris flows into the basin. On-structure in wells, diachronism is much more pronounced, ranging over 2 Ma, or not occurring at all due to palaeoecological exclusion in very shallow-water palaeoenvironments.

Benthic foraminifera

Although the stratigraphic ranges of many planktic and benthic foraminifera are different in the basin than in outcrop, several have utility in well correlations throughout the Valhall Megaclosure. Nevertheless, failure to recognize their diachronism between different palaeobathymetric regimes can lead to erroneous age determinations and correlations. Some biostratigraphic indices have proved to be significantly diachronous not only between outcrop and basin, but within the basin as well. The most prominent example of such a misleading index is *Stensioina granulata polonica*.

The benthic foraminifera *Stensioina granulata polonica* has a very narrow stratigraphic range of lower and middle Santonian in outcrop (Hart *et al.* 1989). In well sections in the Valhall Megaclosure, a total stratigraphic range of upper Coniacian–middle Campanian has been determined for this species, although it is very erratic in stratigraphic and lateral distribution. A Campanian highest occurrence for this species (including the highest common occurrence) is very well constrained by both nannofossil and

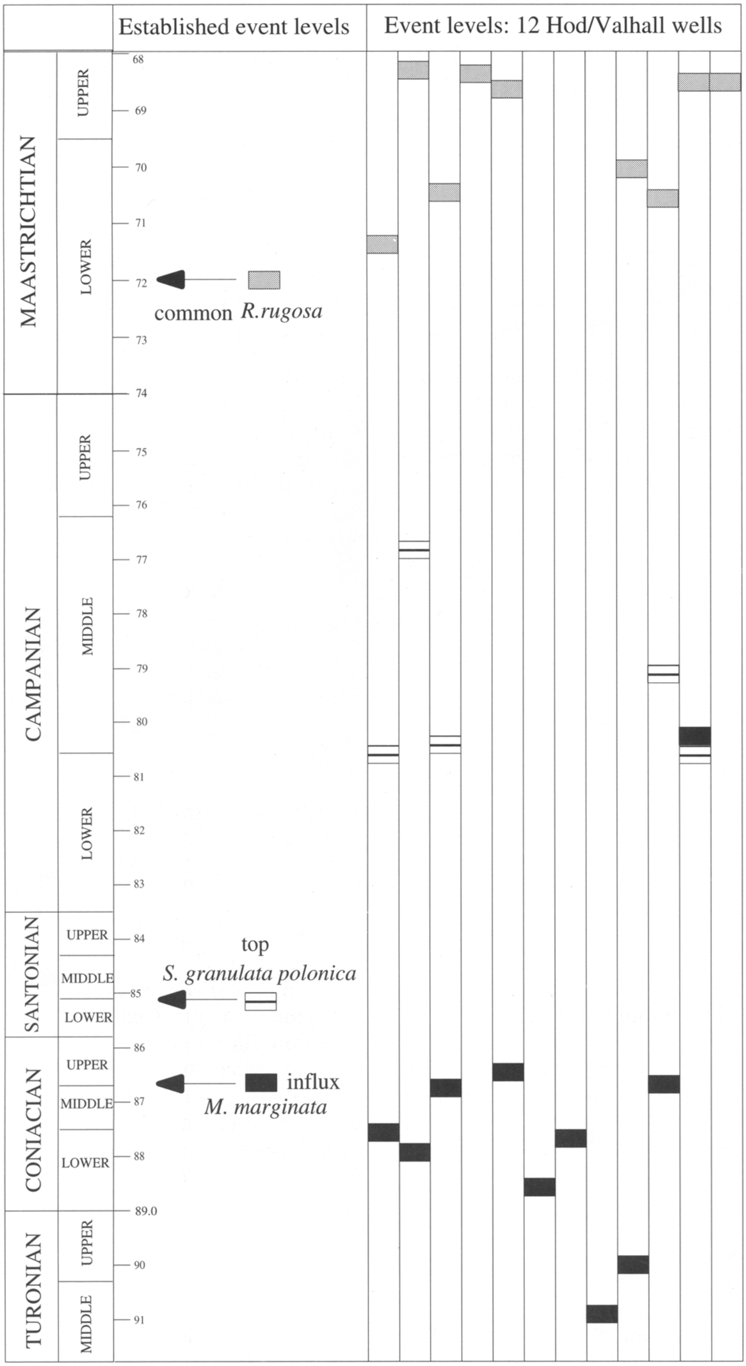

Fig. 5. Chronostratigraphy of Valhall Megaclosure wells (rectangles) and diachronism of three Turonian–Maastrichtian microfossil acmes (arrows at left show accepted biovent levels).

microfossil successions (Fig. 3) in three off-structure wells and in both wells examined from the Hod Field. Its highest occurrence is also highly diachronous amongst these five wells (Figs 5 & 6).

Species of the genus *Stensioina* are deep-water indicators. The occurrence of *S. granulata polonica* in outcrop is probably indicative of a discreet flooding event and does not constitute the entire stratigraphic range of the species. Moving into the basin, however, the stratigraphic range of the species expands in progressively deeper-water facies. However, the distribution of *S. granulata polonica* is discontinuous even within the basin, indicating strong facies dependency. In the Valhall Megaclosure, *S. granulata polonica*

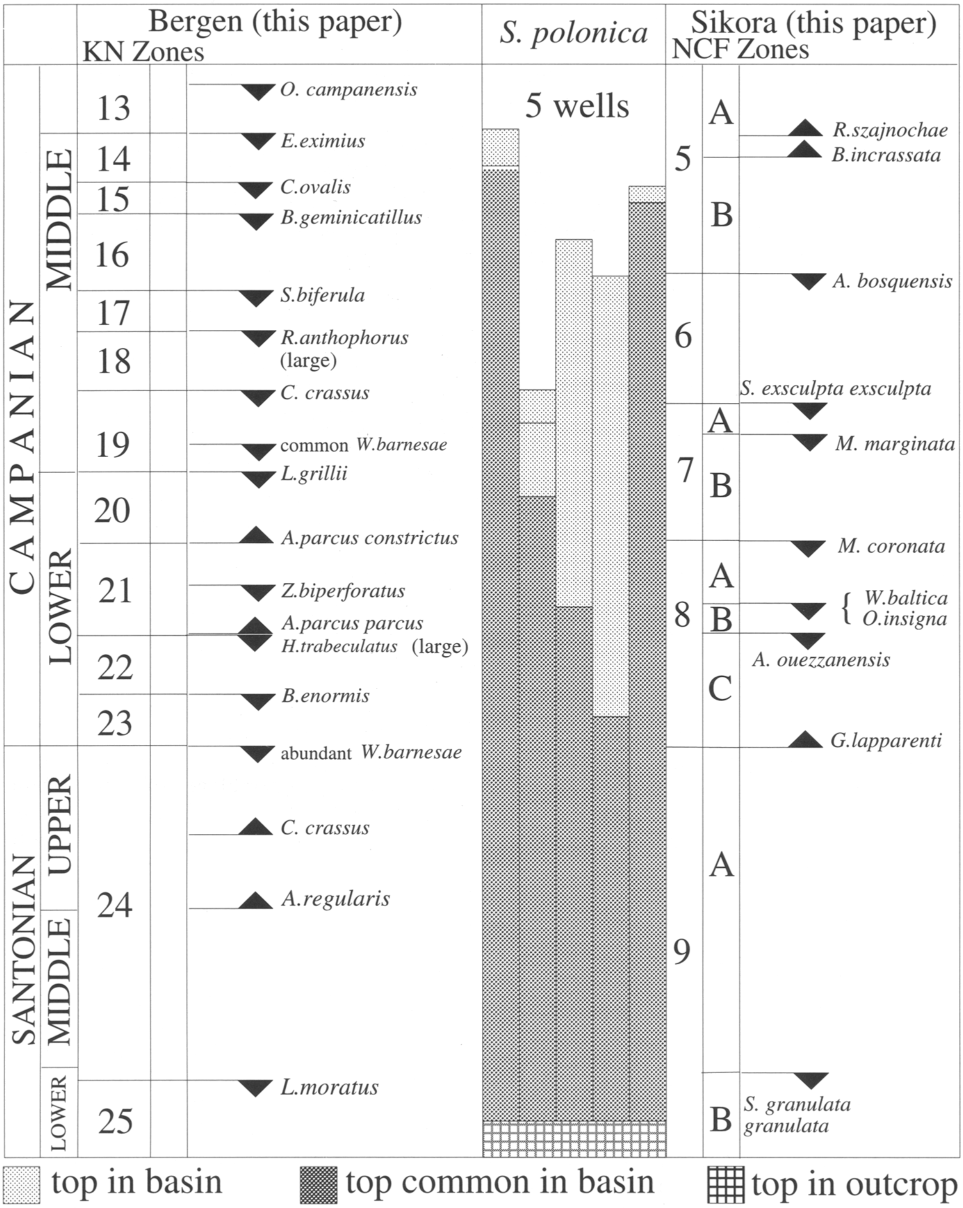

Fig. 6. Integrated microfossil biostratigraphy and diachronism of *Stensioina granulata polonica*.

is characteristic of carbonaceous, pyritic, often laminated chalks signifying low-oxygen palaeoenvironments or, at the very least, depositional environments with a high organic influx. Such palaeoenvironments are highly discontinuous, both geographically and stratigraphically, and tied to local tectonics and palaeoceanographic conditions (Sikora *et al.* 1999). In basinal facies *S. granulata polonica* does not meet the requirements of a good biostratigraphic index. Unfortunately, the species has long been used as a 'golden spike' in most North Sea biozonations, which have assumed that the lower Santonian highest occurrence of the species in outcrop can be applied in the basin. This has exaggerated the amount of Santonian section in the basin at the expense of the Campanian and allowed a major Campanian–Coniacian regional erosional unconformity to go unrecognized. It also has resulted in serious errors in well-to-well correlation, and questions whether existing biozonations are truly integrated amongst various microfossil groups.

