DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/81

Palaeontology, stable isotopes and sedimentology of the Upper Maastrichtian, Danish Central Graben: a record of palaeoclimatic and palaeoceanographic change

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MINISTRY OF THE ENVIRONMENT

G E U S

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Abstract

Palaeoecological data, from semi-quantitative analysis of foraminiferid, coccolith and dinoflagellate faunas and floras integrated with isotopic, palynofacies and sedimentological data, has led to a model for the palaeoceanographic evolution of the Danish Central Graben in the Late Maastrichtian involving two contrasting oceanographic systems: **A**. The lower half of the cored section records a cool-water, stable deep shelf system that was prone to stratification. Short-term cyclic shifts in mean wind stress controlled the degree of watermass stratification and hence bottom water oxygenation. **B**. Breakdown of this stable system was probably precipitated by a long-term gradual fall in sea level, perhaps reflecting a depth-related threshold, beyond which stratification was no longer favoured. The upper half of the cored section thus records an increasingly dynamic and varied mid to deep shelf setting with a complex blend of palaeoecological signals – marked sea-level change, increasingly influential pulses of watermass warming and evidence of low but variable productivity. Following turnover of the stable system, the combined datasets record a progressive shallowing to a peak lowstand located just above the base of the *P. grallator* dinoflagellate and UC20d nannofossil subzone boundaries.

The palaeoceanographic evolution of the Late Maastrichtian, as outlined in this paper, contributes to an understanding of porosity distribution in these reservoir chalks. Although porosity variation in the lower half of the cored section can be explained purely on the basis of differential preservation of depositional fabric (i.e. lamination, degree of bioturbation) in metre-scale cycles (and cycle bundles), this model becomes less convincing in the less clearly cyclic upper levels of the Upper Maastrichtian chalks. In particular, the porosity development of the most important reservoir unit in this region of the Danish Central Graben (the M1b1 reservoir unit of the Dan Field) contrasts with cyclic porosity maxima in the lower levels of the reservoir. This important high porosity layer correlates precisely with the significant lowstand event, demonstrated here by the combined palaeoenvironmental dataset. The suggestion is, therefore, that porosity development at this level is a function of primary depositional texture (biogenic composition, grain size distribution) related to a short-lived and atypical depositional setting rather than to fabric variation imparted on the sediment due to depositional process or subsequent bioturbation.

Introduction

The Upper Cretaceous chalk of the North Sea is a unique and yet intractable deposit. Despite intensive research by academia and industry, driven in particular by the large hydrocarbon reserves in the Central Graben, the fine-grained nature of the sediment and the near ubiquitous bioturbation frustrates attempts at detailed process sedimentology and refined environmental interpretation. Volumetrically insignificant chalk facies – those deposited by sediment gravity flow processes such as slides, slumps, debris flows, concentrated turbidity currents – are the exception. These facies present understandable targets for sedimentologists and have also proven popular with industry as they may display enhanced porosities (Watts *et al.* 1980; Surlyk *et al.* 2003). It might be argued that the uniformity of the lithology may reflect process and environmental uniformity – an ooze primarily of pelagic origin, deposited largely by suspension settling in a low-energy, oxygenated deep shelf setting and locally redeposited by gravity flow processes. Yet tantalising glimpses of primary depositional fabric, for example in the southern Danish Central Graben (Toft *et al.* 1996; Scholle *et al.* 1998; Damholt 2003; Damholt & Surlyk, in press), and large-scale physically constructed morphological features on seismic data (e.g. Lykke-Andersen & Surlyk 2004) suggest that the thick accumulations of "bioturbated pelagic chalk" may have a more varied and complex origin. Gross lithological facies classification of predominately bioturbated chalks provides scanty basis for detailed palaeoenvironmental interpretatation, however, particularly in the distal reaches of the chalk basin.

In attempting to refine our understanding of the palaeoenvironmental and palaeoceanographic origins of the Upper Maastrichtian chalks in the Danish Central Graben, attention was particularly focussed on the nature of the palaeobiological systems responsible for the production of the chalk. This necessitated a high-resolution biostratigraphic and palaeoecological study of the target interval, centred particularly on nannofossil, microfossil and palynological data, integrated with detailed sedimentology, ichnology and stable isotope geochemistry. The detailed results of these disciplines are presented in accompanying reports; the aim of this paper is to present an overview of the research results focussing on the palaeoceanographic evolution of the Upper Maastrichtian in the Danish Central Graben and the potential implications of this model for an understanding of facies distribution and thus porosity variation in these reservoir chalks.

Geological setting

The Maastrichtian of the Danish Central Graben forms part of the Upper Cretaceous – Danian Chalk Group, a chalk succession up to a kilometre thick in the Central Graben that records the existence of an extensive epeiric sea that covered much of northern Europe (Fig. 1; Surlyk *et al.* 2003). This chalk sea existed for more than 35 Ma, from the Cenomanian to the Danian, at a time when global sea-level was at its highest during the Phanerozoic and relative tectonic stability prevailed in the region. Much of the NW European craton was flooded to depths in excess of 50 m. Hinterland relief was low and potential source areas were restricted in extent so siliciclastic supply was limited and a pelagic carbonate drape accumulated, extending from a palaeolatitude of 35°N northwards to 50°N where the carbonates passed into siliciclastic muds (Fig. 1). The biogenic components largely belonged to the heterozoan association that today characterises cool-water, temperate carbonate systems; typical Cretaceous tropical organisms such as reef corals, large foraminifers and rudist bivalves are absent or rare in the chalk of NW Europe. However, direct latitudinal comparison with present-day seas are invalid since the Cretaceous was one of the 'greenhouse' phases of Earth history when equable temperatures extended further poleward than in our present 'icehouse' situation. The chalk sea is thus probably best characterised as ranging from warm temperate to sub-tropical, despite its mid-latitude setting. The overwhelming dominance of coccolithophorid skeletal material suggests that overall the chalk sea was a low nutrient (oligotrophic) setting. Today, shelf seas are separated from the open ocean by shelf break fronts that isolate inshore waters from the open ocean. During maximum sea-level highstand in the Late Cretaceous, the high water depths over the shelf break precluded the development of an effective shelf front and oceanic conditions extended far onto continental shelves and into epeiric seas.

Sea-floor relief in the NW European chalk sea was subdued and the carbonate system is best considered overall as a gently shelving ramp (Surlyk 1997). However, significant depositional relief was developed along structures inherited from Jurassic rift events or related to localised Cretaceous inversion or salt movements. The North Sea Central Graben, for example, was a N–S-trending trough with a complex morphology formed both by the marginal slopes and by intra-basinal ridges and domes along inversion axes and atop salt structures, respectively (Andersen 1995). Such relief led to sediment instability and instigated sediment slumps and gravity flows, resulting in redeposition of the coccolith ooze in deeper depocentres (Watts *et al.* 1980). The depositional relief may also have inhibited bottom water circulation and promoted the periodic development of anoxia/dysoxia in the deeper parts of the Central Graben (Damholt & Surlyk, in press). Facies distribution within the Central Graben demonstates a general decrease in large-scale redeposition towards the south (Andersen 1995; Surlyk *et al.* 2003), reflecting a reduction in intra-basinal relief. This trend is also evident within the confines of the Danish sector, and evidence of major mass flow processes is rare in the study area of the Dan and Tyra SE Fields (Fig. 2). The water depths in the southern Danish Central Graben during the Late Maastrichtian are poorly known; general estimates for the chalk, based on an inferred sea-floor beneath the photic zone, are a minimum of 150–200 m (see discussion in Damholt & Surlyk, in press); microfaunal data

