Abh. Geol. B.-A.	ISSN 0378-0864 ISBN 3-900312-54-0	Band **39**	S. 285–303	Wien, März 1987

A Refined Nannoplankton Zonation for the Danian of the Central North Sea

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With 20 Figures and 1 Plate

North Sea
Calcareous nannoplankton
Danian
Stratigraphy
Taxonomy
Evolution

Contents

Zusammenfassung

Nach dem Aussterben vieler Arten am Ende des Maastrichtiens ermöglicht die Entwicklung vieler neuer kalkiger Nannofossilien im Danien dessen verfeinerte Unterteilung. Einige Gruppen sind besonders häufig und ihre Entwicklung wurde im Detail untersucht. Indem folgende Arten einer Entwicklungsreihe und ihre Zwischenformen zur Charakterisierung gewisser Intervalle herangezogen werden, ist es möglich, eine Unterteilung zu erarbeiten, die nicht nur feiner, sondern auch zuverlässiger ist als eine Zonierung, die nur auf dem Erstvorkommen nicht verwandter Formen aufgebaut ist.

Die Entwicklungsreihen von *Neochiastozygus* und *Cruciplacolithus-Chiasmolithus* wurden speziell untersucht. Die quantitative Analyse der Verteilung der Arten der Gattungen *Cruciplacolithus-Chiasmolithus* ermöglicht die Erfassung fast jeder Unregelmäßigkeit in der stratigraphischen Abfolge im Danien der Nordsee. Durch eine Kombination der quantitativen Methode mit Leitarten können auch kleinere Hiati erfaßt werden oder auch allochthone Einheiten, deren Alter sich von demjenigen des autochthonen Gesteins um weniger als eine Zone unterscheidet, erkannt werden.

Die folgenden neuen Arten und Kombinationen werden eingeführt: *Chiasmolithus edentulus* n. sp., *Chiasmolithus edwardsii* n. comb., *Chiasmolithus inconspicuus* n. sp., *Coccolithus subpertusus* n. comb., *Coccolithus subrotundus* n. comb., *Cruciplacolithus asymmetricus* n. sp. und *Cruciplacolithus intermedius* n. sp.

Abstract

Because calcareous nannofossils show a strong speciation in the Danian following the severe extinctions at the end of the Cretaceous, the appearances of numerous new taxa make a refined subdivision possible. Some groups are particularly common, and their evolution can be studied in detail. By using successive species of an evolutionary lineage and their intermediates to characterise certain intervals, it is possible to obtain a subdivision that is not only more refined, but also more reliable than a zonation based only on first occurrences of unrelated taxa.

Special attention has been paid to the lineages of *Neochiastozygus* and *Cruciplacolithus-Chiasmolithus*. The analysis of the quantitative development within the *Cruciplacolithus-Chiasmolithus* lineage makes it possible to detect almost any irregularity in the stratigraphic record within the Danian. By applying the quantitative method in combination with marker species, minor hiatuses can be recognised, as well as allochthonous units of which the age differs by less than one zone from the autochthonous material.

The following new species and combinations are introduced: *Chiasmolithus edentulus* n. sp., *Chiasmolithus edwardsii* n. comb., *Chiasmolithus inconspicuus* n. sp., *Coccolithus subpertusus* n. comb., *Coccolithus subrotundus* n. comb., *Cruciplacolithus asymmetricus* n. sp. and *Cruciplacolithus intermedius* n. sp.

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1. Introduction

The discovery of hydrocarbons in the Danian Chalk of the Central North Sea in the late sixties resulted in an increasing interest in this interval. The seemingly erratic distribution of the reservoirs posed severe problems for exploration, and it was felt that an improved biostratigraphic zonation might help to solve them. The abundantly occurring calcareous nannofossils were the obvious choice to obtain a subdivision, but the existing zonations proved inadequate, because they were not refined enough, and because several of the conventional marker species are rare or absent.

Over the following years, a more refined zonation was developed. This helped to identify the hiatuses and allochthonous units which were then demonstrated to be the key to the understanding of the reservoir properties (WATTS et al., 1980; NYGAARD et al., 1983).

The study was confined to core material and sidewall samples, as cuttings are generally too contaminated to allow quantitative analysis. Twenty-nine wells, situated in the Norwegian, Danish and British concession areas of the Central North Sea, were examined (Text-Fig. 1).

The samples were crushed and disintegrated by approximately ten minutes of ultrasonic vibrations in distilled water to which a buffer was added. They were then passed through a 200 mesh sieve, allowed to settle for an hour, and decanted. Smear slides were prepared and mounted with Canada balsam.

All preparations were examined exclusively by transmitted light microscopy. A Leitz Ortholux microscope was used, with a magnification of approximately 1100 X and equipped with a polarization unit and a gypsum plate.

2. Taxonomic notes

(For terminology see Text-Fig. 2)

Chiasmolithus HAY, MOHLER & WADE 1966 emend.

Chiasmolithus bidens (BRAMLETTE & SULLIVAN 1961) HAY & MOHLER 1967

(Text-Fig. 3)

This species has a central structure of which the bars consist of two layers of crystals, which in the light microscope seem to be split in two and show a weak birefringence with cross-polarised light. The species is characterised by having a wall with "small tooth-like projections into the central opening" and a finely perforated bottomplate. In this respect the species resembles *C. grandis*, from which it differs "in the much smaller size of the coccoliths and the vagueness of the tooth-like projections". The specimens occurring in the Danian and commonly assigned to *C. bidens*, lack these tooth-like projections or indentations and show a smooth inner wall. A new species is therefore introduced to accomodate these types (*C. edentulus*). *C. bidens* proper (with indentations) does not seem to occur in the Danian.

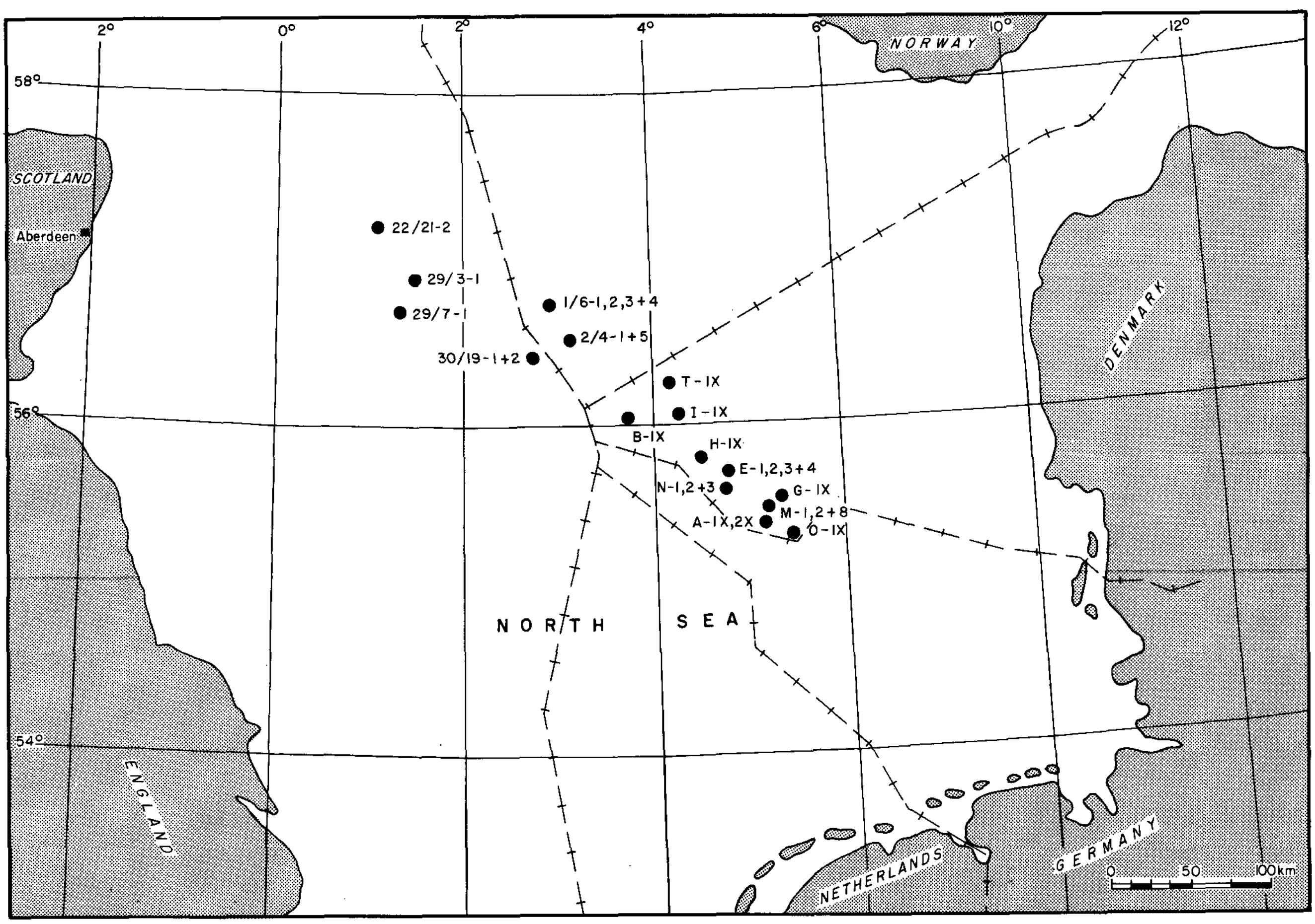

Fig. 1: Locations of the wells in the Central North Sea from which the Danian Chalk has been studied.

