DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/80

Integrated Upper Maastrichtian stratigraphy, Danish Central Graben

M-10X (Dan Field), E-5X (Tyra SE Field)

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A contribution to EFP-2001 (1313/01-0001)

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Abstract

Integration of nannofossil, foraminiferal and dinoflagellate biostratigraphy with stable isotope chemostratigraphy and lithostratigraphy has resulted in a consistent rigorous stratigraphic framework for the upper Upper Maastrichtian of two key wells (M-10X, Dan Field; E-5X, Tyra SE Field) in the southern Danish Central Graben. The M-10X cored section extends from the nannofossil UC19 Zone (dinoflagellate *I. cooksoniae* Zone, FCS 23a foraminiferal Zone) to the uppermost Maastrichtian UC20d nannofossil subzone (dinoflagellate *P. grallator* Zone, FCS 23b foraminiferal Zone); the E-5X cored section extends from the nannofossil UC20b subzone (*P. denticulatum* dinoflagellate Zone, FCS 23a foraminiferal Zone) to the uppermost Maastrichtian UC20d nannofossil subzone (dinoflagellate *P. grallator* Zone, FCS 23b foraminiferal Zone). Quantitative biostratigraphic data provide a second tier of stratigraphic constraints; these include dinoflagellate (*P. denticulatum, P. grallator*) and foraminiferal (*P. laevis, P. elegans*) acme events. On the basis of the tightly constrained integrated biozonation, the stratigraphic validity of the petrophysical (porosity) cyclostratigraphic markers used for reservoir subdivision and correlation in the Danish Central Graben is confirmed.

Introduction

Improved stratigraphic and palaeoenvironmental understanding of the Upper Maastrichtian reservoir chalks of the Danish Central Graben is dependent primarily on a high-resolution stratigraphic framework for the succession. Despite the numerous biostratigraphic studies undertaken on this stratigraphic interval in the Danish sector, much of the information is in the form of company reports, and published data are far and few between (Kristensen *et al.* 1995). Furthermore, as noted by Damholt (2003), the detailed high-resolution biostratigraphy studies undertaken industrially typically rely on semi-quantitative faunal/floral events and are field-specific, rarely correlative between fields and may even be inconsistent within an individual field (e.g. Petersen *et al.* 2003).

The aim within this project, therefore, was firstly to select key wells from different structural settings that could provide continuous pelagic stratigraphic sections, through the target interval, i.e. the main Upper Maastrichtian reservoir interval (the M1 reservoir interval of the Dan Field, see Petersen *et al.* 2003). Secondly, a high-resolution biostratigraphic study was undertaken to identify internationally-recognised biostratigraphic zones related to the dinoflagellate cyst, nannofossil and microfossil floras and faunas; semi-quantitative events (acme) were also identified to provide a second tier of stratigraphic constrains. Detailed stable isotope investigations were also incorporated to examine the potential of chemostratigraphy to further resolve the stratigraphy.

Materials and methods

The two key wells, M-10X and E-5X (Fig. 1) 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) with regard to palynology and Lassen & Rasmussen (2004, this study and Rasmussen & Lassen 2004, this study) on the subject of micropalaeontology.