Redeposition

Redeposition must be considered in any age determinations and correlations within the North Sea chalks. In the current study, the large amount of core material has been essential in identifying redeposition and its affect on well-to-well correlations. In general, episodic redeposition of varying degrees corresponds to the major lithological units recognized in the Valhall Megaclosure (Fig. 1). Redeposition within the highly pelagic Hod Formation (Turonian–lower Santonian) is obvious because it is limited to a few specimens in isolated samples, and biostratigraphic resolution is very high within this unit. The rich Hod assemblages can be problematic in age determinations when remobilized, especially into the base of the overlying Campanian–lowermost Maastrichtian Magne Formation (Fig. 4). Minor amounts of redeposition also were observed at the base of the Tor Formation in the lower Maastrichtian. Taxa redeposited from the Hod Formation are obvious in these assemblages, whereas rare specimens redeposited from the underlying Magne Formation can complicate age determinations.

Recognition of redeposition is more crucial in the upper Maastrichtian–Palaeocene because it is associated with the main reservoir sections throughout the North Sea chalks. During the late Maastrichtian, redeposition is one possible explanation for the apparent diachronism of first appearance data points between the Valhall Megaclosure and well sections to the north and east (see the section on 'Palaeogeography'). Remobilization of upper Maastrichtian chalks into the Danian is a complex problem throughout the southern Norwegian sector of the North Sea. However, a unique situation may exist in the Valhall Megaclosure and is associated with the Cretaceous–Tertiary boundary and the contact between the Tor and Ekofisk formations.

The contact between the Tor and Ekofisk formations is identified on logs by the sharp increase in the gamma ray response at the base of the Ekofisk Formation (Isaksen & Tonstad 1989). The Ekofisk Formation is very thin throughout most the Valhall Megaclosure (1–10 m), but expands considerably in northern chalks fields (Eldfisk, Ekofisk and southeast Tor fields). Within the Valhall Megaclosure, the Ekofisk Formation is often cored along with the main reservoir of the upper Tor Formation. Cores from this interval were densely sampled in the current study (one or more samples per m).

The first well examined for this study yielded unprecedented results about the contact between the Tor and Ekofisk formations, and its relationship to the Cretaceous–Tertiary boundary (Fig. 7). In this well a succession of early Danian foraminifera and nannofossils was observed in the upper 3.75 m of the Tor Formation, which was otherwise dominated throughout by massive redeposition of upper Maastrichtian nannofossils (99%). In contrast, only about 15% of recovered planktic foraminifera from this 5-m interval were reworked Cretaceous species. The co-occurrence of the planktic foraminifera *Parvularugoglobigerina eugubina* and very small specimens of *P. pseudobulloides* (+2.75 m in Fig. 7) indicate an age close to the Pα–P1a zonal boundary (Berggren *et al.* 1995). The next sample down-section +1.75 m) is marked by a low-diversity assemblage of very abundant, minute specimens of *Globigerinelloides messinae* and *Heterohelix globulosa*, probably representing an earliest Danian assemblage of Cretaceous survivor species (zone P0). The subjacent sample (+0.8 m) nearly barren of foraminifera. An influx of Tethyan planktic foraminifera typical of the latest Maastrichtian in the North Sea basin is first observed down-section at −1.75 m, including *Pseudotextularia elegans*, *Pseudoguembelina excolata* and *Contusotruncana contusa*. The base of the nannofossil zone NP1 (Martini 1971) is well constrained by the lowest occurrences of three nannofossils (Fig. 7) with its lower boundary placed at the lowest occurrence of *Neocrepidolithus dirimosus* at 0 m. The NP1–NP2 zonal boundary (Martini 1971) also falls within the Tor Formation in this well and is

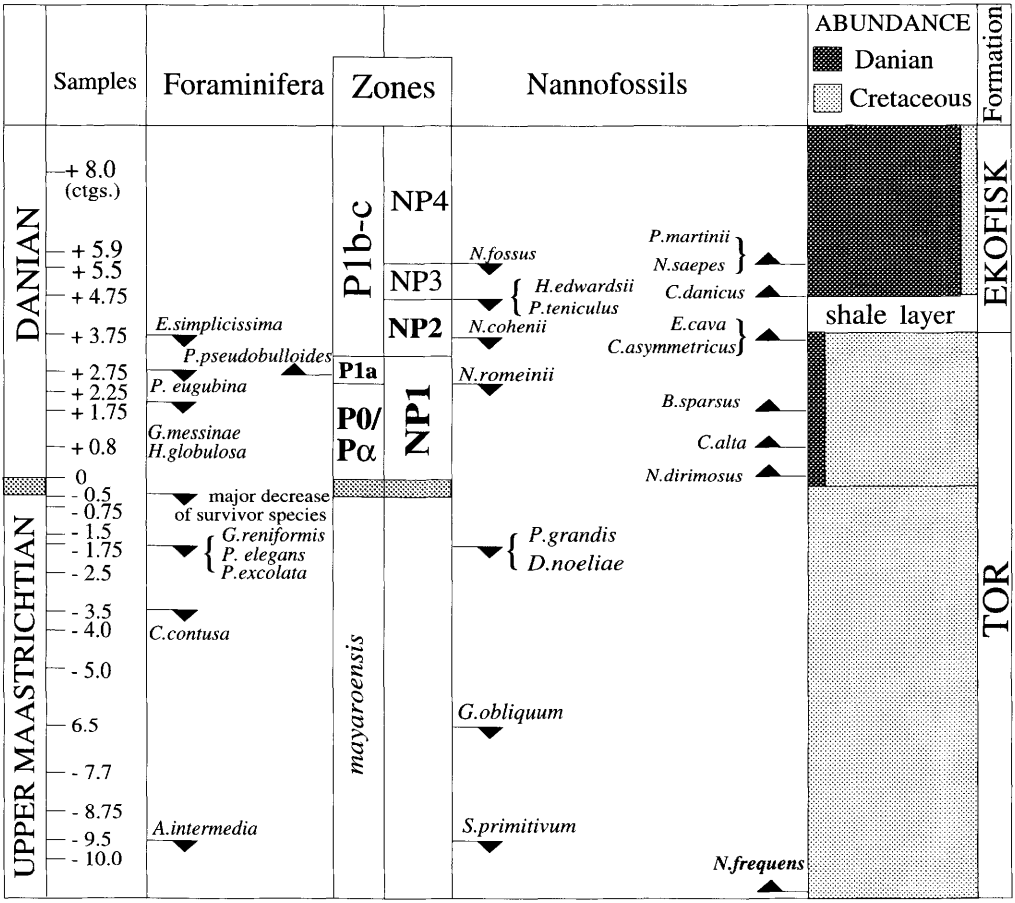

Fig. 7. Cretaceous–Tertiary boundary interval Valhall–Hod reference well.

constrained by the highest occurrence of *Neobiscutum romeinii* at +2.25 m and the lowest occurrences of *Ericsonia cava* and *Cruciplacolithus asymmetricus* at +3.75 m.

Biostratigraphic analyses have identified the Danian section at the top of the Tor Formation in all other wells examined, and this unit has been mapped throughout the Valhall Megaclosure; it is informally termed the Elle Member of the Tor Formation (Fig. 1). The youngest nannofossil assemblages recovered from this unit contain *Chiasmolithus danicus*, which marks the base of zone NP3 (Martini 1971). Nannofossil assemblages in all samples throughout this unit are characterized by massive redeposition from the upper Maastrichtian (nearly 100%), which has obscured previous recognition of this unit as Danian. However, remobilized upper Maastrichtian foraminifera shows trends across the Valhall Megaclosure related to structure and facies.

In the early late Maastrichtian, mudflows and relatively fine-grained debris flows dominated the Valhall region from the structure crest into the basin (Sikora *et al.* 1999). However, by the latest Maastrichtian and continuing into the early Danian (Elle Member of the Tor Formation) shoaling and winnowing of sediment dominated across the central crest feeding coarser-grained, debris flows down the flank. The shedding of coarser-grained bioclasts intensified in the early Danian with erosion of the central crestal zone, whereupon allochthonous sediments contained a very high percentage of reworked Cretaceous material. The amount of reworked material varies with the amount of sorting and transportation which has occurred. Lower Danian chalks from the crestal area are marked by nearly 100% reworked Maastrichtian foraminifera and other microfossils. As mentioned, the amount of redeposited upper

Maastrichtian nannofossils remains nearly constant across the main flank and into the basin. However, the amount of microfossil reworking decreases down the structural gradient to reach a minimum value of about 10% in fine-grained mudflow deposits on the lower flank and into the basin. The larger reworked microfossils were thus substantially sorted out during transportation from the central crestal zone into the basin.

Palaeogeography

Nannofossils

Late Cretaceous palaeoceanographic trends in nannofossil assemblages from the western northern hemisphere are reflected in published results from the Southern Ocean (Wise 1988; Pospichal & Wise 1990; Watkins 1992; Watkins *et al.* 1995). Largely cosmopolitan assemblages were established over a large portion of the western northern hemisphere (North Sea basin, southern Britain, Germany, Gulf of Mexico, Western Interior basin, southern Europe and Tunisia) during the Cenomanian–early Campanian. Nannofossil assemblages recovered from the Southern Ocean, although low in diversity, also consisted largely of cosmopolitan species during this time. However, abundance decreases and extinctions within the genera *Helicolithus* (Coniacian) and *Eprolithus* (Turonian) in the North Sea basin during this time may be an early signal for post-Cenomanian cooling.