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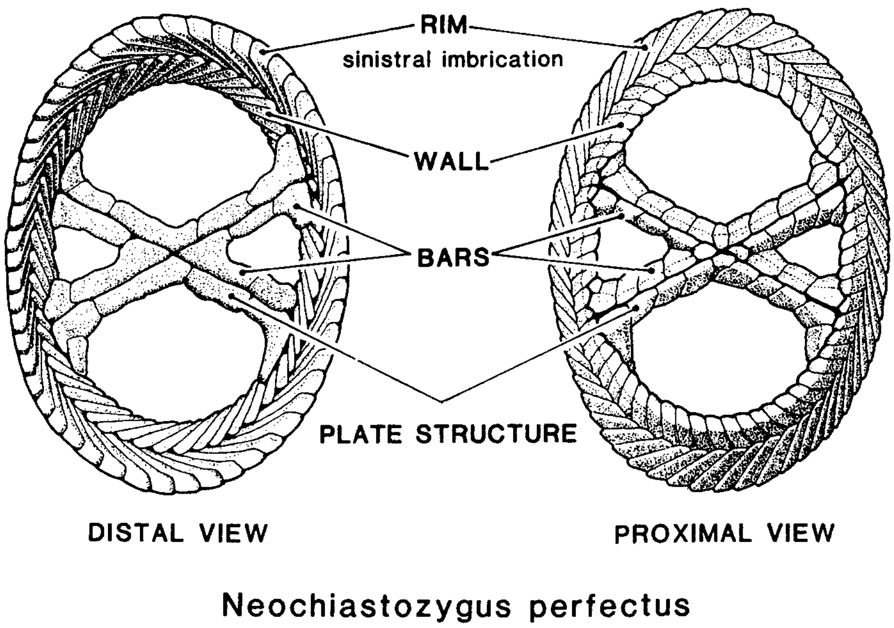

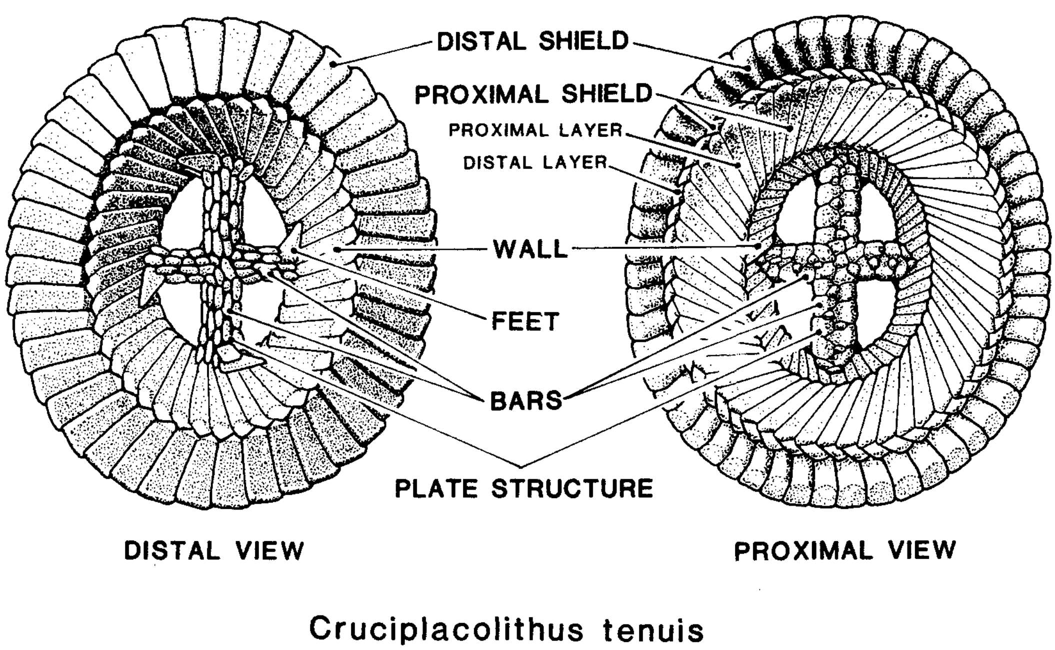

Fig. 2: Schematic drawings, illustrating the morphological terms used.

Chiasmolithus danicus (BROTZEN 1959) ex VAN HECK & PERCH-NIELSEN this volume

(Pl. 1, Figs. 9,10, Text-Figs. 4a–d)

Basionym: *Cribrosphaerella danica* BROTZEN 1959, p. 25, Fig. 9 (invalid).

This species shows a very wide variety of morphologies. The most primitive morphotype (Text-Fig. 4a) has a fairly simple X-shaped central structure in which the bars are of unequal length. The longer bars are slightly bent and off-set from the centre. In a second type (Text-Fig. 4b) the longer bars are more strongly off-set. The X-shaped structure looks very massive but still fairly simple. A third type (Text-Fig. 4c) looks very much like this, but the X-structure seems to be more complex, and is composed of blocks of crystals in different orientations. Of yet another type (Text-Fig. 4d), the bars of the X-structure seem to be split in two, though the X still shows a strong birefringence. More varieties have been observed, but as this group is

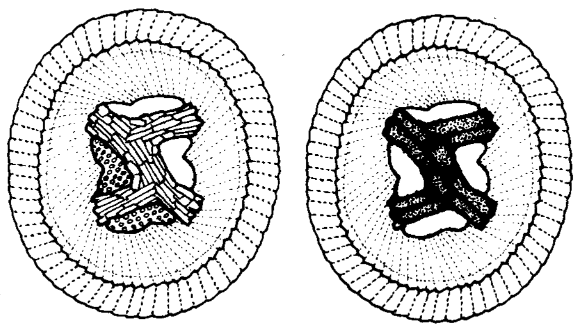

Fig. 3: *Chiasmolithus bidens*.

very complex and the stratigraphic occurrences of the individual types could not be sorted out precisely, no subdivision was attempted.

Chiasmolithus edentulus n. sp.
(Pl. 1, Figs. 13,14; Text-Fig. 5)

Holotype: Pl. 1, Figs. 13,14.

Type level: Paleocene, *Neochiastozygus perfectus* Zone (NP 4).

Type locality: Danish North Sea, well A-2, 5951 ft.

Length of holotype: 9 μm.

Diagnosis: Placoliths having a central opening spanned by an X-shaped structure, consisting of two straight and two sigmoid bars. The bars of the central X consist of two layers of crystals, which in the light microscope seem to be split in two and show a weak birefringence with cross-polarised light. There are no indentations projecting from the wall, and the inside of the wall is smooth, suggesting that a bottomplate is lacking.

Description: The shield area is narrow. Because the shields have many segments the striation of the shields looks rather vague under the light microscope. The proximal shield has a strong birefringence, but this is masked by the thick and wider distal shield with a weak birefringence. Hence, the total shield area appears to have a weak birefringence in cross-polarised light.

Remarks: This species differs from *C. bidens*, *C. eograndis* and *C. grandis* in lacking the indentations; it differs from *C. altus* and *C. oamaruensis* in the sigmoidal shape of two of the bars of the X; it differs from *C. expansus* and *C. solitus* in having a smaller centre and wider shields, it differs from *C. inconspicuus* n. sp. in having clearly visible split bars, and it differs from *C. danicus* and *C. edwardsii* in the different crystallographic construction of its central structure resulting in a weak birefringence in cross-polarised light.

Known range: Paleocene *Chiasmolithus inconspicuus* Zone (NP 4) – NP 10.

Size range: 7–12 μm.

Chiasmolithus edwardsii (ROMEIN 1979) nov. comb., emend.
(Text-Fig. 6)

Basionym: *Cruciplacolithus edwardsii* ROMEIN 1979, p. 101, Pl. 2, Fig. 7.

Emended diagnosis: This species is here restricted to those forms that have a central structure that is an X rather than an off-set cross. The angle between the bars and the long axis of the ellipse is larger than 20°.

Remarks: ROMEIN included in his species also those specimens of which the bars make a much smaller

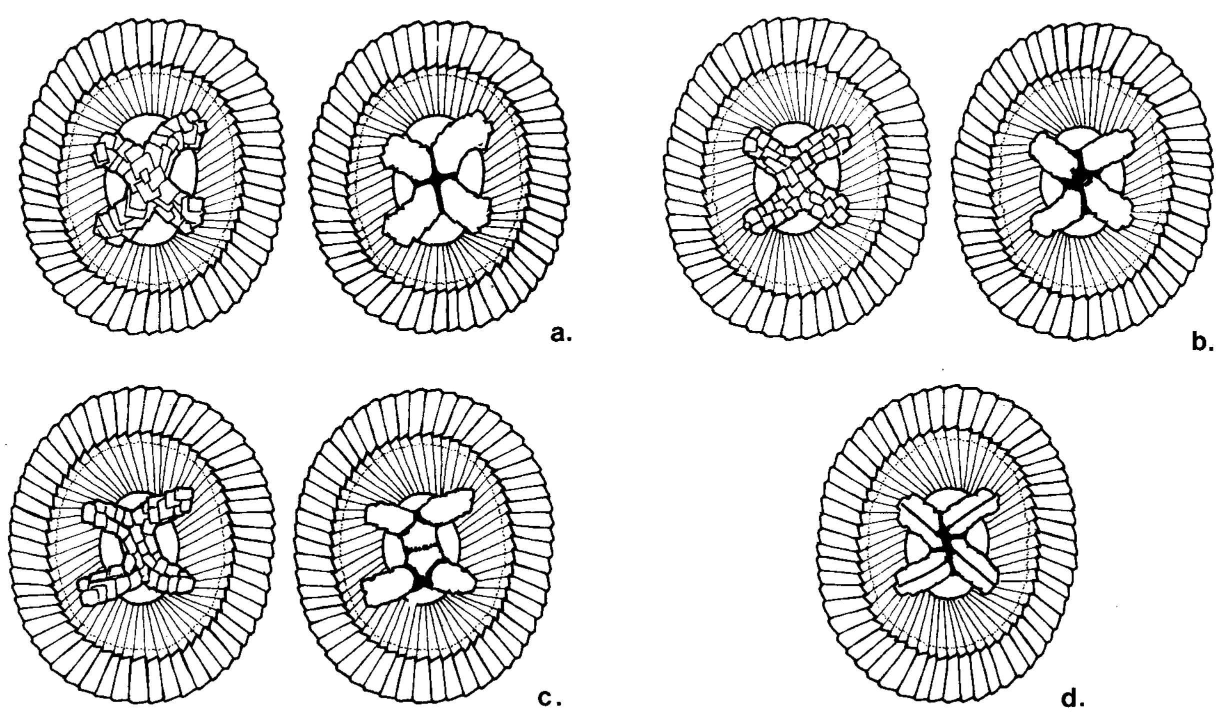

Fig. 4a–d: *Chiasmolithus danicus*.