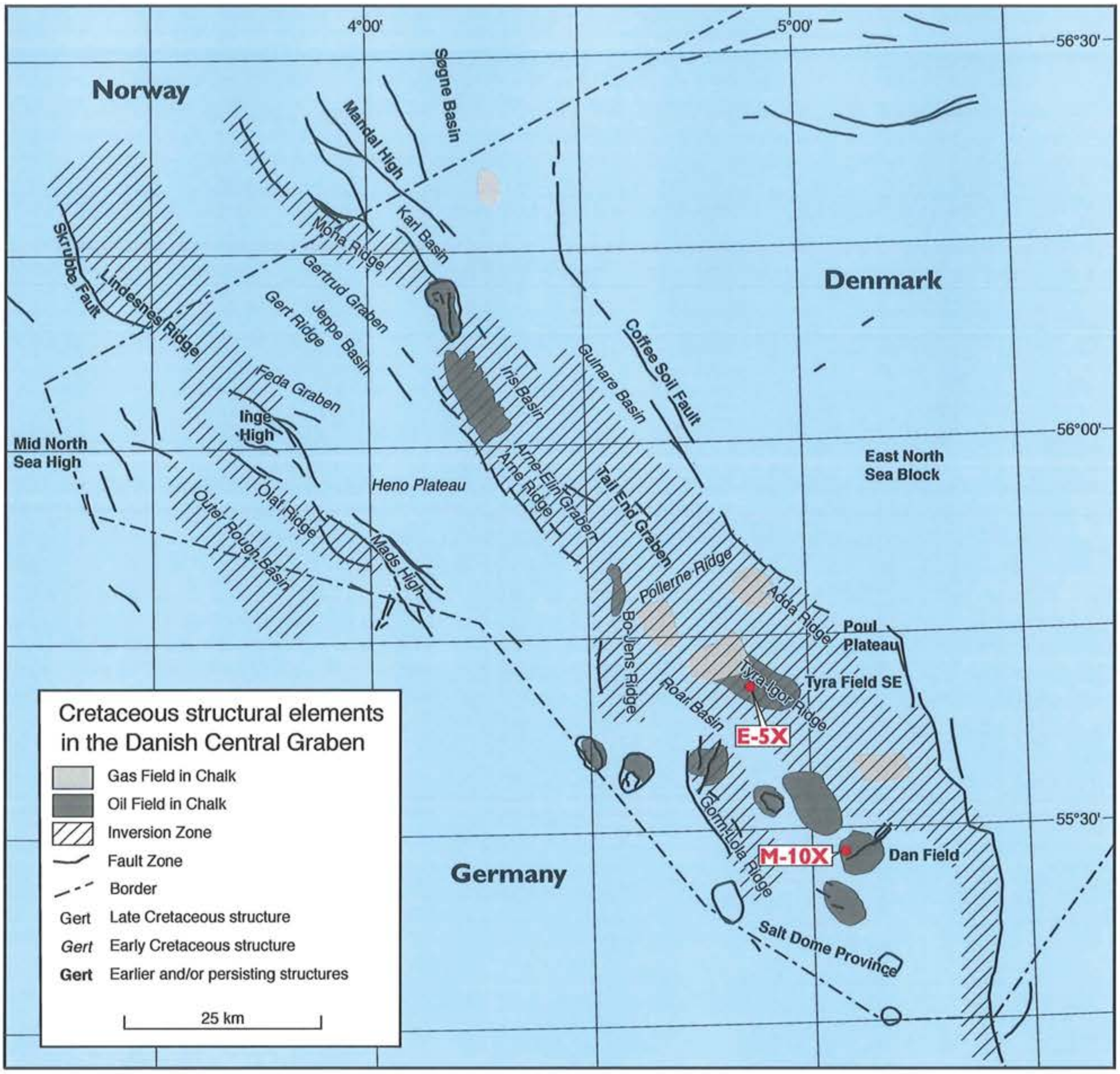

Fig. 1. Late Cretaceous structural framework of the Danish Central Graben showing the position of the M-10X and E-5X wells within the Dan and Tyra SE Fields, respectively.

Stratigraphic framework

Lithostratigraphy

The Upper Maastrichtian–Danian chalks of the southern Danish Central Graben remain formally in stratigraphic limbo. Lieberkind *et al.* (1982) referred the Upper Maastrichtian interval to the informal "chalk unit 5" and the Danian succession to the informal "chalk unit 6". No formal revision has been undertaken in the Danish sector subsequent to Lieberkind *et al.* (1982). In this report, the studied Upper Maastrichtian section is referred loosely to the Tor Formation, as recognised widely in the North Sea (Isaksen & Tonstad 1989), and the Danian succession to the Ekofisk Formation although this does not imply formal recognition of these terms in the Danish sector, at least at the present time.

The homogeneous nature of the Upper Maastrichtian section precludes high-resolution lithostratigraphic subdivisions. Three lithological markers should be noted, however, as they appear to be stratigraphically correlative between the Dan and Tyra SE Fields. The boundary in M-10X between the lower laminated–bioturbated cyclic unit and the upper bioturbated unit can be correlated to E-5X although the regional extent of this lithological boundary is not known. In the upper levels of the Maastrichtian succession, the incoming of increased fine skeletal detritus and a discrete marly chalk bed appear to have correlation potential.

Chemostratigraphy

The $\delta^{13}C$ variation in the M-10X and E-5X wells exhibits a striking overall resemblance (see Schovsbo & Buchardt 2004, this study). Prominent features include a change from a stable stratigraphic trend to a decreasing stratigraphic trend located in the UC20b nannofossil subzone, a local minimum in $\delta^{13}C$ values in the UC20c nannofossil subzone and a local maximum developed in the UC20d nannofossil subzone. These may serve as chemostratigraphic ties. Another obvious correlation level between the two wells is located in the uppermost part of the wells. Here a stratigraphic decreasing trend in $\delta^{13}C$ values reverts to a rapid increase in isotopic composition of 0.2 ‰. The increase in $\delta^{13}C$ values does not exactly correspond to the lithologically defined Maastrichtian–Danian boundary developed in the wells as a distinct hardground. The abrupt increase in $\delta^{13}C$ values occurs in the uppermost Maastrichtian samples picked just below the unconformity in both wells. Since the faunal and floral analysis of the chalk in this interval records a mixed Danian–Maastrichtian fauna, the noted increase in $\delta^{13}C$ values is interpreted to reflect analysis of Danian sediment that filled burrow systems in the hardground surface. Hence the Maastrichtian/Danian boundary as defined by geochemistry is located below the boundary as defined lithologically.