A substantial disconformity separates lower and upper Campanian strata throughout the Southern Ocean. An increase in the number and proportion of high-latitude species during the late Campanian–early Maastrichtian in the Southern Ocean has been attributed to the development of a separate (cooler) surface water mass (Watkins *et al.* 1995). Accompanying these changes was the abundance decline of *Watznaueria barnesae*, which was first observed in higher latitude sites and then progressed towards the equator (Watkins *et al.* 1995). In the northern hemisphere, where the stratigraphic sections are more complete, evidence indicates an earlier breakdown of cosmopolitan assemblages. In the North Sea basin *Watznaueria barnesae* is an abundant constituent of Turonian–Santonian assemblages. This species gradually decreases (except across disconformities) in abundance until its disappearance immediately prior to the terminal Cretaceous, and is never common after the early Campanian. Additional evidence for an earlier breakdown in cosmopolitan assemblages and general cooling are the low-latitude markers species *Bukrylithus hayii* and *Marthasterites furcatus*, which are almost entirely excluded from the lower Campanian in northwestern Europe. Conversely, *Saepiovirgata biferula* and *Bifidilithus geminicatillus* are present in both the North Sea basin and the northern Western Interior basin (South Dakota), but have not been observed in lower–middle Campanian sections in the Gulf of Mexico and Tunisia. As in the Southern Ocean, provincialism appears to have intensified during the late Campanian–earliest Maastrichtian. In the northern hemisphere, several species present in lower latitude sections (Tunisia and southern France) during this time are absent from the North Sea basin or are extremely rare in surrounding outcrops. These include important marker taxa such as *Uniplanarius gothicus*, *Uniplanarius trifidus*, *Gorkaea obliquclausus* and *Bukrylithus magnus*. Conversely, certain taxa present in northwestern Europe (*Orastrum campanensis*, *Tortolithus caistorensis* and *Reinhardtites claviclaviformis*) are absent in sections in southwest France and Tunisia. Other longer-ranging taxa (e.g. *Amphizygus brooksii* and *Amphizygus minimus*) having late Campanian extinctions in lower latitudes have been excluded from upper Campanian deposits in the North Sea basin.

The middle early–early late Maastrichtian is characterized by a number of nannofossil extinctions (*Quadrum gartneri*, *Aspidolithus parcus constrictus*, *Tranolithus phacelosus*, *Reinhardtites levis*). A decrease in endemism is suggested by the fact this succession of nannofossil extinctions (zones KN6–KN8 in Appendix A) can be recognized in lower latitude sections (Gulf of Mexico, southern France, Tunisia). In the Southern Ocean an abundance increase of *Watznaueria barnesae* and decline in high-latitude taxa in more equatorial sites during the mid-Maastrichtian has been used to infer a slight moderation in climate (Watkins *et al.* 1995).

Strong latitudinal segregation during the late Maastrichtian is demonstrated by comparisons of nannofossil assemblages recovered from the North Sea basin and southern high latitudes (Watkins 1992; Watkins *et al.* 1995) to those in circum-Mediterranean sections, such as El Kef (Tunisia). Important marker taxa that appeared during the late Maastrichtian in low latitudes (*Micula prinsii*, *Micula murus* and *Ceratolithoides kamptneri*) are absent in both the North Sea basin and southern high latitudes. Conversely, as many as 20 nannofossil species did not survive the late Maastrichtian in the North Sea basin and this is also evident to some degree (e.g. *Prediscosphaera grandis* and *Gartnerago obliquum*) in southern high latitudes (ODP Site 750, Watkins 1992).

Of particular importance is the appearance of *Nephrolithus frequens*, which is ubiquitous in northern and southern high latitudes. Mortimer (1987) erected the late Maastrichtian *Zygodiscus spiralis* interval range zone (NK3) for the southern Norwegian and Danish chalks, which is defined as the interval between the lowest occurrence of *Nephrolithus frequens* and highest occurrence of *Gartnerago obliquum*. In the Valhall Megaclosure the stratigraphic ranges of these two species overlap (Fig. 8). In wells to the north and east of the Valhall Megaclosure *Nephrolithus frequens* has an apparent older first occurrence, as this species co-occurs with such taxa as *Tranolithus phacelosus* and *Reinhardtites levis*. In the southern high latitudes evidence indicates that *Nephrolithus frequens* migrated towards the equator during the late Maastrichtian, but co-occurs with *Reinhardtites levis* in older sections at higher latitude sites (Pospichal & Wise 1990; Watkins *et al.* 1995). Watkins *et al.* (1995) inferred a cooler late Maastrichtian based on the equatorial migration of *Nephrolithus frequens*, along with the continued decline in Austral flora. In the North Sea this would correspond to its migration south and westward into the Valhall Megaclosure. An alternate explanation to the diachronism of *Nephrolithus frequens* would be redeposition of mid-Maastrichtian chalk, especially considering the sharp difference and short distances between the Valhall Megaclosure and sites to the east and north. Examination of cored upper Maastrichtian sections in the North Sea outside the southern Norwegian sector and sampling for magnetostratigraphy could help resolve these uncertainties.

There is some evidence of a brief warming pulse near the Cretaceous–Tertiary boundary in the Southern Ocean, as increased abundances of *Watznaueria barnesae* exhibited a marked poleward migration near the terminal Cretaceous (Watkins *et al.* 1995). No corresponding increase in this species was observed near the terminal Cretaceous in the southern Norwegian sector of the North Sea. However, three nannofossil species not present in the terminal Cretaceous in the North Sea (zone KN1 in Appendix A) could indicate a very brief warming. *Nephrolithus frequens* and *Cribrosphaerella daniae* are

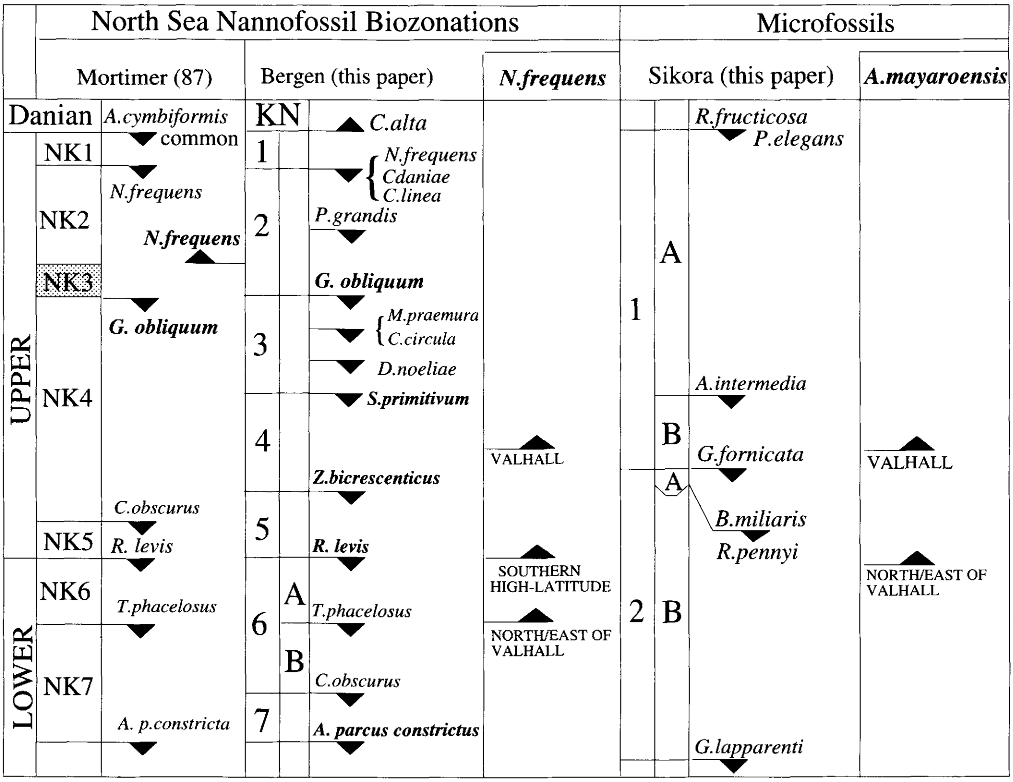

Fig. 8. Mid- to late Maastrichtian biostratigraphy and diachronism.

bipolar species, whereas *Cribrosphaerella ehrenbergii* (taxonomic synonym of *C. linea*) has been noted to have a preference for high southern latitudes (Wise 1988; Pospichal & Wise 1990; Watkins 1992).

Microfossils

Cenomanian–middle Turonian section in the North Sea basin contains planktic foraminifera with marked Tethyan affinities. This includes *Rotalipora* spp. in the Cenomanian Hidra Formation, and a diverse *Praeglobotruncana* assemblage and rare *Helvetoglobotruncana helvetica* in the lower and lower middle Turonian. The Tethyan elements of the planktic foraminifera assemblage began to decrease in the late middle Turonian. Biofacies analysis indicates that the late middle Turonian also was the time of initial uplift of the Valhall anticline (Sikora *et al.* 1999). Thus, the decline of purely Tethyan species at this time indicates a tectonic control on species distribution, probably a poorer connection with the open marine basin.

Planktic foraminifera from the upper middle Turonian–lower middle Campanian chalk section are often dominated by taxa of boreal aspect, such as species of *Whiteinella* and *Hedbergella*. Nevertheless, the presence of often abundant *Archaeoglobigerina cretacea* and species of *Marginotruncana* indicate the presence of an intermediate, rather than fully boreal, water mass. Furthermore, minor Tethyan influences near the Coniacian–Turonian boundary and within the upper Coniacian are indicated by rare occurrences of *Dicarinella* species (mainly *D. imbricata* and, much more rarely, *D. primitiva*). The lower Campanian marks the highest stratigraphic occurrence of this intermediate planktic foraminifera assemblage.

Upper middle Campanian–lower Maastrichtian sections contain evidence of pronounced cooling, marked by planktic foraminifera assemblages dominated by non-keeled taxa, such as species of *Rugoglobigerina*, *Globigerinelloides* and non-tethyan heterohelicids. A minor warming during the middle early Maastrichtian may be indicated by the appearance of rare *Globotruncana* species (mainly *G. lapparenti* and *G. bulloides*), which corresponds to the earliest nannofossil evidence for climatic equability (zone KN8).

