On the origin of laminated-bioturbated chalk cycles in the Upper Maastrichtian, Danish Central Graben

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Jon R. Ineson, Bjørn Buchardt, Susanne Lassen, Jan A. Rasmussen, Niels H. Schovsbo, Poul Schiøler, Emma Sheldon & Finn Surlyk

Contents

Abstract

Metre-scale laminated–bioturbated chalk cycles form a characteristic motif in the lower levels of the Upper Maastrichtian chalks in the Dan Field area, southern Danish Central Graben. They have most recently been interpreted in the literature to reflect cycles of relative oxygenation on the sea floor, the laminated half-cycles recording poorly oxygenated conditions. Sedimentological, isotopic, palynofacies and palaeoecological (nannofossils, dinoflagellates, foraminifers) analysis was undertaken of a close suite of samples across a composite cyclic interval to investigate the validity of this interpretation and the possible factors controlling periodic variation in bottom-water ventilation. The data from benthic organisms clearly demonstrate a hostile sea-floor environment and outline a cyclicity in bottom water conditions that parallels, yet is lightly out of phase with, the laminated–bioturbated cycles. Interestingly, the planktonic foraminiferal data suggest that during periods with the most hostile bottom water conditions, the upper water masses were relatively stable whereas slight amelioration at the sea floor coincided with stressed, changeable conditions in the surface waters. Data from palynofacies and dinoflagellate analysis indicate a low productivity, oligotrophic setting and no evidence of relative sea-level variation in phase with the cycles is observed. Similarly, the calcareous plankton show no indications of major productivity peaks related to the onset of lamination in the sediment; conversely, minor peaks in productivity indicators in the nannofossil dataset correlate with the transition from laminated to bioturbated chalk i.e. are the result, rather than the cause of oxygen deprivation at the sea floor. On the basis of these data, it is proposed that these short-term cycles were probably controlled by cyclic variations in mean wind stress resulting in the alternation of a weakly stratified shelf sea, in which local dysoxia developed in bathymetric lows, with a non-stratified, well-ventilated deep shelf.

Introduction

Upper Cretaceous chalks in NW Europe commonly display a marked rhythmicity, either created lithologically, by regular alternations of chalk and marlstone or flint, or texturally, by regular shifts in the intensity of bioturbation or alternating laminated and bioturbated chalks. Such small-scale cyclicity, particularly in the marly facies of the Cenomanian, have been the subject of considerable detailed research (e.g. Gale 1995). Metre-scale cycles are commonly attributed to climatic forcing in the Milankovitch frequency band and have been correlated for several thousands of kilometres across Europe (Gale 1989, 1995).

Upper Cretaceous–Danian chalks form important hydrocarbon reservoirs in the North Sea petroleum province, particularly in the Danish and southern Norwegian sectors. The importance of cyclicity for reservoir parameters has recently been emphasised by Scholle *et al.* (1998) who described metre-scale laminated–bioturbated cycles from the Upper Maastrichtian (Tor Formation) of the Dan Field in the Danish Central Graben (Fig. 1). These workers proposed a dynamic, essentially process-related origin for the cycles based on sedimentological and geochemical data. Preservation of primary lamination in these cycles was suggested to have been the result of rhythmic episodes of rapid sedimentation, overwhelming the burrowing infauna, and controlled by climatically-induced (Milankovitch) cycles of enhanced bottom currents and winnowing from structural highs.

Detailed facies and ichnological studies by Damholt (2003; Damholt & Surlyk, in press), however, failed to confirm the model of variable sedimentation rates proposed by Scholle *et al.* (1998) and the former workers favoured cyclic shifts in bottom water oxygenation as the dominant factor controlling cycle development.

