DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/85

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## 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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# Contents

# Abstract

In both the E-5X and M-10X wells, nannofossil biostratigraphy demonstrates that a complete Upper Maastrichtian chalk section is present, unconformably overlain by Danian chalk.

In E-5X, Upper Maastrichtian subzones UC20b (pars), UC20c and UC20d are present, apparently with no missing sections. In the Danian, subzones NNTp2E and NNTp2F are present, indicating a hiatus spanning NNTp1A–NNTp2D.

M-10X was cored to a stratigraphically deeper level, with Zone UC19, subzones UC20a, UC20b, UC20c and UC20d present. This Maastrichtian interval is unconformably overlain by Danian chalk assigned to subzones NNTp2E and NNTp2F, again demonstrating a hiatus spanning NNTp1A–2D.

# Introduction

Maastrichtian–Danian chalks include the most important hydrocarbon reservoirs in the Danish sector of the North Sea (Figure 1) and are responsible for the vast majority of present hydrocarbon production. Effective production from existing fields and exploration for subtle flank and off-structure chalk fields in the future will be increasingly dependent on an improved high-resolution chalk stratigraphy and a more detailed understanding of pelagic carbonate productivity and sedimentation processes.

Conventional industrial biostratigraphy, log and seismic data typically has a resolution of tens of metres, but in order to acheive the level of stratigraphic resolution required for detailed correlation and lithological prediction in flank and off-structure exploration, a multidisciplinary approach is necessary. This involves sedimentology, cyclostratigraphy, stable isotope studies and quantitative nannofossil, foraminifera, dinoflagellate and palynofacies analyses.

This nannofossil biostratigraphy study focusses on the cored Upper Maastrichtian–Danian interval of 2 wells with significant stratigraphic overlap from 2 geographically separate areas within the southern Danish Central Graben (also known as the Salt Dome Province). The E-5X and M-10X wells are located in the Tyra SE and Dan Fields respectively. To include the most productive Maastrichtian reservoir levels, the studied stratigraphic interval spans the intra-Late Maastrichtian seismic reflector (top reservoir unit 4 of the Dan Field) to the lower Danian.

Nannofossil, foraminifera and palynological biostratigraphic data will be integrated with petrophysical logs, stable isotope curves and sedimentological data. When tightly constrained, this technique can potentially yield a high degree of stratigraphic resolution.

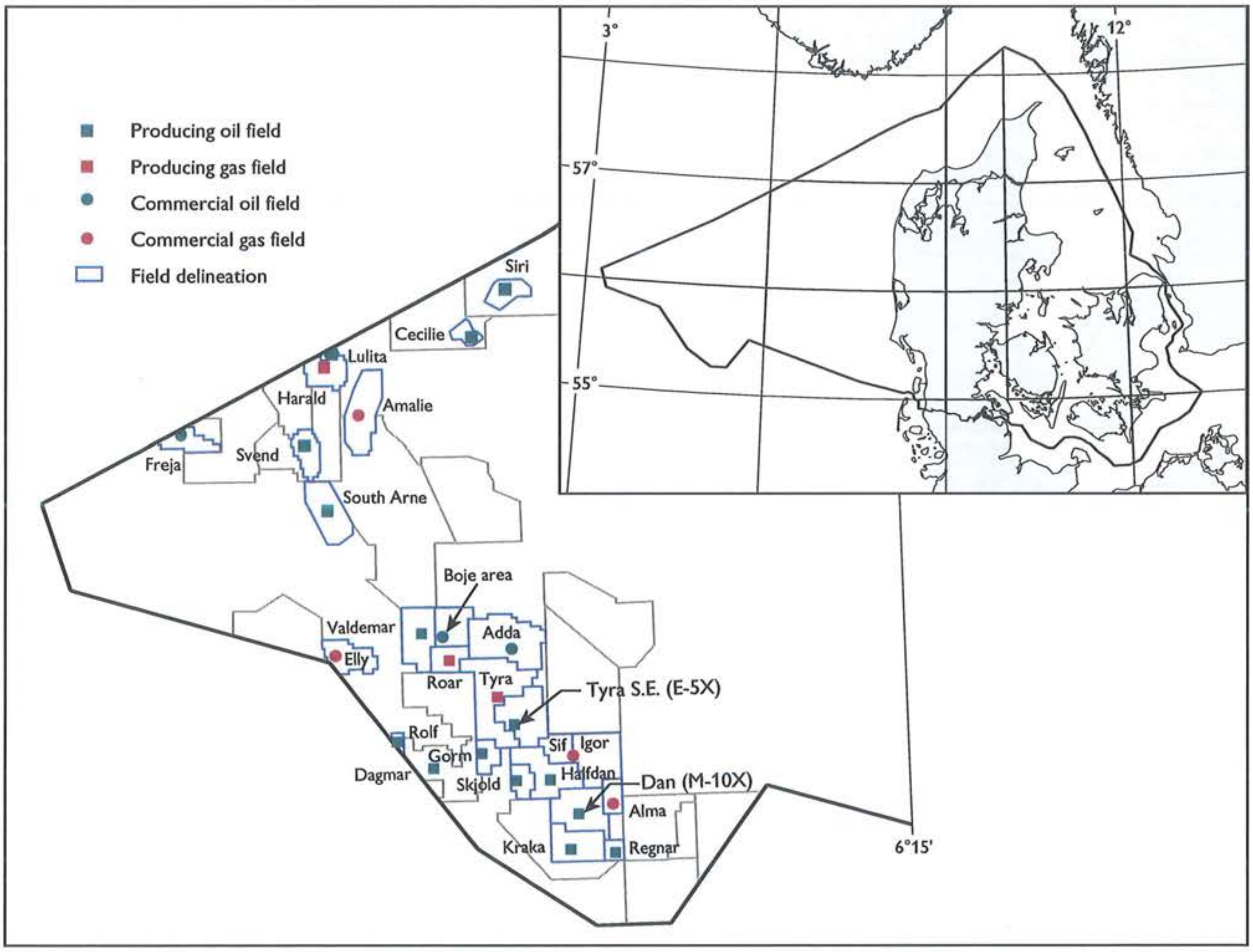


Fig. 1. Danish oil and gas fields
(Figure taken from 'Oil and Gas Production in Denmark 2003'; the Danish Energy Authority).

# Geological setting

The fine-grained Maastrichtian–Danian chalks of the Denmark comprise coccolith and foraminifera-rich cool water carbonates deposited in water depths of up to several hundred metres (Surlyk & Håkansson 1999). The maximum thickness of these pelagic sediments deposited in the Late Cretaceous–Danian is c. 2 km in the Danish Basin with maximum thicknesses of 700 m in the Maastrichtian and 350 m in the Danian (Stenestad 1972).

The Dan and Tyra SE Fields lie approximately 30 km apart and are located in the southern part of the Danish sector of the North Sea, in the so-called 'Salt Dome Province'. The structures in this area are controlled by the diapiric nature of the salt and tectonic uplift.
The Dan Field is an anticlinal structure, partly induced through salt tectonics, while the Tyra SE Field is an anticlinal structure created by inversion of Upper Cretaceous chalk layers (DEA 2003).

# Method

Core chips were taken from the Upper Maastrichtian and Lower Danian chalk of the E-5X and M-10X wells (Figure 1).

62 samples were taken from E-5X and 104 from M-10X (Appendix I). Sample spacing was approximately 3 feet in the uniform chalk. Closer sample spacing (every 5 to 6 inches) was undertaken at critical horizons; namely the Cretaceous/Tertiary boundary and an interval of M-10X examined for cyclicity (Ineson *et al.* 2004a, this study).

Nannofossil smear slides were prepared using the simple smear slide technique described in Bown & Young (1998), that is, a small amount of chalk was scraped from a freshly broken surface and placed on a glass slide and a drop of water added to make a sediment suspension. The suspension was smeared back and forth over the slide until a uniform rippled effect was obtained and the slide quickly dried. An epoxy resin (Norland Optical Adhesive©) was added to a coverslip and this was placed face down on the glass slide. The slide was then left to cure under UV light (sunlight) for 24 hours before analysis.

As the core was drilled in major hydrocarbon reservoir levels, core chips were often still saturated in oil when they were processed. As smear slides are prepared using water, 'clumping' was often a minor problem. This occurs where the mixture of oil and water prevents the chalk from disaggregating. To alleviate this, a mild detergent (washing-up liquid) can be added to the suspension.

The prepared slides were examined using a Leitz Labrolux 8 light microscope. Simple relative abundance counting (Bown & Young 1998) was utilised in this study, i.e. a minimum of 300 specimens were counted (the number generally regarded as statistically valid) from each slide so as to record the presence of rare taxa (Appendices IIIa & IIIb).

## Preservation

As has been noted in the foraminiferal studies (Lassen & Rasmussen 2004, this study), diagenetic overgrowth is a problem that has to be taken into account when processing and analysing samples. In the present nannofossil study, it was noted that the chalk in M-10X in particular suffered calcite overgrowth. In some cases (particularly in the Danian, and as might be expected, around the Upper Maastrichtian hardground), the overgrowth prevented certain nannofossils from being identified to species level. In comparison, nannofossil assemblages from the E-5X well were extremely well preserved, with even the most delicate forms remaining in pristine condition. (Surprisingly, this is not in agreement with the foraminifera study from this well, Lassen & Rasmussen 2004, this study).

The cause of the difference in degree of calcite overgrowth between the 2 wells is not certain. However, the fact that the same chalk reservoir levels in two relatively closely spaced wells exhibit extreme differences in preservation could reflect differences in the timing of initial oil invasion. Migration of hydrocarbons into pore spaces essentially halts diagenesis so the earlier the migration, the more restricted the carbonate diagenesis. The fact that the reservoir interval in E-5X showed less diagenetic overgrowth is thus compatible with the proposal that the Tyra Field was filled earlier than the Dan Field (Røgen & Fabricius 2004).