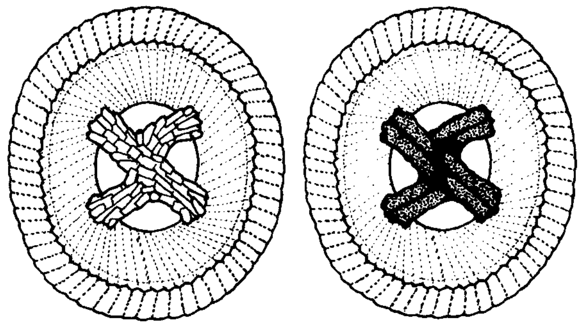

Fig. 5: *Chiasmolithus edentulus* n. sp.

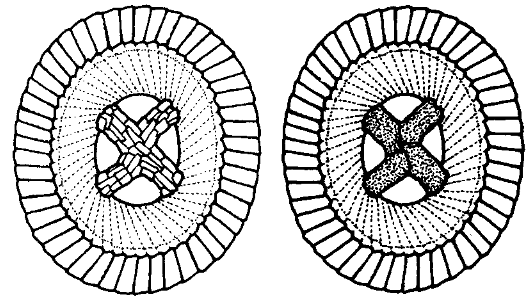

Fig. 7: *Chiasmolithus inconspicuus* n. sp.

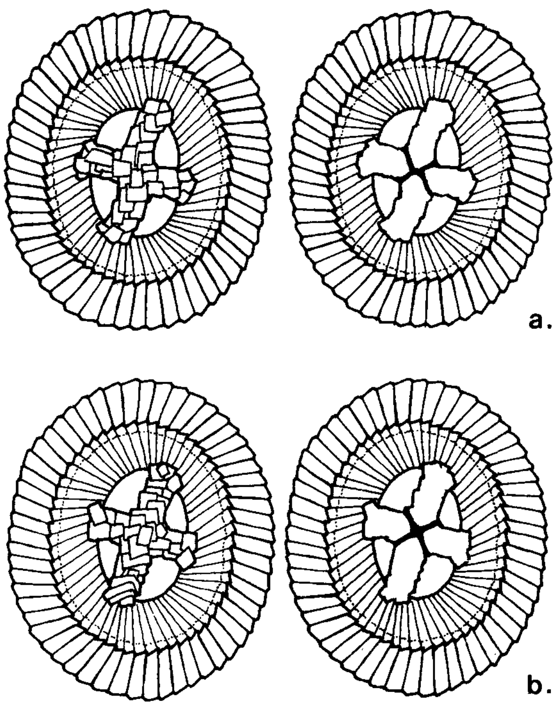

Fig. 6a–b: *Chiasmolithus edwardsii* nov. comb.

angle with the long axis of the ellipse. Because these specimens are more primitive, and have a different stratigraphic range, they are here regarded as a separate species (*C. asymmetricus*), which is assigned to *Cruciplacolithus*. The holotype of *C. edwardsii* is shown in a slightly tilted position, making the angle between the bars and the long axis of the ellipse appear smaller than it is.

Chiasmolithus inconspicuus n. sp.

(Pl. 1, Figs. 11,12; Text-Fig. 7)

= *Chiasmolithus danicus* (BROTZEN); PERCH-NIELSEN 1972, Pl. 4, Fig. 3.

Holotype: Pl. 1, Figs. 11,12.

Type level: Paleocene, *Chiasmolithus inconspicuus* Zone (NP 4).

Type locality: Danish North Sea, well A-2, 5957 ft.

Length of holotype: 5,5 µm.

Diagnosis: Placoliths having a central opening spanned by a slender X-shaped structure, of which the bars are not split and hardly penetrate the wall. The bars of the central X consist of two layers of crystals, which in the light microscope show a weak birefringence with cross-polarised light.

Description: The shield area is narrow, and because the shields have many segments, the striation of the shields looks rather vague under the light microscope.

Remarks: This species differs from most other Paleocene species of *Chiasmolithus* in its relatively small overall size and small centre, and in lacking the split bars. It differs from *C. danicus* and *C. edwardsii* in having a central structure which shows a weak birefringence with cross-polarised light.

Known range: Paleocene *Neochiastozygus saepes* Zone – *Neochiastozygus perfectus* Zone (NP 3–NP 4).

Size range: 5–10µm.

Coccolithus SCHWARZ 1894

Coccolithus subpertusus (HAY & MOHLER 1967) nov. comb.

Basionym: *Ericsonia subpertusa* HAY & MOHLER 1967, p. 1531, Pl. 198, Fig. 18.

Coccolithus subrotundus (PERCH-NIELSEN 1969) nov. comb.

Basionym: *Cruciplacolithus subrotundus* PERCH-NIELSEN 1969, p. 59, Pl. 2, Fig. 11.

Cruciplacolithus HAY & MOHLER 1967

Cruciplacolithus asymmetricus nov. sp.

(Pl. 1, Figs. 5–8; Text-Figs. 8a,b)

Holotype: Pl. 1, Figs. 6,7.

Type level: Paleocene *Cruciplacolithus asymmetricus* Zone (NP 2)

Type locality: Danish North Sea, well T-1X, 7398 ft.

Length of holotype: 10 µm.

Diagnosis: A species of *Cruciplacolithus* in which the central cross-structure is slightly rotated in a clockwise direction when viewed from the distal side, but not so far as to form an X. The angle between the long bars and the long axis of the ellipse is less than 20°.

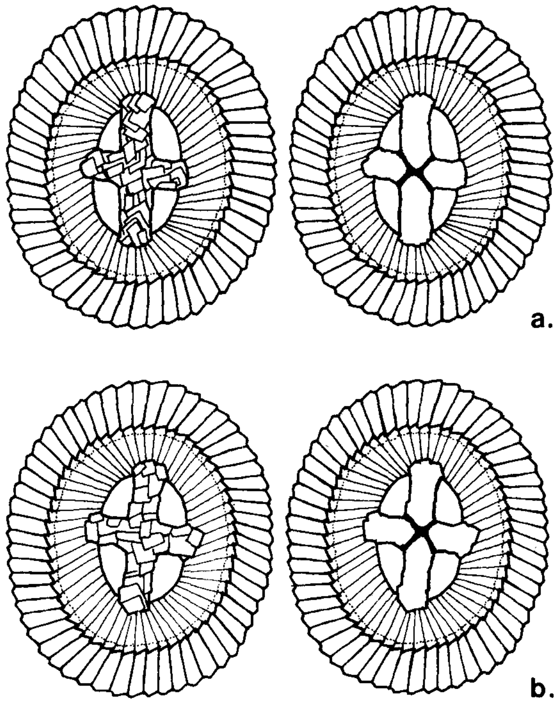

Fig. 8a–b: *Cruciplacolithus asymmetricus* n. sp.

Remarks: Two varieties can be recognised within this species. In one variety the long bars of the central structure are oriented along the long axis of the coccolith, while the short bars are slightly rotated (text-fig. 8a). In the other variety the whole cross is rotated (text-fig. 8b). Because both morphotypes appear at the same level, and show the same quantitative development, they are united in the same species.

Known range: Paleocene *Cruciplacolithus asymmetricus* Zone – *Chiasmolithus inconspicuus* Zone (NP 2–NP 4).

Size range: 7–12 μm.

Cruciplacolithus intermedius n. sp.

(Pl. 1, Figs. 1–3; Text-Fig. 9)

Holotype: Pl. 1, Figs. 1,2.

Type level: Paleocene *Cruciplacolithus intermedius* Zone (NP 2).

Type locality: Danish North Sea, well T-1X, 7398 ft.

Length of holotype: 8,5 μm.

Diagnosis: A species of *Cruciplacolithus* consisting of larger specimens (>7 μm), carrying a rather heavy cross aligned with the axes of the coccolith. Basal blocks ("feet") near the contact-points of the bars of the cross with the wall are small or lacking.

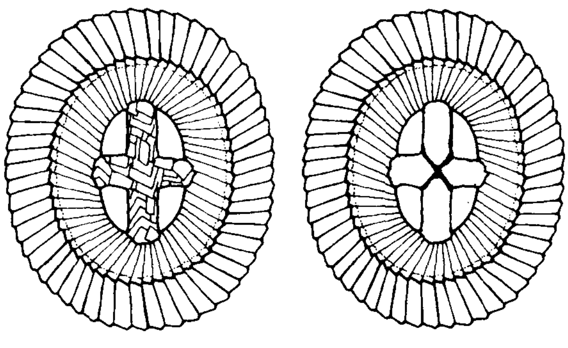

Fig. 9: *Cruciplacolithus intermedius* n. sp.

Remarks: The species differs from *C. primus* in its larger size and somewhat more robust cross. It differs from *C. tenuis* in lacking the distinct blocks at the base of the bars.

Known range: Paleocene *Cruciplacolithus intermedius* Zone – *Chiasmolithus inconspicuus* Zone (NP 2–NP 4).

Size range: 7–12 μm.

Cruciplacolithus primus PERCH-NIELSEN 1977

(Text-Fig. 10)

Specimens smaller than 7 μm, carrying a slender cross, of which the bars are oriented along the axes of the coccolith and lack the basal blocks ("feet") near the contact-points of the bars with the wall.

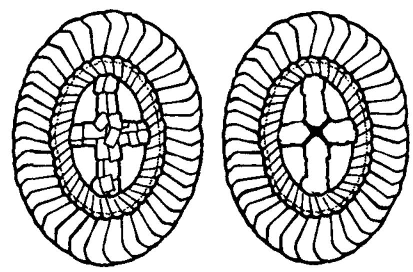

Fig. 10: *Cruciplacolithus primus.*

Cruciplacolithus tenuis (STRADNER 1961) HAY & MOHLER 1967

(Pl. 1, Fig. 4; Text-Fig. 11)

= *Cruciplacolithus notus* PERCH-NIELSEN 1977.

Specimens assigned to this species are, on average, larger than those assigned to *C. intermedius*, but are most clearly recognised by the triangular blocks at the contact-points of the bars with the wall ("feet").