As part of a larger-scale palaeoecological study of the Upper Maastrichtian Tor Formation in the Danish Central Graben, a *c.* 8 ft section was selected from the M-10X well of the Dan Field (Figs 1, 2) that shows the laminated–bioturbated cycles described in these previous studies. The aim was to investigate the faunal/floral composition of the chalk across the sedimentary cycles and thus, together with sedimentological and stable isotope geochemical data, contribute to the understanding of the origin of these bioturbated–laminated chalk cycles in the Danish Central Graben.
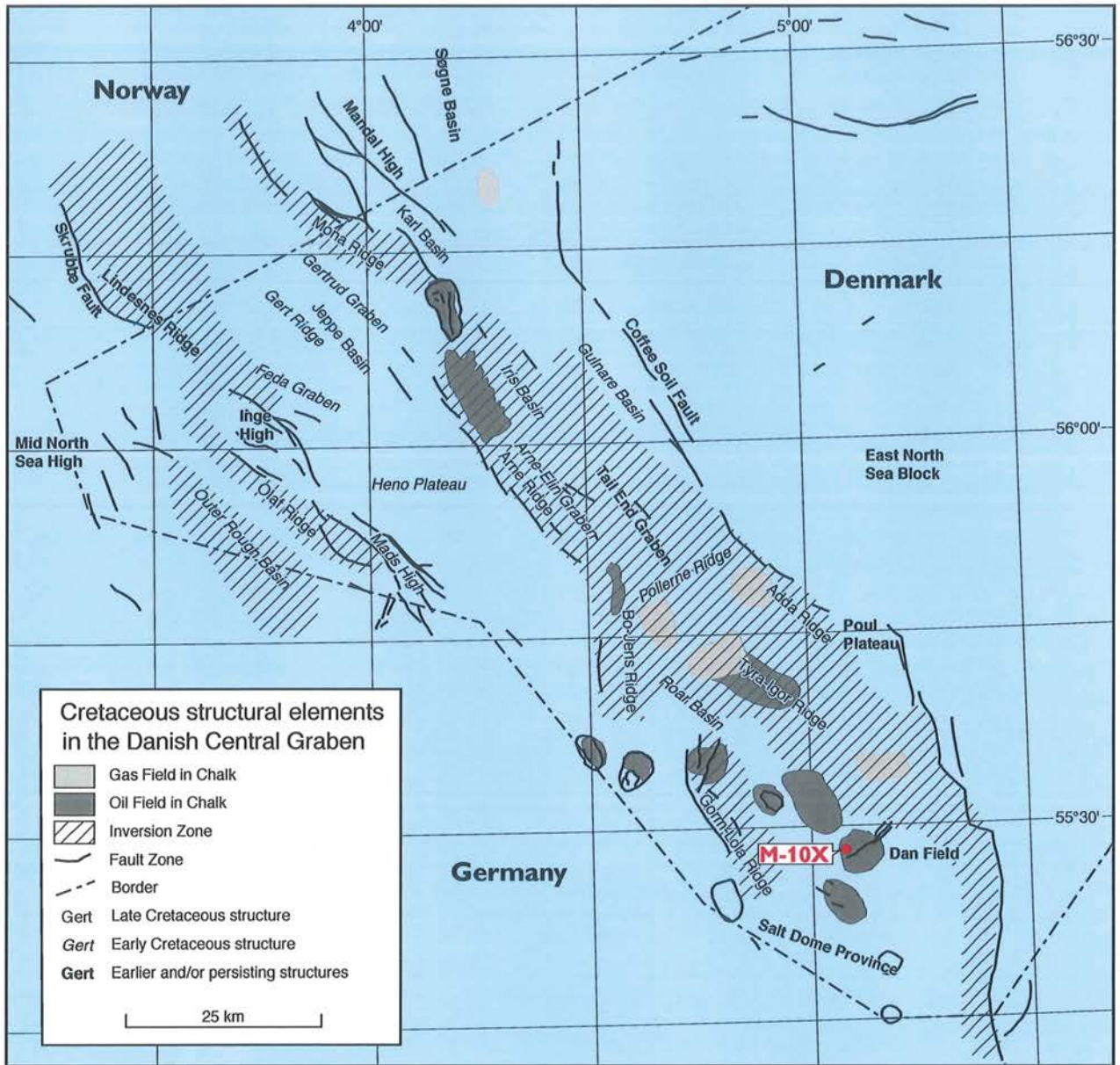
Fig. 1. Late Cretaceous structural framework of the Danish Central Graben showing the position of the M-10X well on the western flank of the Dan Field.

M-10X: Schematic sedimentology

"Maastrichtian hardground"

Marly chalk } Fine skeletal influx

Bioturbated chalk

Incipient hardgrounds

Laminated–bioturbated cyclic chalk

Detailed cyclic study

Chalk mudstone

Enhanced lam/bio cyclicity
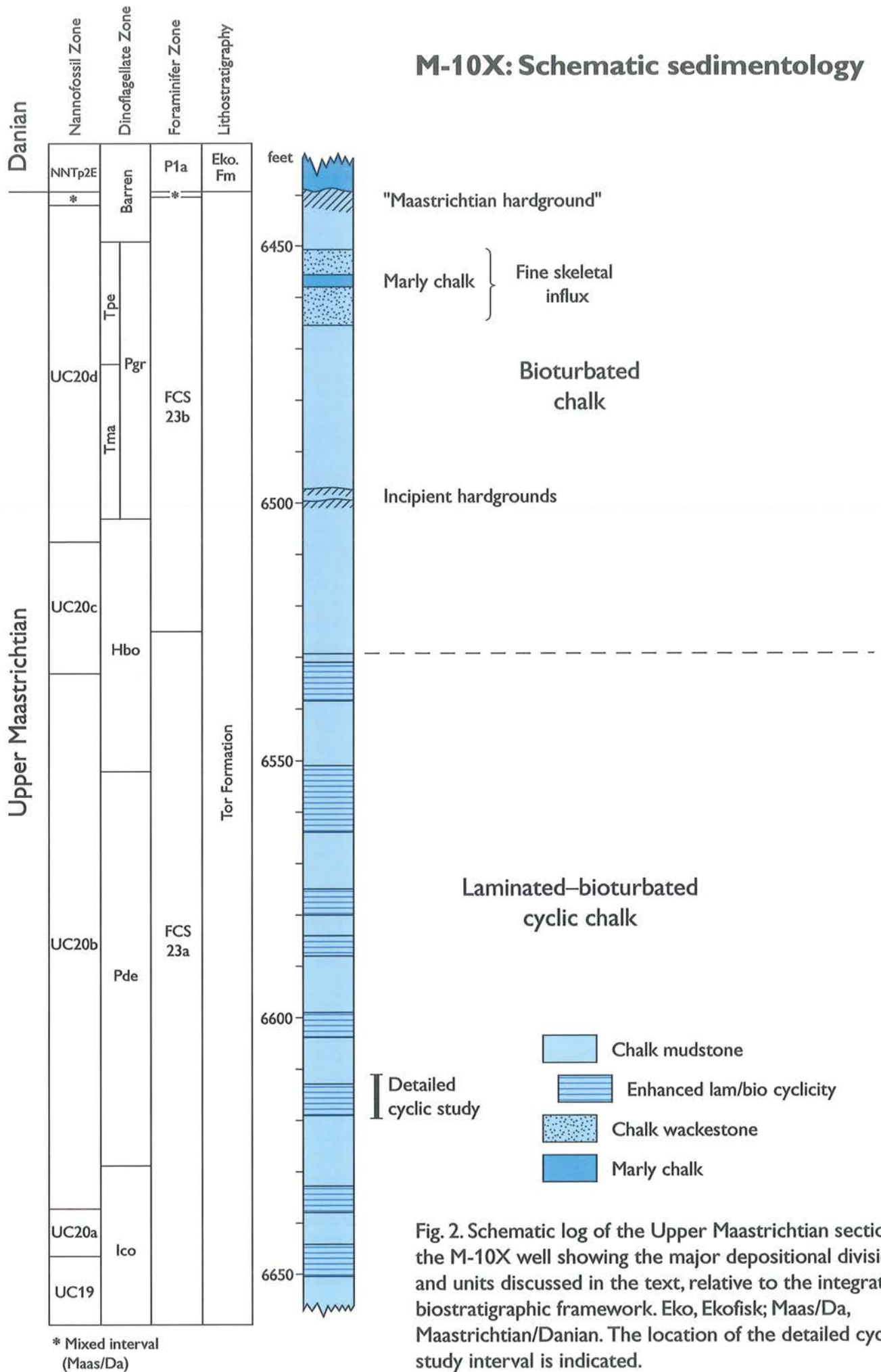
Chalk wackestone