In order to evaluate the stratigraphic variation further, the short-term (metre-scale) variability of 0.1 ‰ is used to construct a data envelope (see Schovsbo & Buchardt 2004, this study). From evaluation of the data envelope, the curves are divided into units with characteristic trends in the data variation. The boundaries between each unit then subsequently serve as correlation horizons. The result of this produces a correlation which focuses on local or absolute maxima, minima and curve inflection points. The benefit of this graphic approach is that information on the short term variability of the data can be integrated directly into the analysis. Enhancing the short term variability generally leads to broader envelopes with less characteristic bends.

By applying this method, the stratigraphic $\delta^{13}C$ variation in the M-10X well is broken down into seven units termed, A – G (Fig. 2). In a similar manner, the stratigraphic $\delta^{13}C$ variation in the E-5X well results in a subdivision of the cored interval into five units. The depth intervals and a brief description of the units A – G follows below:

Unit A (M-10X: 6456.8–6440.6´, E-5X: 6828.0–6820.8´)
Decreasing $\delta^{13}C$ values (0.2 ‰) located in the uppermost part of the UC20d nannofossil subzone.

Unit B (M-10X: 6481.0–6460.0´, E-5X: 6849.8–6829.8´)
Stable $\delta^{13}C$ values in the middle part of the UC20d nannofossil subzone. In the E-5X well the base of this unit is unconstrained due to poor recovery. In the M-10X well, the boundary to the overlying unit A is marked by a shift towards more positive values. This feature is not observed in the E-5X well.

Unit C (M-10X: 6523.5–6483.8´, E-5X: 6885.4–6862.0´)
Increasing $\delta^{13}C$ values (0.2 ‰) located in the UC20c nannofossil subzone extending into the lowermost part of the UC20d nannofossil subzone. The increase approximates to 0.2 ‰ in the E-5X well, whereas the increase is smaller in the M-10X well.

Unit D (M-10X: 6553.8–6525.9´, E-5X: 6930.5–6886.3´)
Decreasing $\delta^{13}C$ values (0.2 ‰) located in the upper part of the UC20b nannofossil subzone extending to the lower part of the UC20c nannofossil subzone.

Unit E (M-10X: 6610.6–6558.6´, E-5X: 6971.7–6935.8´)
Stable $\delta^{13}C$ values in the middle part of the UC20b nannofossil subzone.

Unit F (only present in M-10X: 6644.1.0–6611.6´)
A 0.2 ‰ decrease in $\delta^{13}C$ values located in the uppermost part of the UC20a nannofossil subzone extending into the lowermost part of the UC20b nannofossil subzone.

Unit G (only present in the M-10X: 6655.6–6647.0´)
A >0.1 ‰ decrease in $\delta^{13}C$ values located in the UC20a nannofossil Zone. The base of this unit is not known.