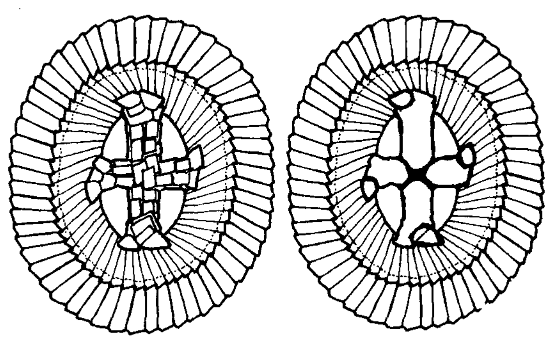

Fig. 11: *Cruciplacolithus tenuis.*

Neochiastozygus PERCH-NIELSEN 1971

Neochiastozygus eosaepes PERCH-NIELSEN 1981

(Pl. 1, Figs. 20,21; Text-Fig. 12)

Small species resembling *N. saepes*, of which the central structure may be slightly rotated. The specimens are smaller than those of *N. saepes*, and occur slightly earlier in the stratigraphic record.

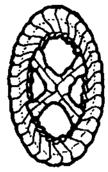

Fig. 12: *Neochiastozygus eosaepes.*

Neochiastozygus modestus PERCH-NIELSEN 1971
(Pl. 1, Figs. 15,16; Text-Fig. 13a,b)

Morphotypes assigned to this species show some variation. The earlier types are somewhat smaller and more slender. As the species evolves, the outline becomes broader, the bars of the X wider, and the diameter increases.

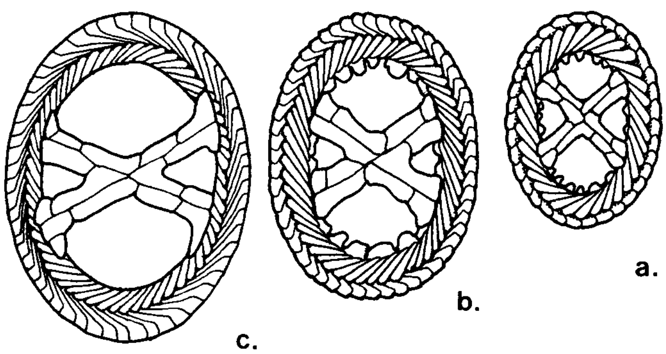

Fig. 13
a) *Neochiastozygus modestus*, early form.
b) *Neochiastozygus modestus*, late form.
c) *Neochiastozygus perfectus.*

Neochiastozygus perfectus PERCH-NIELSEN 1971
(Pl. 1, Fig. 19; Text-Fig. 13c)

Having evolved from *N. modestus, N perfectus* is larger, has a narrower wall and a more slender central structure. As a result it looks more elegant than the rather robust *N. modestus.*

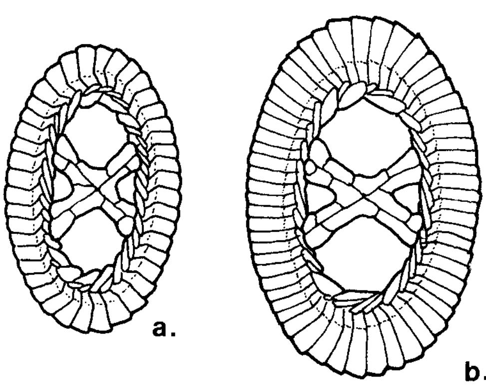

Fig. 14
a) *Neochiastozygus saepes*, early form.
b) *Neochiastozygus saepes*, late form.

Neochiastozygus saepes PERCH-NIELSEN 1971
(Pl. 1, Figs. 22–24,27,28; Text-Figs. 14a,b).

This species evolved in the Danian from *N. eosaepes* and shows a further increase in size throughout its range. Highly developed morphotypes are large specimens in which the bars of the X-structure are rather broad and compressed towards the short axis of the coccolith (Text-Fig. 14b). The rim is then wider and more irregular, although the overall outline with the pointed poles is still conspicuous.

"Asymmetrical species"
(Text-Fig. 15 a–c)

In the light-microscope we found it virtually impossible to distinguish between the several forms with a rotated central structure such as described by PERCH-NIELSEN 1981. Therefore such forms as *Chiastozygus ultimus* (Text-Fig. 15a), *N. primitivus* (Text-Fig. 15b) and *N. denticulatus* (Text-Fig. 15c) are here united in this category, although we do not deny the existence of these separate species.

Fig. 15: "Asymmetrical species"
a) *Chiastozygus ultimus.*
b) *Neochiastozygus primitivus.*
c) *Neochiastozygus denticulatus.*

Thoracosphaera KAMPTNER 1927
Thoracosphaera crassa n. sp.
(Pl. 1, Fig. 25)

Holotype: Pl. 1, Fig. 25.

Type level: Paleocene *Neochiastozygus modestus* Zone (NP 3).

Type locality: Danish North Sea well A-2, 6092 ft.

Diameter holotype (operculum): 9 µm.

Diagnosis: A species of *Thoracosphaera* of which the crystals are almost twice as coarse as those of *T. operculata*. In all other respects there seems to be no difference between *T. crassa* and *T. operculata*.

Remarks: No transitional forms have been observed, though both forms can be quite common. So far, no complete specimens have been found, but only opercula and fragments of the sphere.

Known range: Paleocene *Cruciplacolithus asymmetricus* Zone – *Neochiastozygus saepes* Zone (NP 2–NP 3).

Size range operculum: 8–10 µm.

3. Evolutionary Lineages
(Text-Fig. 16)

3.1. The *Cruciplacolithus* – *Chiasmolithus* Lineage

The first representatives of *Cruciplacolithus* in our samples are small and slender specimens, here assigned to

Cruciplacolithus primus. They show a wide variety in relative proportions of rims and cross. It has been suggested (ROMEIN, 1979) that they evolved from the Cretaceous genus *Sollasites*, and PERCH-NIELSEN (1981) found representatives of the apparently transitional species *Cruciplacolithus inseadus* in the lowermost Danian of Tunisia. However, no representatives of *Cruciplacolithus* were found in the lowermost Danian of the Central North Sea.

Cruciplacolithus primus evolved into larger specimens which still have a simple cross, consisting of four solid bars as observed in cross-polarised light. These are here called *Cruciplacolithus intermedius* n. sp. ROMEIN (1979) included them in *C. primus*, but especially the larger specimens are generally included in *Cruciplacolithus tenuis* by other authors. *C. tenuis* appeared soon thereafter, and seems to have evolved from *C. intermedius* by developing triangular blocks (commonly referred to as "feet") at the points where the bars of the cross penetrate the wall.

Another development, which occurs at roughly the same level, involves the rotation of the bars of the cross. In some specimens only the short bar seems to be rotated, while in others both bars are rotated. These two varieties have been grouped together as *Cruciplacolithus asymmetricus* n. sp., as they appear at the same level and show the same quantitative behaviour.

When the rotation of the cross has reached the stage that it is more a rotated X than a rotated cross, these forms are no longer regarded as *Cruciplacolithus*. They are here assigned to *Chiasmolithus*. The transition between these two genera is gradual, and the boundary between them therefore arbitrary. The boundary was drawn at the stage where the long bars form an angle of 20° with the long axis of the ellipse. However, in routine investigations it was found impractical to measure this angle, and experience shows that it is relatively easy to estimate whether the bars are closer to the position of a cross or to the position of an X. *C. edwardsii* (emend) is regarded as the first representative of *Chiasmolithus*.

Very soon after the appearance of *C. edwardsii* the first representatives of *Chiasmolithus danicus* can be found. This species evolved from *C. edwardsii* by a further rotation of the central structure. It rapidly developed a wide variability, and several morphotypes can be distinguished. In most types the bars of the X become offset, to a varying degree. In some cases the X becomes more complex, consisting of more blocks. Two blocks seem to form a central (vertical) bar, with four smaller blocks attached to it in the shape of an X. Somewhat later one can recognise a longitudinal division in the bars, although the birefringence in cross-polarised light is still very strong.

When *C. danicus* reached about 50 % of the *Cruciplacolithus-Chiasmolithus* assemblage a new form evolved. When it appeared for the first time is not precisely known, as it is small and rather inconspicuous. For the same reason it is not known from which form it developed, although small varieties of *C. danicus* seem the most likely candidates. The species has a slender X-structure, which shows a very weak birefringence in cross-polarised light. It is here called *Chiasmolithus inconspicuus* n. sp. The species gradually develops a wider range in size, with the larger specimens reaching about 10 μm.

The next form to appear is normally referred to as *Chiasmolithus bidens*. As with *C. inconspicuus* the central X shows a weak birefringence in cross-polarised light, but the species differs from the latter in the longitudinal subdivision of the bars. GARTNER (1970) and later ROMEIN (1979) already remarked that the early representatives of this form lack the characteristic indentations that give *C. bidens* its name. As there is a difference in stratigraphic occurrence, differentiation between these forms is useful and the early forms are therefore assigned to a new species, *Chiasmolithus edentulus*. During this study, no specimens of *C. bidens* ss. have been observed in the Danian of the Central North Sea.

3.2. The *Neochiastozygus* Lineage

Most species of *Neochiastozygus* have been introduced by PERCH-NIELSEN, who published several phylogenetic trends (1981a, b). The results presented here are partly based on her findings, and will therefore be compared with them.

The earliest forms that occur have an X that is rotated. PERCH-NIELSEN described *Chiastozygus ultimus* crossing the Cretaceous – Tertiary boundary, and evolving into *Neochiastozygus primitivus* in the lowermost Danian. As we were unable to distinguish between the various morphotypes with a rotated X under the light-microscope, we grouped them under "asymmetrical species". We have not observed any *Neochiastozygus* in the lowermost Danian in the North Sea Basin, the earliest appearing after the first occurrence of *Cruciplacolithus asymmetricus*.

As described by PERCH-NIELSEN, the next species to appear is *N. modestus*. It occurs after the first appearance of *C. danicus*, and is derived from the "asymmetrical species". Later on, *N. modestus* evolved into *N. perfectus*. Another branch of this lineage, *N. concinnus*, has not been recognised by us in the Danian.