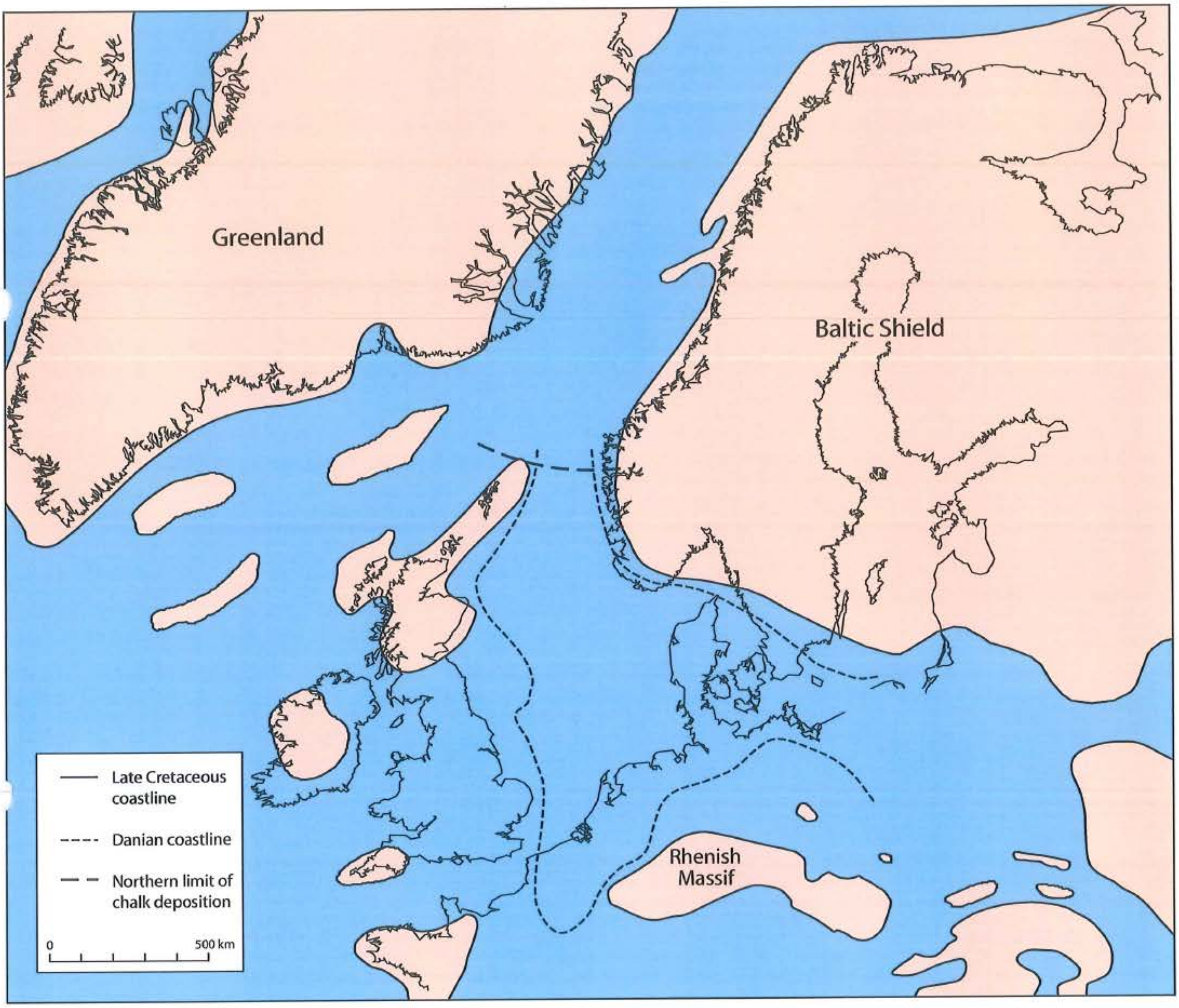


Fig. 1. Late Cretaceous – Danian palaeogeography of the North European – North Atlantic region showing the land:sea distribution and the northward limit of the chalk facies in the North Sea region (at a palaeolatitude of *c.* 50°N).

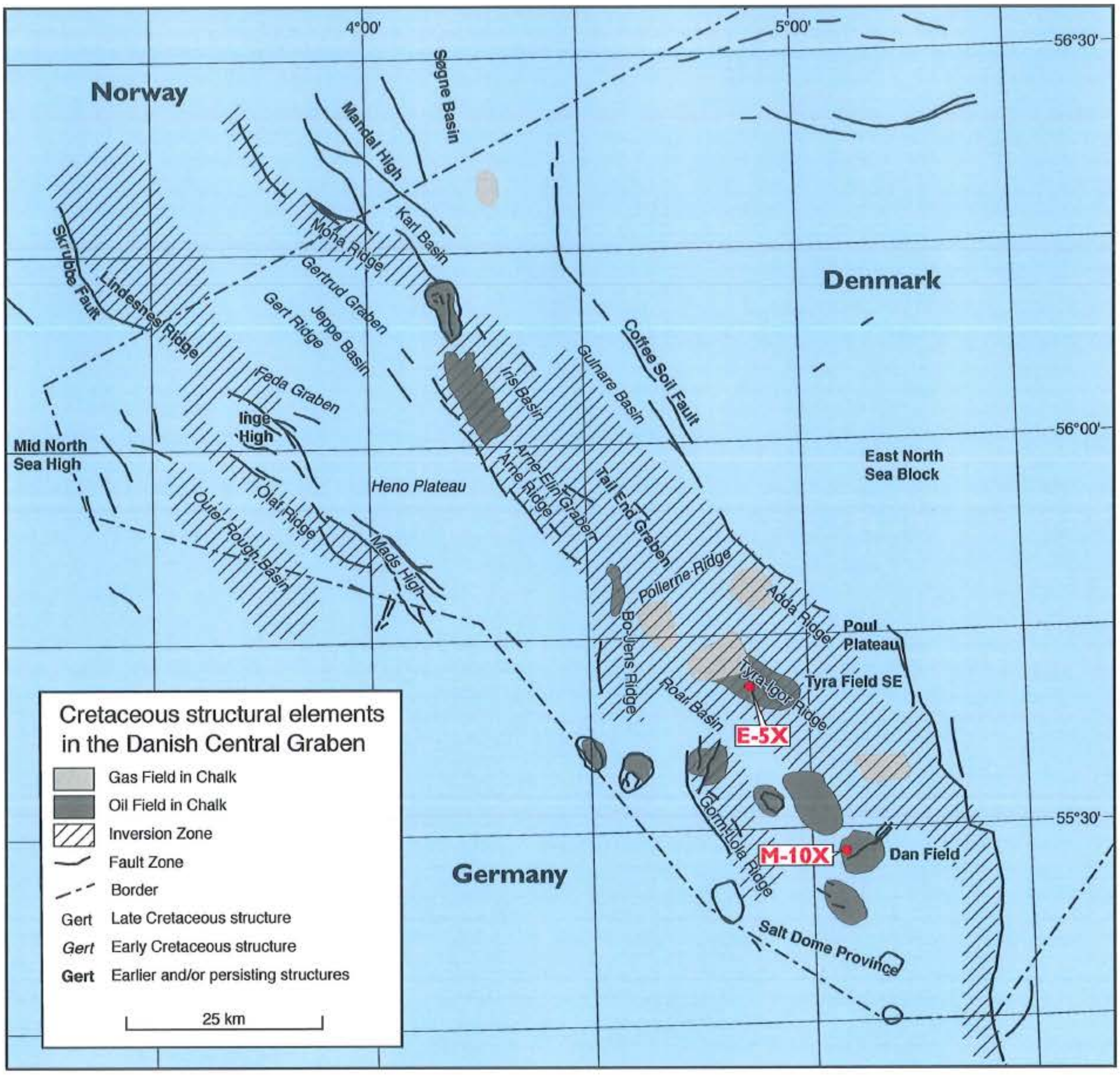


Fig. 2. Late Cretaceous structural framework of the Danish Central Graben showing the position of the M-10X and E-5X wells within the Dan and Tyra SE Fields, respectively.

indicate predominantly "outer shelf" depths (see Rasmussen & Lassen 2004, this study) and depths in the order of several hundreds of metres are likely during deposition of much of the study interval.