The uppermost lower–upper Maastrichtian is marked by frequent changes in the composition of planktic foraminifera assemblages. The uppermost lower Maastrichtian is marked by a return of the boreal assemblage, which characterized most of the middle Campanian–early Maastrichtian. However, the lower upper Maastrichtian chalks are characterized by an influx of relatively Tethyan species of *Globotruncanella*, first appearing in southern Valhall sites about 69 Ma BP and reaching more northern sites (Block 2/5) at approximately 68 Ma BP. This corresponds to a time (nannofossil zones KN6–KN7) when *Nephrolithus frequens* was present only in wells to the north and east of the Valhall Megaclosure. In the Southern Ocean, a similar poleward migration of planktic foraminifers was associated with nannofossil assemblage changes indicating climatic moderation near the early–late Maastrichtian boundary (Huber & Watkins 1992; Watkins *et al.* 1995). Later in the Maastrichtian (approximately 66.7 Ma BP), *N. frequens* extended across the southern Norwegian North Sea and *Globotruncanella* had completely withdrawn. Thus, an early late Maastrichtian warming followed by cooling during the middle late Maastrichtian is indicated.

However, evidence contradictory of this middle late Maastrichtian cooling as defined by nannofossils is provided by another influx of Tethyan planktic foraminifera. This middle late Maastrichtian Tethyan influx in the North Sea has been long known (e.g. Koch 1977) and has been a widely used biostratigraphic datum. Principally, it involves Tethyan heterohelicids, such as *Pseudotextularia elegans*, *Racemiguembelina fructicosa* and *Pseudoguembelina excolata*, but also includes rare to frequent globotruncanids such as *Contusotruncana contusa* and *Abathomphalus mayaroensis*. Most of these species have much longer cosmopolitan stratigraphic ranges, the influx in the North Sea indicative of a local palaeoceanographic change. However, the present study indicates that the appearance of this Tethyan fauna is highly erratic and diachronous across the region. The oldest occurrences of this Tethyan fauna occurs in basinal localities to the north of Valhall. First occurrences of the assemblage occur much later on structure (e.g. the Balder Ridge) or do not occur at all (e.g. on the Valhall anticline). Such a pattern would suggest that the Tethyan fauna is indicative of a deeper water mass, and its influx in the latest Maastrichtian marks improved deep-water connections with the open marine basin as has been previously postulated (Schonfeld & Burnett 1991). However, this pattern would also suggest a transgression of structure during the latest Maastrichtian, whereas biofacies analysis indicates a regressive section (Sikora *et al.* 1999). This contradiction, together with nannofossil evidence of climactic cooling, indicates that further study is needed to fully resolve the palaeoceanographic implications of this Tethyan incursion, as well as the possibility of redeposition.

Conclusions

Detailed examination of post-Cenomanian Upper Cretaceous chalks in the southern Norwegian Sea has produced an integrated, high-resolution calcareous microfossil biozonation and identified numerous stratigraphic discontinuities within these Upper Cretaceous chalks. The stratigraphic units bounded by these discontinuities form the basic unit for mapping and their integration a necessary component of a robust geological model. A high-resolution chronostratigraphy is necessary for operations (biosteering), but also fundamental to understanding facies distributions, especially within reservoir units.

A strong palaeoenvironmental signal has been recorded in the microfossil and nannofossil assemblages within these North Sea chalks, which has been magnified by their high palaeolatitude. Because of this, caution must be exercised in the application of acme and benthic foraminifera events in correlation, both within the basin and from basin to outcrop. Tectonic movements and growth of the Valhall anticline from middle Turonian to Danian time is another important control on the distribution of microfossil assemblages, especially in redeposition across major lithostratigraphic boundaries and the downslope movement and sorting of assemblages during the Maastrichtian–early Danian. Cooling during the post-Cenomanian late Cretaceous is evident in Turonian–early Campanian assemblages recovered from these chalks, although assemblages were generally cosmopolitan during this time. Palaeogeographic segregation from lower latitudes first occurred during the late early Campanian and these trends mirror those observed in the Southern Ocean until the terminal Maastrichtian. Additional study of Campanian–Maastrichtian chalks of the North Sea, including isotope geochemistry and magnetostratigraphy, is needed to address palaeogeographic parameters and redeposition and their effect on chronostratigraphic correlations.

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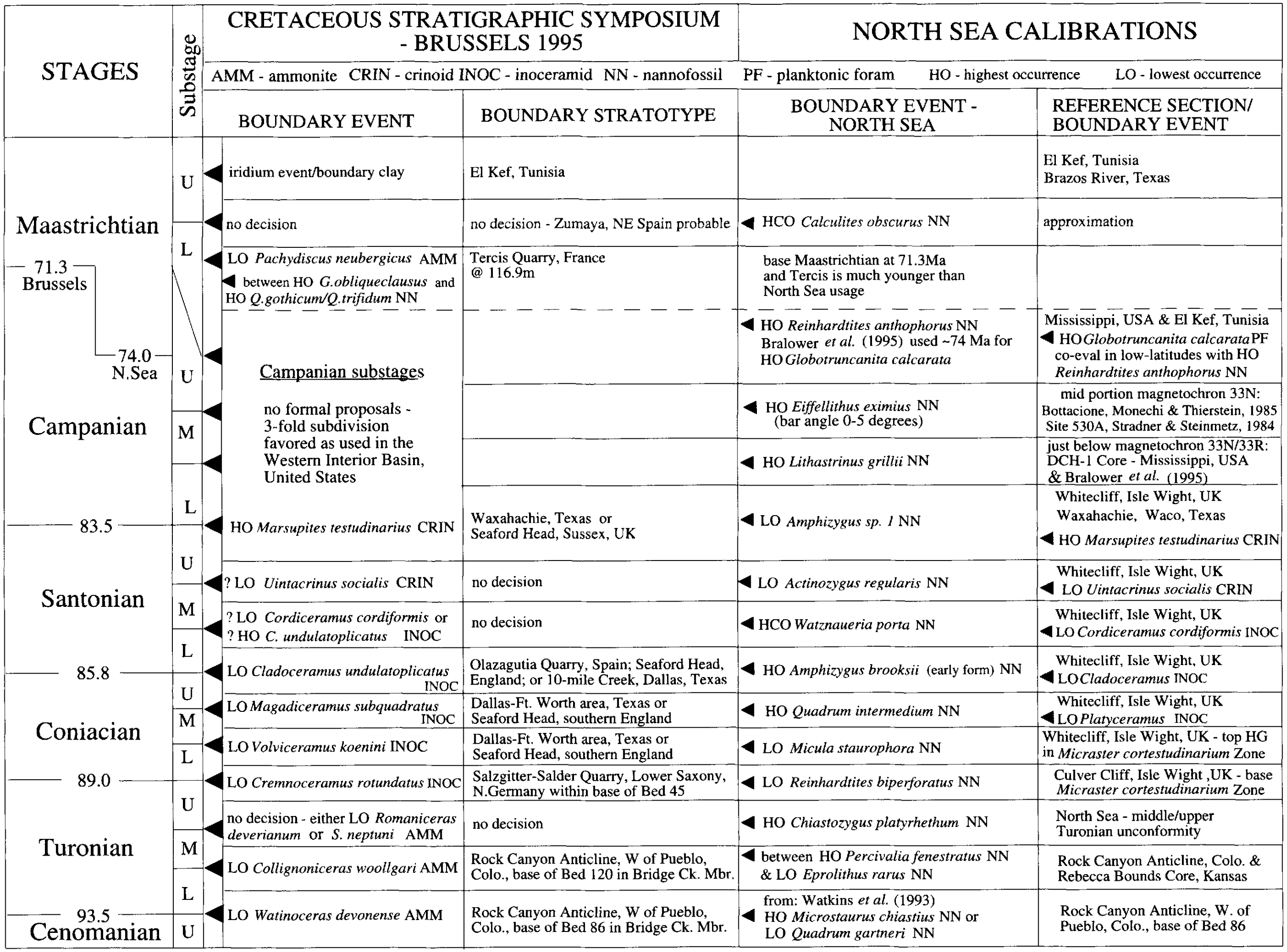
Appendices

The biozonations described herein stress the sequences of calcareous nannofossil and microfossil events. The time scale used is that of Gradstein *et al.* (1995). The results of the second International Symposium on Cretaceous Stage Boundaries, held in Brussels during September of 1995, were published by Rawson *et al.* (1996). Concrete recommendations resulting from this symposium included subdivisions of the Upper Cretaceous stages (i.e. two- or three-fold), as well as potential boundary stratotype sections and/or fossil criteria for both stage and substage boundaries (Fig. 9). Calibration of the North Sea chalk biozonations proposed herein to Upper Cretaceous stage and substage definitions is preliminary and based mainly on nannofossil correlations, but includes both unpublished and published data from recommended global stratotypes and/or correlation to recommended fossil criterion for these boundaries in circum-North Sea outcrops (Fig. 9). Scaling of these events in geological time will undergo significant revision with enhanced correlations to: (1) the $^{40}Ar/^{39}Ar$ radiometric ages of Obradovich (1993); (2) Campanian–Maastrichtian magnetostratigraphy; and (3) orbital periodicities identified in marine stratigraphic records. A final step is the correlation of the current chronostratigraphic framework for the southern Norwegian chalks to sequence stratigraphy (e.g. Gale 1996).

Zones and subzones are described and numbered from the top of the Cretaceous down-section. Abbreviations are used for the first downhole occurrence (FDO) and lowest downhole occurrence (LDO) in both the nannofossil and microfossil biozonations.