## Oil saturation

We tested the implication that oil saturation might reduce diagenetic overgrowth by checking the percentage levels of the solution resistant nannofossils (e.g. *Micula decussata*) against significant hydrocarbon saturation levels (GOC, 50%Sw and OWC). In both E-5X and M-10X, the only notable increase in *M. decussata* occurred around the Upper Maastrichtian hardground. Increases in *M. decussata* were not noted in the regions with lower hydrocarbon saturation levels, i.e. below the OWC. However, it should be noted that residual oil below the OWC implies previous saturation in oil.

Samples from around the Upper Maastrichtian hardground level were more difficult to prepare and analyse than the softer chalk from the reservoir levels. This is reflected in the low species richness at this level in both wells. Species that are solution resistant are present in favour of those that are susceptible to dissolution. This is discussed in further detail in the nannofossil palaeoecology report (Sheldon 2004, this study).

## Reworking and caving

As core material has primarily been used in this study, caving is not a problem. Although reworking is potentially a complicating factor, the sedimentology indicates that pelagic settling and small-volume dilute density flows dominated the depositional system and significant 'stratigraphic' redeposition (i.e. by slumps, slides and debris flows) was rare or absent in this part of the Danish Central Graben (Ineson 2004, this study).

# Previous work / zonation schemes

The biostratigraphic zonation scheme primarily used for the Upper Cretaceous is the 'UC' scheme of Burnett (1998) (Figure 2b). This scheme has been supplemented further by observations of 'Network Stratigraphic' from the report 'A Joint Chalk Stratigraphic Framework' (Fritsen 1999, Figure 2b). Comparison with the 'CC' Zonation scheme of Sissingh (1977), and the 'NK' scheme of Mortimer (1987) is also used where relevant.

The zonation scheme of Varol (1998) has been used for the Paleocene of the North Sea (Figure 2a). Correlation is made with the 'NP' zonation of Martini (1971).

In this study, where cored intervals are assigned to a nannofossil zone or subzone, the 'Interval Zone' convention of Hedberg (1976) is followed.

# Nannofossil biostratigraphy of E-5X

## Subzone UC20b

6975.17′ (lowest sample examined)–6910.25′

### Definition

The base of this subzone in the 'boreal province' is marked by the FO of *Nephrolithus frequens* and the top by the FO of *Arkhangelskiella maastrichtiana* (Burnett 1998).

### Floral characteristics

A high abundance and diversity nannofossil assemblage including *Prediscosphaera cretacea*, *Kamptnerius magnificus*, *Cribrosphaerella ehrenbergii*, *Eiffelithus turriseiffelii*, *Lucianorhabdus cayeuxii*, *Placozygus fibuliformis*, *Prediscosphaera stoveri* and *N. frequens*. Low numbers of *'A. maastrichtiana*-like' forms of *Arkhangelskiella* (see remarks below) up to 6912.41′ indicate assignment of this interval to subzone UC20b. The presence of *N. frequens* indicates that the underlying subzone, UC20a has not been sampled in this well.

### Thickness

The combined thickness of subzones UC20b–d is equal to the total range of *N. frequens* and the total minimum thickness of these subzones in E-5X is calculated to be 137.17′. (Note the base of subzone UC20b is not seen in this well). Since the K/T boundary is dated as 65 Ma and the FO of *N. frequens* at 65.8 Ma (Bralower *et al.* 2002), this gives a minimum sedimentation rate of 5.2 cm per 1000 years.

### Remarks

Subzones UC20b and UC20c are subdivided on the presence/absence of *Arkhangelskiella maastrichtiana* (Burnett 1998). *A. maastrichtiana* is equivalent to the large–very large variety of *Arkhangelskiella* with a broad rim (Varol 1989). This species has not been identified with confidence in this study so the subdivision of these subzones is only tentative. The subdivision in the present study is based upon a morphometric analysis carried out on specimens of *A. cymbiformis* in which the length and rim width of each specimen recorded was measured.

In the present study, specimens with rim widths of 2, 2½ and 3 microns were included in the 'wide' category and those with rim widths of less than 2 in the 'narrow' group. Using this definition of 'wide' rims, there is an increase in the *Arkhangelskiellas* with a rim width of 2½ microns or more from 6910.25′ upwards. This method of defining the boundary between subzones UC20b and UC20c is not entirely consistent with that in M-10X, but as the FO of *A. maastrichtiana* is not as clear-cut as suggested in Burnett (1998), this method made optimal use of the data in the present study (Appendix IIIc).

To be consistent with Varol's study, coccolith length was also taken into account, but once plotted, the large (length >10-18 microns) specimens showed neither a sudden, nor a gradual increase in number anywhere in the section. (A variety of size range plots were made, but did not reveal any patterns).

This subzone coincides with the lower part of subzone UC20i (Network Stratigraphic, in Fritsen 1999).

## Subzone UC20c

6910.25′–6875.33′

### Definition

The base of subzone UC20c of the 'boreal' province is marked by the FO of *Arkhangelskiella maastrichtiana* and the base by the FO of *Cribrosphaerella daniae* (Burnett 1998).

### Floral characteristics

The continued common occurrence of *N. frequens* in a high diversity and abundance nannofossil assemblage (including common to abundant *Arkhangelskiella cymbiformis*, common *Micula decussata*, *L. cayeuxii*, *K. magnificus*, *P. fibuliformis*, *P. cretacea* and *P. stoveri* and present *Biscutum* spp., *Chiastozygus amphipons*, *C. ehrenbergii*, *E. turriseiffelii*, *Prediscosphaera spinosa*, *Eiffelithus gorkae* and *Retecapsa crenulata*) with the absence of *C. daniae* assigns this interval to Upper Maastrichtian subzone UC20c. An increase in numbers of '*A. maastrichtiana* – like' forms of *Arkhangelskiella* from 6910.25′ assigns this interval to subzone UC20c (see remarks above).

### Remarks

This subzone coincides with the upper part of subzone UC20i (Network Stratigraphic, in Fritsen 1999).

## Subzone UC20d

6875.33′–6820.00′

## Definition

The base of subzone UC20d of the 'boreal' province is defined by the FO of *Cribrosphaerella daniae*, and the top by the LO of unreworked, non-survivor taxa (Burnett 1998).

## Floral characteristics

This interval is characterised by an assemblage rich in calcareous nannofossils. Assignment to subzone UC20d is indicated by the co-occurrence of *C. daniae* with common *N. frequens*. The assemblage comprises abundant *M. decussata* (especially in the uppermost part of the interval; probably associated with the hardground at the top of the Maastrichtian) *P. stoveri, A. cymbiformis*, common to abundant *L. cayeuxii*, common *P. cretacea, Ch. amphipons, E. turriseiffelii, K. magnificus and P. fibuliformis.* Species showing low abundances include *Ahmuellerella octoradiata*, *C. ehrenbergii*, *Munarinus* spp., *P. spinosa* and *Watznaueria barnesae*.

## Thickness

Subzone UC20d is equal to the total range of *C. daniae* and the total thickness of this subzone in E-5X is calculated to be 55.33′. Since the K/T boundary is dated at 65 Ma and the FO of *C. daniae* at 65.5 Ma (pers. comm. P. Bown), this gives a sedimentation rate of 3.4 cm per 1000 years.

## Remarks

This subzone coincides with subzone UC20ii (Network Stratigraphic, in Fritsen 1999).

# 'Mixed Zone'

6820.00′–6819.17′

## Definition

From a biostratigraphic point of view, this interval is unofficially termed the 'mixed zone' as it comprises a relatively diverse mix of nannofossils, some common only to the Danian and some only to the Maastrichtian, in addition to those 'survivor' species that were apparently unaffected by the K/T event (Burnett 1998). Due to hardground formation and burrowing (see Ineson 2004, this study), it is difficult to locate oneself using biostratigraphy alone. Each sample in the 'mixed zone' is described below.

## Floral characteristics

6820.00′

This sample is dominated by *M. decussata* and *A. cymbiformis* with common *K. magnificus* and *C. ehrenbergii*. The presence of *N. frequens* and absence of *C. daniae* (along with a fairly diverse flora including *E. turriseiffelii*, *Ch. amphipons*, *A. octoradiata*, *P. stoveri*, *P. cretacea*, *R. crenulata* and *L. cayeuxii*) indicates that the Upper Cretaceous component of this sample is assigned to subzone UC20c. However, the presence of chalk from subzone UC20d cannot be ruled out as *C. daniae* is often very rare and may have existed in numbers too low to be included in the 300 counts for each sample in this study. In addition, evidence of subzone UC20d was noted in the overlying sample. This sample from the 'mixed zone' is dominated by Upper Cretaceous forms and the only evidence of Danian flora are rare occurrences of *Prinsius dimorphosus* and *Placozygus sigmoides,* very tentatively indicating assignment to subzones NNTp2D–E.

6819,50´

A patchy differential cementation was noted at this level with hardened matrix chalk and softer chalk, probably within *Thalassinoides* galleries (Ineson 2004, this study). Two samples were thus taken at this level, one from a softer area of chalk and one from a hard region. They were analysed as two separate samples.

6819,50´ (soft chalk)

The mainly Upper Cretaceous nannofossil assemblage in this sample is dominated by *M. decussata* (a robust species associated with hardground levels). Also showing high abundances are *A. cymbiformis*, and *C. ehrenbergii*. Common constituents include *E. turriseiffelii* and *P. cretacea*. The absence of the uppermost Maastrichtian marker species *C. daniae* and *N. frequens* suggest the Maastrichtian flora is assigned to subzone UC20b, UC20a or the upper part of zone UC19 (UC19iii - Network Stratigraphic, in Fritsen 1999). An alternative explanation is that *C. daniae* and *N. frequens* are in fact present at this level but in abundances too low to show up in 300 counts. However, low numbers of Danian nannofossils (plus the high abundance of *Thoracosphaera* spp.) including *P. dimorphosus*, *P. sigmoides*, *Cruciplacolithus asymmetricus* and *Cruciplacolithus intermedius* indicate that a Danian age (probably NNTp2D–E) for components of this sample cannot be discounted.