The two key wells under consideration here are the M-10X well on the western flank of the Dan Field and the E-5X well of the Tyra SE Field (Fig. 2). The Dan Field is a roughly circular field reflecting its origin above a salt dome; although much of the structural development of the field postdated chalk sedimentation, weak syndepositional relief during sedimentation is indicated by reservoir thickness distributions (Scholle *et al.* 1998). The Tyra Field, in contrast, forms part of a major NNW–SSE Late Cretaceous inversion ridge (Tyra–Igor ridge; Fig. 2) and this contrast in structural setting is relevant to explanations of a number of differences in sedimentary evolution between the two wells.

Stratigraphy

The cored sections studied within the project span the upper Tor Formation (Upper Maastrichtian, part of the Chalk 5 unit of Lieberkind *et al.* 1982) and the lowermost levels of the Danian Ekofisk Formation (Chalk 6 unit of Lieberkind *et al.* 1982). As shown in Fig. 3, the M-10X cored section extends stratigraphically deeper into the Tor Formation than the E-5X cored section. The former extends from the nannofossil UC19 Zone through the UC20a–d subzones of the Late Maastrichtian; the equivalent dinoflagellate and planktonic foraminifer zones are indicated on Fig. 3 and the integrated dataset indicates a continuous record through the late Late Maastrichtian (see Ineson *et al.* 2004a, this study). The "Maastrichtian hardground" at top Tor Formation is succeeded by middle Danian (NNTp2E nannofossil subzone) strata indicating a significant hiatus at the Cretaceous/Danian boundary (see Lassen & Rasmussen 2004, this study; Schiøler 2004, this study; Sheldon 2004a, this study). The cored Maastrichtian section in M-10X is 219 ft (66.25 m) thick; the lowermost 6 ft of the Danian section was logged and sampled in this project.

As noted above, the E-5X cored section does not extend stratigraphically as low as that in M-10X – the base of the section lies within the UC20b nannofossil subzone (Pde dinoflagellate Zone; Fig.3). The cored Upper Maastrichtian section also appears stratigraphically complete, within the attainable biostratigraphic resolution. Indeed, the thicknesses of the biozones are broadly comparable between the two wells, suggesting similar sedimentation rates although an exception is noted in the upper levels where the uppermost biozones (UC20d, Pgr, FCS 23b) are significantly thinner in the E-5X well; furthermore, dinoflagellate quantitative data indicate that this section may be incomplete, although poor core coverage in the lower half of the Pgr dinoflagellate Zone precludes confirmation. A hiatus comparable to that in M-10X is demonstrable at the Maastrichtian/Danian boundary in E-5X – UC20d nannofossil subzone succeeded by middle Danian, NNTp2E nannofossil subzone. The cored Upper Maastrichtian section in E-5X is 156 ft thick (47.53 m); the lowermost 19 ft of the Danian section was logged and sampled in this project.

In general, the two sections are stratigraphically comparable and the sedimentological, palynofacies, palaeoecological and isotopic observations can be confidently compared, given the consistent and well-resolved nature of the stratigraphic framework.

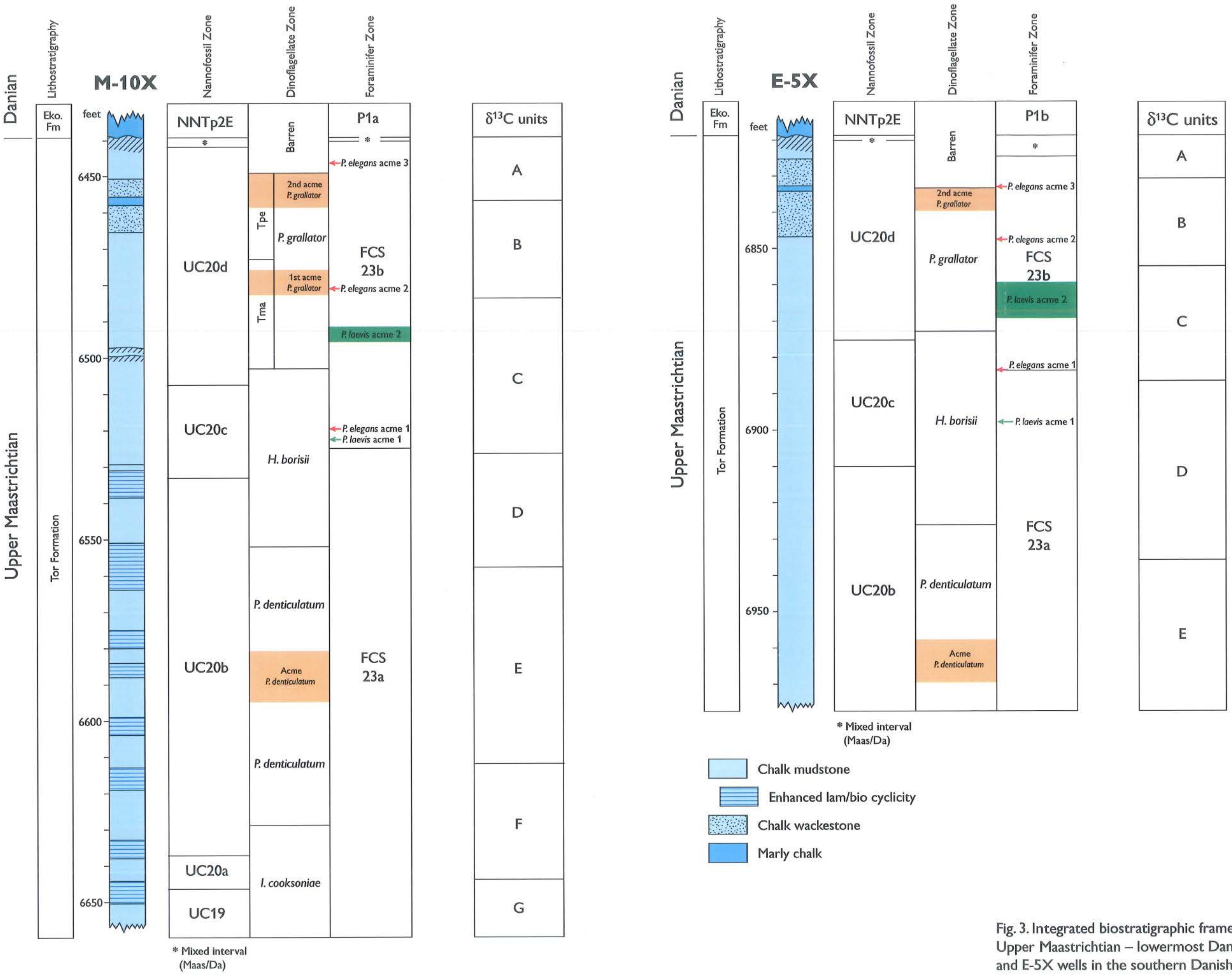


Fig. 3. Integrated biostratigraphic framework for the Upper Maastrichtian – lowermost Danian of the M-10X and E-5X wells in the southern Danish Central Graben.

Materials and methods

The two key wells, M-10X and E-5X (Figs 2, 3) were selected on the basis of their continuous core coverage of the target stratigraphic interval (albeit locally degraded due to excessive sampling) and their stratigraphic completeness through this interval according to previous published and industrial reports (e.g. Kristensen *et al.* 1995.). Of equal importance, these two wells are treated as the "type sections" of their respective fields, commonly appearing in correlation lines and summary diagrams in published papers and in-house reports. Thus, prior studies of biostratigraphy (Kristensen *et al.* 1995), cyclostratigraphy (Toft *et al.* 1996; Petersen *et al.* 2003) and sedimentology (Damholt 2003; Damholt & Surlyk, in press) could be utilised and directly tested.