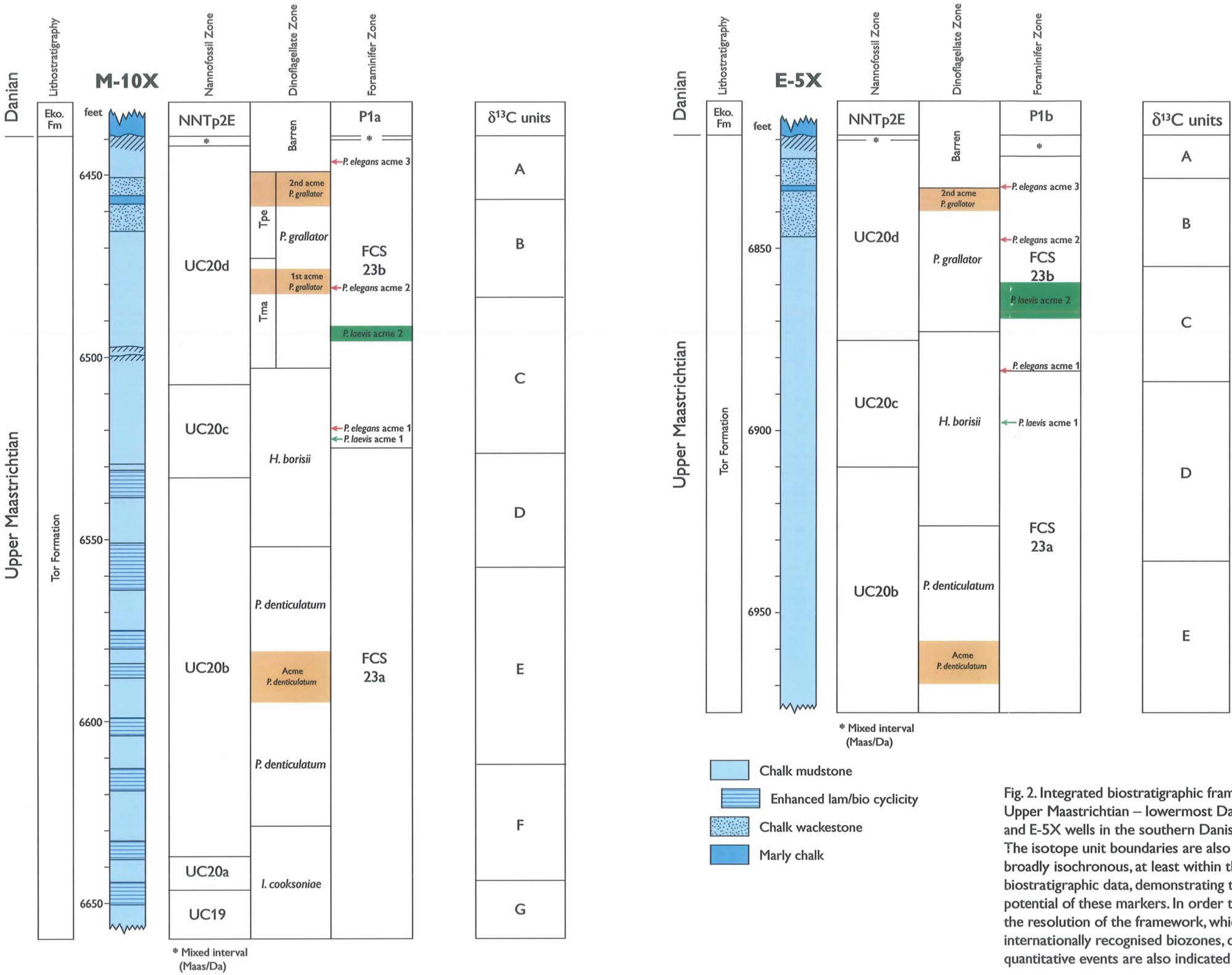

Fig. 2. Integrated biostratigraphic framework for the Upper Maastrichtian – lowermost Danian of the M-10X and E-5X wells in the southern Danish Central Graben. The isotope unit boundaries are also shown and appear broadly isochronous, at least within the resolution of the biostratigraphic data, demonstrating the stratigraphic potential of these markers. In order to further resolve the resolution of the framework, which is based on internationally recognised biozones, correlative semi-quantitative events are also indicated (i.e. acme).

Biostratigraphy

Dinoflagellate cysts

A dinoflagellate zonation for the Maastrichtian strata of the Dan Field was proposed by Schiøler & Wilson (1993). The M-10X well was one of five wells upon which that zonation was based. Subsequent biostratigraphic work has shown that this zonation is also applicable outside the Dan Field (Schiøler *et al.* 1997); therefore the zonation scheme of Schiøler & Wilson (1993) is used herein.

M-10X

The top of the *Isabelidinium cooksoniae* (Ico) Zone is at 6629.33´, at the highest occurrence (HO) of the nominate species. The base of the Ico Zone is at the HO of *Triblastula utinensis*. As the latter species was not encountered in the core, it may be inferred that the base of the Ico Zone was not reached. The top of the *Palaeocystodinium denticulatum* (Pde) Zone, that overlies the Ico Zone, is at the lowest occurrence (LO) of *Hystrichostrogylon borisii*, at 6552.25´. The top of *the Hystrichostrogylon borisii* (Hbo) Zone, that overlies the Pde Zone is at the base of the overlying *Palynodinium grallator* (Pgr) Zone, at 6503.25´, at the LO of the nominate species. Technically, the top of the Pgr Zone is at the HO of *P. grallator*. This normally coincides with the top of the Tor Formation and the Maastrichtian–Danian boundary. However, in M-10X samples from the uppermost 10.3´ of the Tor Formation in addition to all studied samples above this level are barren of dinoflagellates. Therefore, the top of the Pgr Zone must be placed at 6449.50´, 10.5´ below the Maastrichtian-Danian boundary at 6439.0´.

The Pgr Zone was subdivided into two subzones by Hansen (1977); a lower *Tanyosphaeridium magdalium* (Tma) Subzone and an upper *Thalassiphora pelagica* (Tpe) Subzone, separated at the LO of the dinoflagellate *Thalassiphora pelagica*. In a previous biostratigraphic study of core samples from M-10X, the base of the Tpe Subzone was located at 6473´ in that core (Schiøler & Wilson 1993). The Danian samples studied herein could not be assigned to any dinoflagellate zones, as they are all barren.