Marly chalk

Fig. 2. Schematic log of the Upper Maastrichtian section in the M-10X well showing the major depositional divisions and units discussed in the text, relative to the integrated biostratigraphic framework. Eko, Ekofisk; Maas/Da, Maastrichtian/Danian. The location of the detailed cyclic study interval is indicated.

Danian

Upper Maastrichtian

Nannofossil Zone

Dinoflagellate Zone

Foraminifer Zone

Lithostratigraphy

NNTp2E

*

Barren

Tpe

Pgr

Tma

Hbo

Pde

Ico

UC20d

UC20c

UC20b

UC20a

UC19

P1a

*

FCS 23b

FCS 23a

Eko. Fm

Tor Formation

feet

6450

6500

6550

6600

6650

* Mixed interval (Maas/Da)

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 (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. 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 Field (Fig. 1). 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

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 M-10X well under consideration here was drilled on the western flank of the Dan Field (Fig. 1). 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).

Stratigraphy

The cored section in M-10X included in the wider study (see Ineson *et al.* 2004a, b, this study) spans 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. 2, the M-10X cored section 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. 2 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.

The cored Upper Maastrichtian section in M-10X is dominated overall by thoroughly bioturbated chalks but, as described in detail by Damholt (2003) and Damholt & Surlyk (in press), chalks showing diffuse primary lamination are preserved and indeed, due to slightly higher porosities, are an important reservoir facies (Scholle *et al.* 1998). Detailed logging as part of the larger-scale study of the Upper Maastrichtian chalks (see Ineson 2004, this study) has revealed that the cyclic laminated–bioturbated pattern described by former workers is essentially confined to the lower half of the cored section in M-10X (Fig. 2). Indeed, as discussed in Ineson (2004, this study), this cyclic facies is also geographically restricted, being only poorly developed in the Tyra SE Field at the same stratigraphic level.

The cyclic interval studied in detail here is 6620–6611 ft, in the lower *P. denticulatum* dinoflagellate Zone, equivalent to the lower UC20b nannofossil subzone and the FCS 23a foraminiferal Zone (Figs 2, 3). Stratigraphically, this level is broadly equivalent to the "M1 cycle" illustrated by Scholle *et al.* (1998, fig. 15); these authors also illustrate data from cyclic intervals from deeper stratigraphic levels, beneath the base of the cored M-10X section.
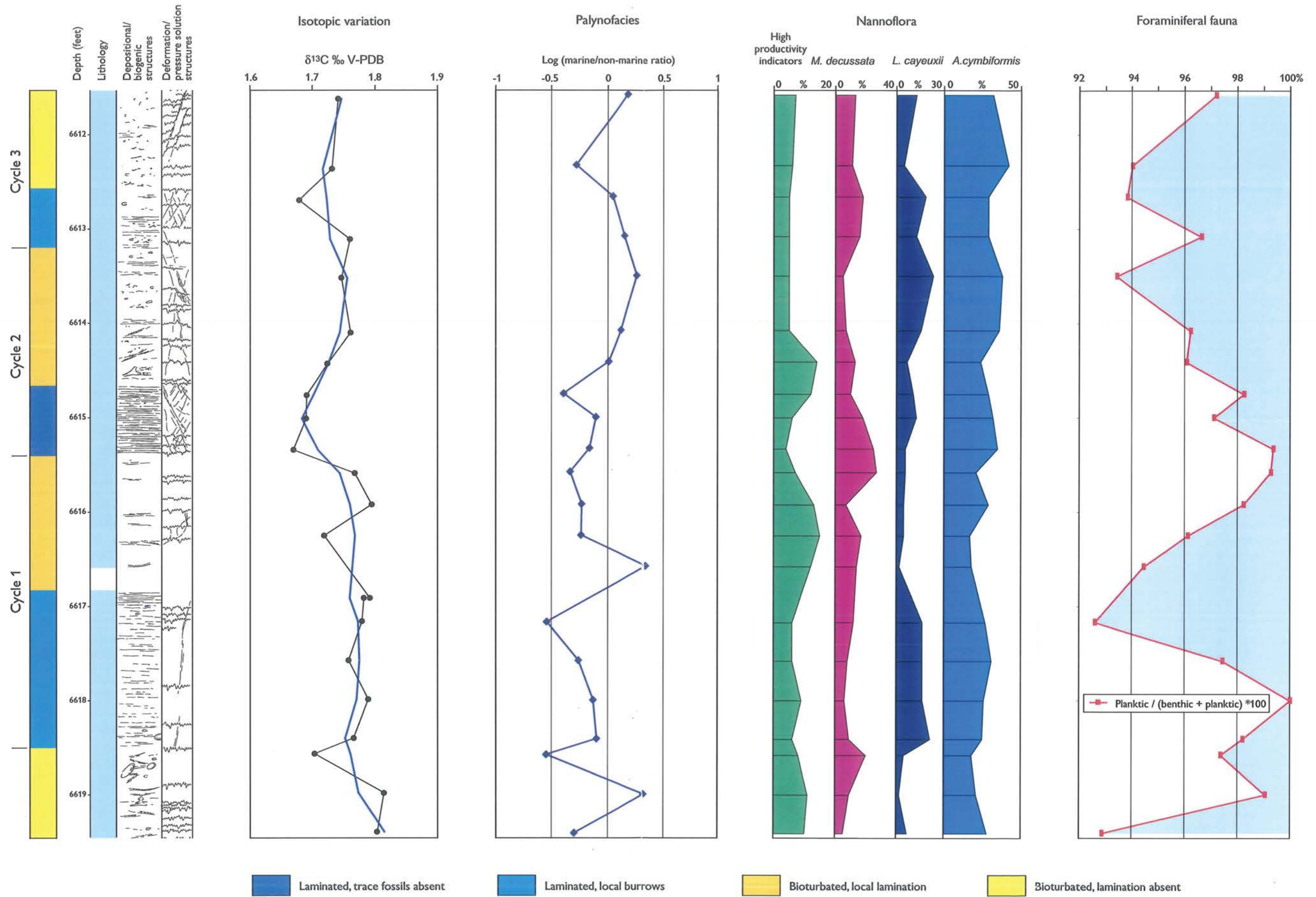
M-10X: Laminated–bioturbated cycles