The cored sections were logged sedimentologically at a scale of 1:5 (see Ineson 2004, this study, Appendices 1, 2) with particular focus on depositional and ichnological fabrics. Sampling was undertaken at *c.* 3 ft intervals to give a homogeneous data spread; more focussed "geological" sampling strategies were employed where appropriate e.g. across the top Maastrichtian hardground and within a cyclic interval selected for detailed study of controls on small-scale cyclicity (see Ineson *et al.* 2004b, this study).

The samples were processed and analysed according to their respective disciplines – for details, see Schovsbo & Buchardt (2004, this study) concerning stable isotopes, Sheldon (2004a, b, this study) regarding nannofossils, Schiøler (2004, this study) concerning palynology and Lassen & Rasmussen (2004, this study; Rasmussen & Lassen 2004, this study) with reference to micropalaeontology. A short summary of the interpretive procedure/criteria is included below as background for the evolutionary account that follows.

Sedimentology

On the basis of the detailed core logs, eight lithofacies and five ichnofabrics were recognised. Analysis of the distribution of these parameters permits the identification of evolutionary depositional trends and geographical variation in certain environmental factors.

Palynology

Palynological study of the two cored sections involved both palynofacies analysis (i.e. a study of changes in the kerogen assemblages) and palaeoecological analysis of the dinoflagellate cysts. The former provides a measure of lateral movements of the coastline i.e. a measure of relative sea-level variation, whereas study of the composition of the dinoflagellate population (diversity, species distribution) provides a measure of "oceanality" (i.e. linked to relative sea level) and productivity. Details of the basis and methodology for such interpretations are given by Schiøler (2004, this study).

Stable isotopes

As discussed by Schovsbo & Buchardt (2004, this study), the $\delta^{18}O$ isotopic composition of the chalk succession is overwhelmingly dominated by diagenetic calcite precipitation, and although widely used as a seawater temperature proxy, such an application was deemed inappropriate here. The $\delta^{13}C$ isotopic composition is regarded as essentially a primary signal, however, and to a large extent can be interpreted in terms of long-term secular change in seawater chemistry. Although alternative interpretations are evident in the literature, long-term $\delta^{13}C$ curves are commonly regarded as reflecting sea-level change, positive excursions recording transgressive events and negative excursions being related to regression. Thorough discussion of the use and interpretative limitations of stable isotope data is given here in Schovsbo & Buchardt (2004, this study).

Nannofossil palaeoecology

Palaeoecological interpretation of nannofossils is dependent on the inferred environmental preferences of certain key taxa, in addition to overall parameters, such as species richness. As noted by Sheldon (2004b, this study), few Cretaceous species are extant, so that the inferred environmental preferences or tolerances of the fossil flora is largely dependent on published data on the latitudinal and environmental ranges of different taxa (e.g. Lees 2002). As such, the precise environmental parameters controlling the distribution of a particular species can be difficult to isolate. A species showing a preference for an inner shelf, shallow water setting, for example, may be controlled by salinity, temperature or nutrient levels, or may be more tolerant to a variable, fluctuating environment with respect to all these factors; water depth *per se* may be the least important factor to such a pelagic organism confined to the photic zone. Interpretation of the fossil record is thus open to discussion; the interpretations given here are based on common environmental associations of specific taxa to be found in the literature (see Sheldon 2004b, this study).

Microfossil palaeoecology

This study area focusses particularly on foraminifers of both benthic and planktic origin, and the particular environmental signals associated with this fauna, both generally (i.e. planktic/benthic (P/B) ratio, epifaunal/infaunal ratio) and specifically with respect to individual species with known/inferred preferences or tolerances. Discussion of the advantages and limitations of the different palaeoecological approaches utilised in such studies is given by Rasmussen & Lassen (2004, this study). It should be noted that the P/B ratio is routinely used in palaeo-water depth interpretations yet as indicated by Rasmussen & Lassen (2004, this study), modern clastic ocean-facing continental shelves may not be wholly appropriate analogues for the Late Cretaceous epeiric chalk sea in NW Europe so direct depth comparisons should be treated with caution.

Integrated palaeoceanographic framework

The central North Sea in the Late Maastrichtian was, prior to the end-Cretaceous pyrotechnics, a particularly peaceful depositional setting. A weak long-term downward trend in both global sea level and temperature created little major disturbance to the pelagic carbonate factory that produced a thick blanket of pure coccolith ooze. Tectonic inversion and major salt diapirs created highs flanked by remobilised ooze, but such features became more subdued towards the south in the Danish Central Graben and only locally in this area was resedimentation by large-scale gravity flow processes an important part of the depositional system. The role of long-term bottom current systems in constructing the architecture of these chalk oozes in the Danish Central Graben, as described recently from the Upper Cretaceous of the Danish Basin (Lykke-Andersen & Surlyk 2004) is presently unknown.

The palaeoecological and palaeoenvironmental results of this study, overall, conform to this picture, testifying to a particularly stable, low nutrient (oligotrophic) setting in mainly cool-water conditions. Water depths were probably in the order of several hundred metres for much of the time and sedimentation rates were low, probably in the range of 3–5 cm per 1000 years (Damholt 2003; Sheldon 2004a, this volume).

Palaeoecological analysis and interpretation of such a stable deep shelf system dominated by pelagic carbonate production is clearly a challenge, and certain analytical disciplines may be approaching the limit of their resolution. Despite the overall stability of the depositional system and the necessity to focus, sometimes perhaps too closely, on minor variations in the datasets, this study has revealed certain significant evolutionary trends in the Upper Maastrichtian chalk succession. These trends provide some control on the changing palaeoceanography of the chalk sea in this period and furthermore display an apparent link to the nature of porosity variation in the Upper Maastrichtian chalk hydrocarbon reservoirs.

In the following integrated interpretation of the Upper Maastrichtian chalks of the southern Danish Central Graben, the generalised interpretations are reliant on the separate contributions presented here (Ineson 2004, this study; Lassen & Rasmussen 2004, this study; Rasmussen & Lassen 2004, this study; Schovsbo & Buchardt 2004, this study; Schiøler 2004, this study; Sheldon 2004a, b, this study); incessant citation of these reports will not be undertaken in the following overview. For the purposes of this paper, the succession under study is described on the basis of two major evolutionary stages (A, B), each being subdivided into evolutionary units (A1, A2 etc.; Figs 4–6), This bipartite subdivision is based on an overall "oceanographic" conceptual model that attempts to include all parameters in the marine system (sea level, temperature, watermass stability, trophic level etc.); focus on an individual parameter, such as sea level, would clearly give a different major subdivision of the succession although the smaller building blocks would be the same (see Fig. 6). Subdivision into these major evolutionary stages and their component units is based on the full integrated dataset (only selected data are shown on Figs 5, 6) and the boundaries are thus defined on the basis of different criteria, wholly dependent on the local resolution and distinctiveness of the independent data.