Appendix A: Calcareous nannofossil biostratigraphy

Four cosmopolitan Upper Cretaceous nannofossil biozonations have been published over the past two decades (Fig. 10). The CC zones of Sissingh (1977, 1978) are based largely on low- to middle-latitude outcrop sections, whereas the NC zones of Roth (1978) are founded on deep-sea sections. Perch-Nielsen (1985) refined the biozonation of Sissingh (1977, 1978), whereas Bralower *et al.* (1995) modified the biozonation of Roth (1978). Upper Cretaceous nannofossil biozonations of circum-North Sea outcrop sections have excluded the Maastrichtian, but are based on study of the Cenomanian–mid-Campanian of southern England (Crux 1982) and the German Campanian–lowermost Maastrichtian (Burnett 1991). Application



AMM - ammonite CRIN - crinoid INOC - inoceramid NN - nannofossil PF - planktonic foram HO - highest occurrence LO - lowest occurrence

STAGES	Substage	CRETACEOUS STRATIGRAPHIC SYMPOSIUM - BRUSSELS 1995		NORTH SEA CALIBRATIONS	
		BOUNDARY EVENT	BOUNDARY STRATOTYPE	BOUNDARY EVENT - NORTH SEA	REFERENCE SECTION/ BOUNDARY EVENT
Maastrichtian	U	iridium event/boundary clay	El Kef, Tunisia		El Kef, Tunisia Brazos River, Texas
	U	no decision	no decision - Zumaya, NE Spain probable	HCO *Calculites obscurus* NN	approximation
71.3 Brussels	L	LO *Pachydiscus neubergicus* AMM	Tercis Quarry, France @ 116.9m	base Maastrichtian at 71.3Ma and Tercis is much younger than North Sea usage	
74.0 N.Sea	L	between HO *G.obliqueclausus* and HO *Q.gothicum/Q.trifidum* NN		HO *Reinhardtites anthophorus* NN Bralower *et al.* (1995) used ~74 Ma for HO *Globotruncanita calcarata*	Mississippi, USA & El Kef, Tunisia HO *Globotruncanita calcarata* PF co-eval in low-latitudes with HO *Reinhardtites anthophorus* NN
Campanian	U	Campanian substages no formal proposals - 3-fold subdivision favored as used in the Western Interior Basin, United States		HO *Eiffellithus eximius* NN (bar angle 0-5 degrees)	mid portion magnetochron 33N: Bottacione, Monechi & Thierstein, 1985 Site 530A, Stradner & Steinmetz, 1984
	M			HO *Lithastrinus grillii* NN	just below magnetochron 33N/33R: DCH-1 Core - Mississippi, USA & Bralower *et al.* (1995)
83.5	L	HO *Marsupites testudinarius* CRIN	Waxahachie, Texas or Seaford Head, Sussex, UK	LO *Amphizygus sp. 1* NN	Whitecliff, Isle Wight, UK Waxahachie, Waco, Texas HO *Marsupites testudinarius* CRIN
Santonian	U	? LO *Uintacrinus socialis* CRIN	no decision	LO *Actinozygus regularis* NN	Whitecliff, Isle Wight, UK LO *Uintacrinus socialis* CRIN
	M	? LO *Cordiceramus cordiformis* or ? HO *C. undulatoplicatus* INOC	no decision	HCO *Watznaueria porta* NN	Whitecliff, Isle Wight, UK LO *Cordiceramus cordiformis* INOC
85.8	L	LO *Cladoceramus undulatoplicatus* INOC	Olazagutia Quarry, Spain; Seaford Head, England; or 10-mile Creek, Dallas, Texas	HO *Amphizygus brooksii* (early form) NN	Whitecliff, Isle Wight, UK LO *Cladoceramus* INOC
Coniacian	U	LO *Magadiceramus subquadratus* INOC	Dallas-Ft. Worth area, Texas or Seaford Head, southern England	HO *Quadrum intermedium* NN	Whitecliff, Isle Wight, UK LO *Platyceramus* INOC
	M	LO *Volviceramus koenini* INOC	Dallas-Ft. Worth area, Texas or Seaford Head, southern England	LO *Micula staurophora* NN	Whitecliff, Isle Wight, UK - top HG in *Micraster cortestudinarium* Zone
89.0	L	LO *Cremnoceramus rotundatus* INOC	Salzgitter-Salder Quarry, Lower Saxony, N.Germany within base of Bed 45	LO *Reinhardtites biperforatus* NN	Culver Cliff, Isle Wight ,UK - base *Micraster cortestudinarium* Zone
Turonian	U	no decision - either LO *Romaniceras deverianum* or *S. neptuni* AMM	no decision	HO *Chiastozygus platyrhethum* NN	North Sea - middle/upper Turonian unconformity
	M	LO *Collignoniceras woollgari* AMM	Rock Canyon Anticline, W of Pueblo, Colo., base of Bed 120 in Bridge Ck. Mbr.	between HO *Percivalia fenestratus* NN & LO *Eprolithus rarus* NN	Rock Canyon Anticline, Colo. & Rebecca Bounds Core, Kansas
93.5	L	LO *Watinoceras devonense* AMM	Rock Canyon Anticline, W of Pueblo, Colo., base of Bed 86 in Bridge Ck. Mbr.	from: Watkins *et al.* (1993) HO *Microstaurus chiastius* NN or LO *Quadrum gartneri* NN	Rock Canyon Anticline, W. of Pueblo, Colo., base of Bed 86
Cenomanian	U				

Fig. 9. Turonian–Maastrichtian stage and substage boundary criteria: global v. North Sea (after Burnett 1996).

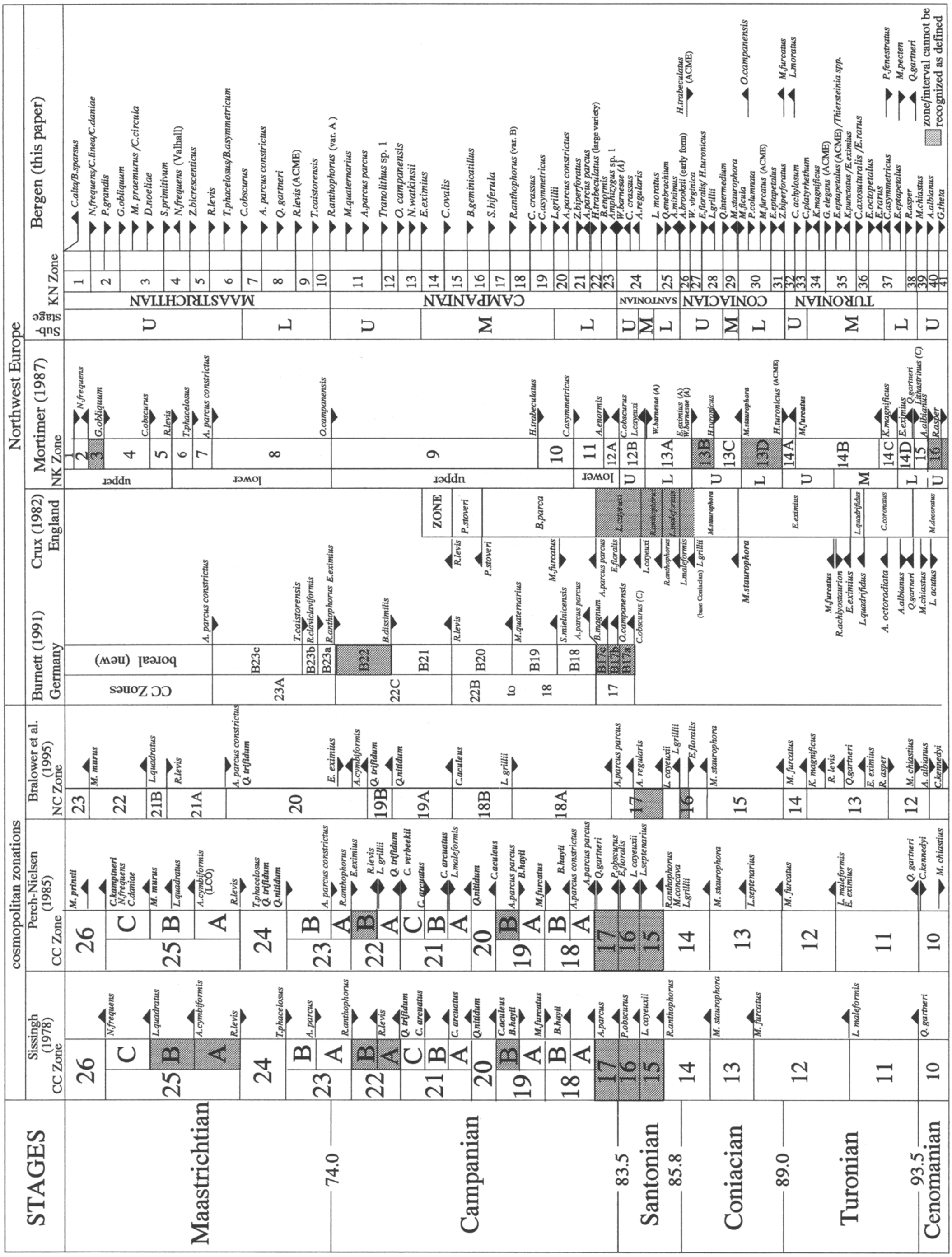


Fig. 10. Turonian–Maastrichtian nannofossil biozonations.

of all these biozonations (Fig. 10) to operational work in the North Sea is reduced by their reliance on first occurrence events and the use of several low-latitude events in the cosmopolitan biozonations, especially for the Campanian–Maastrichtian.

Mortimer (1987) published the only Upper Cretaceous nannofossil biozonation for the southern Norwegian and Danish sectors of the North Sea basin, which relied heavily on acme events on first occurrence data points in the Santonian–Turonian (Fig. 10). Mortimer (1987) included two summary range charts illustrating the occurrences on many useful secondary events. The Turonian–Maastrichtian biozonation presented herein (see below) is for the southern sector of the Norwegian North Sea and includes three-fold subdivisions of the Coniacian–Campanian stages (Fig. 10).