E-5X

The LO of *H. borisii* and the base of the Hbo Zone in the E-5X core is at 6926.17´. *Isabelidinium cooksoniae* was not encountered; thus, the base of the core is in the Pde Zone. The base of the Pgr Zone is at 6872.66´, at the LO of *P. grallator*. As in M-10X, the HO of *P. grallator* (and the top of the Pgr Zone) is at 6833.5´, 14.2´ below the top of the Tor Formation (at 6819.3´), at the base of a barren interval that ranges to the top of the section. The Pgr Zone could not be subdivided in E-5X, as the index species for the Tpe Subzone was not encountered in the core. As in M-10X, all Danian samples are barren of age-diagnostic dinoflagellates.

Nannofossils

The biostratigraphic zonation scheme primarily used for the Upper Cretaceous is the 'UC' scheme (boreal province) of Burnett (1998). The zonation scheme of Varol (1998) has been primarily used for the Paleocene of the North Sea.

M-10X

Almost all samples in M-10X contained diverse and abundant nannofossil assemblages. Zone UC19 is defined as the interval between the last occurrence (LO) of *Reinhardites levis* and the top by the first occurrence (FO) of *Lithraphidites quadratus*. Neither of these marker species were encountered in this study. However, the absence of *R. levis* implies that this interval is no older than Zone UC19. The presence in this interval of *Gartnerego segmentatum*, *Biscutum magnum* and *Zeugrhabdotus bicrescenticus* (species found in Zone UC19 or older zones) assigns it to UC19. The base of the overlying biostratigraphic unit, subzone UC20a (6647′–6637.33′) is defined by the FO of *Lithraphidites quadratus* and the top by the FO of *Nephrolithus frequens*. As *L. quadratus* was not recognised in this study, the absence of *N. frequens* in addition to the absence of marker species from stratigraphically older levels, suggests the presence of Subzone UC20a.

The base of the overlying subzone UC20b (spanning 6637.33′–6533,17′) is marked by the FO of *N. frequens* and the top by the FO of *Arkhangelskiella maastrichtiana*. The overlying biostratigraphic unit, subzone UC20c, spans the 6533.17′–6507.66′ interval. The base of this subzone is marked by the FO of *Arkhangelskiella maastrichtiana* and the top by the FO of *Cribrosphaerella daniae*. The presence, in fairly high numbers, of *'A. maastrichtiana*-like' forms of *Arkhangelskiella* assigns this interval to subzone UC20c.

Subzone UC20d (6507.66–6441.92′) is defined by the FO of *C. daniae*, and the top by the LO of unreworked, non-survivor taxa. The informal 'mixed zone' (6441,92′–6439′) overlying subzone UC20d is characterised by the co-occurrence of a relatively diverse mix of nannofossils, some common only to the Danian (probably burrow fills) and some only to the Maastrichtian (typifying UC20d), as well as those 'survivor' species that were apparently unaffected by the K/T event.

The lowermost Danian biostratigraphic unit encountered in M-10X is the middle Danian subzone NNTp2E (6439′–6436.83′). The base of this subzone is defined by the FO of abundant *P. dimorphosus*, while the top is marked by the FO of *Chiasmolithus danicus* and/or *Hornibrookina edwardsii*.

E-5X

As in the M-10X well, diverse and abundant nannofloral assemblages characterised the samples from E-5X. The biostratigraphic break-down of E-5X is similar to that of M-10X, with the exception that M-10X was drilled to a deeper biostratigraphic level (UC19) than E-5X (UC20b).

Nannofossil assemblages characterising subzone UC20b were found in the interval 6957.17′ to 6910.25′. The presence of *N. frequens* indicates that the underlying subzone, UC20a has not been sampled in E-5X. In addition, the base of subzone UC20b was not seen in this well. The overlying biostratigraphic unit, subzone UC20c, was observed within the 6910.25´–6875.33´ interval.

Subzone UC20d (6875.33´–6820´) is equivalent to the total range of *C. daniae*. The uppermost part of the Maastrichtian is characterised by the 'mixed zone' (6820´–6819,17´), which comprises a mixed flora with both Maastrichtian and Danian elements. The Danian elements of this biostratigraphic unit may tentatively be assigned to subzone NNTp2D–E.

Subzone NNTp2E (middle Danian) was encountered within the 6819,17´–6814.17´ interval.

Microfossils

The foramiferal zonation of the North Sea chalk facies proposed by King *et al.* (1989) has been applied to the Upper Maastricthian interval. The interval spans Zone FCS23 and includes the Subzones FCS23a and FCS23b. The Danian zonation is based on the biozonation scheme of Berggren and Miller (1998) which in this study includes the subzones P1a to P1c.