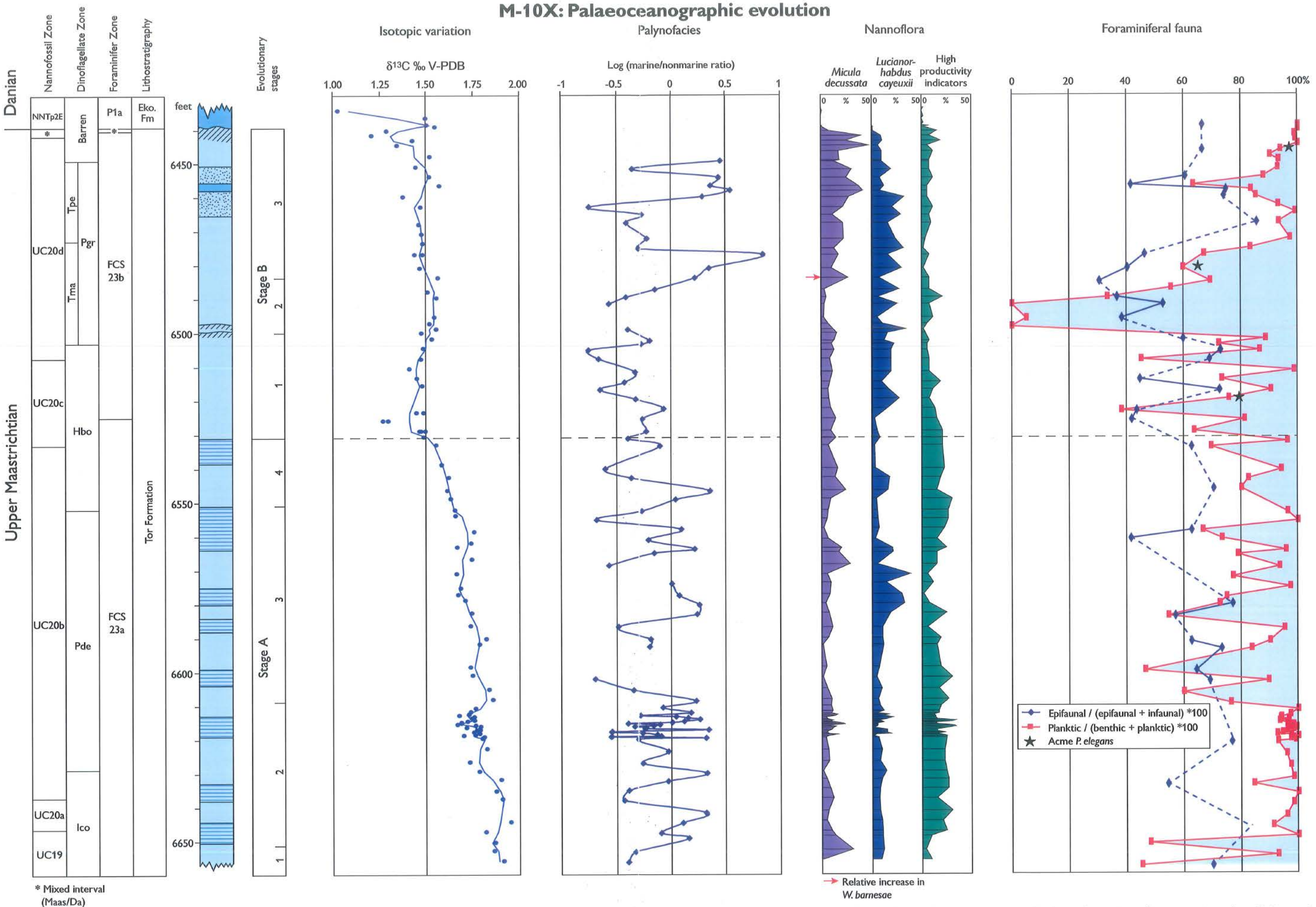
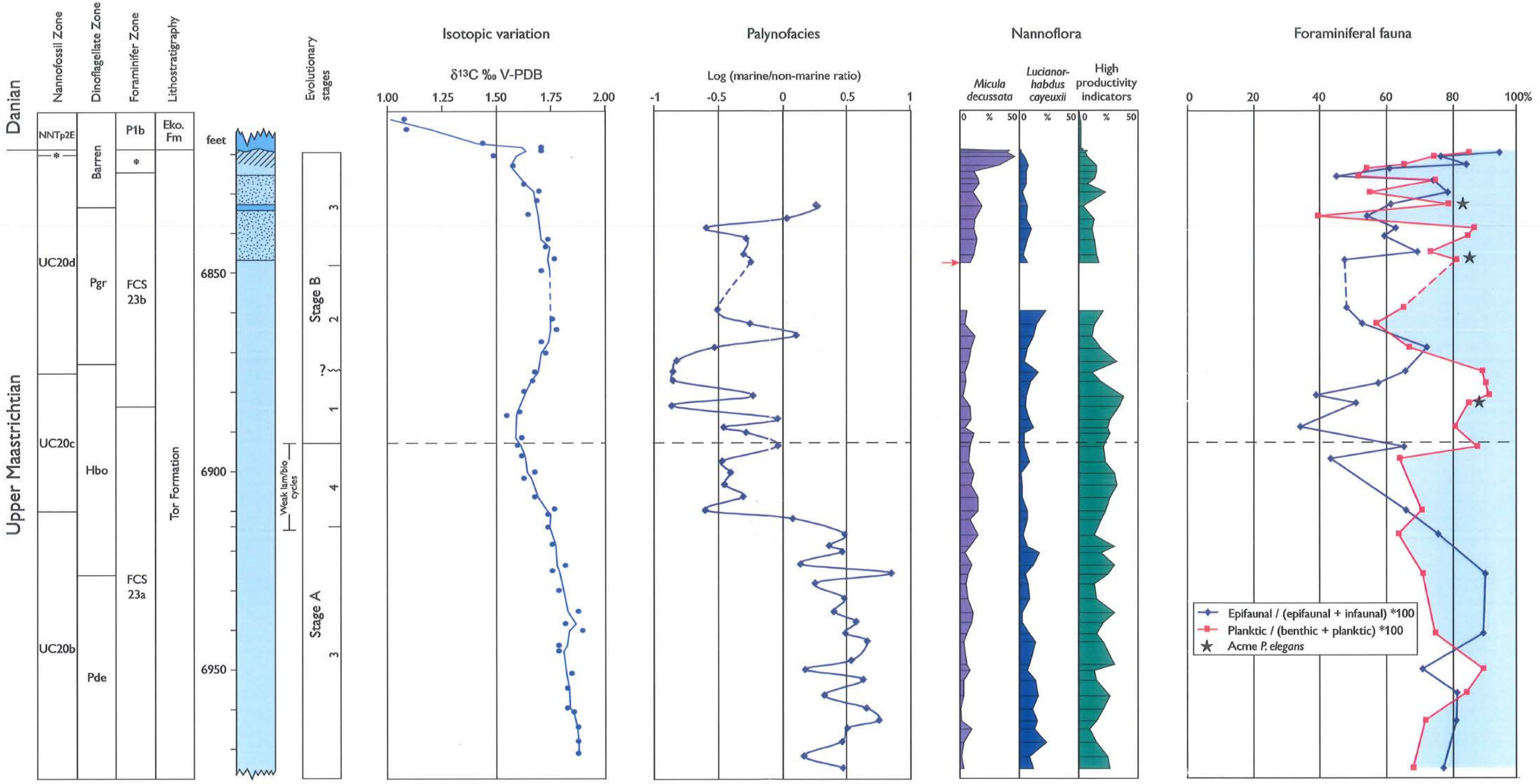


Fig. 4. Palaeoceanographic evolution of the Upper Maastrichtian of the M-10X well based on integration of selected stratigraphic, isotopic, palynofacies and palaeoecological data; full datasets are given in Ineson (2004, this study), Rasmussen & Lassen (2004, this study), Schiøler (2004, this study), Schovsbo & Buchardt (2004, this study) and Sheldon (2004, this study). The evolutionary stages are described in the text.


E-5X: Palaeoceanographic evolution

* Mixed interval (Maas/Da)

→ Relative increase in *W. barnesae*

Fig. 5. Palaeoceanographic evolution of the Upper Maastrichtian of the E-5X well based on the integration of selected stratigraphic, isotopic, palynofacies and palaeoecological data; full datasets are given in Ineson (2004, this study), Rasmussen & Lassen (2004, this study), Schiøler (2004, this study), Schovsbo & Buchardt (2004, this study) and Sheldon (2004, this study). The evolutionary stages are described in the text.

Stage A

This evolutionary stage broadly forms the lower half of the cored sections in both the M-10X and E-5X wells, corresponding to the Upper Mastrichtian Ico – mid Hbo dinoflagellate Zones, the upper UC19 – intra UC20c nannofossil Zones and the FCS 23a microfossil Zone (Figs 5, 6). It was characterised by a particularly stable, cool-water, oligotrophic system that was prone to watermass stratification. Relative to the subsequent evolutionary stage (Stage B), relative sea level was high, though showing a weak, overall downward trend and productivity, relative to Stage B, was high though fluctuating. It should be emphasised here that description of water depth, productivity, temperature etc. is largely relative, in comparison with Stage B. Absolute values, for example of productivity, were only obtained in the palynological study and as noted by Schiøler (2004, this study) these data describe a low productivity system in absolute terms (for the dinoflagellate group, at least) when compared with modern marine systems.