Another development leads from the "asymmetrical species" via *N. eosaepes* to *N. saepes*. *N. eosaepes* is very small like most of the "asymmetrical species", and its central stucture is also more or less rotated, but it has pointed poles and vertical rim elements like *N. saepes*. The transition to *N. saepes* involves a rapid increase in size, while at the same time the bars of the central structure rotate to a more symmetrical position and shift from compressed towards the long axis to a more perpendicular angle. The size continues to increase, while the bars eventually become somewhat compressed towards the short axis of the ellipse. As the specimens get larger, their rim seems to become more irregular. It is therefore fairly easy to distinguish between early and later representatives of this species. The first representatives of *N. eosaepes* occur somewhat later than *N. modestus*.

4. Zonation

(Text-Figs. 16, 17)

The zonation outlined below was developed as a practical tool to subdivide the Danian in the Central North Sea. Work was started in 1973, and was based initially on the zonation published by MARTINI (1971) and on a zonation developed by PERCH-NIELSEN, known to us at the time, but not published until 1979 in a

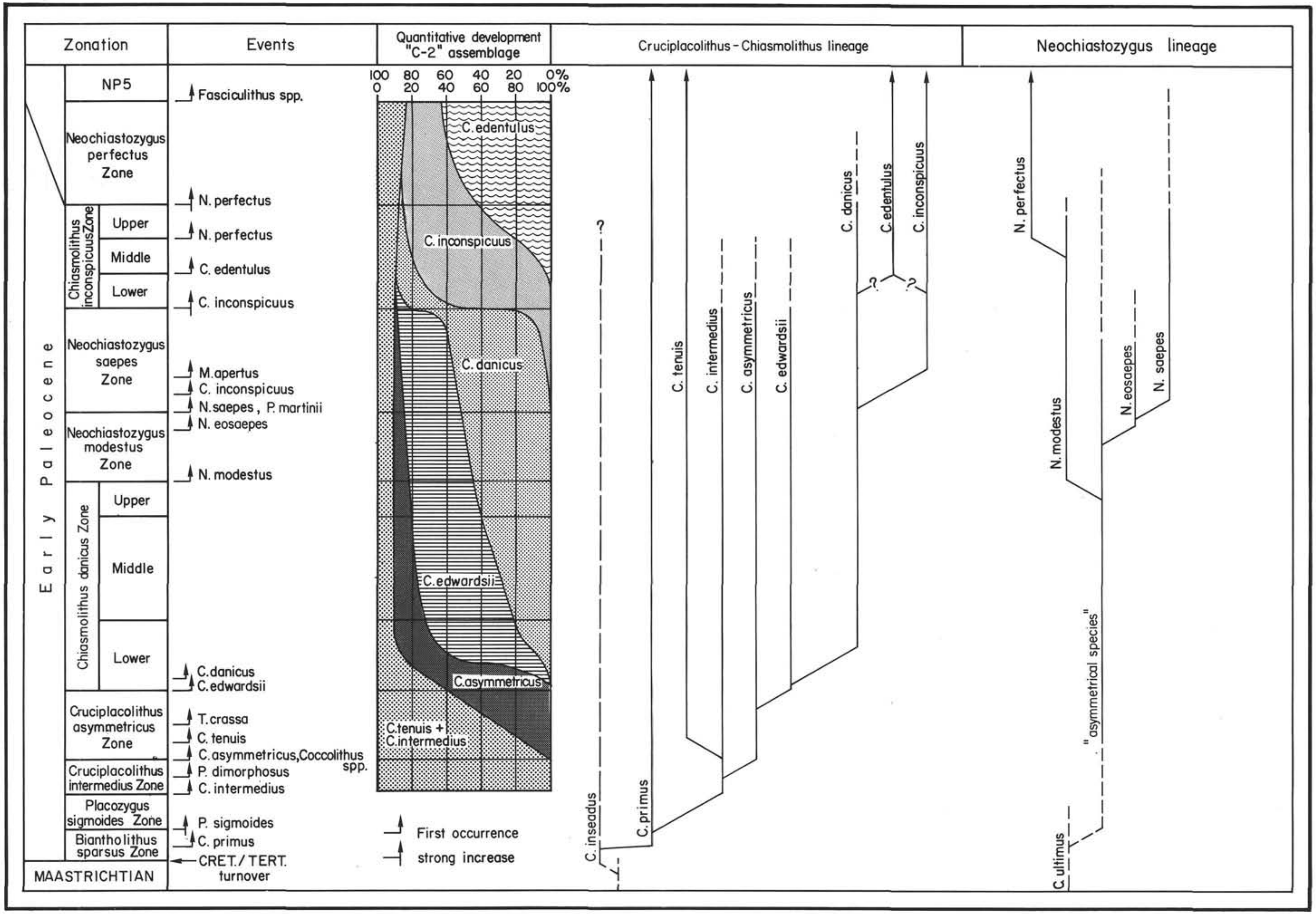

Fig. 16: Diagram, showing from left to right: 1 = zonation; 2 = biostratigraphic events; 3 = generalised quantitative development of the "C-2" assemblage; 4 = evolutionary lineages of *Cruciplacolithus*, *Chiasmolithus* and *Neochiastozygus*.

somewhat modified form. The use of new appearances, combined with evolutionary lineages and quantitative analysis made it possible to recognise an even finer subdivision.

The quantitative analysis used here is applied only to the *Cruciplacolithus-Chiasmolithus* ("C-2") assemblage. When new species evolve, they are rare when they first appear, but normally occur in increasing quantities once they are established. By counting as few as fifty specimens of the "C-2" assemblage it is usually possible to get a fairly precise idea from which stage of the evolution the sample is derived. However, since fluctuations always occur, this method should only be applied to a series of samples. Specimens of *Cruciplacolithus primus* were not included in the counts because, as a result of their small size, they are easily obscured, overlooked or dissolved. Specimens that were damaged or overgrown to such an extent that they could not be assigned to a particular species were ignored. In poorly preserved assemblages, where the amount of unidentifiable specimens was too high (>50 %) no quantitative analysis was carried out. Although fifty specimens seems a low number to count for a quantitative analysis, repeated counts of the same samples over a period of several years showed the results to be surprisingly consistent.

The zonation has been tested and applied in about 30 wells in the Danish, Norwegian and British sector of the North Sea (Text-Fig. 1). It should be stressed that the criteria may not be applicable outside this area, and almost certainly not outside the North Sea Basin. Only core samples and sidewall samples were used, with a sample spacing of about one meter on average, less where necessary, but often more where no samples were available. When sampling on a finer scale, boundaries become diffuse, and may be hard to recognise. On the other hand, when samples are further apart, thin stratigraphical units may be missed. Because of the nature of the sample material no type sections have been indicated, as the material is not accessible to the public at large.

As a considerable number of new taxa developed during the Danian, the possibilities for subdivision seem almost without limit. However, the practical approach requires that only those forms that occur fairly regularly are used. In many instances only the first appearance of a form was used as an "event" to mark a certain level, its presence not being recorded consistently at higher levels. For this reason, and because reworking occurred frequently throughout the Danian, the total range of several forms is not known precisely.

The zonation will therefore be described as a succession of events by which the Danian can be subdivided, with additional criteria where known. Correlation with the zonations of MARTINI (1971), PERCH-NIELSEN (1979) and ROMEIN (1979) is shown in Text-Fig. 17.

4.1. The *Biantolithus sparsus* Zone

Definition: Interval from the Maastrichtian – Danian boundary to the marked increase in *Placozygus sigmoides*.

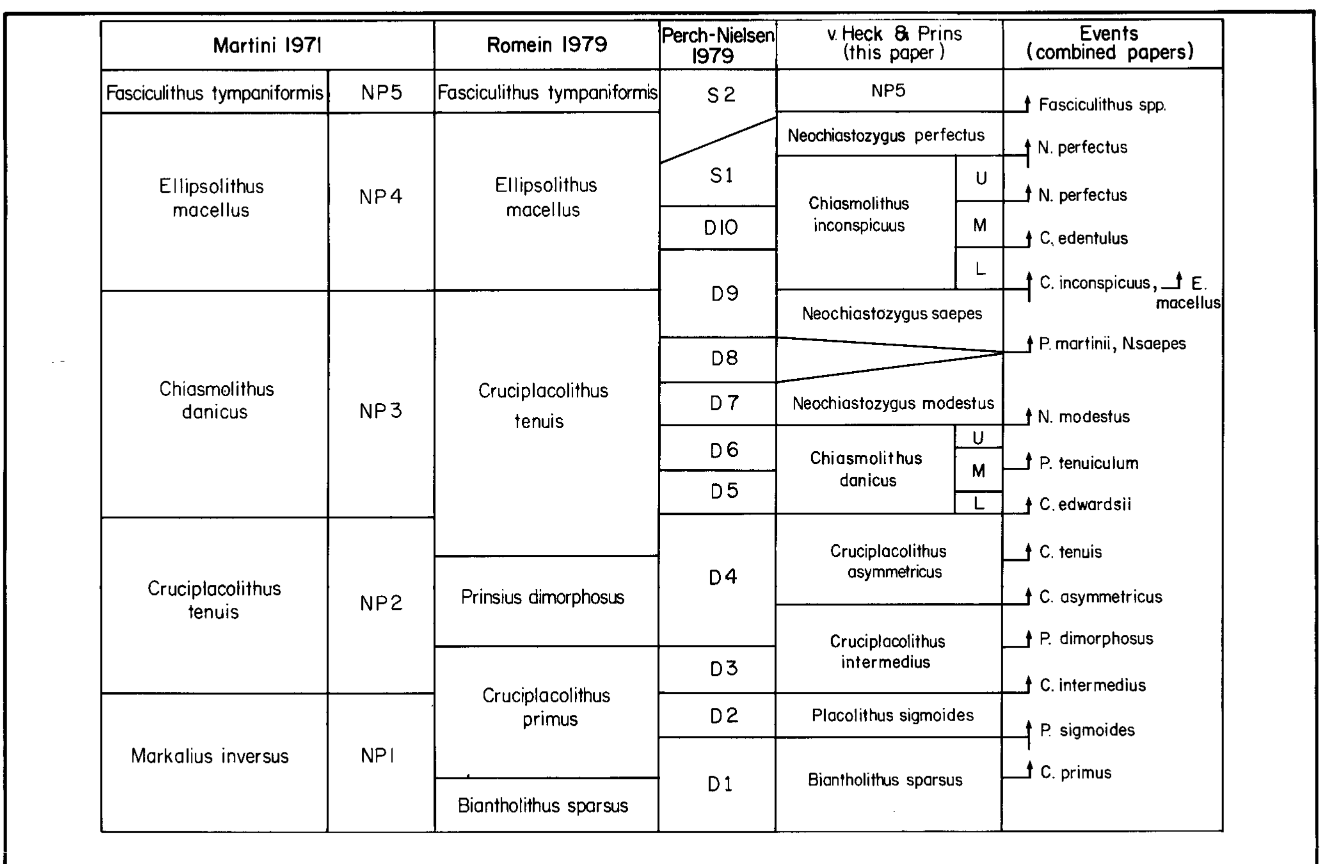

Fig. 17: Diagram showing correlation of the zonation presented here with those of MARTINI (1971), ROMEIN (1979) and PERCH-NIELSEN (1979). For *Placolithus sigmoides* read *Placozygus sigmoides*.