6819,50´ (hard chalk)

This sample is interesting as some nannofossil species exhibit similar patterns and some show totally different patterns to those in the soft chalk sample from the same depth. In this sample, the abundance of *Thoracosphaera* spp. was negligable, whereas in the soft chalk, it was a dominant species. Similarly, *C. ehrenbergii* was present in the current sample, but was abundant in the soft chalk and in the same way *P. cretacea* was common in the soft chalk sample but was seen to be rare in the current sample. Also present in this sample (along with a high diversity assemblage including *K. magnificus*, *E. turriseiffelii*, *A. octoradiata*, *L. cayeuxii* and *W. barnesae*) was *N. frequens*, indicating that this level can in fact be assigned to subzone UC20c (or upper UC20i - Network Stratigraphic, in Fritsen 1999). Apart from the abundance of *Thoracosphaera* spp., the sparse Danian flora did not differ markedly between the two samples; low numbers of *Chiasmolithus* spp. and *P. dimorpho-*

*sus* also tentatively indicate an age of NNTp2D–E for the Danian component of this 'mixed' sample.

### Remarks

The calcareous dinoflagellate cyst, *Thoracosphaera* spp., is found sporadically throughout the Upper Maastrichtian, but is restricted in the Danish area to the Danian and younger sediments (Perch-Nielsen 1979). It appears to 'bloom' or at least becomes the dominant species in the oldest Danian sediments (Perch-Nielsen 1985) and has also been observed in this study (Sheldon 2004, this study).

According to Mortimer (1987) and Network Stratigraphic (in Fritsen 1999), there exists a Maastrichtian nannofossil zone above UC20d. The base of these zones, NK1 and UC20iii respectively, is marked by the LO *N. frequens* and the top by the LO non-reworked Cretaceous taxa. These authors suggest that the low diversity assemblages are either due to hardground formation or that *N. frequens* and *C. daniae* are missing in this zone due to a short climatic change prior to the K/T boundary.
It is possible that the samples assigned to the 'mixed zone' in this study could be assigned to these zones, but as the samples do contain *N. frequens* and *C. daniae*, albeit in low numbers, it is considered here that the Maastrichtian component of these samples is assigned to subzone UC20d and not to UC20iii or NK1.

### Hiatus

In most Cretaceous–Tertiary boundary sections in the North Sea area, Zones NP1 and NP2 (NNTp1A–NNTp2E) are missing or thin, in contrast to onshore Denmark, where complete sections are present (Perch-Nielsen 1979) from the base of the Danian (at the base of the fish clay). Where the fish clay is absent, a hardground is often developed at this level with an accompanying hiatus. This is the case in the wells in this study, with the hiatus apparently spanning NNTp1A–NNTp2D.The two 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.

## Subzone NNTp2E (middle Danian)

6819.17′–6814.17′

### Definition

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* (Varol 1998).

## Floral characteristics

A rich nannofossil assemblage including abundant *P. dimorphosus*, *Cruciplacolithus primus* and *Thoracosphaera* spp., common *Coccolithus pelagicus*, *Cruciplacolithus asymmetricus*, *Cruciplacolithus tenuis*, *Markalius inversus* and *P. sigmoides* and present *Biscutum* spp., *Cruciplacolithus edwardsii*, *Cruciplacolithus intermedius* and *Neocrepidolithus cohenii*. This assemblage, together with the absence of *Ch. danicus* and *H. edwardsii* (marker species for the overlying zone) assigns this interval to NNTp2E.

Rare reworking is present from Upper Maastrichtian subzone UC20d.

## Remarks

NNTp2E coincides with upper Zone NP2 (Martini1971)

# Subzone NNTp2F (middle Danian)

6814.17′–6809.25′ (uppermost sample examined)

## Definition

The base of this subzone is defined by the FO of *Chiasmolithus danicus* and/or *Hornibrookina edwardsii*. The top is defined by the FO of *Coccolithus subpertsus* and/or the FO of *Prinsius tenuiculus* (Varol 1998).

## Floral characteristics

The co-occurrence of *H. edwardsii* and *Ch. danicus* in a fairly high diversity assemblage of nannofossils (including *C. pelagicus*, *Cr. asymmetricus*, *Cr. primus*, *M. inversus, P. sigmoides* and *Cr. edwardsii* with abundant *P. dimorphosus* and *Thoracosphaera* spp.) assigns this interval to subzone NNTp2F.

Rare reworking is present from Upper Maastrichtian Zone UC20.

## Remarks

NNTp2F coincides with lower Zone NP3 (Martini 1971).

# Nannofossil biostratigraphy of M-10X

## Zone UC19

6655.58´ (lowest sample examined)–6647.00´

### Definition

The base of this zone is marked by the last occurrence (LO) of *Reinhardites levis* and the top by the first occurrence (FO) of *Lithraphidites quadratus* (Burnett 1998).

### Floral characteristics

A high abundance and diversity Maastrichtian flora (including abundant *Arkhangelskiella cymbiformis* and *Prediscosphaera cretacea*, and common *Micula decussata*, *Lucianorhabdus cayeuxii*, *Kamptnerius magnificus*, *Prediscosphaera stoveri* and *Placozygus fibuliformis)*, characterised by the absence of *Nephrolithus frequens* and *Cribrosphaerella daniae* (marker species for stratigraphically younger subzones). Also of note is the presence of *Biscutum magnum*, *Gartnerego segmentatum* and *Zeugrhabdotus bicrescenticus* suggesting assignment to Zone UC19.

Reworking from the Campanian is present in the form of rare *Quadrum gartneri*.

### Remarks

The absence of *R. levis* indicates that this interval is no older than Zone UC19.

As mentioned above, the presence of *G. segmentatum*, *B. magnum* and *Z. bicrescenticus* in this interval signals the presence of Zone UC19. When broken, or poorly preserved, there can be a degree of uncertainty surrounding the identification of these marker species. *B. magnum* (a species with a large hole in the central area) is sometimes confused with *Seribiscutum primitivum* (with a characteristic 'zig-zag' central area) with missing central areas (pers. comm. M. Hampton). The LO of *S. primitivum* marks the top of subzone UC19ii (Network Stratigraphic, in Fritsen 1999), as does the LO of *Gartnerego obliquum*. *G. segmentatum* and *G. obliquum* are also often confused with each other due to preservational effects (Burnett 1998).

Subzone UC19ii is equivalent to the middle of Zone UC19.

According to Burnett (1998) and (Network Stratigraphic, in Fritsen 1999), Zone UC19 is characterised by low diversity assemblages. This interval in M-10X does not exhibit low species richness, but due to the appearance of the afore-named species, it is considered probable that this interval is assigned to Zone UC19.

## Subzone UC20a

6647′–6637.33′

### Definition

In the 'boreal' province, the base of this subzone is marked by the FO of *Lithraphidites quadratus*, and the top by the FO of *Nephrolithus frequens* (Burnett 1998).

### Floral characteristics

As is common in the Upper Maastrichtian, the assemblages are characterised by a rich nannoflora including *K. magnificus*, *P. cretacea*, *P. fibuliformis*, *Watznaueria barnesae* and *Arkhangelskiella cymbiformis*. The continued absence of *C. daniae* and *N. frequens*, in addition to the absence of marker species from stratigraphically older levels, suggests the presence of subzone UC20a. There is no evidence of reworking in this interval.

### Remarks

As *L. quadratus* has not been identified in this study, referral to this subzone is somewhat tentative. Assignment to subzone UC20a is based on the absence of marker species from the underlying UC19 Zone and the overlying subzone UC20b.

This subzone is equivalent to the upper part of subzone UC19iii (Network Stratigraphic, in Fritsen 1999).

## Subzone UC20b

6637.33′–6533.17′

### Definition

The base of this subzone in the 'boreal' province (referring to latitudes equal to, or greater than 50°N) is marked by the FO of *N. frequens* and the top by the FO of *Arkhangelskiella maastrichtiana* (Burnett 1998).

### Floral characteristics

A rich nannofossil flora continues to characterise assemblages from this subzone. Assemblages include *A. cymbiformis*, *M. decussata*, *K. magnificus*, *L. cayeuxii*, *P. cretacea*, *P. stoveri*, *P. fibuliformis* and *N. frequens*. Large specimens of *A. cymbiformis* assigned to the '*A. maastrichtiana*-like' forms are present, but only in low numbers in this subzone (see explanation below).

Reworking from the Campanian is represented by rare occurrences of *Orastrum campanensis*, *Monomarginatus* spp. and *Q. gartneri*.

### Thickness

The combined thickness of subzones UC20b–d is equal to the total range of *N. frequens* and the total thickness of these subzones in M-10X is calculated to be 195.41′. Since the K/T boundary is dated as 65 Ma and the FO of *N. frequens* at 65.8 Ma (Bralower *et al.* 2002), this gives a sedimentation rate of 7.4 cm per 1000 years.

### Remarks

Subzones UC20b and UC20c are subdivided on the presence/absence of *Arkhangelskiella maastrichtiana* (Burnett 1998). *A. maastrichtiana* is equivalent to the large–very large variety of *Arkhangelskiella* with a broad rim (Varol 1989). This species has not been identified with confidence in this study so the subdivision of these subzones is only tentative.

The subdivision in the present study is based upon a morphometric analysis carried out on specimens of *A. cymbiformis* in which the length and rim width of each specimen recorded was measured. In the present study, specimens with rim widths of 2, 2½ and 3 microns were included in the 'wide' category and those with rim widths of less than 2 in the 'narrow' group (Appendices IIIc & IIId). Using these definitions, there is a shift to higher numbers of the 'wide' rimmed varieties from 6533.17′ upwards.