Of particular importance is the inability to reproduce any of the existing Santonian nannofossil biozonations schemes. When coupled with North Sea microfossil biozonations founded on benthic foraminifera successions in outcrop (King *et al.* 1989), this has lead to erroneous correlations within the North Sea basin. Also important is the definition of the Campanian–Maastrichtian boundary. An older definition of this boundary is maintained in this paper (highest occurrence of the calcareous nannofossil *Reinhardtites anthophorus*) consistent with historical usage within the North Sea basin (Mortimer 1987; Burnett 1991), as opposed to correlations to the potential boundary stratotype near Tercis, France (Odin 1996). This situation is further complicated by the condensed nature of the boundary interval within the study area and palaeogeographic endemism.

The biozonation described below will be revised to: (1) extend to the base of the Upper Cretaceous; (2) include subzone definitions; (3) emend taxonomic concepts and assignments; (4) illustrate all taxa; and (5) establish authorship. The nannofossil binomials used herein can be found in Perch-Nielsen (1985), Varol (1992), Varol & Girgis (1994) and Bralower & Bergen (1998).

Arkhangelskiella cymbiformis *zone (KN1)*

Age: late Maastrichtian.

Definition: interval from the LDO of *Cyclagelosphaera alta* or *Biantholithus sparsus* to the FDO of *Nephrolithus frequens*, *Cribrosphaerella linea* or *Cribrosphaerella daniae*.

Remarks: this zonal definition differs from Mortimer (1987), who used the FDO of common Cretaceous nannofossils to define the Cretaceous–Tertiary boundary.

Nephrolithus frequens *zone (KN2)*

Age: late Maastrichtian.

Definition: interval from the FDO of *Nephrolithus frequens*, *Cribrosphaerella linea* or *Cribrosphaerella daniae* to the FDO of *Gartnerago obliquum*.

Remarks: this zonal definition differs from Mortimer (1987), who used the total range of *Nephrolithus frequens*.

Gartnerago obliquum *zone (KN3)*

Age: late Maastrichtian.

Definition: interval from the FDO of *Gartnerago obliquum* to the FDO of *Seribiscutum primitivum*.

Remarks: Mortimer (1987) used the HO of *Calculites obscurus* to mark the base of this zone.

Seribiscutum primitivum *zone (KN4)*

Age: late Maastrichtian.

Definition: interval from the FDO of *Seribiscutum primitivum* to the FDO of *Zeugrhabdotus bicrescenticus*.

Zeugrhabdotus bicrescenticus *zone (KN5)*

Age: late Maastrichtian.

Definition: interval from the FDO of *Zeugrhabdotus bicrescenticus* to the FDO of *Reinhardtites levis*.

Remarks: *Zeugrhabdotus bicrescenticus* (Stover, 1966) is a senior synonym of the basionym *Zygolithus compactus* Bukry (1969).

Reinhardtites levis *zone (KN6)*

Age: late Maastrichtian.

Definition: interval from the FDO of *Reinhardtites levis* to the FDO of *Calculites obscurus*.

Remarks: Mortimer (1987) used the HO of *Tranolithus phacelosus* to mark the base of this zone.

Calculites obscurus *zone (KN7)*

Age: early Maastrichtian.

Definition: interval from the FDO of *Calculites obscurus* to the FDO of *Aspidolithus parcus constrictus*.

Remarks: Mortimer (1987) used different criteria for definition of this zone.

Aspidolithus parcus constrictus *zone (KN8)*

Age: early Maastrichtian.

Definition: interval from the FDO of *Aspidolithus parcus constrictus* to the FDO of the acme of *Reinhardtites levis*.

Markalius apertus *zone (KN9)*

Age: early Maastrichtian.

Definition: interval from the FDO of the acme of *Reinhardtites levis* to the FDO of *Tortolithus caistorensis*.

Tortolithus caistorensis *zone (KN10)*

Age: early Maastrichtian.

Definition: interval from the FDO of *Tortolithus caistorensis* to the FDO of *Reinhardtites anthophorus* (var A).

Remarks: smaller forms of *Reinhardtites anthophorus* having greater rim to central area width ratios are referred to variation A and mark the extinction of the species.

Reinhardtites anthophrous *zone (KN11)*

Age: late Campanian.

Definition: interval from the FDO of *Reinhardtites anthophorus* (var. A) to the FDO of *Tranolithus* sp. 1.

Remarks: *Tranolithus* sp. 1 is reserved for forms having four bright (first-order white birefringence) blocks in the central area.

Chiastozygus fessus *zone (KN12)*

Age: late Campanian.

Definition: interval from the FDO of *Tranolithus* sp. 1 to the FDO of *Orastrum campanensis*.

Orastrum campanensis *zone (KN13)*

Age: late Campanian.

Definition: interval from the FDO of *Orastrum campanensis* to the FDO of *Eiffellithus eximius*.

Remarks: Mortimer (1987) used the FDO of *Helicolithus trabeculatus* to mark the base of this zone, but this species was described from the Maastrichtian.

Eiffellithus eximius *zone (KN14)*

Age: middle Campanian.

Definition: interval from the FDO of *Eiffellithus eximius* to the FDO of *Calculites ovalis*.

Calculites ovalis *zone* (KN15)

Age: middle Campanian.

Definition: interval from the FDO of *Calculites ovalis* to the FDO of *Bifidalithus geminicatillus*.

Bifidalithus geminicatillus *zone (KN16)*

Age: middle Campanian.

Definition: interval from the FDO of *Bifidalithus geminicatillus* to the FDO of *Saepiovirgata biferula*.

Saepiovirgata biferula *zone (KN17)*

Age: middle Campanian.

Definition: interval from the FDO of *Saepiovirgata biferula* to the FDO of *Reinhardtites anthophorus* (var B).

Remarks: larger forms of *Reinhardtites anthophorus* having lower rim to central area width ratios are referred to as variation B.

Reinhardtites anthophorus *(var. B) zone (KN18)*

Age: middle Campanian.

Definition: interval from the FDO of *Reinhardtites anthophorus* (var. B) to the FDO of *Cylindralithus crassus*.

Cylindralithus crassus *zone (KN19)*

Age: middle Campanian.

Definition: interval from the FDO of *Cylindralithus crassus* to the FDO of *Lithastrinus grillii*.

Lithastrinus grillii *zone (KN20)*

Age: early Campanian.

Definition: interval from the FDO of *Lithastrinus grillii* to the LDO of *Aspidolithus parcus constrictus*.

Aspidolithus parcus parcus *zone (KN21)*

Age: early Campanian.

Definition: interval from the LDO of *Aspidolithus parcus constrictus* to the LDO of *Aspidolithus parcus parcus*.

Helicolithus trabeculatus *zone (KN22)*

Age: early Campanian.

Definition: interval from the LDO of *Aspidolithus parcus parcus* to the FDO of *Broinsonia enormis*.

Remarks: Mortimer (1987) used different criteria for the definition of this zone.

Broinsonia enormis *zone (KN23)*

Age: early Campanian.

Definition: interval from the FDO of *Broinsonia enormis* to the FDO of abundant *Watznaueria barnesae*.

Remarks: Mortimer (1987) defined this zone.

Watznaueria barnesae *zone (KN24)*

Age: late–middle Santonian.

Definition: interval from the FDO of abundant *Watznaueria barnesae* to the FDO of *Lithastrinus moratus*.

Lithastrinus moratus *zone (KN25)*

Age: early Santonian.

Definition: interval from the FDO of *Lithastrinus moratus* to the LDO of *Amphizygus minimus* or the FDO of *Amphizygus brooksii* (early form).

Remarks: early forms of *Amphizygus brooksii* have a broad, bright inner rim cycle and a relatively narrow, faint outer rim cycle in cross-polarized light (see Bralower & Bergen 1998, plate 2, Fig. 7).

Kamptnerius punctatus *zone (KN26)*

Age: late Coniacian.

Definition: interval from the LDO of *Amphizygus minimus* or the FDO of *Amphizygus brooksii* (early form) to the FDO of *Watznaueria virginica*.

Watznaueria virginica *zone (KN27)*

Age: late Coniacian.

Definition: interval from the FDO of *Watznaueria virginica* to the FDO of *Eprolithus floralis* or *Helicolithus turonicus*.

Helicolithus turonicus *zone (KN28)*

Age: late Coniacian.

Definition: interval from the FDO of *Eprolithus floralis* or *Helicolithus turonicus* to the FDO of *Quadrum intermedium*.

Quadrum intermedium *zone (KN29)*

Age: middle Coniacian.

Definition: interval from the FDO of *Quadrum intermedium* to the FDO of *Miravetesina ficula* or LDO *Micula staurophora*.

Miravetesina ficula *zone (KN30)*

Age: early Coniacian.

Definition: interval from the FDO of *Miravetesina ficula* or LDO *Micula staurophora* to the FDO of *Eprolithus eptapetalus*.

Eprolithus eptapetalus *zone (KN31)*

Age: early Coniacian.

Definition: interval from the FDO *Eprolithus eptapetalus* to the LDO of *Zeugrhabdotus biperforatus* or *Marthasterites furcatus*.

Cylindralithus coronatus *zone (KN32)*

Age: late Turonian.

Definition: interval from the LDO of *Zeugrhabdotus biperforatus* or *Marthasterites furcatus* to the FDO of *Stoverius achylosus*.

Stoverius achylosus *zone (KN33)*

Age: late Turonian.

Definition: interval from FDO of *Stoverius achylosus* to the FDO of *Chiastozygus platyrhethum*.

Chiastozygus platyrhethum *zone (KN34)*

Age: middle Turonian.