Fig. 3. Sedimentological log through the composite cyclic interval showing three variably developed laminated–bioturbated cycles (1–3) in relation to selected high resolution isotopic, palynofacies and palaeoecological datasets.

Sedimentology

The alternation of laminated and bioturbated chalks on a metre-scale has been reported from the Dan Field area by a number of workers (e.g. Dons *et al.* 1995; Toft *et al.* 1998; Scholle *et al.* 1998; Damholt 2003; Damholt & Surlyk, in press) and is the dominant feature of the lower half of the cored section in the M-10X well studied here (Fig. 2). A detailed description of the lithology of the cycles is given by Damholt & Surlyk (in press). As discussed in Ineson (2004, this study), definition of these cycles is variable through the section and identification of cycle boundaries in poorly defined intervals is a subjective process. The following brief description of the two end-member facies in the cyclic section is adapted from Ineson (2004, this study); note that intermediate, partially laminated, bioturbated chalks are also represented, typically at the transition between the two end-members.

Laminated chalk mudstone

Description. This lithofacies is dominated by a lime mudstone fabric; local concentrations of coarse silt – very fine sand grade skeletal material (foraminifers, brachiopod/bivalve fragments etc.) in certain laminae may elevate the fabric locally to a sparse wackestone category. The diagnostic feature of the lithofacies is the presence of diffuse parallel lamination, defined by slight variations in porosity and thus degree of oil staining (Fig. 4). The more porous, more heavily stained laminae are up to a few mm thick and although commonly extending across the full core width, may wedge out laterally, such laminae are defined locally by weak concentrations of fine skeletal detritus. Detailed descriptions of this laminated facies, both macroscopically and microscopically, are presented by Damholt (2003) and Damholt & Surlyk (in press). Isolated burrows (typically *Chondrites*) are locally seen to truncate the diffuse lamination. The laminated facies forms units (beds) ranging from a few cm to 50 cm thick, typically 10–20 cm thick, and are bounded by thoroughly bioturbated chalks or by weakly/locally laminated chalks. Where non-stylolitic, the boundaries are commonly gradational.

Interpretation. The origin of these laminated chalks, in tems of process sedimentology, has been discussed in detail by Damholt (2003) and Damholt & Surlyk (in press). These workers interpreted the lamination to reflect an alternation of pelagic (less porous) and turbiditic (more porous) deposits, individual porous laminae recording the depositional input of a single small-volume dilute turbidity current into a region receiving a background rain of pelagic carbonate. Detailed petrographic study has not been undertaken here and the process interpretation of Damholt & Surlyk (in press) is followed. The nature of the factors controlling preservation of these subtle stuctures is discussed further below but has been interpreted to have resulted from dysoxic–anoxic conditions on the sea floor (Damholt 2003; Damholt & Surlyk, in press).
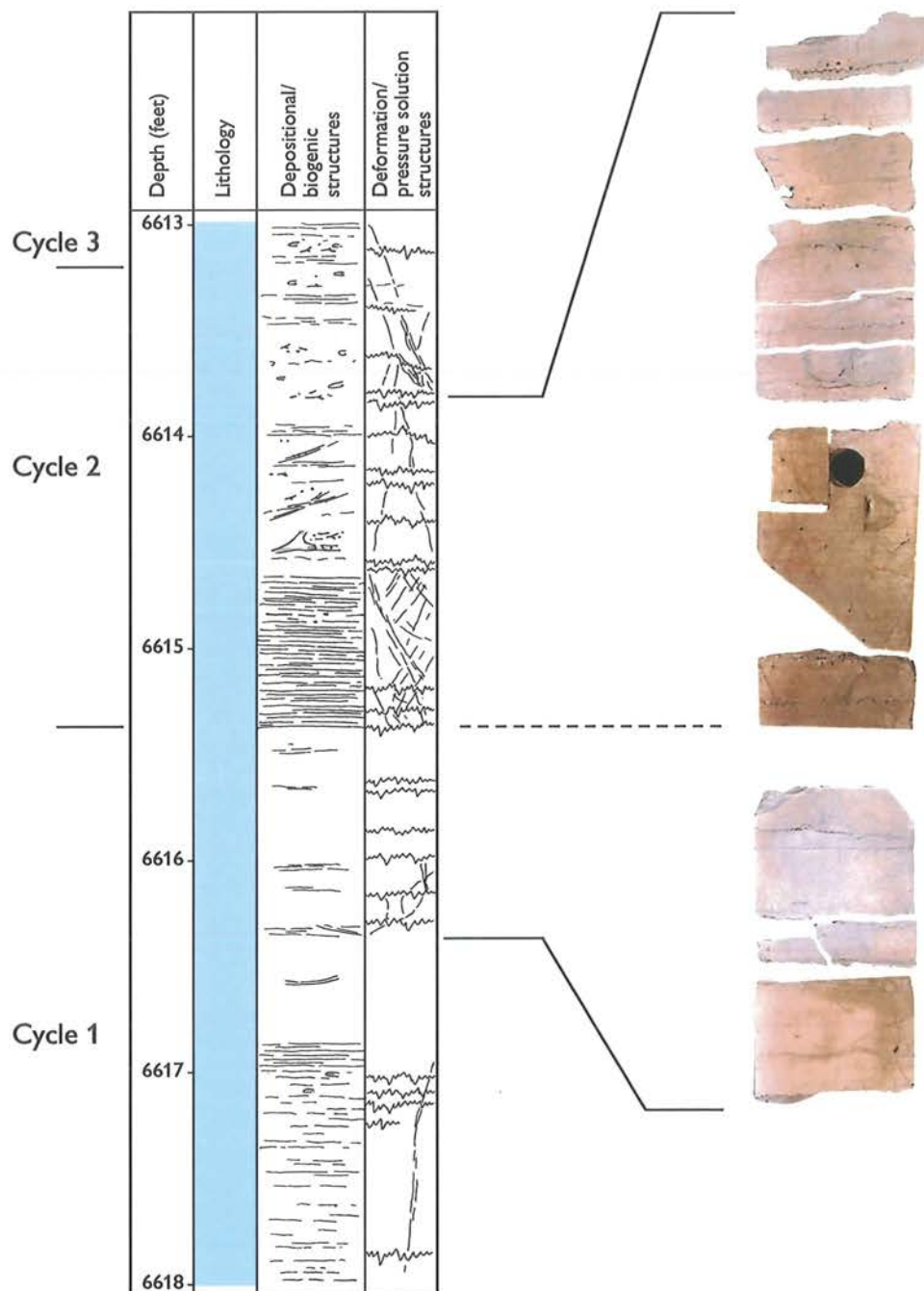
Fig. 4. Core photograph of the uppermost levels of Cycle 1 and lower Cycle 2 showing the enhanced (brown) hydrocarbon staining in the more porous laminated half-cycle relative to the intervening bioturbated chalks.