As the criteria for identifying the boundary between subzones b and c differ slightly between E-5X and M-10X, this boundary should be taken as tentative. However, stratigraphically, it is in accordance with the stratigraphy from micropalaeontological (Lassen & Rasmussen 2004, this study) palynological (Schiøler 2004, this study) and isotope (Schovsbo & Buchardt 2004, this study) investigations.

In order to be consistent with the study of Varol (1989), coccolith length was also taken into account, but once plotted, the large (length >10–18 microns) specimens demonstrated neither a sudden, nor a gradual increase in number anywhere in the section. (A variety of size range plots were made, but did not reveal any patterns).

This subzone coincides with the lower part of subzone UC20i (Network Stratigraphic, in Fritsen 1999).

## Subzone UC20c

6533.17′–6507.66′

### Definition

The base of subzone UC20c of the 'boreal' province is marked by the FO of *Arkhangelskiella maastrichtiana* and the base by the FO of *Cribrosphaerella daniae* (Burnett 1998).

### Floral characteristics

The nannofloral assemblage is very similar to that in the underlying interval. *C. daniae* is absent while *N. frequens* is present, indicating the continuation of Upper Maastrichtian sediments. As in the previous subzone, the assemblage comprises a high abundance and diversity of nannofossils, including *K. magnificus*, *P. fibuliformis*, *Cribrosphaerella ehrenbergii*, *E. turriseiffelii*, *P. cretacea*, *P. stoveri*, *Ahmuellerella octoradiata* and *W. barnesae*. The presence, in fairly high numbers, of '*A. maastrichtiana*-like' forms of *Arkhangelskiella* assigns this interval to subzone UC20c (see remarks above).

Reworking from the Lower Maastrichtian is indicated by the occasional occurrence of *Calculites obscurus* and *Tranolithus orianatus* and from the Campanian as indicated by *Orastrum campanensis*.

### Remarks

For discussion of *A. maastrichtiana,* see remarks on subzone UC20b and Appendices IIIc & IIIb.

This subzone coincides with the upper part of subzone UC20i (Network Stratigraphic, in Fritsen 1999).

## Subzone UC20d

6507.66–6441.92′

### Definition

The base of subzone UC20d of the 'boreal' province is defined by the FO of *Cribrosphaerella daniae*, and the top by the LO of unreworked, non-survivor taxa (Burnett 1998).

### Floral characteristics

This interval is characterised by high abundance and diversity assemblages typical of the Upper Maastrichtian. The rich nannoflora is dominated by *M. decussata*, *L. cayeuxii* and *A. cymbiformis*. Other common species are *K. magnificus*, *E. turriseiffelii*, *C. ehrenbergii*, *Chiastozygus amphipons*, *P. cretacea* and *P. stoveri*. In addition, the co-occurrence of *N. frequens* and *C. daniae* assign this interval to subzone UC20d. This interval is also characterised by low numbers of other species present throughout the Upper Cretaceous such as *A. octoradiata, P. fibuliformis*, *W. barnesae*, *Octocyclus reinhardtii*, *Retecapsa crenulata*, *Prediscosphaera grandis*, *Prediscosphaera spinosa,* and *Cretarhabdus conicus*.

The presence of *Percivalia fenestrata* and *Q. gartneri* indicates reworking from the Campanian.

### Thickness

Subzone UC20d is equal to the total range of *C. daniae* and the total thickness of this subzone in M-10X is calcuated to be 65.74'. Since the K/T boundary is dated at 65 Ma and the FO of *C. daniae* at 65.5 Ma (pers. comm P. Bown), this gives a sedimentation rate of 4 cm per 1000 years.

### Remarks

This subzone coincides with subzone UC20ii (Network Stratigraphic, in Fritsen 1999).

According to Bergen & Sikora (1998), *P. grandis* has its LO in the lower part of Zone CC26 of Sissingh (1977) in the chalk of southern Norwegian hydrocarbon fields. This is equivalent to the lower part of subzone UC20d of Burnett (1998). This event is also seen in M-10X in subzone UC20d, before the FO of *C. daniae* (see Appendix IIIb).

## 'Mixed Zone'

6441.92′–6439.00′

### Definition

From a biostratigraphic point of view, this interval is unofficially referred to the 'mixed zone' as it comprises a relatively diverse mix of nannofossils, some common only to the Danian and some only to the Maastrichtian, as well as those 'survivor' species that were apparently unaffected by the K/T event (Burnett 1998). Due to hardground formation and burrowing (see Ineson 2004, this study), it is difficult to accurately date the three samples assigned to this interval using biostratigraphy alone. Each sample in the 'mixed zone' is described below.

## Floral characteristics

6441.92´

Although this sample is almost completely dominated by Upper Cretaceous flora, the common occurrence of *Thoracosphaera* spp. would not rule out the possibility that this sample contains Danian elements. However, the lack of any other Danian nannofossils makes it impossible to assign this sample to a particular Danian nannofossil zone. The Upper Cretaceous flora shows fairly high diversity (comprising abundant *M. decussata* and *A. cymbiformis,* common *L. cayeuxii* and lower numbers of *E. turriseiffelii*, *K. magnificus*, *Ch. amphipons, P. stoveri*, *A. octoradiata* and *C. ehrenbergii*), but the lack of the Upper Maastrichtian marker species *Nephrolithus frequens* and *Cribrosphaerella daniae* enables only a general Upper Cretaceous age to be assigned to this sample.

6440.50´

While just over half of the nannofossils counted in this sample are assigned to the middle Danian subzone NNTp2E (represented by common *Prinsius dimorphosus*, *Cruciplacolithus asymmetricus*, large specimens of *Placozygus sigmoides* and abundant *Thoracosphaera* spp.), 40% of the flora is assigned to the Upper Cretaceous (Upper Maastrichtian subzone UC20d). The Upper Cretaceous assemblage includes *C. ehrenbergii*, *A. cymbiformis, W. barnesae*, *N. frequens*, *C. daniae*, *E. turriseiffelii, P. fibuliformis* and *C. conicus.* On the basis of biostratigraphic data alone, it cannot be determined whether this sample represents Upper Maastrichtian reworking within Danian chalk, or Danian forms introduced by burrowing into Maastrichtian chalk. Based on regional stratigraphy and sedimentological observations, the latter is deemed most likely (Ineson *et al.* 2004b, this study).

6439.33´

This sample is dominated by Danian flora, although 8% of the total flora is assigned to the Upper Maastrichtian. The Danian flora comprises abundant *P. dimorphosus*, *Cruciplacolithus primus*, *P. sigmoides* and *Thoracosphaera* spp., and present *Cr. asymmetricus*, *Cruciplacolithus intermedius, Coccolithus pelagicus* and *Biscutum* spp. The Danian assemblage in this sample (due to the absence of *Chiasmolithus danicus*, a marker species for the overlying subzone NNTp2F) is assigned to nannofossil subzone NNTp2E.

Upper Maastrichtian nannofossils are assigned to subzone UC20d (Burnett 1998) and are represented by low numbers of *C. daniae*, *N. frequens*, *E. turriseiffelii*, *A. octoradiata*, *L. cayeuxii*, *P. stoveri, M. decussata* and *K. magnificus*.

Although dominated by Danian forms, regional considerations indicate an origin as open burrow fills at the Maastrichtian hardground (see above).

## Remarks

The calcareous dinoflagellate cyst, *Thoracosphaera* spp., is found sporadically throughout the Upper Maastrichtian, but is restricted in the Danish area to the Danian and younger sediments (Perch-Nielsen 1979). It appears to 'bloom' or at least becomes the dominant species in the oldest Danian sediments (Perch-Nielsen 1985), and has also been observed in this study (Sheldon 2004, this study).

According to Mortimer (1987) and Network Stratigraphic (in Fritsen 1999), there exists a Maastrichtian nannofossil zone above UC20d. The base of these zones, NK1 and UC20iii respectively, is marked by the LO *N. frequens* and the top by the LO non-reworked Cretaceous taxa. These authors suggest that the low diversity assemblages are either due to hardground formation or that *N. frequens* and *C. daniae* are missing in this zone due to a short climatic change prior to the K/T boundary.

It is possible that the samples assigned to the 'mixed zone' in this study could be assigned to these zones, but as the samples do contain *N. frequens* and *C. daniae*, albeit in low numbers, it is considered here that the Maastrichtian component of these samples should be assigned to subzone UC20d and not to UC20iii or NK1.

### Hiatus

In most Cretaceous–Tertiary boundary sections in the North Sea area, Zones NP1 and NP2 (NNTp1A–NNTp2E) are missing or thin, in contrast to onshore Denmark, where complete sections are present (Perch-Nielsen 1979) from the base of the Danian (at the base of the fish clay). Where the fish clay is absent, a hardground is often developed at this level with an accompanying hiatus. This is the case in the wells in this study, with the hiatus apparently spanning NNTp1A–NNTp2D.The two 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.

## Subzone NNTp2E (middle Danian)

6439.00′–6436.83′

### Definition

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* (Varol 1998).

### Floral characteristics

This interval is characterised by high abundance and fairly high diversity nannofossil assemblages. The samples are particularly rich in *P. dimorphosus*, the calcareous dinoflagellate cyst *Thoracosphaera* spp. and *Cr. primus*. Other common to present constituents are *Chiasmolithus edwardsii, C. pelagicus, Cr. asymmetricus, Cruciplacolithus intermedius, P.*

*sigmoides* and *Markalius inversus*. *Cruciplacolithuis tenuis*, *Neocrepidolithus dirimosus* and *Biscutum* spp. are found in low numbers.

Minor reworking of Upper Cretaceous sediments into the Danian is indicated by rare occurrences of *W. barnesae, A. cymbiformis,* and *K. magnificus*.