Definition: interval from FDO of *Chiastozygus platyrhethum* to the FDO of the acme of *Glaukolithus elegans* (*sensu* Roth & Thierstein, 1972).

Glaukolithus elegans *zone (KN35)*

Age: middle Turonian.

Definition: interval from the FDO of the acme of *Glaukolithus elegans* (*sensu* Roth & Thierstein 1972) to the FDO of *Calculites axosuturalis*.

Calculites axosuturalis *zone (KN36)*

Age: middle Turonian.

Definition: interval from the FDO of *Calculites axosuturalis* to the FDO of *Eprolithus octopetalus*.

Eprolithus octopetalus *zone (KN37)*

Age: middle–early Turonian.

Definition: interval from the FDO of *Eprolithus octopetalus* to the FDO of *Rhagodiscus asper*.

Rhagodiscus asper *zone (KN38)*

Age: early Turonian.

Definition: interval from the FDO of *Rhagodiscus asper* to the FDO of *Microstaurus chiastius*.

Remarks: Mortimer (1987) defined the base of this zone on the FDO of small to medium-sized *Seribiscutum primitivum*.

Microstaurus chiastius *zone (KN39)*

Age: late Cenomanian.

Definition: interval from the FDO of *Microstaurus chiastius* to the FDO of *Axopodorhabdus albianus*.

Axopodorhabdus albianus *zone (KN40)*

Age: late Cenomanian.

Definition: interval from the FDO of *Axopodorhabdus albianus* to the FDO of *Gartnerago theta*.

Gartnerago theta *zone (KN41)*

Age: middle Cenomanian.

Definition: interval from the FDO of *Gartnerago theta* to the FDO of *Gartnerago nanum*.

Appendix B: Microfossil biostratigraphy

The following microfossil biozonation for the Valhall Megaclosure (Fig. 11) employs a mixture of planktic and benthic foraminifera events, as well as a single radiolarian event. Abundance events have been avoided because of potential diachronism and redeposition. The stratigraphic ranges of the benthic foraminifera are not based solely upon their ranges in outcrop, but have been calibrated through other microfossil groups (nannofossils and palynomorphs) to the stage and substage terminology. Many zonal and subzonal taxa have rare, yet consistent, occurrences within the basin, such as the highest occurrences of *Globotruncana fornicata* in the middle late Maastrichtian and *Dicarinella imbricata* in the late Coniacian. Other marker taxa occur more frequently, but are obscured by more abundant occurrences of longer-ranging species within the same genus (e.g. *Whiteinella aprica* or *Marginotruncana coronata*). Thus, careful examination of washed residues and the use of thin sections in more indurated lithologies is required. Although this is more time-consuming, the use of more quickly determined and easily recognized data points (such as abundance events) can result in reduced stratigraphic resolution and erroneous correlations.

Pseudotextularia elegans *zone (NCF1)*

Age: late Maastrichtian.

Definition: interval from the FDO of the Tethyan heterohelicids *Pseudotextularia elegans* and *Racemiguembelina fructicosa* to the FDO of *Globotruncana fornicata*.

Remarks: the top of this zone is often marked by the FDO of several other Tethyan planktic species including *Pseudoguembelina excolata*, *Pseudoguembelina palpebra*, *Abathomphalus mayaroensis* and *Contusotruncana contusa*. Benthic species having the highest occurrences at the top of this zone include *Bolivinoides draco*, *Cibicidoides voltziana* and *Stensioina pommerana*. Recognition of zone NCF1 is often problematic in the North Sea chalk. In fine-grained, allochthonous chalks found well off-structure in the Valhall Megaclosure, the primary zonal markers have often been winnowed out. The appearances of the Tethyan planktic foraminifera taxa are diachronous regionally. Finally, the characteristic assemblage is often abundantly reworked into the basal Danian in the Valhall Megaclosure, so that careful comparisons must be made with other microfossil disciplines so that the top of the zone is not identified prematurely in well sections.

Subzone definition. *Pseudotextularia elegans* subzone (NCF1a): interval from the FDO of *P. elegans* and/or *R. fructicosa* to the FDO of the planktic foraminifer *Abathomphalus intermedia*.

Abathomphalus intermedia subzone (NCF1b): interval from the FDO of *A. intermedia* to the FDO of *G. fornicata*.

Rugoglobigerina pennyi *zone (NCF2)*

Age: late–early Maastrichtian.

Definition: interval from the FDO of *Globotruncana fornicata* to the FDO of the planktic species *Globotruncana lapparenti* and/or the morphologically similar taxon *Globotruncana linneiana*.

Remarks: the top of the zone is marked by the FDO of *Globotruncana fornicata*, but is also characterized for most of its duration by common occurrences of the another planktic species, *Rugoglobigerina pennyi*. Subsidiary components include often diverse *Globotruncanella* species, including *G. havanenesis* and *G. petaloidea*. The zone is easily recognized both on- and off-structure throughout the Valhall Megaclosure, although much of the lower portion of the zone is usually composed of poorly fossiliferous, fine-grained allochthonous chalks.

Subzone definition. *Globotruncana fornicata* subzone (NCF2a): interval from the FDO of the nominate species to the FDO of the planktic foraminifer *Rugoglobigerina pennyi* and/or the benthic foraminifer *Bolivinoides miliaris*.

Rugoglobigerina pennyi subzone (NCF2b): interval from the FDO of *R. pennyi* and/or *B. miliaris* to the FDO of *G. lapparenti* and/or *G. linneiana*.

Globotruncana lapparenti *zone (NCF3)*

Age: middle early Maastrichtian.

Definition: interval from the FDO of *G. lapparenti* and/or *G. linneiana* to the FDO of the large agglutinated benthic foraminifer *Tritaxia capitosa*.

Remarks: this zone is characterized by autochthonous chalks with diverse assemblages of planktic and benthic foraminifera. This facies marks a prominent change from the fine-grained allochthonous chalks characteristic of the lower portion of the overlying zone NCF2.

Tritaxia capitosa *zone (NCF4)*

Age: early Maastrichtian.

Definition: interval from the FDO of *T. capitosa* to the FDO of the benthic foraminifer *Gavelinella monterelensis*.

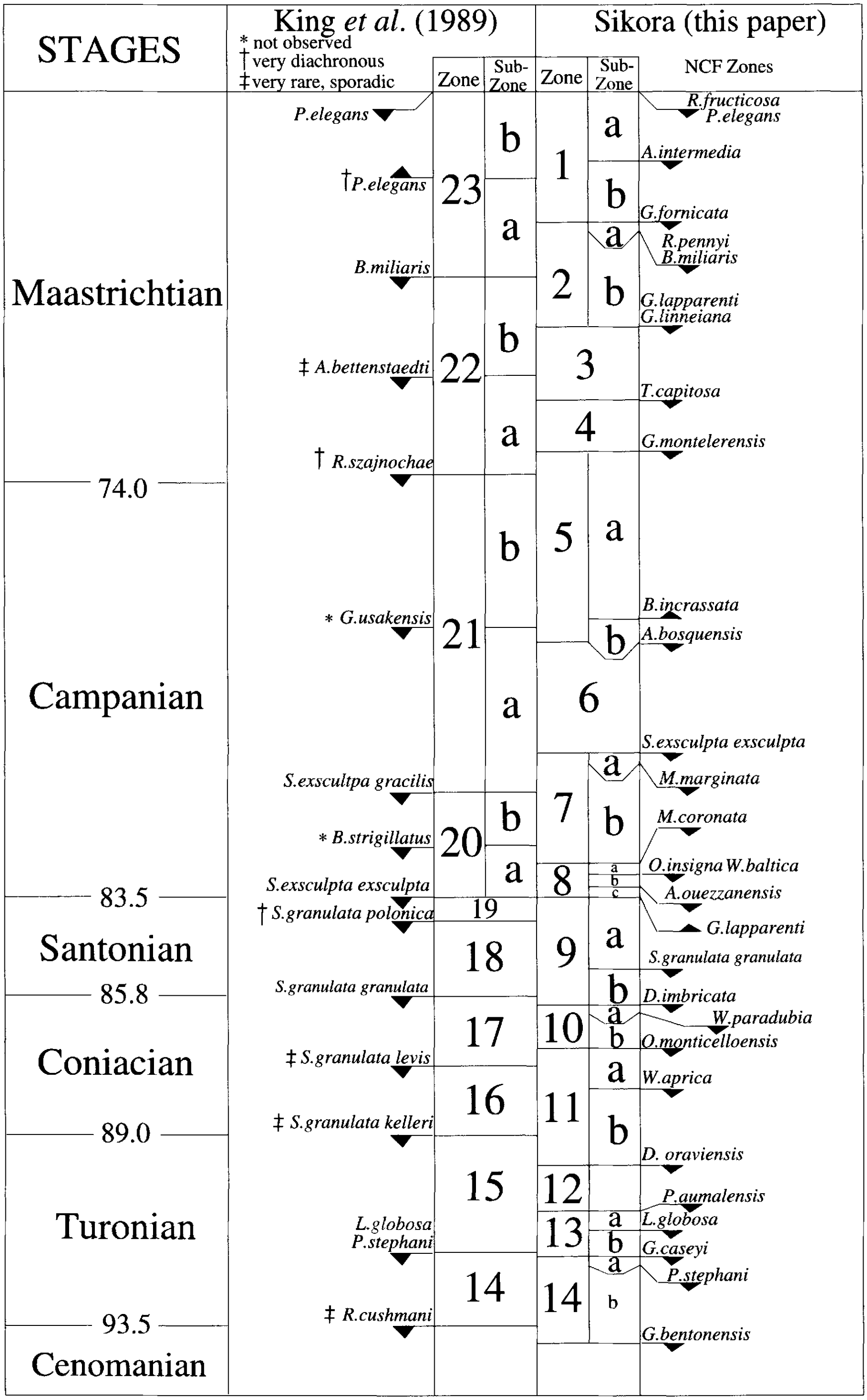


Fig. 11. Comparison of North Sea microfossil biozonations.