The lower boundary of this zone is the Cretaceous / Tertiary boundary, characterised by the mass extinction of Cretaceous species. Lately, much discussion has been going on about the exact definition of this boundary. See for instance the many publications of PERCH-NIELSEN and various co-authors (e. g. PERCH-NIELSEN et al., 1982) and of ROMEIN (e. g. ROMEIN, 1982). For all practical purposes, the boundary can be drawn at the sudden change of assemblages that is observed. The very rich and diverse assemblage of the Upper Maastrichtian with genera such as *Watznaueria, Cretarhabdus, Chiastozygus, Arkhangelskiella, Micula, Ahmuellerella, Cribrosphaerella, Lucianorhabdus, Nephrolithus, Biscutum, Prediscosphaera, Eiffellithus* and many others, is suddenly replaced by a very poor assemblage.

Most species of the *Biantholithus sparsus* Zone can be found in the Maastrichtian, where they usually are rare to extremely rare. Such species are *Thoracosphaera operculata, Biscutum panis, Braarudosphaera* spp., *Neocrepidolithus neocrassus, Cyclagelosphaera reinhardtii, Markalius astroporus* and *Placozygus sigmoides*. One species generally believed to be "new" is *Biantholithus sparsus*, but even that species has been observed on rare occasions in assemblages which otherwise are Maastrichtian. Some species more recently described as appearing in the earliest Danian, such as *Biscutum? romeinii* PERCH-NIELSEN 1981, had not been published at the time of the investigation and were not recognised by us.

Subdivision of this zone may be possible by using the first appearance of *Cruciplacolithus primus*.

4.2. The *Placozygus sigmoides* Zone

Definition: Interval from the marked increase of *Placozygus sigmoides* to the first occurrence of *Cruciplacolithus intermedius*.

Placozygus sigmoides is usually extremely rare in the *Biantholithus sparsus* Zone and often absent. The increase that defines the lower boundary of the *Placozygus sigmoides* Zone therefore often appears as a first occurrence.

In the Central North Sea, *Neocrepidolithus cohenii* seems to have its first occurrence in this zone.

4.3. The *Cruciplacolithus intermedius* Zone

Definition: Interval from the first ocurrence of *Cruciplacolithus intermedius* to the first occurrence of *Cruciplacolithus asymmetricus*.

As *Cruciplacolithus intermedius* evolved gradually from *Cruciplacolithus primus*, the lower boundary may be vague when working in very great detail. For routine-type analyses, however, it is usually easily recognisable. Because most authors have assigned this species to *Cruciplacolithus tenuis*, the lower boundary of this zone is believed to coincide with the conventional boundary between NP 1 and NP 2.

The first specimens of *Prinsius dimorphosus* occur in this zone, which may help to obtain a further subdivision. It has not been used as a zonal marker here, because the first specimens to occur are very small and rare, and are therefore easily overlooked.

4.4. The *Cruciplacolithus asymmetricus* Zone

Definition: Interval from the first occurrence of *Cruciplacolithus asymmetricus* to the first occurrence of *Chiasmolithus edwardsii*.

The first appearance of *Cruciplacolithus asymmetricus* more or less coincides with the first occurrence of *Coccolithus* spp. and with a marked increase in *Prinsius dimorphosus*, which is abundant throughout this zone.

The quantitative analysis of the "C–2" assemblage shows that *Cruciplacolithus asymmetricus* increases from less than 1 % at the beginning of the zone to about 60 % at the top of this zone. Intermediate values can be used to determine the relative position within this zone. *Cruciplacolithus tenuis* occurs shortly after the first appearance of *Cruciplacolithus asymmetricus*. It was counted together with *Cruciplacolithus intermedius* as one category because it may be difficult to distinguish between both species when preservation is poor.

Thoracosphaera crassa has its first appearance in this zone.

4.5. The *Chiasmolithus danicus* Zone

Definition: Interval from the first occurrence of *Chiasmolithus edwardsii* to the first occurrence of *Neochiastozygus modestus*.

As the forms that are here assigned to *Chiasmolithus edwardsii* have been assigned by most authors to *Chiasmolithus danicus*, the lower boundary of this zone is believed to coincide with the conventional boundary between Zones NP 2 and NP 3.

Soon after the first appearance of *Chiasmolithus edwardsii*, one can observe the first specimens of *Chiasmolithus danicus*. The quantitative development of the "C-2" assemblage shows a very rapid increase of *Chiasmolithus edwardsii* in the lower part of this zone, increasing from less than 1 % to 50 %, while in the same interval *Chiasmolithus danicus* increases from 0 to 20 %. Over the next interval *Chiasmolithus danicus* shows an increase from 20 % to 40 %, while the percentage of *Chiasmolithus edwardsii* is reduced to 40 %. In the upper part of this zone these percentages show some minor fluctuations, with a slight increase in the amount of *Chiasmolithus danicus*. With the aid of this quantitative development, the zone can easily be subdivided into a lower, a middle and an upper part.

The first specimens of "asymmetrical species" of *Neochiastozygus* have been found in this zone.

4.6. The *Neochiastozygus modestus* Zone

Definition: Interval from the first occurrence of *Neochiastozygus modestus* to the first occurrence of *Prinsius martinii*.

Quantitative analysis of the "C-2" assemblage shows little change over this interval. *Chiasmolithus danicus* may increase slightly to about 50 %. In this interval it develops some more complex morphotypes, as described in the preceding paragraphs.

Some new species are observed towards the top of this zone. The first circular representatives of *Coccolithus* appear in the form of *Coccolithus subrotundus*. In the *Neochiastozygus* lineage, the first specimens of *Neochias-*

tozygus eosaepes develop from "asymmetrical species" of *Neochiastozygus*.

4.7. The *Neochiastozygus saepes* Zone

Definition: Interval from the first occurrence of *Prinsius martinii* to the sudden increase in the amount of *Chiasmolithus inconspicuus*.

The various species of *Prinsius* are normally common to abundant throughout most of the Danian. For this reason *Prinsius martinii* was chosen as the zonal marker, but we found the first occurrence of this species to coincide with the first occurrence of *Neochiastozygus saepes*. Therefore the first occurrence of either species is considered as indicative of the lower boundary of this zone.

The first specimens of *Chiasmolithus inconspicuus* can be found in this interval. They occur in variable quantities but rarely amount to more than 20 % of the "C-2" assemblage. Several small circular species of *Coccolithus* occur, which have not yet been described. *Markalius apertus* first appears in this zone. Towards the end of the interval specimens of *Neochiastozygus saepes* may become as large as 12 µm. The presence of these large forms is indicative of the upper part of the zone.

Remarks: PERCH-NIELSEN (1979) uses *Prinsius martinii* and *Neochiastozygus saepes* as markers for two different zones. Because both species were seen to appear simultaneously in our material, these two zones could not be distinguished. Our *Neochiastozygus saepes* Zone is therefore believed to correspond to Zones D 8 and D 9 of PERCH-NIELSEN (1979).

4.8. The *Chiasmolithus inconspicuus* Zone

Definition: Interval from the sudden increase in amount of *Chiasmolithus inconspicuus* to the common occurrence of *Neochiastozygus perfectus*.

The event marking the boundary between NP 3 and NP 4 is the first occurrence of *Ellipsolithus macellus*. Because this species is extremely rare in the Central North Sea, and usually absent, it had to be replaced by an other criterion. From the rare occasions where it has been found, it seemed to have its first occurrence shortly before *Chiasmolithus edentulus*. As this view is confirmed by literature (for instance ROMEIN, 1979), the increase in percentage of *Chiasmolithus inconspicuus* was chosen as the boundary marker because this event is probably closest to the first appearance of *Ellipsolithus macellus*.

This interval may be subdivided by using the following events: The first appearance of *Chiasmolithus edentulus* marks the boundary between the lower and the middle part, and the first appearance of *Neochiastozygus perfectus* marks the boundary between the middle and upper part. *Coccolithus subpertusus* and *Toweius pertusus* usually first occur at the base of this zone, although *C. subpertusus* has been recorded from the upper part of the previous zone.

4.9. The *Neochiastozygus perfectus* Zone

Definition: Interval from the first common occurrence of *Neochiastozygus perfectus* to the first occurrence of *Fasciculithus*.

Because *Neochiastozygus perfectus* is rare in the lower part of its range, it is often a matter of chance whether the first representatives are found. Therefore the first common occurrence of this species is used to mark the lower boundary. "Common occurrence" is understood to be such that, with a quick scan of the slide several specimens can be found.

Several additional representatives of the *Prinsius-Toweius* lineage develop in this interval (see ROMEIN, 1979; PERCH-NIELSEN; 1979) but because they are usually difficult to distinguish, they were not used for further subdivision. However, the common occurrence of *Toweius* spp. can be regarded as an additional criterion for recognition of this zone.

It may be argued that this zone cannot be assigned to the Danian (see PERCH-NIELSEN, 1979), but because higher Paleocene intervals in the Central North Sea are usually barren of nannofossils, this interval has here been included. For the same reason the upper boundary of this zone is difficult to define in the Central North Sea, but representatives of both *Sphenolithus* and *Fasciculithus* have been found, and the first occurrence of the latter is believed to coincide in this area with the conventional boundary between NP 4 and NP 5.

5. Applications

A few examples are presented here to illustrate the application of the quantitative analysis of the "C-2" assemblage.