Bioturbated chalk mudstone

Description. In common with lithofacies 1 and 2, the chalks of this lithofacies comprise lime mudstones with a scatter of coarse silt – very fine sand grade skeletal grains (visual estimate < 5%), typically foraminifers, inoceramid prisms and fragmented thin-shelled bivalves/ostracods. Small (up to 1 cm) brachiopods are observed locally. Where visible, skeletal grains are typically dispersed randomly but may be concentrated in burrow fills (*Planolites*). In the well-laminated cyclic sections, these burrowed chalks typically display diffuse bio-mottling with local definable trace fossils (typically *Chondrites* and/or *Zoophycos*); more complex, diverse ichnofabrics occur rarely in such sections.

Interpretation. Since biogenic fabrics mask primary depositional features in this facies, the nature of the depositional process is a matter of conjecture. Given the intimate alternation of this facies with the laminated chalks and, in particular, the transitional facies in which "windows" of primary lamination are visible, a comparable depositional process is deemed likely. Following Damholt (2003) and Damholt & Surlyk (in press), therefore, the bioturbated chalk mudtones are attributed primarily to an intimate interlamination of turbiditic and pelagic chalk mudstones, the record of which processes has been lost due to comprehensive bioturbation.

M-10X Cyclic section

The c. 8 ft section selected for study exhibits an alternation of well-laminatd, poorly (locally) laminated and non-laminated, bioturbated chalks (Figs 3, 4). Two discrete laminated intervals (lower levels of Cycle 1 and Cycle 2 on Fig. 3) define two well-developed cycles but lamination is noted locally in the intervening burrowed chalks and a third weakly developed cycle (Cycle 3) is also recognised at the top of the interval. This sampled interval has the character of a composite cycle as described from the succession by Damholt (2003). Even within the lower two cycles, it is important to note the distinction between Cycle 2 in which lamination is recognisable throughout the half cycle and Cycle 1, in which lamination is diffuse and burrows are locally evident.

The section was sampled at c. 10 cm intervals for detailed palaeoecological, palynofacies and isotopic study. The results and interpretations of these individual disciplines are given below; details of sample processing, analytical methods and interpretative criteria are given in Rasmussen & Lassen (2004, this study), Schovsbo & Buchardt (2004, this study), Schiøler (2004, this study) and Sheldon (2004b, this study).

Stable isotope geochemistry

As indicated on Fig. 3, the $\delta^{13}C$ values measured for the cyclic study interval range between 1.7 ‰ and 1.8 ‰ (i.e. within a range of 0.1 ‰). The base of the Cycle 2 is marked by a shift in isotopic composition of approximately 0.1 ‰ towards more negative values whereas a gradual return to more positive $\delta^{13}C$ values occurs in the bioturbated part of the cycle (Fig. 3). In Cycle 1, a 0.1 ‰ shift towards more negative values is observed just below the base of the laminated interval. A few centimetres above the base of the laminated chalk, more positive values are observed. From here and in the upper bioturbated part of the cycle, stable carbon isotopic values are observed.

The $\delta^{18}O$ variation shows no obvious relationship with the laminated to bioturbated cycles (see Schovsbo & Buchardt 2004, this study). The samples vary from -4.6 ‰ to -4.1 ‰, i.e. approximately ± 0.25 ‰, which may be taken as an estimate of the short-term (m-scale) variation.

Interpretation. In a study from the Dan Field, Scholle *et al.* (1998) observed a tendency for laminated chalk samples to have slightly more negative $\delta^{13}C$ values compared to bioturbated chalk samples. Scholle *et al.* (1998) were not, however, able to document this feature since the statistical separation between the groupings was too low. Of the lithological cycles studied here, only Cycle 2 displayed a systematic relationship between lithology and $\delta^{13}C$ variation (Fig. 3). Here more negative $\delta^{13}C$ values were measured in the laminated part whereas the bioturbated part was characterised by more positive values. According to Scholle *et al.* (1998), the laminated samples might be expected to have received a higher proportion of isotopically light cement derived from CO_2 that was produced from reoxidation of organic matter. Hence, the isotope signature was not derived from the water column but is an overprint formed in the sediment due to a specific early diagenetic environment. The return to more positive values in the bioturbated intervals reflects venting of the pore waters by infaunal organisms which prevented a special diagenetic signature precipitating from the pore-water.