M-10X

The lowermost subzone is FCS23a. The basal boundary (6655.58´, lowest sample examined) is defined by the lack of *B. miliaris* and the top (6528.92´) by the FO of *Pseudotextularia elegans* (King *et al.* 1989). This subzone is characterised by high dominance and abundance of the planktic genus *Heterohelix* and a poorly represented benthic fauna. The planktic/benthic ratio is remarkably high in the interval studied at high resolution. An acme of *Praebulimina laevis* is observed at the very top of this subzone.

The overlying subzone FCS23b resembles the underlying subzone, but contains sporadic occurrences of the nominate taxa *P. elegans* in low numbers. This subzone also generally exhibits higher planktic/benthic ratios. The top of the subzone (6441.92´) is defined by the LO of Cretaceous taxa (King *et al.* 1989).

Three acmes of *P. elegans* have been found in this subzone in addition to one acme of the benthic species *Praebulimina laevis*. The latter acme is concurrent with very low planktic/benthic ratios.

The interval between subzone FCS23b and the Danian is informally defined as the "mixed interval" (between 6440.50´–6439.41´) which comprises both Cretaceous and Danian planktic taxa. Benthic taxa are absent. The first pure Danian zone is subzone P1a defined on the occurrence of the nominate taxon *Parasubbotina pseudobulloides* (Berggren & Miller 1998).

E-5X

As in M-10X, *Heterohelix* dominates the planktic foraminiferal faunas in E-5X through subzone FSC23a (6975.17´–6889.33´). However, the trends are less pronounced and the levels found in the lowermost part of M-10X are never reached. Thus, it is suggested that FCS23a in M-10X reaches an older stratigraphic level than in E-5X. Subzone FCS23b in E-

5X demonstrates higher abundances of the nominate taxon *P.elegans* compared with M-10X. Furthermore, in this well the appearance of keeled globotruncanids was observed in the upper part of FCS23b whereas such forms were not observed in M-10X. This might suggest that M-10X contains a hiatus spanning the upper part of subzone FCS23b. Another explanation is that the difference in the foraminiferal fauna is due to the environmental diversity between the two wells.

The "mixed interval" in E-5X is overlain by the Danian subzone P1b and thus suggests the presence of a hiatus spanning and overall longer period of time compared with M-10X.

K-T boundary hiatus

The boundary between the Upper Maastrichtian and the Danian in the M-10X and E-5X cored sections is marked by a distinctive hardground developed in the upper 2–4 feet of the Tor Formation. The association of complex cross-cutting *Thalassinoides* networks, the cemented and bored upper layer and the irregular, pitted, glauconite-impregnated upper surface is indicative of a mature, evolved hardground surface, recording a protracted period of non-sedimentation at the sea floor (see description in Ineson 2004, this study). The occurrence of mixed Late Maastrichtian and early Danian faunal and floral assemblages within the upper few feet beneath the hardground surface suggests that the burrow systems remained open into Danian time, thus accumulating complex multi-generational fills.

The missing nanno- and microfossil zones represent the extent of this hiatus in the two wells. Thus, nannofossil zones NNTp1A–NNTp2D are missing in both wells. The foraminiferal biostratigraphy suggests the hiatus spans more time in E-5X as the Zones P0–P1a are missing here whereas only P0 and Pα are missing in M-10X.

In most Cretaceous boundary sections in the Danish North Sea area, nannofossil zones NP1 and NP2 (NNTp1A–NNTp2E) are missing or thin, in contrast to onshore Denmark, where complete sections are present (Perch-Nielsen 1979). This is confirmed by foraminiferal studies. To our knowledge, the only reports of foraminiferal faunas from the P0 or Pα zones are from outside the Danish North Sea area, e.g. the Norwegian Valhall and Hod fields (Bergen & Sikora 1999).

The M-10X and E-5X wells were drilled on the flanks of their fields; at crestal sites, it may be expected that the hiatus might span a larger period of time, due to erosion or increased winnowing (Scholle *et al.* 1998), and conversely, in off-structure depocentres, that more complete sections may exist.

Integrated stratigraphy: resolution and implications

The integrated stratigraphic scheme presented in Fig. 2 is clearly highly consistent between the two fields in the Danish Central Graben and provides a rigorous framework within which local field-specific stratigraphies can be more tightly constrained. The addition of other biostratigraphic disciplines (nannofossils, microfossils and palynology), together with a stable isotope chemostratigraphic subdivision and lithostratigraphic observations has resulted in a higher degree of resolution than in previously published studies (Kristensen *et al.* 1995).