This assemblage (along with the absence of *Ch. danicus*, the marker nannofossil for the overlying NNTp2F subzone) assigns this interval to the NNTp2E nannofossil subzone of Varol (1998).

### Remarks

NNTp2E coincides with upper Zone NP2 (Martini 1971)

## Subzone NNTp2F (middle Danian)

6436.83′–6433.58′ (uppermost sample examined)

### Definition

The base of this subzone is defined by the FO of *Chiasmolithus danicus* and/or *Hornibrookina edwardsii*. The top is defined by the FO of *Coccolithus subpertsus* and/or the FO of *Prinsius tenuiculus* (Varol 1998).

### Floral characteristics

The occurrence of *Ch. danicus* and absence of *C. pertusus* and *P. tenuiculus*, indicates the presence of subzone NNTp2F. This interval is also characterised by abundant *P. dimorphosus*, common *C. pelagicus* and *Cr. primus.* The remainder of the assemblage includes low numbers of *Ch. edwardsii*, *Cr. asymmetricus*, *M. inversus*, *Biscutum harrisonii*, *Cr. intermedius*, *Chiasmolithus inconspicuus*, *P. sigmoides* and *Thoracosphaera* spp.

Minor reworking of Upper Cretaceous sediments into this interval of the Danian is indicated by rare occurrences of *E. turriseiffelii*, *M. decussata, A. cymbiformis* and *C. conicus*.

### Remarks

NNTp2F coincides with lower Zone NP3 (Martini 1971).

## Correlation of wells

The following table shows the thickness of each biostratigraphic unit, allowing comparison between the two wells. This is also illustrated on Figure 3.

| | E-5X | | | M-10X | | |
|---|---|---|---|---|---|---|
| | Base | Top | Thickness | Base | Top | Thickness |
| NNTp2F | 6814.17′ | 6809.25′ | 4.92′ (min) | 6436.83′ | 6433.58′ | 3.25′ (min) |
| NNTp2E | 6819.17′ | 6814.17′ | 5.00′ | 6439.00′ | 6436.83′ | 2.17′ |
| 'Mixed Zone' | 6820.00′ | 6819.17′ | 0.83′ | 6441.92′ | 6439.00′ | 2.92′ |
| UC20d | 6875.33′ | 6820.00′ | 55.33′ | 6507.66′ | 6441.92′ | 65.74′ |
| UC20c | 6910.25′ | 6875.33′ | 34.92′ | 6533.17′ | 6507.66′ | 25.51′ |
| UC20b | 6975.17′ | 6910.25′ | 64.92′ (min) | 6637.33′ | 6533.17′ | 104.16′ |
| UC20a | - | - | - | 6647.00′ | 6637.33′ | 9.67′ |
| UC19 | - | - | - | 6655.58′ | 6647.00′ | 8.58′ (min) |

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# Appendix I: Sample lists

## M-10X

List of samples from M-10X (in feet)

| | | |
|---|---|---|
| 6434.58 | 6522.25 | 6616.58 |
| 6436.33 | 6525.25 | 6617.17 |
| 6436.83 | 6528.92 | 6617.58 |
| 6438.17 | 6531.00 | 6618.00 |
| 6438.83 | 6533.17 | 6618.41 |
| 6439.00 | 6539.92 | 6618.58 |
| 6439.33 | 6542.58 | 6619.00 |
| 6440.50 | 6546.41 | 6619.41 |
| 6441.92 | 6548.92 | 6623.00 |
| 6443.41 | 6552.25 | 6626.41 |
| 6444.83 | 6554.83 | 6629.33 |
| 6446.50 | 6557.58 | 6631.66 |
| 6448.17 | 6560.75 | 6634.41 |
| 6449.50 | 6563.41 | 6637.33 |
| 6451.83 | 6564.66 | 6641.00 |
| 6454.33 | 6568.25 | 6644.00 |
| 6456.75 | 6571.17 | 6647.00 |
| 6458.17 | 6573.66 | 6648.50 |
| 6460.00 | 6577.08 | 6652.58 |
| 6463.00 | 6579.83 | 6655.58 |
| 6465.25 | 6582.58 | |
| 6467.66 | 6586.25 | |
| 6472.33 | 6590.00 | |
| 6475.17 | 6592.00 | |
| 6477.00 | 6598.50 | |
| 6481.00 | 6601.58 | |
| 6483.83 | 6604.92 | |
| 6487.25 | 6608.08 | |
| 6489.50 | 6610.00 | |
| 6491.50 | 6611.58 | |
| 6495.60 | 6612.33 | |
| 6497.33 | 6612.66 | |
| 6499.00 | 6613.08 | |
| 6500.08 | 6613.50 | |
| 6502.33 | 6614.08 | |
| 6503.25 | 6614.41 | |
| 6505.08 | 6614.58 | |

| | |
|---|---|
| 6507.66 | 6615.00 |
| 6511.50 | 6615.33 |
| 6514.50 | 6615.58 |
| 6516.65 | 6615.92 |
| 6519.41 | 6616.25 |

## E-5X

List of samples from E-5X (in feet)

| | | |
|---|---|---|
| 6809.25 | 6847.83 | 6919.17 |
| 6812.41 | 6859.83 | 6920.75 |
| 6814.17 | 6863.33 | 6923.83 |
| 6817.58 | 6866.25 | 6926.17 |
| 6818.66 | 6869.33 | 6928.58 |
| 6818.92 | 6872.66 | 6932.41 |
| 6819.17 | 6875.33 | 6935.83 |
| 6819.50 (hard chalk) | 6877.66 | 6938.33 |
| 6819.50 (soft chalk) | 6881.41 | 6941.17 |
| 6820.00 | 6883.92 | 6943.25 |
| 6821.08 | 6887.25 | 6948.92 |
| 6823.33 | 6889.33 | 6950.41 |
| 6824.83 | 6890.66 | 6952.92 |
| 6826.66 | 6894.00 | 6956.83 |
| 6827.92 | 6897.92 | 6960.17 |
| 6830.00 | 6900.75 | 6963.17 |
| 6833.50 | 6903.75 | 6965.17 |
| 6836.83 | 6906.83 | 6968.58 |
| 6839.25 | 6910.25 | 6972.17 |
| 6841.92 | 6912.41 | 6975.17 |
| 6845.83 | 6916.33 | |

# Appendix II: Species list

*Arkhangelskiella cymbiformis*
*Ahmuellerella octoradiata*
*Biantholithus sparsus*
*Biscutum dissimilis*
*Biscutum ellipticum*
*Biscutum harrisonii*
*Biscutum magnum*
*Biscutum meleniae*
*Biscutum* spp.
*Braarudosphaera bigeloweii*
*Calculites obscurus*
*Chiasmolithus danicus*
*Chiasmolithus inconspicuus*
*Chiastozygus amphipons*
*Coccolithus pelagicus*
*Cretarhabdus conicus*
*Cribrosphaerella daniae*
*Cribrosphaerella ehrenbergii*
*Cruciplacolithus asymmetricus*
*Cruciplacolithus edwardsii*
*Cruciplacolithus intermedius*
*Cruciplacolithus primus*
*Cruciplacolithus tenuis*
*Cyclagelosphaera reinhardtii*
*Cylindralithus sculptus*
*Cylindralithus* spp.
*Discorhabdus ignotus*
*Eiffelithus gorkae*
*Eiffelithus turriseiffelii*
*Gartnerego segmentatum*
*Gartnerego theta*
*Haquis circumradiatus*
*Hornibrookina edwardsii*
*Kamptnerius magnificus*
*Lucianorhabdus cayeuxii*
*Markalius apertus*
*Markalius astroporus*
*Markalius inversus*
*Microrhabdulus decoratus*
*Micula decussata*
*Micula praemurus*
*Micula swastica*
*Monomarginatus* spp.
*Munarinus* spp.

*Neocrepidolithus cohenii*
*Neocrepidolithus cruciatus*
*Neocrepidolithus dirimosus*
*Neocrepidolithus neocrassus*
*Neocrepidolithus ruegenensis*
*Nephrolithus frequens*
*Octocyclus reinhardtii*
*Octolithus multiplus*
*Orastrum campanensis*
*Ottavanius* spp.
*Percivalia fenestrata*
*Placozygus fibuliformis*
*Placozygus sigmoides*
*Pontosphaera* spp.
*Prediscosphaera arkhangelskeyi*
*Prediscosphaera cretacea*
*Prediscosphaera grandis*
*Prediscosphaera spinosa*
*Prediscosphaera stoveri*
*Prinsius dimorphosus*
*Prinsius* coccosphere
*Quadrum gartneri*
*Reinhardites anthophorus*
*Retecapsa crenulata*
*Retecapsa surirella*
*Rhagodiscus indistinctus*
*Rhagodiscus reniformis*
*Rhagodiscus splendens*
*Staurolithites laffittei*
*Staurolithites minutus*
*Staurolithites mutterlosei*
*Staurolithites* spp.
*Thoracosphaera crassa*
*Thoracosphaera operculata*
*Thoracosphaera* spp.
*Tranolithus orianatus*
*Watznaueria barnesae*
*Zeugrhabdotus bicrescenticus*
*Zeugrhabdotus spiralis*