The defining sedimentological feature of Stage A is the presence of small-scale (2–4 ft) laminated–bioturbated cycles throughout this interval in the M-10X well and in the upper part of the E-5X interval, and cycles defined by ichnofabric variation in the lower part of Stage A in the E-5X section (Figs 5, 6). As discussed in Ineson *et al.* (2004, this study), this cyclicity is interpreted to reflect cyclic variations in bottom-water oxygenation (Damholt 2003; Damholt & Surlyk, in press), probably reflecting watermass stratification controlled by climatic forcing (wind stress) within the Milankovitch band. Bundling of such cycles at a 20–30 ft scale, recognisable both on sedimentological logs and petrophysical logs, correlates broadly with minor productivity peaks according to the coccolith data, and, in some cases, also to productivity peaks in the dinoflagellate data.

The inferred long-term overall fall in relative sea level through Stage A, following a peak near the base of the section, is reflected in the marine/non-marine ratio (palynofacies) and by overall trends in certain nannofossils (i.e. *M. decussata*, a species inferred to record high stands of sea level); the palaeoecological data based on foraminifers reflects a marked fluctuation in bottom conditions (as also indicated by the ichnofossil data) although overall a progressive upward decrease in P/B ratio is supportive of a gradual fall in relative sea level during Stage A. Such a trend is also compatible with the $\delta^{13}C$ curve, showing gradually decreasing values (Figs 4, 5).

Four units are described below, identifying periods in Stage A with characteristic features, superimposed on the general evolution described above.

Unit A1

This phase, recorded only in M-10X (below the stratigraphic range of the E-5X cores), is known only from a limited number of samples; it contrasts markedly with unit A2 and is thus differentiated here but its downward extent is unknown. The interval records a weak rising sea-level trend on the basis of palynofacies parameters (peaking in the succeeding unit A2) and shows a distinctive coccolith assemblage (a peak in *P. stoveri* perhaps reflecting cooler waters) and a relatively abundant and diverse benthic foraminiferal fauna (P/B of 45–50%).

Unit A2

This unit is perhaps the most distinctive, palaeoecologically, of Stage A; as for A1, it is only recorded in the stratigraphically deeper cored section in M-10X. On the basis of the palynofacies parameters, it records a broad peak in relative sea level, culminating at about 6625 ft. The unit spans two core sections that show enhanced laminated–bioturbated cycle development and the uppermost of these coincides with indications of high relative productivity, based on both palynological and nannofossil data. The unit is characterised particularly, however, by the foraminiferal data that indicate a period of especially hostile bottom conditions. The P/B ratio is very high (> 90%) and the benthic fauna is both impoverished and of low diversity. This is compatible with the sedimentological data indicating enhanced laminated–bioturbated cycle development at this time.

Unit A3

This interval, observed in both E-5X and M-10X, is particularly variable, in terms of inferred minor sea-level trends and benthic conditions. Despite the long-term falling sea-level trend, the palynofacies and nannofossil data appear to record a subordinate relative sea-level cycle. In M-10X, this inferred cycle is focussed around a minor lowstand at 6571 ft, coincident with indications of a productivity decrease, rising subsequently to a relative high in the upper levels of unit A3. This possible sea-level perturbation, based on subtle nannofossil assemblage fluctuations, is compatible with conclusions derived from the stratigraphic distribution of *Impagidinium*, a dinoflagellate genus of oceanic affinities.

The foraminiferal data of A3 contrast markedly with those from the underlying unit A2; P/B values are typically variable in M-10X but decrease locally to nearly 45%, in which samples the benthic assemblage is abundant and diverse. In comparison to unit A2, this clearly records more hospitable, well-oxygenated conditions, although the fluctuating P/B ratios suggest that conditions varied significantly in the short-term. The data testify to an overall weak deterioration in sea-floor conditions (increase in P/B values) upwards, concomitant with the inferred minor rise in relative sea level above 6575 ft. It is noteworthy that this inferred minor rise in relative sea level at roughly 6575–6565 ft correlates with a minor plateau on the generally falling $\delta^{13}C$ curve (Fig. 4).

In E-5X, the palynofacies data indicate a gradual sea-level fall (Fig. 5); indications of a peak in sea level near the base of the section (see Schiøler 2004, this study) may be largely an artefact produced by trend curves near the limits of the dataset. The nannofossil data are in conflict with this falling sea-level trend; an overall upward increase in *M. decussata* parallels an upward decrease in *L. cayeuxii*. Such a combination is suggestive of an overall weak rise in sea level (see discussion by Sheldon (2004b, this study); the reasons for this apparent contradiction are not fully understood but is is possible that the relatively high proportion of *L. cayeuxii* near the base of this section correlates with the minor sea-level lowstand inferred within unit A3 in the M-10X well. The foraminiferal data from unit A3 in E-5X show trends compatible with M-10X i.e. a moderately rich and diverse benthic fauna (P/B of 70–80%) showing relatively consistent levels. Note, however, that the spacing of the analysed samples is greater in E-5X so that it is not clear if the fluctuating benthic conditions indicated by the M-10X data were indeed experienced in the Tyra Field area, or as suggested by the sedimentology and ichnology, that bottom conditions were generally more favourable in this area at this time.

Unit A4

The uppermost part of Stage A appears to record a time of change – a transition between the stable, rhythmically stratified watermass of Stage A and the more variable, dynamic conditions recorded by the succession above (Stage B). The $\delta^{13}C$ curve dispalys a distinct increase in gradient at the base of this unit, correlative with a marked palynofacies shift, particularly in E-5X but also suggested in the lower levels of A4 in the M-10X well. These data can be interpreted to indicate an increase in the rate of relative sea-level fall, recorded also by a clear shift in the long-term trends within the nannofossil population (decreasing *M. decussata* trends in both wells). The foraminiferal data shows a fluctuating but broadly decreasing trend in P/B ratio, particularly evident in the more closely-spaced dataset in M-10X; this is compatible with the inferred relative shallowing indicated by the other datasets.

Stage B

The boundary between Stages A and B is defined in particular by an abrupt shift in depositional style, marked by the disappearance of the characteristic cyclicity of Stage A. The chalks of the uppermost unit of Stage A (A4) shows a cyclic laminated–bioturbated development in both wells; this grades upwards into predominately bioturbated chalks with rare thin laminated beds. In the M-10X well, where the laminated–bioturbated cycles are best developed, the boundary between Stages A and B is also marked by a notable increase in the diversity and density of trace fossil assemblages, testifying to a marked shift to more consistently well-oxygenated bottom waters (see Ineson 2004, this volume, fig. 9). This event, within the resolution of the integrated stratigraphic framework (Fig. 3), appears to be broadly isochronous, occuring in the mid- Hbo dinoflagellate Zone, just beneath the top of the foraminiferal FCS 23a Zone. This boundary is suggested to represent a significant oceanographic shift in the basin from a stable deep shelf setting prone to watermass stratification, to a better circulated, more uniformly oxygenated and generally shallower (mid–deep shelf) setting. As discussed below, this "turnover" of the basinal chalk environment occurred during an ongoing long-tem sea-level fall and may reflect an oceanographic threshold, given the particular characteristics of the Maastrichtian North Sea basin in terms of bathymetry, basin morphology and circulatory systems.

This boundary is marked isotopically by an important inflection in the $\delta^{13}C$ curve, the gradually falling trend of Stage A shifting to relatively constant values (much of substage B1). Accepting this curve as a proxy for relative sea level, this might suggest that the lowest point in relative sea level is reached at this stratigraphic level, but the weight of evidence indicates that the lowest sea-level stand recorded in this succession is located higher in the succession (see unit B2).