The isotopic variation in the lower and upper cycles (Cycles 1 and 2) does not show any clear relationship with lithology (Fig. 3). This might be ascribed to the weak lamination and sporadic signs of bioturbation; these features might suggest that the depositional environment was characterised by a more open pore-water system such that cement with light $\delta^{13}C$ isotope compositions did not form in sufficient quantities to affect the whole rock isotopic signature. Hence, it is assumed that only minor differences in the degree of bioturbation and thus openness of the pore-water system have a significant influence on the isotope signature.

The laminated lithofacies have been interpreted to reflect either anoxic to dysoxic bottom water conditions (Damholt 2003; Damholt & Surlyk, in press) or high sedimentation rates (Scholle *et al.* 1998). The isotopic signature discussed above can result from either of the scenarios and hence does not bring any new conclusive evidence to this debate. The geochemical signature is interpreted to reflect a poorly vented pore-water system in which isotopically light cement formed as a consequence of organic matter remineralization. Such an

environment might result from anoxic conditions at the seafloor, which prevented an infau-nal community from developing, according to the model of Damholt (2003) and Damholt & Surlyk (in press), or might be the result of rapid sedimentation events that sealed off the pore-water system by adding a thick pile of sediments, as postulated by Scholle *et al.* (1998).

Nannofossil palaeoecology

The nannofossil assemblages from the cyclic section are diverse and abundant with a continuous species richness of around 30–33. Overall, this indicates a fairly stable, cool water, oligotrophic environment. However, when focussing in on small-scale trends in nannofossil abundances, certain fluctuations, which could be due to minor palaeoenvironmental changes, are observed.

Increased productivity

Biscutum spp., *Discorhadbus* spp., and *Zeugrhabdotus* spp. are considered to reflect changes in productivity. These species thrive in areas of high surface water fertility in low diversity assemblages (Watkins 1989; Erba 1992; Gardin 2001). *Chiastozygus* spp. is also considered to be a high productivity indicator (K. Cooper, pers. comm.). In this study, the high productivity indicators *Biscutum* spp., *Discorhabdus ignotus*, *Placozygus fibuliformis* (as related to *Zeugrhabdotus*, J. Lees, pers. comm.) and *Chiastozygus amphipons* have been grouped together to reinforce their significance (coloured green on Fig. 3).

The grouped high productivity indicators demonstrate 2 peaks. The first peak of *P. fibuliformis* and *Ch. amphipons* occurs within the bioturbated interval of Cycle 1; both *P. fibuliformis* and *Biscutum* spp. peak in Cycle 2 at the transition from the laminated interval and the overlying bioturbated interval. *Chiastozygus amphipons* peaks at 6614.41 ft, within the bioturbated portion of Cycle 2 (Fig. 3). The upper weak cycle shows no productivity signal.

Water depth

The palynofacies data of Schiøler (2004, this study) from this cyclic interval do not show any indication of coastal migration, i.e. sea-level change, related to the cyclicity. However, abundances of *M. decussata,* a nannofossil species commonly inferred to increase in abundance with rising sea-levels, fluctuate quite markedly (Fig. 3). Particularly notable is an influx from 6615.58–6615.00 ft (coinciding with an interval of relatively low productivity). This peak is concurrent with a drop in *A. cymbiformis* (at 6615.58 ft). Both parameters are suggestive of an increase in water depth at this point. It is also noted that from 6818.41–6617.17 ft and from 6614.08–6613.50 ft, *M. decussata* demonstrate fairly low abundances whilst these intervals show high numbers of *L. cayeuxii* (shallow and cool water indicators). *A. cymbiformis* follow the same trends as *L. cayeuxii* in these intervals, suggesting a relative sea-level shallowing. These intervals coincide with the laminated portion of Cycle 1 and the bioturbated portion of Cycle 2.

Temperature

W. barnesae is thought be a taxon associated with warmer temperatures (Watkins 1992; Lees 2002). A relative increase in this species is observed over the middle part of the cyclic

study interval i.e upper Cycle 1 – lower Cycle 2, roughly correlating with a decrease in abundance of *L. cayeuxii* (an indicator of cool, fairly shallow waters). This could be inferred to represent a minor warming at the sea surface, although the seawater in the region was considered at this time to be generally cool.

Several nannofossil species are known to be indicators of both cool and relatively shallow water. As previously mentioned, between 6618.41 ft and 6617.17 ft, there exists an interval of increased *L. cayeuxii* and *A. cymbiformis*, coinciding with the laminated portion of Cycle 1. This coincides with reduced numbers of *K. magnificus*. As well as indicating a relative shallowing in sea level, these parameters could suggest a cooling episode. *L. cayeuxii* and *K. magnificus* are both indicators of high latitude, marginal conditions (Roth 1973; Thierstein 1976; Perch-Nielsen 1979; Pospichal & Wise 1990). However their relative abundance patterns show opposing trends. One explanation for this could be that as they occupy the same niche, they may be in direct competition, with one species being a better temperature or sea-level indicator than the other at that particular time. The interval between 6614.08 ft and 6612.66 ft also exhibits relatively high *L. cayeuxii* abundances; this also coincides with a relative increase in *A. cymbiformis*, suggesting a cooler period.

Summary

In general, the overall nannofossil assemblage patterns and unchanging species richness levels demonstrate a cool, oligotrophic, relatively shallow palaeoenvironment. In more detail, minor fluctuations in certain groups indicate short-lived palaeoecological variations, probably due to changes in nutrients and temperature. Minor water depth variations can also be inferred from the nannofossil data, but other datasets (e.g. palynofacies) indicate that this is unlikely to be a significant factor.