# Appendix III: Range Charts

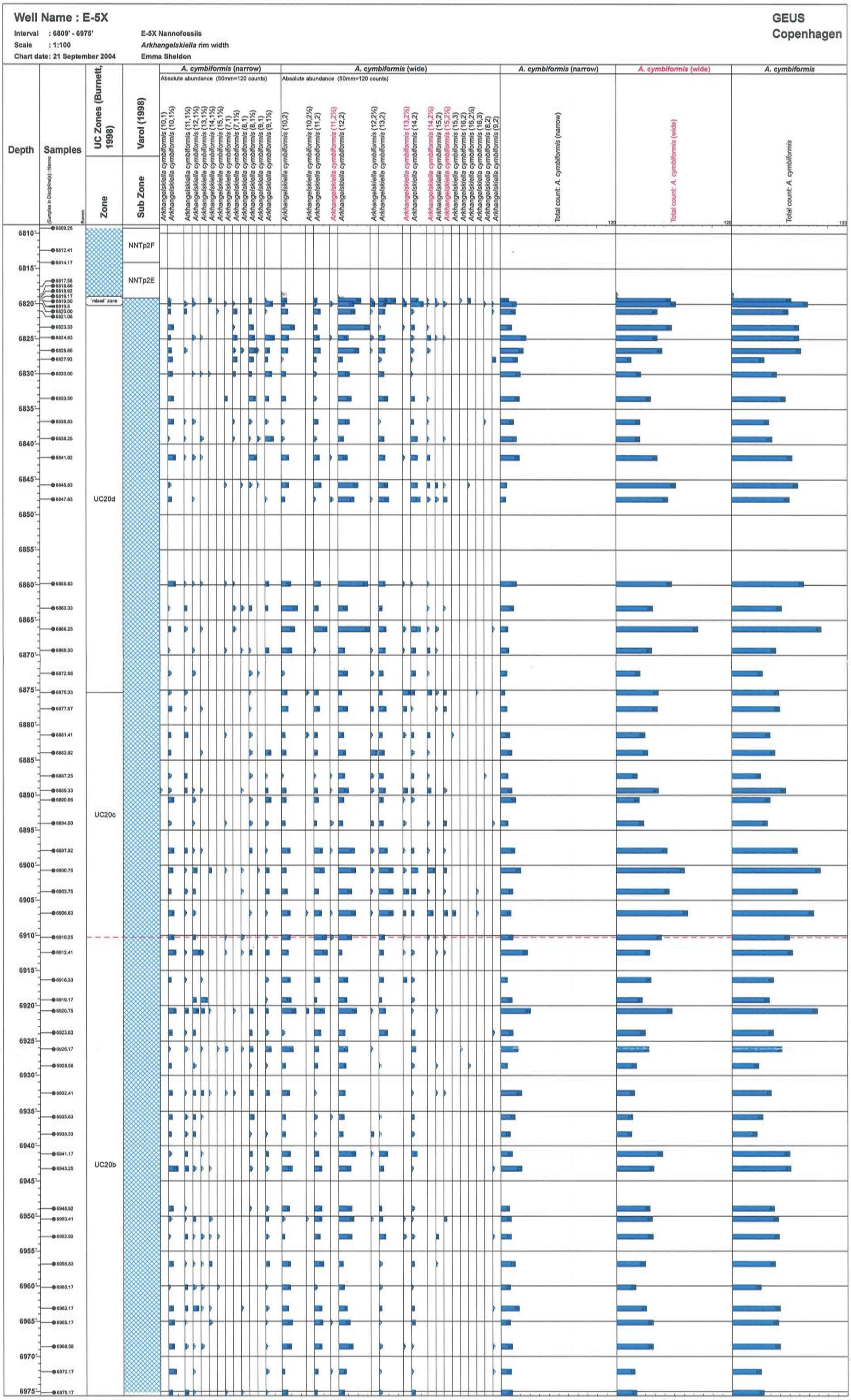
**IIIa** E-5X Nannofossil distribution chart (total abundance)

**IIIb** M-10X Nannofossil distribution chart (total abundance)

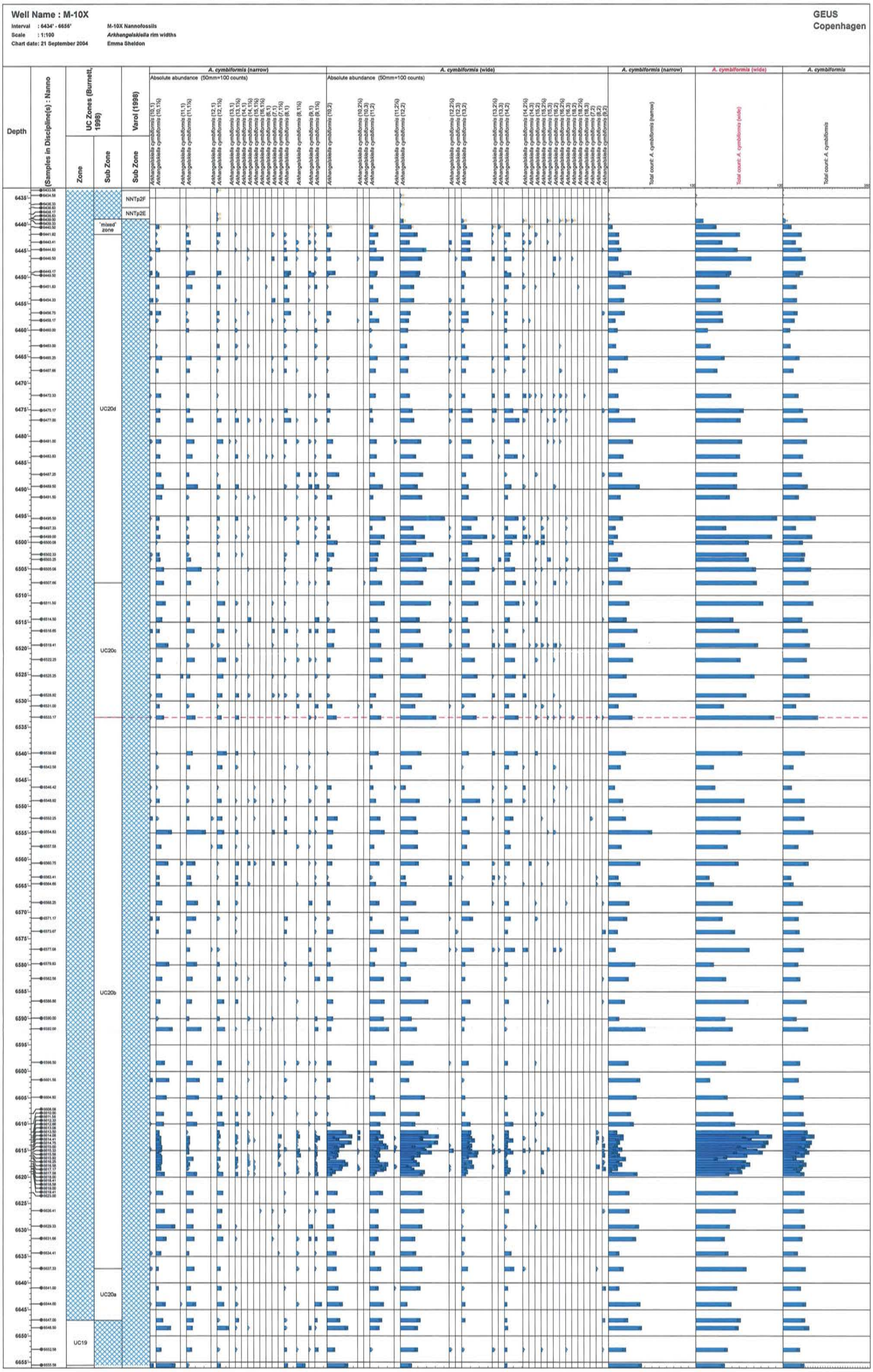
**IIIc** E-5X *Arkhangelskiella cymbiformis* morphometric study