The overall characteristics of Stage B indicate a more dynamic, changeable and generally shallower environment in which the sea floor was generally moderately–well oxygenated.

Relative sea level was more variable with at least one significant lowstand of sea level. Productivity fluctuated but overall was lower than during Stage A, and the faunal/floral assemblages indicate the influence of warmer watermasses on occasion, particularly in the latest Maastrichtian.

Unit B1

In both the M-10X and E-5X wells, the data indicate a continued fall in relative sea-level during this period. In both wells, the parallel upward decrease in the proportion of *M. decussata* and increase in *L. cayeuxii* are compatible with the evidence of a continued fall in sea level from palynofacies data. The nannofossil data from M-10X suggest a gradual fall in productivity through this interval, compatible with a general productivity low between 6550 ft and 6500 ft in this well according to dinoflagellate data. This interval in E-5X records a consistent fall in sea level (palynofacies/nannofossil data) analagous to that in M-10X yet contrasts with the latter well concerning productivity indices. Both dinoflagellate and nannofossil parameters suggest upwardly increasing and relatively high productivities.

Unit B2

This unit records a significant lowstand of sea level and subsequent rise. The data are particularly illustrative in the M-10X well, where two thin incipient hardgrounds define the base of the unit and record a period of low sedimentation rates, probably associated with gentle winnowing at the sea floor (see discussion in Ineson 2004, this volume). The associated sediments at this level demonstrate a dramatic change in the microfauna, being dominated overwhelmingly by benthic taxa (P/B of 0–10%) indicating a well-oxygenated and nutrient-rich benthic environment; the reason for the near-disappearance of planktic foraminifera at this level is not clear. This inferred lowstand of relative sea level indicated by the foraminiferal and sedimentological data is supported strongly by the low marine/non-marine ratio (palynofacies) and the nannofossil assemblage (low relative abundance of *M. decussata*, continued high/fluctuating proportion of *L. cayeuxii*). Productivities were low, according to the dinoflagellate data.

In the upper levels of unit B2 in M-10X, the palynofacies, nannofossil and foraminiferal data document convincingly a relative rise in sea level; interestingly, levels of *L. cayeuxii* (regarded as a an indicator of relatively shallow conditions) remain high although fluctuate markedly. The foraminiferal P/B ratio falls progressively, mirroring the increasing palynofacies marine/non-marine ratio and the increase in *M. decussata* (inferred deeper water form).

The evolution exhibited by the E-5X well at this level is somewhat ambiguous. The palynofacies data indicate a relative sea-level low in the interval 6880–6870 ft, compatible with low relative values of the nannofossil *M. decussata*. The foraminiferal data, however, do not exhibit the unequivocal data exhibited by the M-10X well, although samples between 6873 ft and 6860 ft contain a benthic fauna indicative of shallower conditions relative to the chalks below and above. For example, this interval yields significant numbers of *P. laevis*, a benthic foraminifera of mid-shelf affinities. Given that the sedimentology and structural position suggest that E-5X lay bathymetrically higher than the M-10X well, the absence in E-5X of the benthic-dominated lowstand event seen in M-10X is not fully understood. It is possible that the base of unit B2 in E-5X is a hiatal surface, such that peak lowstand deposits are not recorded in this well. Core preservation/recovery is poor in this interval and such a hiatal surface has not been recognised. The possibility of a minor fault at this level cannot be precluded.

Thus, although the peak lowstand deposits are not recognised in E-5X, the data are in agreement with the M-10X well in that a relative sea-level low was located at the base of unit B2, followed by a rise in relative sea level. This evolution is indicated by the palaeoecological data, palynofacies and the positive trend in the $\delta^{13}C$ curve at this level. The upper levels of unit B2 were not observed in E-5X (note the data gap indicated on Fig. 5), and the position of the B2/B3 boundary is placed somewhat arbitrarily, above the core gap.

Unit B3

The base of this unit is defined by the synchronous significant influx of warm-water indicators with Tethyan affinities – the planktic foraminifera *P. elegans* and the coccolithophorid *W. barnesae*. Both species are recorded in low numbers lower in the succession (*P. elegans* has its first appearance at the base of the FCS 23b Zone; Figs 4, 5) but become significant components of the total fauna/flora at the base of B3 and occur consistently, with certain acme events, above this level.The base of unit B3 thus marks a significant water-mass warming event, the influence of which was apparently variable (see the localised acme of *P. elegans*) but continued through much of the unit.

Sea-level signals are complex through this unit. Although most data indicate resumed high sea levels, relative at least to the marked lowstand event in unit B2, subordinate fluctuations are indicated by several lines of evidence. The palynofacies data in M-10X is suggestive of a relative fall in sea level in the interval 6475–6460 ft, compatible with a broad peak in the nannofossil *L. cayeuxii*; this interpretation is not supported by the foraminiferal data, however, that suggests particularly poor bottom conditions (P/B > 80%). The increase in the proportion of fine skeletal detritus at this level, including bryozoan fragments, indicates either enhanced sediment transport or winnowing of the fine fraction (i.e. increased energy levels) or a change in the *in situ* benthic fauna; bioturbation precludes differentiation of allochthonous and autochthonous skeletal elements. In either case, shallowing would be a likely interpretation. It is notable that a discrete marly chalk bed occurs in the upper levels of this wackestone-rich interval in the uppermost Maastrichtian. This bed corresponds to an apparent deepening trend based on palynofacies data, compatible with nannofossil trends, and may record reworking and basinward dispersal of shore-derived muds during a minor transgressive pulse. This bed is marked by a distinctive foraminiferal event in the M-10X well.

Evolutionary patterns in the uppermost levels of the Maastrichtian are largely obscured due to the marked diagenetic effects of the "Maastrichtian hardground" capping the Upper Maastrichtian succession. The uppermost levels of unit 3 are barren with respect to dinoflagellates, for unknown reasons (see Schiøler 2004, this study), whilst the foraminiferal fauna suggests relatively poor benthic conditions in the uppermost levels (high P/B ratio). An observation of note, however, is the decrease in the relative abundance of *W. barnesae* (warm-water indicator) in the upper *c.* 10 ft of the M-10X Maastrichtian section and the upper *c.* 4 ft of E-5X. This is compatible with slight variations in the planktic foraminiferal fauna in E-5X (see Rasmussen & Lassen 2004, this study) and may reflect a slight end Cretaceous cooling event, as recorded recently from the Danish Basin (Hart *et al.* 2004).

Discussion and conclusions

Late Maastrichtian palaeoceanography

Palaeoecological data, from semi-quantitative analysis of foraminiferid, coccolith and dinoflagellate faunas and floras integrated with isotopic, palynofacies and sedimentological data, has led to a model for the palaeoceanographic evolution of the Danish Central Graben in the Late Maastrichtian, summarised in Fig. 6.

This model involves two contrasting oceanographic systems:

The lower half of the cored section records a cool-water, stable deep shelf system that was prone to stratification. Cyclic shifts in mean wind stress controlled the degree of watermass stratification and hence bottom water oxygenation. Minor fluctuations in planktic populations thought to be sensitive to temperature may reflect varying degrees of thermal stratification. Although a nutrient-poor, oligotrophic system showing intermediate–low levels of productivity, weak long-term oscillations in productivity are evident in the data and broad productivity peaks commonly coincide with intervals of enhanced oxic/dysoxic cycle development. Sea levels were high and stable but a consistent overall fall in sea level is indicated by several datasets.