Text-Fig. 16 shows a generalised picture of the quantitative development of the "C-2" assemblage, constructed after comparison of the results of the wells that were studied. In reality, there is more variation (Text-Figs. 18–20).

C. asymmetricus and *C. edwardsii* are shown to disappear in the *C. inconspicuus* Zone, but one will notice that in reality these species also occur above this level, albeit in low numbers. However, this is believed to be the result of reworking.

The examples are chosen not to illustrate the general development, but to demonstrate how exceptions to this general scheme have been interpreted. Age determinations are based on the criteria outlined earlier, which will not be discussed here. Instead, attention is focused on how the analysis of the quantitative development, in combination with the other criteria, can help to recognise anomalies such as hiatuses and allochthonous units.

All examples are taken from the Danish North Sea. The intervals that were studied are in all cases determined by the availability of cores or sidewall samples.

5.1. Well T-1X
(Text-Fig. 18)

The first hiatus to be encountered in this well can be found at 7400'. The absence of an interval in which *C. intermedius* is the only representative of the "C-2" assemblage, indicates that the *C. intermedius* Zone is missing. However, the "C-2" assemblage at the base of the *C. asymmetricus* Zone already contains more than 40 % of *C. asymmetricus*, indicating that most of this zone is missing as well.

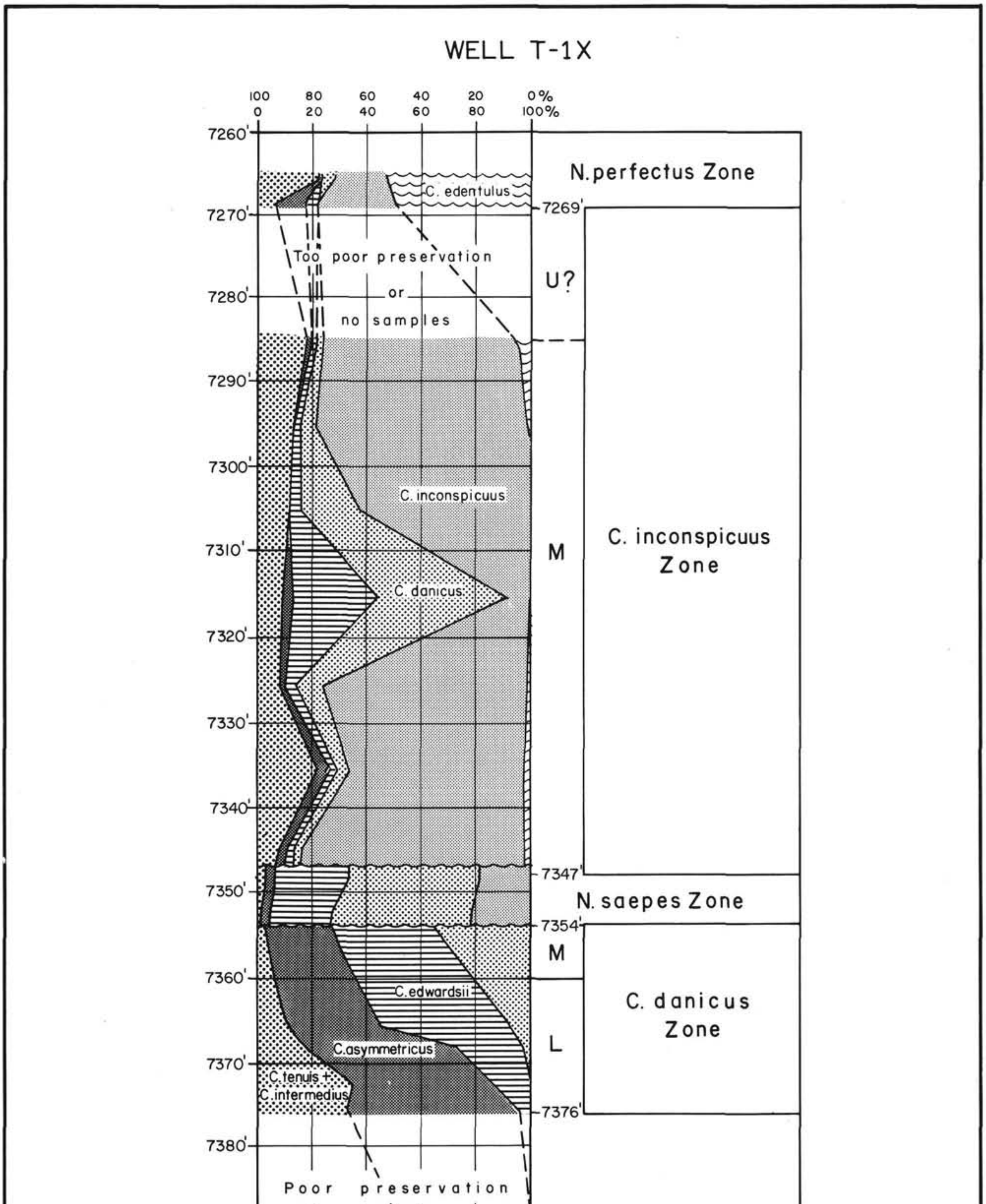

Fig. 18: Quantitative development of the „C-2" assemblage in Danish North Sea well T-1X.

The second hiatus can be found at 7354'. Here, not only the *N. modestus* Zone is absent, but also part of the preceding and possibly of the following zone. At the top of the interval assigned to the *C. danicus* Zone, *C. danicus* has not yet reached 40 % of the "C-2" assemblage, indicating that the whole upper part of the zone is absent. The succeeding interval starts with the presence of *C. inconspicuus* comprising about 20 % of the "C-2" assemblage, which is rather exceptional, and may suggest that the lowest part of the *N. saepes* Zone is missing.

The next hiatus, at 7347', may comprise the top of the *N. saepes* Zone, as suggested by the absence of very large representatives of *N. saepes*. However, as these forms are not always present, this is rather speculative. It is fairly certain, however, that the lower part of the *C. inconspicuus* Zone is absent, as the interval starts with the presence of *C. edentulus* right at the base. Also the percentage of *C. inconspicuus* (>80 % of the "C-2" assemblage) is far higher than would be expected in the lower part of this zone.

The sample at 7315' shows a percentage distribution comparable to that of the *N. saepes* Zone. However, as *C. edentulus* is present, this is not an allochthonous body but the result of an unusually high degree of reworking.

The remainder of this well shows an apparently normal distribution.

5.2. Well E-4

(Text-Fig. 19)

Following the Maastrichtian, the Danian succession begins with the *C. asymmetricus* Zone. The high percentage of *C. asymmetricus* indicates that this sample represents the very top of the zone, which is supported by the presence of one questionable specimen of *C. edwardsii*. Therefore, the *B. sparsus* Zone, the *P. sigmoides* Zone, the *C. intermedius* Zone, and the major part of the *C. asymmetricus* Zone are missing.

The *C. asymmetricus* Zone is followed by a thin allochthonous unit of Maastrichtian age (*N. frequens* Zone). The next interval, assigned to the *C. danicus* Zone, is in sequence with the previous Danian interval. Only one specimen of *C. edwardsii* was found, and the percentages of the "C-2" assemblage are very similar. No time seems to be missing between the two Danian units, indicating that the Maastrichtian unit was deposited instantaneously.

A hiatus is present at 6612'. Although the intervals below and above are assigned to the lower part of the *C. danicus* Zone, the increase in percentages is too sharp to represent a normal sequence.

The sudden increase in percentages at about 6605' indicates another hiatus. Here the percentage of *C. danicus* jumps from 10 % to 40 % of the "C-2" assemblage, which means that at least the middle part of the *C. danicus* Zone is absent.

The rest of the sequence shows a normal development.

5.3. Well E-1X

(Text-Fig. 20)

The Danian sequence begins with the lowermost part of the *C. danicus* Zone, as indicated by the low percentage of *C. edwardsii* in the "C-2" assemblage and the absence of *C. danicus*. This implies that the *B. sparsus* Zone, the *P. sigmoides* Zone, the *C. intermedius* Zone and the *C. asymmtericus* Zone are missing.

The interval to follow is an allochthonous body of Maastrichtian age, which in turn is overlain by a unit assigned to the *C. asymmetricus* Zone. As this Danian interval is older than the *C. danicus* Zone below, it must also be allochthonous.

The next interval again belongs to the lower part of the *C. danicus* Zone, and the percentages indicate that it forms a natural continuation from the previous interval assigned to the same zone. Again, this suggests that the deposition of both allochthonous bodies were more or less instantaneous events.

Only a minor hiatus seems to be present between the lower and the middle part of the *C. danicus* Zone, at 6850'. This is indicated by the rapid increase in the percentage of *C. danicus*, which is generally very much slower in this interval.

The sequence seems to be undisturbed up to the top of the *N. saepes* Zone. The relatively high percentage of *C. inconspicuus* at the base of the *N. saepes* Zone does not coincide with any other irregularities, and must therefore be excepted as part of the rather erratic quantitative behaviour of this species.

A hiatus is present at 6780'. The situation is very similar to that in well T-1X. Large representatives of *N. saepes* are absent in the *N. saepes* Zone, suggesting that the top of this zone may be missing, and *C. edentulus* is present right at the base of the *C. inconspicuus* Zone. This, in combination with the extremely high percentage of *C. inconspicuus* (almost 80 % of the "C-2" assemblage) indicates that the lower part of this zone is absent.

The remainder of the sequence seems to show a normal development.

*

It is not the intention of this paper to go into the geological significance of the discontinuities described above. However, if their succession, stratigraphical and geographical occurrence should be recorded from all available wells and analysed, an interesting pattern might emerge, from which the migration of seismic zones during the Early Paleocene could be deduced.

Although the quantitative development of the "C-2" assemblage as described above can only be applied in the North Sea Basin, similar analyses may be applicable elsewhere.

Acknowledgements

The authors wish to thank Shell Internationale Petroleum Maatschappij, The Hague, for giving permission to publish this paper. Thanks are also due to KATHARINA PERCH-NIELSEN for valuable comments (although the opinions presented herein are not necessarily hers), for her help during preparation of the manuscript. Miss G. GRIFFITHS and Dr. K. GLENNIE are thanked for the correction of the English, Dr. C. KOK for help with the photographs and for critically reading the manuscript during preparation, and the drafting office of Shell EXPRO, U. K., for drawing part of the text-figures.