**IIId** M-10X *Arkhangelskiella cymbiformis* morphometric study

## Appendix III (c) E-5X *Arkhangelskiella cymbiformis* morphometric study

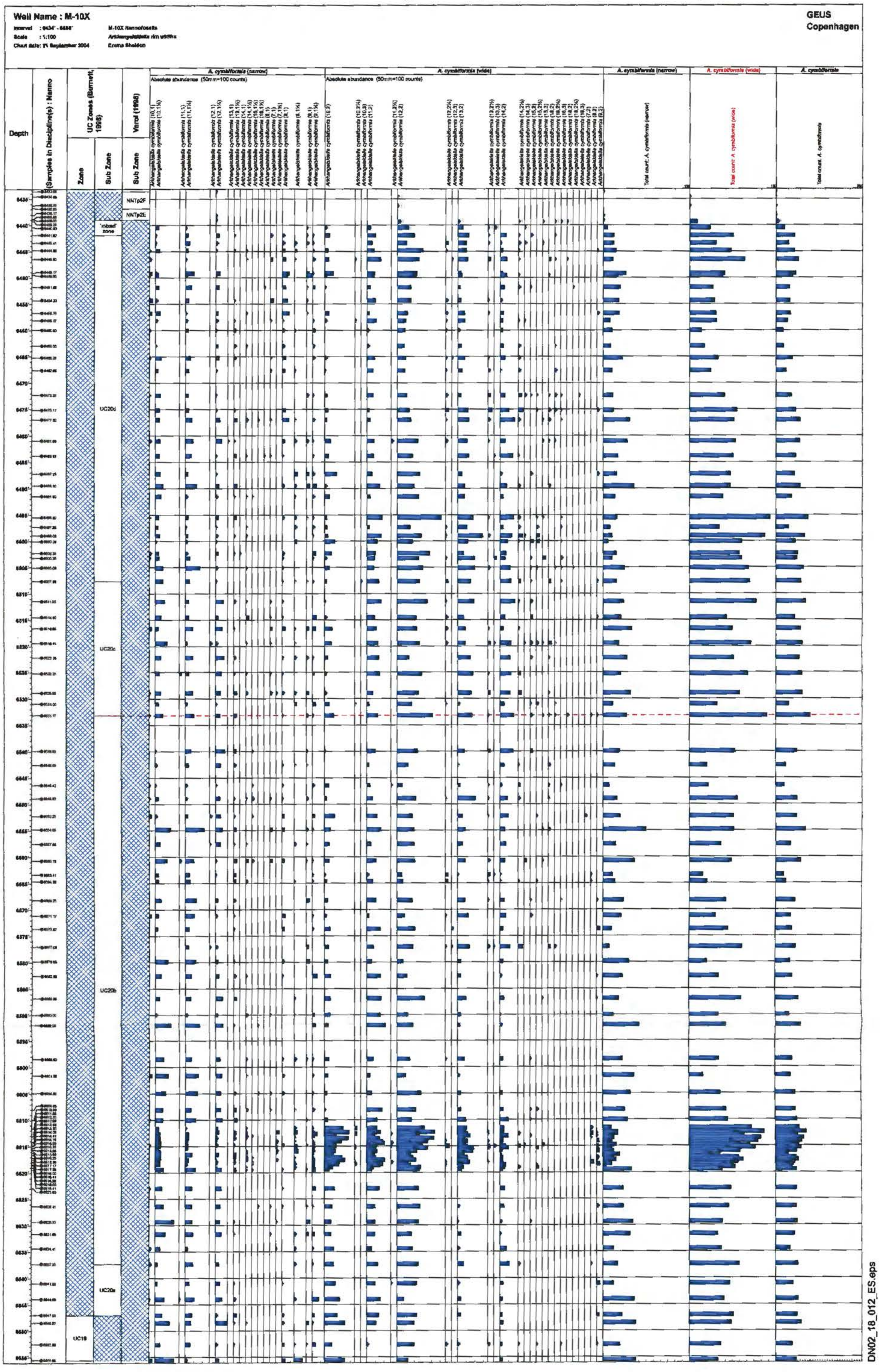


# Appendix III (d) M-10X *Arkhangelskiella cymbiformis* morphometric study

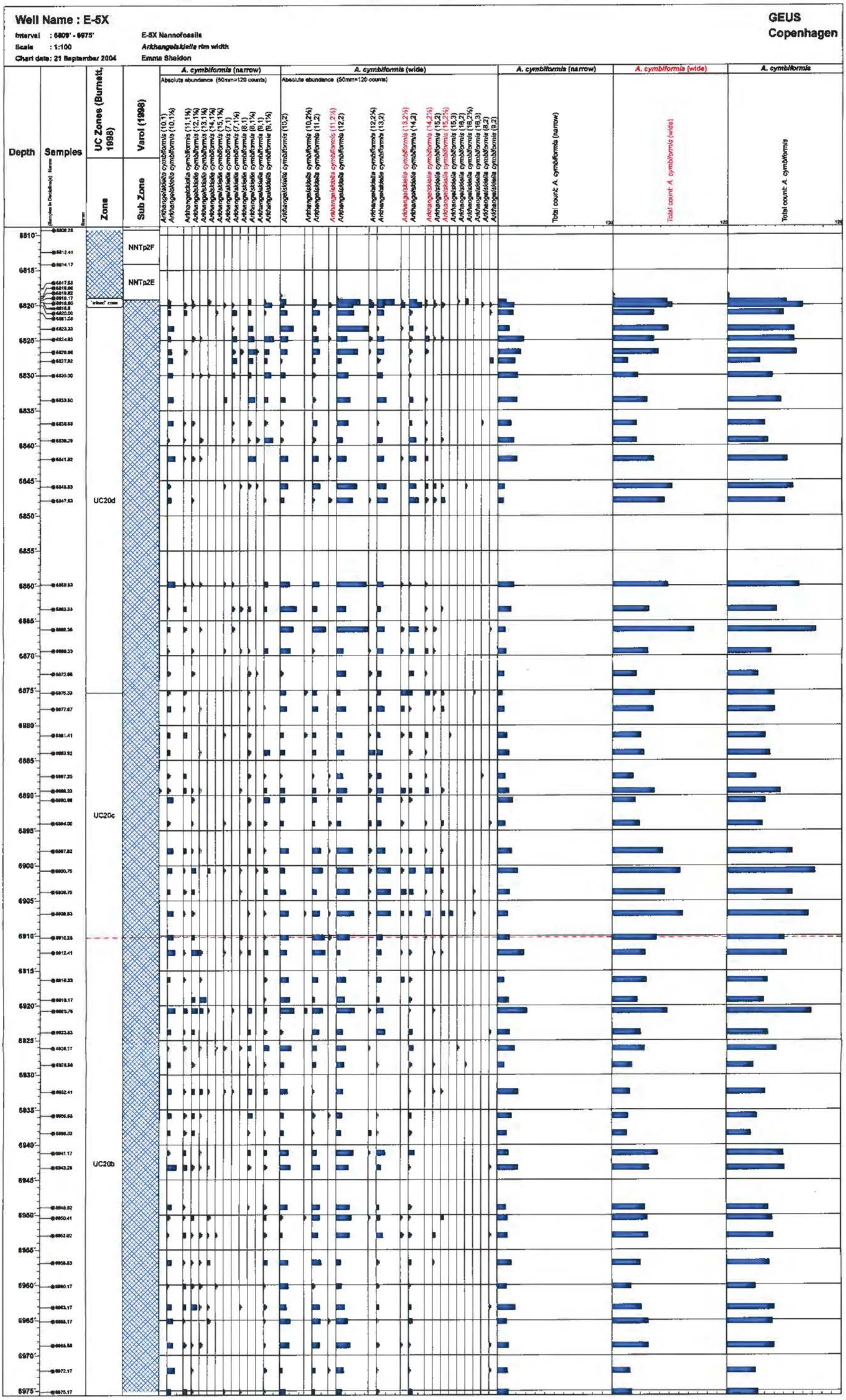



DN02_18_012_ES.eps

# Appendix III (d) M-10X *Arkhangelskiella cymbiformis* morphometric study



# Appendix III (c) E-5X *Arkhangelskiella cymbiformis* morphometric study



# Figures

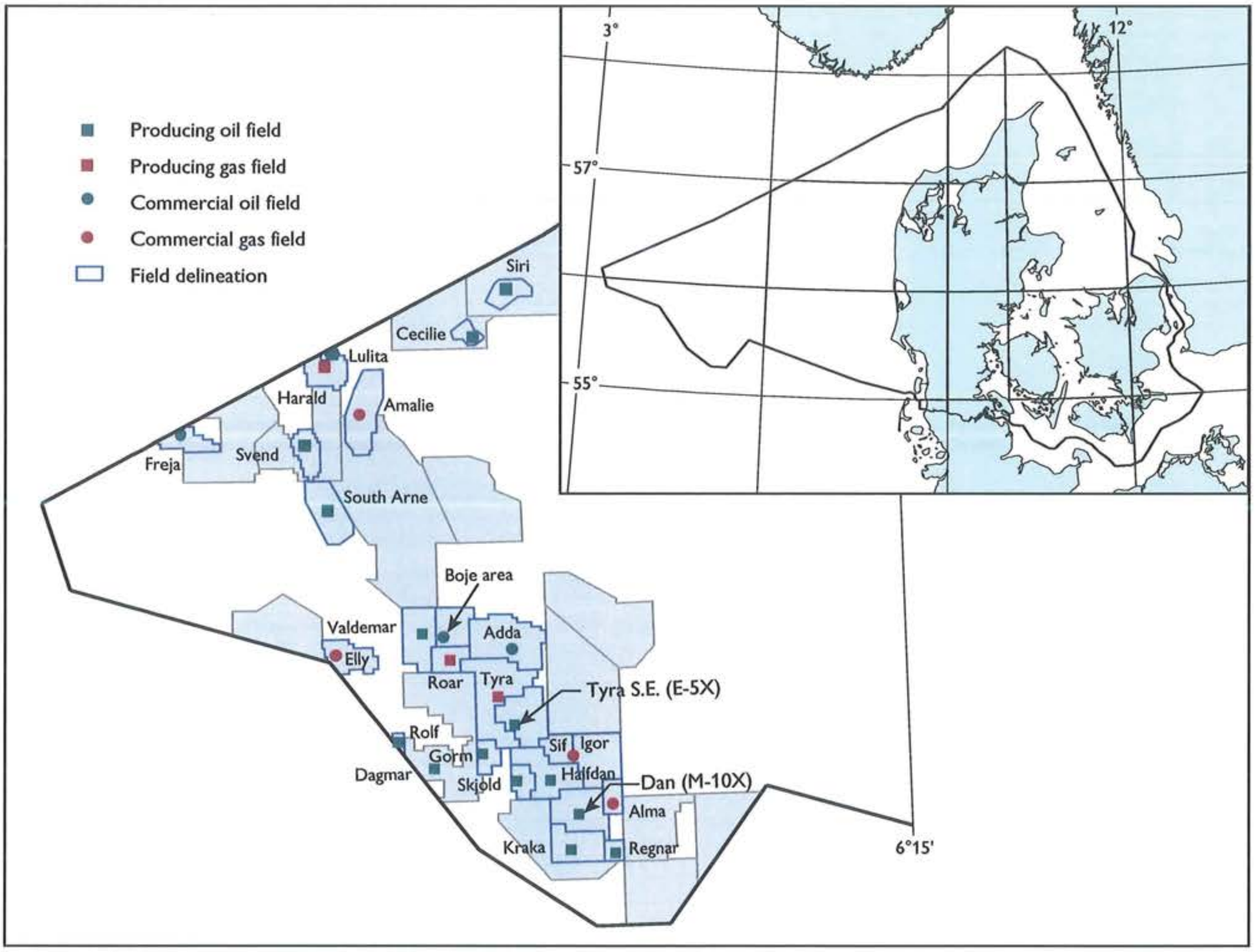



Fig. 1. Danish oil and gas fields
(Figure taken from 'Oil and Gas Production in Denmark 2003'; the Danish Energy Authority).