Remarks: the extinction of *Tritaxia capitosa* has previously been used to approximate the terminal Campanian in the North Sea basin (King *et al.* 1989), but correlation to the nannofossil succession shows it to range higher than *Reinhardtites anthophorus* (zone KN11) and roughly coincident with the FDO of common *Reinhardtites levis* (zone KN9). Zone NCF4 is similar in foraminiferal composition to the overlying *G. lapparenti* zone (NCF3), but is much more stratigraphically and geographically discontinuous across the Valhall Megaclosure.

Gavelinella monterelensis *zone (NCF5)*

Age: earliest Maastrichtian–late middle Campanian.

Definition: interval from the FDO of *G. monterelensis* to the FDO of the planktic foraminifer *Archaeoglobigerina bosquensis.*

Remarks: although the highest occurrence of *Gavelinella monterelensis* has been used to approximate the terminal Campanian in outcrop (Hart *et al.* 1989), this event consistently occurs immediately above the FDO of the calcareous nannofossil *Reinhardtites anthophorus* (var. A) in the wells studied. This interval includes autochthonous chalks that are often condensed, but are characterized by abundant and diverse assemblages of planktic and benthic foraminifera assemblages. Most of these foraminifer taxa range into the overlying zones NCF3 and NCF4. Zone NCF5 also includes discontinuous occurrences of pyritic chalks containing *Stensioina granulata polonica*, whose extinction previously has been used to mark the top of the middle Santonian.

Subzone definition. Gavelinella monterelensis subzone (NCF5a): interval from the FDO of *G. monterelensis* to the LDO of the benthic foraminifer *Brizalina incrassata.*

Brizalina incrassata subzone (NCF5b): interval from the LDO of *B. incrassata* to the FDO of *A. bosquensis.*

Archaeoglobigerina bosquensis *zone (NCF6)*

Age: middle Campanian.

Definition: interval from the FDO of the planktic foraminifer *Archaeoglobigerina bosquensis* to the FDO of the benthic foraminifer *Stensioina exsculpta exsculpta.*

Remarks: consistent, yet rare, occurrences of *A. bosquensis* mark the top of this zone. Otherwise, the zone is generally characterized by diverse assemblages of planktic and benthic foraminifera very similar to those noted for zone NCF5.

Stensioina exsculpta exsculpta *zone (NCF7)*

Age: early middle–late early Campanian.

Definition: interval from the FDO of the benthic foraminifera *Stensioina exsculpta exsculpta* to the FDO of the planktic foraminifer *Marginotruncana coronata.*

Remarks: *Stensioina exsculpta exsculpta* and the commonly associated taxon *S. exsculpta gracilis* extend into much younger section in the basin than in outcrop. The respective highest occurrences of *Stensioina exsculpta exsculpta* and *S. exsculpta gracilis* in outcrop occur at the top of the Santonian and within the lower Campanian (Hart *et al.* 1989), whereas both species occur well into the middle Campanian in the basin. Furthermore, the only consistent occurrences of *S. exsculpta gracilis* in the basinal chalk sections are within this zone.

Subzone definition. Stensioina exsculpta exsculpta subzone (NCF7a): interval from the FDO of *Stensioina exsculpta exsculpta* to the FDO of the planktic species *Marginotruncana marginata.*

Marginotruncana marginata subzone (NCF7b): interval from the FDO of *M. marginata* to the FDO of *M. coronata.* The top of subzone NCF7b is often marked by the first down-section occurrence of common spherical radiolarians.

Marginotruncana coronata *zone (NCF8)*

Age: earliest Campanian.

Definition: interval from the FDO of the planktic foraminifer *M. coronata* to the LDO of the planktic foraminifer *Globotruncana lapparenti.*

Remarks: although of short duration, this zone is characterized by condensed, autochthonous chalks containing extremely diverse planktic foraminifera and deep-water benthic foraminifera. It marks both a major flooding event and the culmination of a period of climatic warming.

Subzone definition. Marginotruncana coronata subzone (NCF8a): interval from the FDO of *M. coronata* to the FDO of the planktic foraminifer *W. baltica* and/or the cosmopolitan benthic foraminifer *Osangularia insigna.*

Whiteinella baltica subzone (NCF8b): interval from the FDO of *W. baltica* and/or *Osangularia insigna* to the FDO of the benthic foraminifer *Aragonia ouezzanensis.*

Aragonia ouezzanensis subzone (NCF8c): interval from the FDO the nominate species to the LDO of *Globotruncana lapparenti.* This subzone contains the total stratigraphic range within the basinal chalk section of the benthic foraminifer *A. ouezzanensis.* The basal Campanian subzone NCF8c was encountered in only two well sections in the Valhall Megaclosure.

Stensioina granulata granulata *zone (NCF9)*

Age: Santonian–latest Coniacian.

Definition: interval from the LDO the planktic foraminifer *Globotruncana lapparenti* to the FDO of the planktic foraminifer *Dicarinella imbricata.*

Remarks: the lowest occurrences of several other taxa also mark the top of this zone, including the benthic foraminifera *Aragonia ouezzanensis* and *Stensioina pommerana.*

Subzone definition. Gavelinella cristata subzone (NCF9a): interval from LDO of *G. lapparenti* to FDO of the benthic foraminifer *Stensioina granulata granulata*. This subzone is recognized in outcrop (Whitecliff, Isle of Wight, UK), but has not been encountered in the Valhall Megaclosure.

Stensioina granulata granulata subzone (NCF9b): interval from the FDO of *S. granulata granulata* to the FDO of *Dicarinella imbricata*. In the basin subzone NCF9b is only present in thin intervals located off the anticlinal crest.

Dicarinella imbricata *zone (NCF10)*

Age: late–middle Coniacian.

Definition: interval from the FDO of the planktic foraminifer *D. imbricata* to the FDO of the radiolarian *Orbiculoformis monticelloensis*.

Remarks: the top of zone NCF10 is immediately below the terminal Coniacian and marks the first down-section occurrence of the typical highly pelagic facies of the Hod Formation. The interval is usually dominated by stratigraphically long-ranging planktic foraminifera, such as *Marginotruncana marginata* and *Whiteinella baltica*. The zone is often absent from crestal Valhall due to erosional truncation.

Subzone definition. Dicarinella imbricata subzone (NCF10a): interval from the FDO of the nominate species to the FDO of the planktic foraminifer *Whiteinella paradubia*.

Whiteinella paradubia subzone (NCF10b): interval from the FDO of *W. paradubia* to the FDO of the radiolarian *Orbiculoformis monticelloensis*.

Whiteinella aprica *zone (NCF11)*

Age: early middle Coniacian–latest Turonian.

Definition: interval from the FDO of the radiolarian *Orbiculoformis monticelloensis* to the FDO of the planktic foraminifer *Dicarinella(?) oraviensis* (a provisional species designation by Robaszynski *et al.* 1990).

Remarks: the zone is characterized by monotonous, expanded sections of massive chalks dominated by planktic foraminifera and radiolarians.

Subzone definition. Orbiculoformis monticelloensis subzone (NCF11a): interval from the FDO of *O. monticelloensis* to the FDO of the planktic foraminifer *Whiteinella aprica*.

Whiteinella aprica subzone (NCF11b): interval from the FDO of the nominate species to the FDO of the planktic foraminifer *Dicarinella(?) oraviensis*.

Dicarinella(?) oraviensis *zone (NCF12)*

Age: late Turonian.

Definition: interval from the FDO of the planktic foraminifer *D.(?) oraviensis* to the FDO of the planktic foraminifer *Praeglobotruncana aumalensis*.

Remarks: a regional Turonian–Coniacian unconformity is present in the Valhall Megaclosure. Therefore, calibration of the boundary between zones NCF11 and NCF12 is provisional and will be refined with study of additional sections. The specific composition of zone NCF12 is similar to that of zone NCF11, although there is a general increase in the abundance of keeled planktic foraminifera indicating deeper water deposition and/or warmer water masses.

Praeglobotruncana aumalensis *zone (NCF13)*

Age: late middle Turonian.

Definition: interval from the FDO of the planktic foraminifer *P. aumalensis* to the FDO of the planktic foraminifer *Globigerinelloides caseyi*.

Remarks: this zone is characterized by an influx of *Praeglobotruncana* species, also including *P. kalaati* and *P. hilalensis*. Many of the constituent planktic foraminifera have Tethyan affinities and this zone marks the first major Tethyan influx down-section in the chalk succession below the upper Maastrichtian.

Subzone definitions. Praeglobotruncana kalaati subzone (NCF13a): interval from the FDO of *P. aumalensis* to the FDO of the deep-water benthic foraminifera *Lingulogavelinella globosa*. The LDO the planktic foraminifer *Marginotruncana coronata* is near the base of the subzone.

Lingulogavelinella globosa subzone (NCF13b): interval from the FDO of *L. globosa* to the FDO of *Globigerinelloides caseyi*. Rare and sporadic occurrences of the planktic foraminifer *Helvetoglobotruncana helvetica* also occur within this zone.

Praeglobotruncana stephani *zone (NCF14)*

Age: early middle Turonian–latest Cenomanian.

Definition: interval from the FDO of the planktic foraminifer *Globigerinelloides caseyi* to the FDO of the planktic foraminifer *Globigerinelloides bentonensis*.

Remarks: Planktic diversity remains high within this zone, which is also often marked by an increase in radiolarian abundance.

Subzone definition. Globigerinelloides caseyi subzone (NCF14a): interval from the FDO of the nominate species to the FDO of the planktic foraminifer *Praeglobotruncana stephani*.

Praeglobotruncana stephani subzone (NCF14b): interval from the FDO of the nominate species to the FDO of *G. bentonensis*. *P. stephani* is common throughout the lower portion of this subzone.

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