Palynology

Palynological analysis of the cyclic section in Fig. 3 involved the full range of palynofacies parameters utilised in the wider stratigraphic study (see Schiøler 2004, this study). The marine/non-marine ratio, included on Fig. 3, is representative of the full dataset as no significant variation was observed between the palynofacies indices and the small-scale cycles. This suggests that the cycles observed in the chalks of the Danish Central Graben are unlikely to be linked to minor sea-level cycles or cyclic variations in run-off. The productivity index utilised in the palynological study showed no correlation to the small-scale cycles in the study interval and is indicative of a low productivity, oligotrophic system.

Foraminiferal palaeoecology

In general, the foraminiferal faunas in the detailed cyclic study interval are very uniform with very high numbers of planktic foraminiferids in relation to benthic foraminiferids. The ratio between planktic and benthic Foraminifera (P/B) is always higher than 92% (Fig. 3). The planktic faunas are dominated by more than 70% *Heterohelix globulosa*. However, small faunal differences occur and based on these it has been possible to subdivide the interval into two foraminiferal biofacies (PB1, PB2), which display a cyclic pattern in the studied interval (see Rasmussen & Lassen 2004, this study). The three main parameters utilised are P/B ratios and the relative abundance of *Guembelitria cretacea* and *Hedbergella monmouthensis*. Keller (2003, p. 94)) regarded *Guembelitria* as an opportunistic species, which tends to bloom in high stress environments, most notably during times of high nutrient, eutrophic conditions (high content of organic carbon) and disruption of watermass stratification. Keller & Pardo (in press) showed that the largest *Guembelitria* blooms took place in low and middle latitudes, and only smaller blooms occurred in high latitudes. The latter authors also suggested that a major ecologic crisis, which may have lead to the exclusion of ecological specialists and most generalists, would be followed by 1) a bloom of *Guembelitria*, 2) an increase in small low-O_2-tolerant heterohelicids followed by 3) an increase in small trochospiral and planispiral species.

Biofacies PB1 is recognised at 6619.41 ft, 6617–6616.25 ft and 6614.41–6611.58 ft in the detailed section. It is characterised by the lowest P/B ratios in the interval, together with minor increases in the relative abundance of *Guembelitria cretacea* (up to 7%). The sparse benthic foraminiferal faunas are characterised by *Stensioeina* ex gr. *beccariformis*, gavelinellids and *Pyramidina minuta*.

Interpretation. Gumbelitria species were restricted to the surface layer above the thermocline and occurred in both open marine and shallow neritic nearshore environments. The genus seems to have tolerated a fluctuating palaeoenvironment with regard to salinity, temperature, oxygen and nutrients. Thus, opportunistic blooms of *Guembelitria* have been reported from neritic palaeoenvironments reaching a crisis level, characterised by a strong decrease in the normal population (Keller *et al.* 2002). The increase in *Guembelitria* found in this biofacies is diminutive, and does not reach the same degree as seen, for example, at the K-T boundary and at the Cenomanian–Turonian transition in other regions (Keller 2003). In the PB1 biofacies recognised in this cyclic study interval, however, its relative abundance seems to increase weakly in the intervals with relatively low (but still more than 92%) P/B ratios. This situation does not correspond to the severe ecological stress that occurred around the K-T and Cenomanian–Turonian boundaries but might indicate that the surface system was stressed and possibly unstable during these periods. In contrast, the sparse benthic fauna suggests that the sea bottom conditions were marginally better during PB1 biofacies times than during PB2, when the benthic fauna was almost absent.

Biofacies PB2 is recognised at 6619 ft–6617.58ft and 6615.92–6614.75. The highest P/B ratios are found in this biofacies (>97%), resulting from an almost complete lack of benthic foraminiferids. In addition to the dominant planktic foraminiferal species *H. globulosa*, the biofacies is characterised by *Hedbergella monmouthensis*, comprising up to 7% of the planktic assemblage.

Interpretation. H. monmouthensis is not regarded as an opportunistic species, as is the case for *G. cretacea* (Keller *et al.* 2002). Thus, the increase of this species within the low-ermost part of Biofacies PB2 might point toward more stable surface conditions compared to Biofacies PB1. The extremely low numbers of benthic foraminiferids suggest very poor conditions on the sea floor during the PB2 period.

Summary

Heterohelix globulosa is by far the most common species in the closely analysed interval, and relative changes in the abundance of other species are difficult to detect. Although highly tentative, it seems possible to subdivide the section into five intervals, based on changes in P/B ratios, and the relative abundances of *G. cretacea* and *H. monmouthensis*. Thus, the high resolution interval comprises two and a half cycles from biofacies PB1 to PB2 (see Rasmussen & Lassen 2004, this study). The PB1 biofacies are characterised by a relatively low P/B ratio averaging 95%, an increased number of *Guembelitria* (2–7%), and the occurrence of benthic (although very few) Foraminifera. Following the model of Keller & Pardo (in press), PB1 is interpreted as the first slightly opportunistic stage in the cyclic de-velopment. The following PB2 biofacies is only slightly different from PB1, being character-ised by a slightly higher P/B ratio averaging 98%, an increased number of the low trocho-spiral *Hedbergella monmouthensis* (2–7%), and the virtual absence of guembelitrids and benthic Foraminifera. PB2 is interpreted to record more stable conditions above the ther-mocline, but very poor conditions on the sea floor.

Thus, unstable conditions in the surface system were contemporaneous with a slightly im-proved sea bottom environment whereas relatively stable surface conditions were associ-ated with very poor conditions for the benthic community.