Breakdown of this stable system was probably precipitated by the long-term gradual fall in sea level, perhaps reflecting a depth-related threshold, beyond which stratification was no longer favoured. The upper half of the cored section thus records an increasingly dynamic and varied mid to deep shelf setting with a complex blend of palaeoecological signals – marked sea-level change, increasingly influential pulses of watermass warming and evidence of low but variable productivity. Following turnover of the stable system, the combined datasets record a progressive shallowing to a peak lowstand located just above the base of the *P. grallator* dinoflagellate and UC20d nannofossil subzone boundaries, corresponding to *c.* 65.5 Ma. Although recognised in both wells, the lowstand is particularly well-defined in the M-10X well, both palaeoecologically and sedimentologically. Although such low sea levels are not indicated again in the latest Maastrichtian, minor fluctuations in sea level are recorded. Invasions of warm-water plankton with Tethyan affinities are first indicated soon after the breakdown of the stratified system. The first indications are weak but intensify in the uppermost Maastrichtian and may signal the widely reported latest Maastrichtian warming event (65.4–65.2 Ma). Nannofossil data from the uppermost few feet of the succession, just below the top-Maastrichtian hardground, are suggestive of an end-Cretaceous cooling, also recently inferred by other workers from onshore Denmark.

Sequence stratigraphy and correlation

Although the Late Maastrichtian evolution of the Danish Central Graben has been described in this paper in terms of the oceanographic system as a whole, a sequence strati-

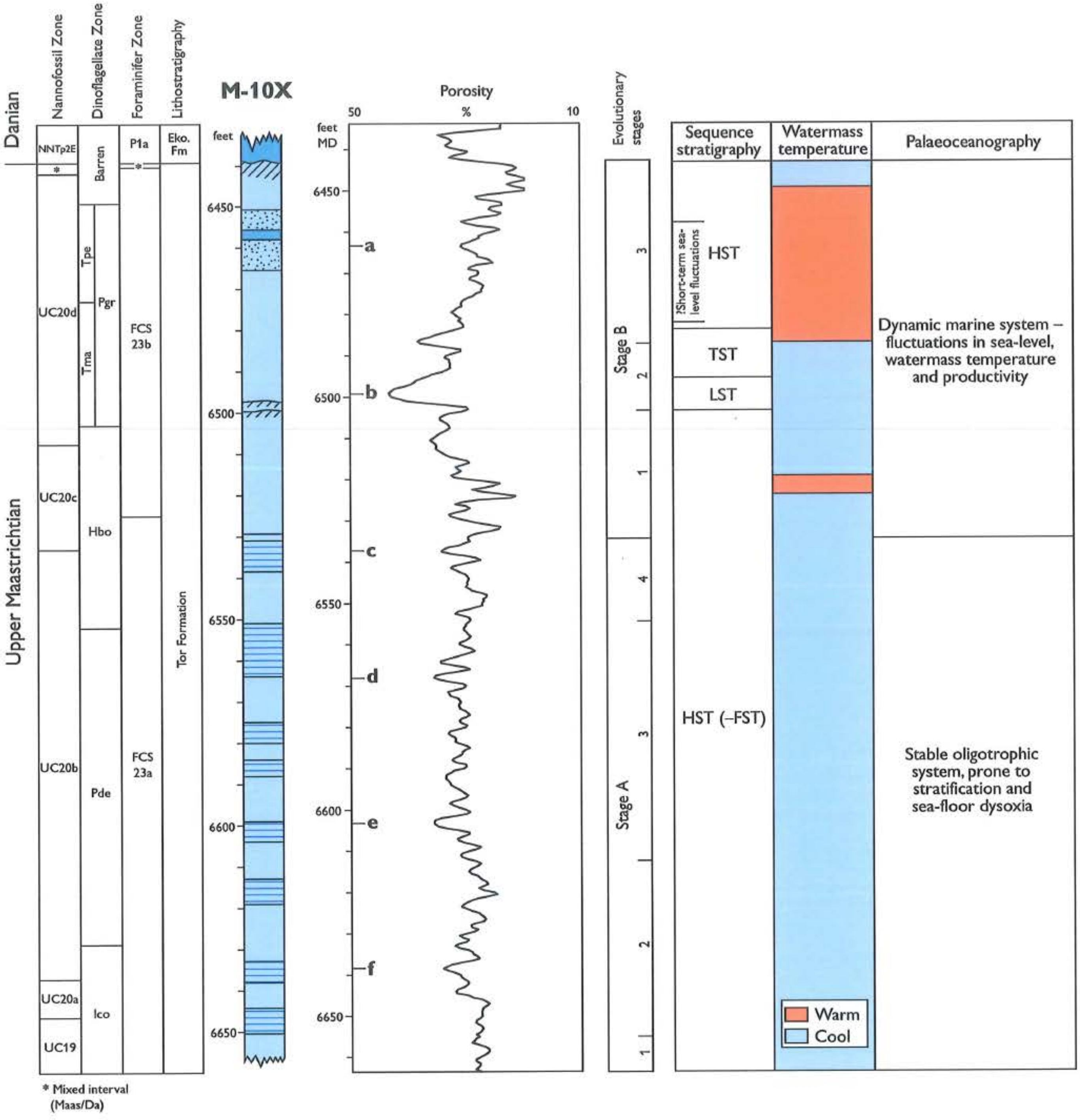


Fig. 6. Schematic figure based on the M-10X section showing the main Late Maastrichtian evolutionary events in the Danish Central Graben with respect to relative sea level (i.e. a sequence stratigraphic subdivision), watermass temperature and overall palaeoceanographic character of the basin. The biostratigraphic framework and porosity distribution log are indicated for reference. LST, lowstand systems tract; TST, transgressive systems tract; HST, highstand systems tract; FST, falling stage systems tract.

graphic approach focussing particularly on the sea-level history of the basin is a viable alternative mode of analysis. Given such an approach, the most significant genetic boundary in the study interval is the base of the marked lowstand unit (base of B2), marked by incipient hardground development in the M-10X section. This surface can be regarded as a candidate sequence boundary, and given the palaeogeographic position of the Central Graben, would be expected to be a "correlative" conformity" in sequence stratigraphic parlance; it occurs near the base of the *P. grallator* dinoflagellate Zone (Fig. 6). Schiøler (2004, this study) discussed the correlation of this surface to the type Maastrichtian stage in The Netherlands where a sequence boundary is recognised at the same stratigraphic level.

Porosity development and palaeoenvironment

Regional porosity variation in Upper Cretaceous – Danian reservoir chalks of the central North Sea is attributed primarily to overpressure and timing of hydrocarbon invasion. On a local, intra-field scale, however, porosity variation is typically related to preservation of early depositional fabrics in the chalk ooze, since comprehensive biogenic reworking is considered to result in progressive dewatering and re-structuring of the sediment with consequent loss of porosity. Thus, thick redeposited chalk units and facies retaining primary lamination often show enhanced porosities, relative to associated bioturbated "pelagic" chalks, and thus are important exploration and production targets.

Comparison of the results of the palaeoceanographic study of the Upper Maastrichtian chalks of the southern Danish Central Graben with the porosity distribution in this stratigraphic interval suggests that the depositional fabric concept, although clearly important, may not be the whole answer. Although porosity variation in the lower half of the cored section can be explained purely on the basis of differential preservation of depositional fabric (i.e. lamination, degree of bioturbation) in metre-scale cycles (and cycle bundles), this model becomes less convincing in the less clearly cyclic upper levels of the Upper Maastrichtian chalks. In particular, the porosity development of the most important reservoir unit in this region of the Danish Central Graben (the M1b1 reservoir unit of the Dan Field) contrasts with cyclic porosity maxima in the lower levels of the reservoir. This important high porosity layer correlates precisely with the significant lowstand event, demonstrated here by the combined palaeoenvironmental dataset from the M-10X and E-5X wells. The suggestion is, therefore, that porosity development at this level is a function of primary depositional texture (biogenic composition, grain size distribution), related to a short-lived and atypical depositional setting, rather than to fabric variation imparted on the sediment due to depositional process or subsequent bioturbation. This project has been concerned primarily with stratigraphic and palaeoenvironmental aspects and has not involved detailed microfacies or diagenetic studies. Thus, although a striking correlation can be documented, the sedimentary explanation (in terms of microfacies) clearly forms an important topic for future focussed research.

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