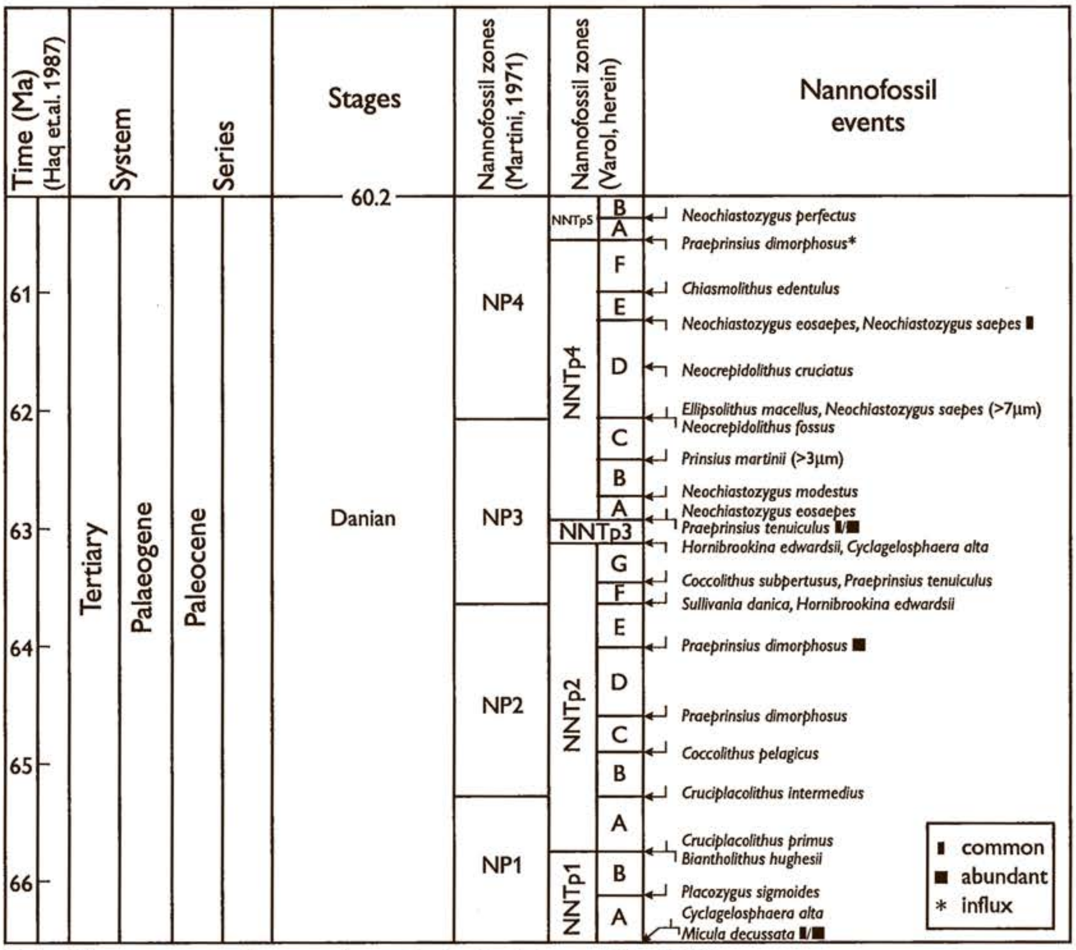



Fig. 2a. Paleocene nannofossil zones and events for the North Sea area (Varol 1998)

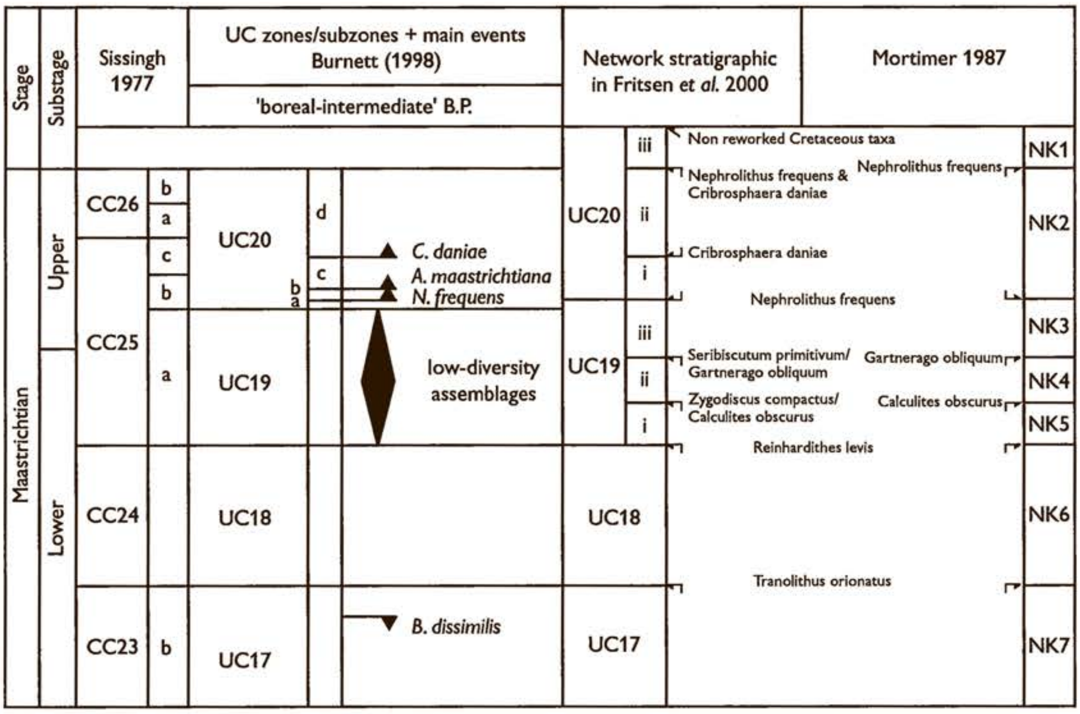



Fig. 2b. Maastrictian nannofossil zonation schemes for Europe (Sissingh 1977) and the 'boreal' province (Burnett 1998)

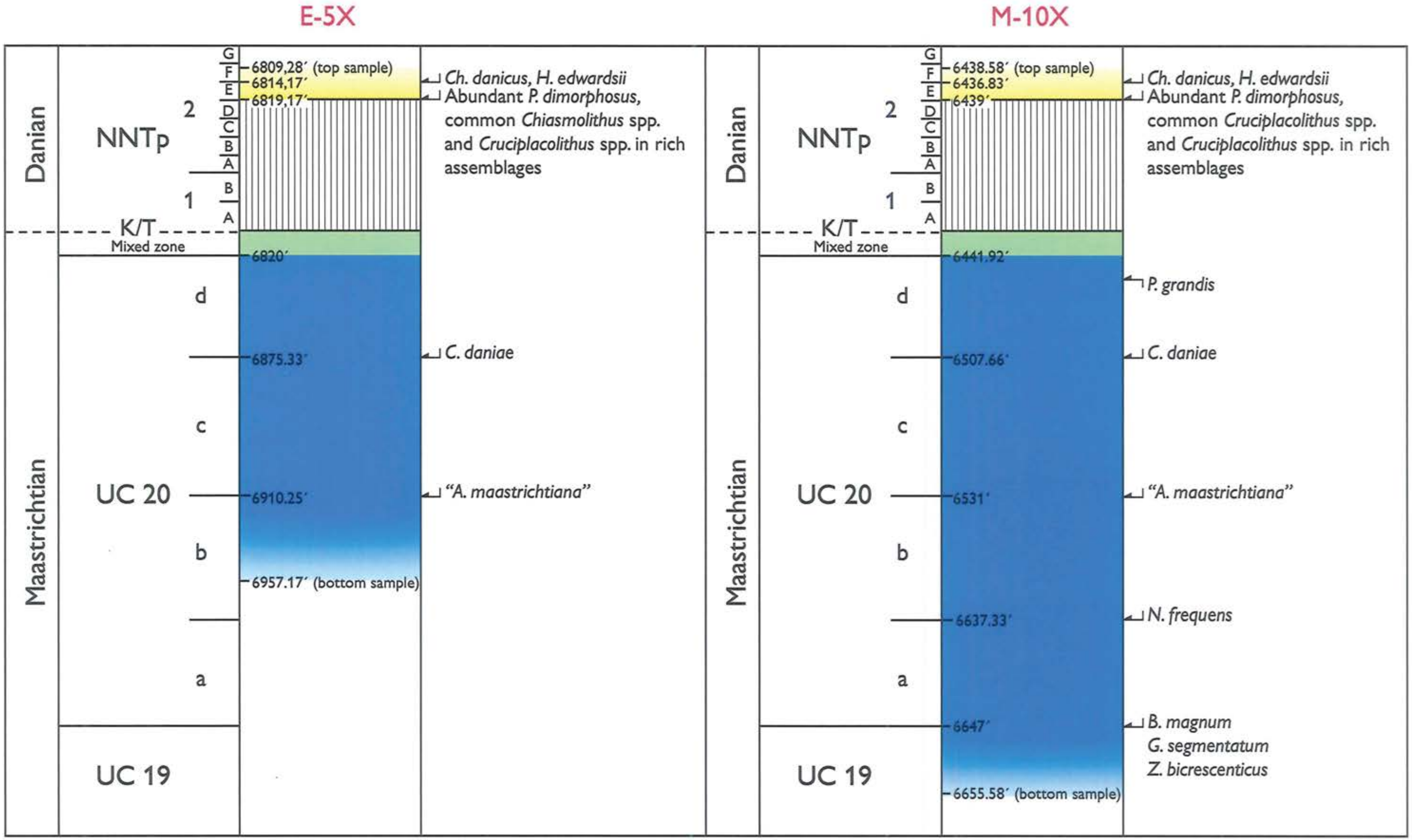



Fig. 3. Upper Maastrichtian – Danian nannofossil biostratigraphy of E-5X and M-10X