Given this framework, it is possible to investigate the stratigraphic validity of petrophysical log-based cyclostratigraphic markers that are widely applied in reservoir subdivisions at a field scale, and in correlation between fields in the Danish Central Graben (Toft *et al.* 1996; Petersen *et al.* 2003). The cyclostratigrahic markers a–f in the M-10X well indicated on Fig. 3 are taken from Toft *et al.* (1996); markers b–d in E-5X (Fig. 4) are taken from Damholt (2003). Marker b is in the lower *P. grallator* dinoflagellate Zone (lower UC20d, lower FCS23b) in both wells. Marker c is within the mid *H. borisii* dinoflagellate Zone and upper FCS23a foraminiferal subzone; it lies close to the UC20b/UC20c nannofossil subzone boundary although this boundary proved difficult to locate in both wells (see Sheldon 2004, this study). Marker d lies within the upper levels of the *P. denticulatum* dinoflagellate Zone (mid UC20b, upper FCS23a).

The cyclostratigraphic markers thus show consistent stratigraphic positions, according to the framework presented here, confirming their stratigraphic validity as tools for correlation and reservoir subdivision in this part of the Danish Central Graben. As discussed elsewhere in this report, the apparent isochronous nature of these markers is consistent with the observation that they coincide with intervals of enhanced sedimentological cyclicity which are probably the result of climatic forcing.

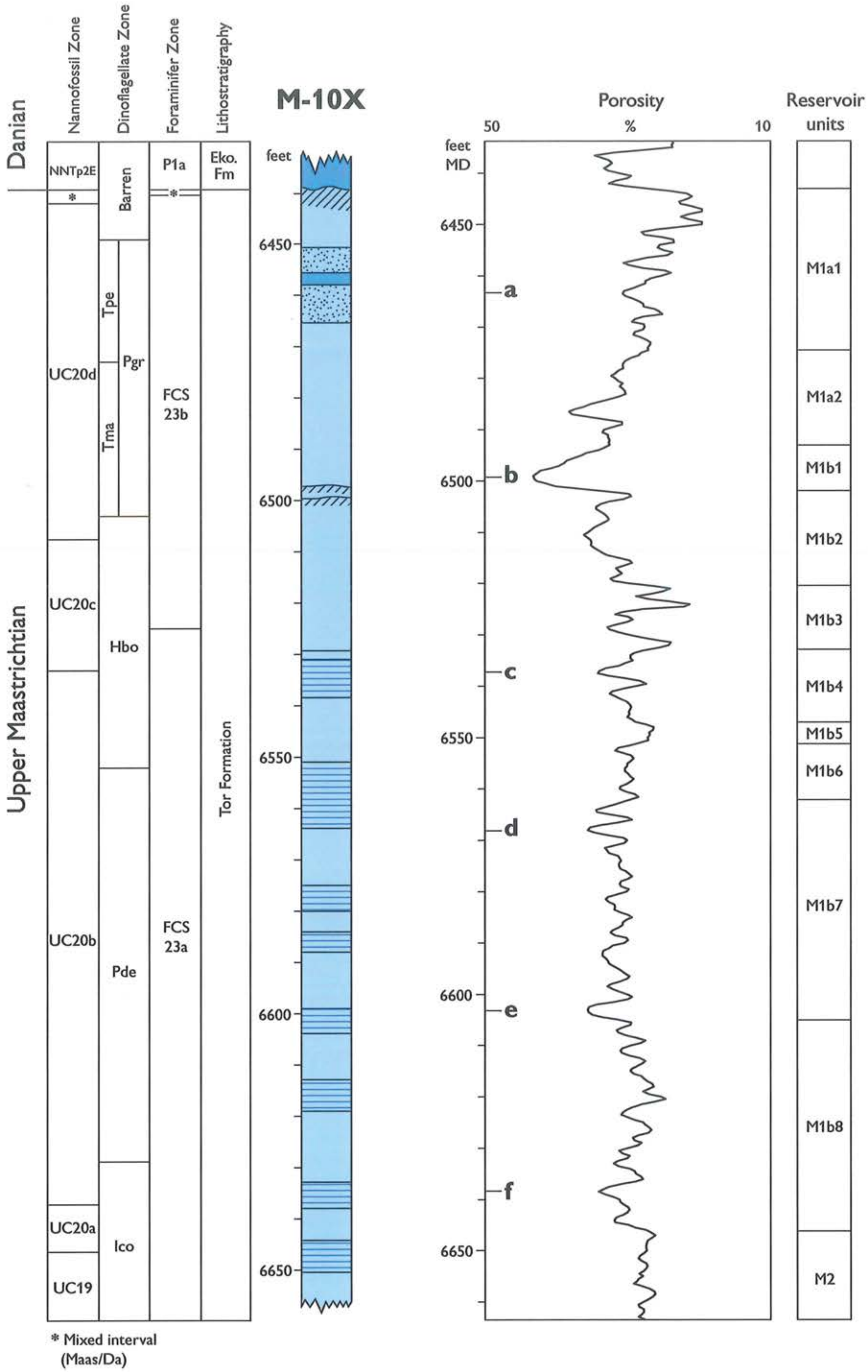

Fig. 3. Cyclostratigraphic porosity markers of Toft *et al.* (1996) in the M-10X well, in relation to the biostratigraphic framework presented here and the main lithological subdivisions of the cored Upper Maastrichtian succession. Note, in particular, the location of the most significant high porosity marker (b; reservoir unit M1b1 of Petersen *et al.* 2003), immediately above the thin incipient hardgrounds (see text for discussion) and the coincidence of markers c–f with chalks showing well-developed laminated–bioturbated cycles.