Discussion

The palaeoecological, palynofacies and isotopic data presented here from the detailed section through laminated–bioturbated chalk cycles in the Upper Maastrichtian of the Danish Central Graben are characterised overall by the weak, subtle nature of the signals. Clearly, the cyclicity does not reflect major perturbations in the oceanographic system which was consistently stable and oligotrophic. The palaeoecological data from the nannofossil and foraminiferal groups do, however, display recognisable variations that relate to the sedimentary cyclicity, and allow a model to be proposed to account for these short-term cycles that is compatible with the sedimentological and isotopic data.

The benthic environment

The laminated–bioturbated cycles have been interpreted to represent cyclic variation in the degree of bottom water oxygenation i.e. redox cycles (Damholt & Surlyk, in press). The foraminiferal data confirm the generally hostile sea-floor conditions at this stratigraphic level, with sparse and low diversity benthic faunas and a high to very high P/B ratio (Fig. 3). Of particular note, however, is the cyclic variation in the P/B values through the detailed cyclic interval, at the same frequency as the sedimentological cycles. Interestingly, however, the cycles overlap with but do not always exactly match the sedimentary cycles. Thus, the lower peak in P/B, recording particularly adverse bottom conditions, straddles the base of Cycle 1; similarly the second peak culminates just below the base of the Cycle 1. This offset between the faunal cycles and the sedimentary cycles may in part be explained by differing tolerance thresholds concerning low oxygen levels for the foraminiferal fauna and the burrowing infauna (see Rhoads & Morse 1971). In general, however, the sparse and cyclically fluctuating benthic fauna support the model of Damholt & Surlyk (in press) viz. that these are redox cycles. As noted above, the isotopic data are also compatible with such a redox cyclic model.

The planktic environment

Nannofossil and dinoflagellate data indicate a stable, oligotrophic upper watermass, with no evidence of major productivity shifts. The nannofossil data, however, display minor peaks in productivity indicators that correlate not with the onset of the preservation of lamination but with the transition from laminated to bioturbated chalk, or lie wholly within burrowed facies above the laminated chalks. Note that this offset can in part be explained by bioturbation of the laminated facies after re-ventilation of the sea-floor. It is clear, however, that these minor productivity peaks post-date the phase of oxygenation starvation i.e. are the result, rather than the cause, of oxygen deprivation at the sea floor. Fluctuations in the nannofossil assemblages correlate at some levels with the sedimentary cycles; in the absence of palynofacies evidence of significant sea-level variation related to the cyclicity, these fluctuations are suggested to represent minor shifts in temperature distribution within the photic zone.

The planktic foraminiferal fauna also display a weak cyclicity, in phase with the benthic patterns, suggesting periods of stable surface conditions, correlating with the most adverse bottom conditions, alternating with unstable stressed surface conditions, possibly related to the breakdown of stratification in the watermass.

Origin of cyclicity

The combined data suggest that the redox cycles inferred by Damholt & Surlyk (in press) on the basis of sedimentological observations were probably controlled by cyclic phases of watermass stratification. In the absence of evidence for major productivity pulses related perhaps to variation in sea level or run-off, it is suggested that the cyclic development of stratification in the chalk sea was controlled physically by periodic shifts in mean wind stress, controlled ultimately by climatic cycles in the Milankovitch frequency band (Fig. 5). During "calm" periods, inefficient watermass circulation led to internal stratification and progressive depletion of oxygen in bottom waters, particularly in local topographic lows. The upper watermasses were stable, as reflected by the planktic foraminiferal data, and variation in the degree of thermal stratification of the upper layers may have influenced the composition of the floral population. Incomplete decomposition of settling organic matter in the anoxic/dysoxic bottom waters resulted in a weak build-up of nutrients in the stratified lower watermass and surficial sediments. As the system moved into a "stormy" phase, enhanced circulation resulted in breakdown of the weakly stratified system, ventilation of the sea floor and release of the dilute nutrient pool to the photic zone resulting in the minor productivity peaks observed in the nannofossil dataset.

Low wind stress:
Stratified watermass
Local sea-floor dysoxia, weak nutrient storage

Photic
zone

Tyra

Dan
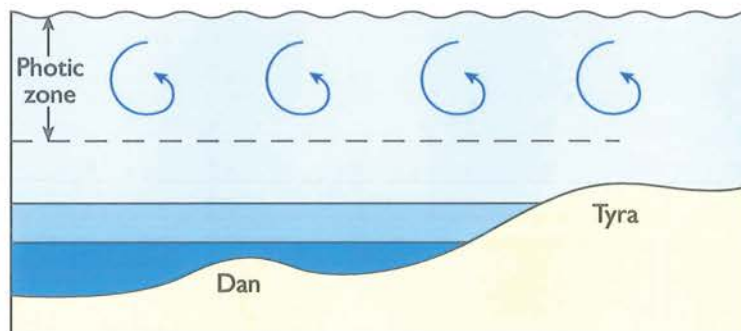
High wind stress:
Stratification breakdown
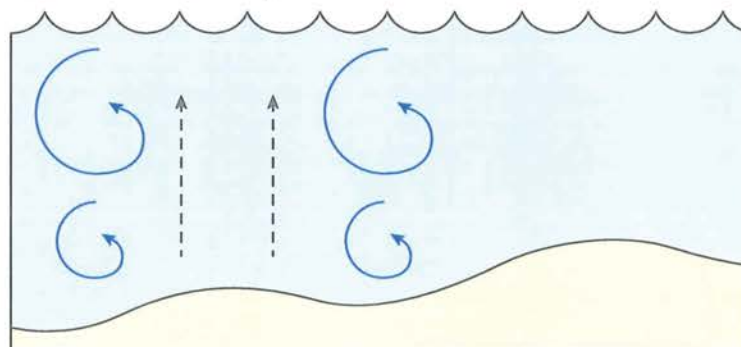Nutrient release to photic zone

Fig. 5. Cartoon illustrating a model for the generation of
m-scale bioturbated–laminated cycles in the Danish
Central Graben in the Late Maastrichtian. See text for
discussion.

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