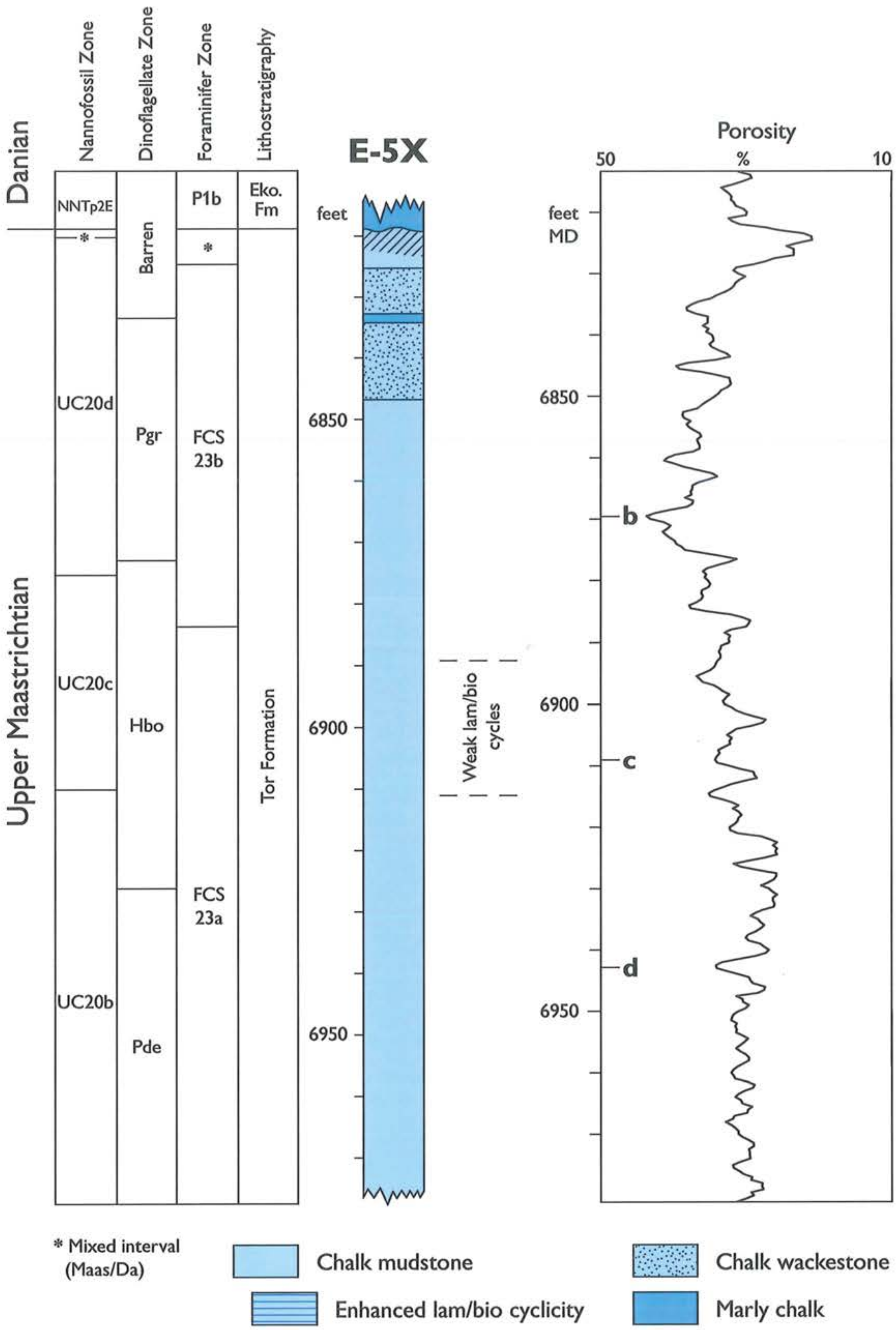

Fig. 4. Cyclostratigraphic porosity markers of Toft *et al.* (1996) in the E-5X well, in relation to the biostratigraphic framework presented here and the main lithological subdivisions of the cored Upper Maastrichtian succession. Log markers from Damholt (2003).

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