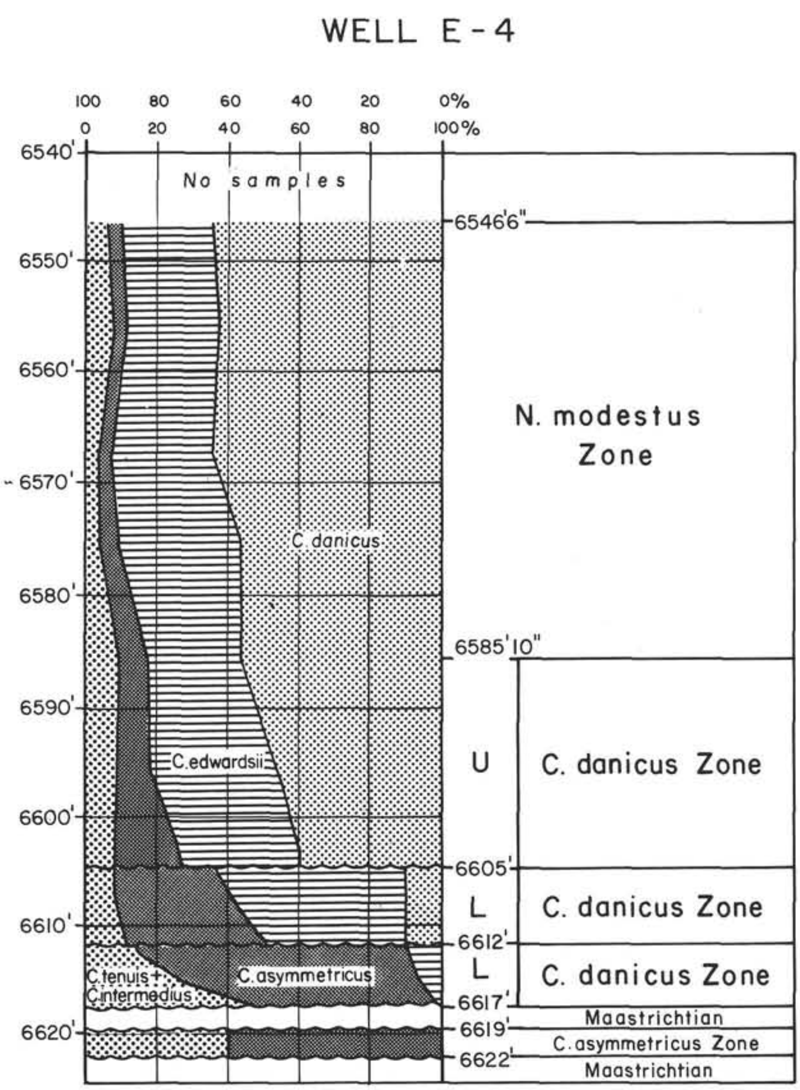

Fig. 19: Quantitative development of the „C-2" assemblage in Danish North Sea well E-4.

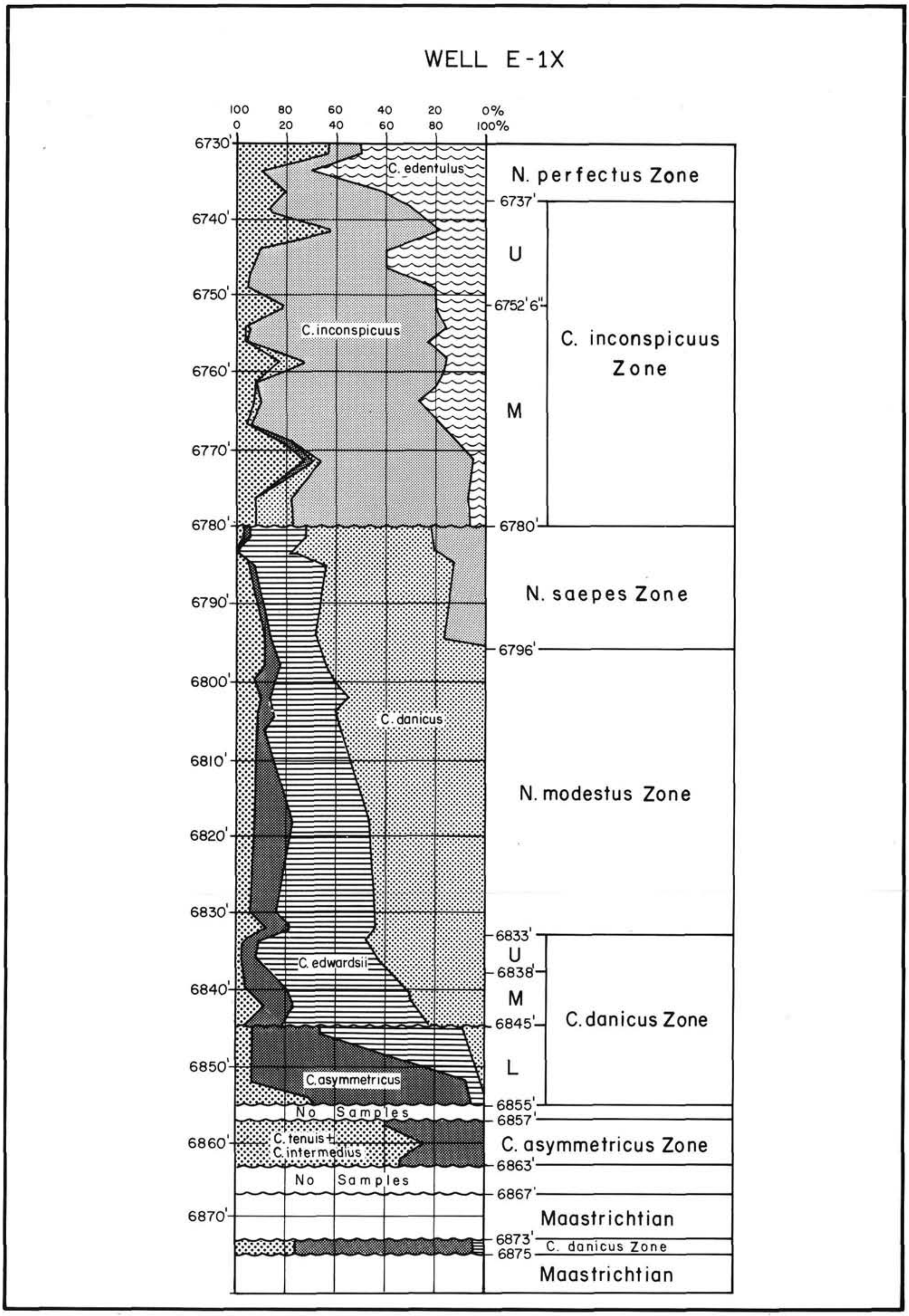

Fig. 20: Quantitative development of the „C-2" assemblage in Danish North Sea well E-1X.

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Plate 1

Figs. 1–3: *Cruciplacolithus intermedius* n. sp.
1: Proximal view, DN T-1, 7398 ft, 8,5 μm. *C. asymmetricus* Zone. Holotype.
(EP/12, 113.9/15.5).
2: Same specimen, ×nicols aligned with axes.
3: Distal view, DN T-1, 7359 ft, 8 μm. ×nicols aligned with axes. *C asymmetricus* Zone.
(UEE/32, 26.0/97.0).

Fig. 4: *Cruciplacolithus tenuis.*
Distal view, DN A-2, 5951 ft, 10 μm. ×nicols aligned with axes. *N. perfectus* Zone.
(EP/12, (oo), 115.9/8.2).

Figs. 5–8: *Cruciplacolithus asymmetricus* n. sp..
5: Proximal view, DN T-1, 7398 ft, 10 μm. ×nicols aligned with axes. *C. asymmetricus* Zone. Only the short bars are slightly rotated.
Holotype.
(EP/12, 111.0/13.05).
6: Proximal view, DN T-1, 7395 ft, 8.5 μm. ×nicols aligned with axes. *C. asymmetricus* Zone. Both bars are slightly rotated.
(UEE/32, 28.9/113.4).
7: Same specimen, ×nicols 45° with axes.
8: Proximal view, DN T-1, 7398 ft, 9 μm. ×nicols aligned with axes. *C. asymmetricus* Zone. The central structure is more rotated (15°).
(UEE/32, 29.9/95.94).

Figs. 9–10: *Chiasmolithus danicus.*
9: Proximal view, DN A-2, 6092 ft, 7.5 μm. ×nicols 45° with axes. *N. modestus* Zone.
(EP/12, (o), 115.5/14.7).
10: Proximal view, DN A-2, 5990.7 ft, 10 μm. ×nicols aligned with axes. *N. saepes* Zone. Specimen with complex central structure.
(EP/12, (o), 115.45/5.2).

Figs. 11–12: *Chiasmolithus inconspicuus* n. sp..
11: Proximal view, DN A-2, 5957 ft, 5.5 μm. *C. inconspicuus* Zone. Holotype.
(EP/12, (o), 125.9/5.55).
12: Same specimen, ×nicols aligned with axes.

Figs. 13–14: *Chiasmolithus edentulus* n. sp.
13: Proximal view, DN A-2, 5951 ft, 9 μm. *N. perfectus* Zone. Holotype.
(EP/12, (oo), 116.0/3.25).
14: Same specimen, ×nicols 45° with axes.

Figs. 15–16: *Neochiastozygus modestus.*
15: Distal view, DN A-2, 6052.9 ft, 6.5 μm. *N. modestus* Zone.
(EP/12, (o), 125.05/15.05).
16: Same specimen, ×nicols aligned with axes.

Figs. 17–18: Specimen intermediate between *Neochiastozygus modestus* and *Neochiastozygus perfectus.*
17: Distal view, DN A-2, 5951 ft, 7 μm. *N.perfectus* Zone.
(EP/12, (oo), 114.85/11.5).
18: Same specimen. ×nicols aligned with axes.

Fig. 19: *Neochiastozygus perfectus.*
Proximal view, DN A-2, 5951 ft, 9 μm. ×nicols aligned with axes. *N. perfectus* Zone.
(EP/12, (o), 127.6/12.0).

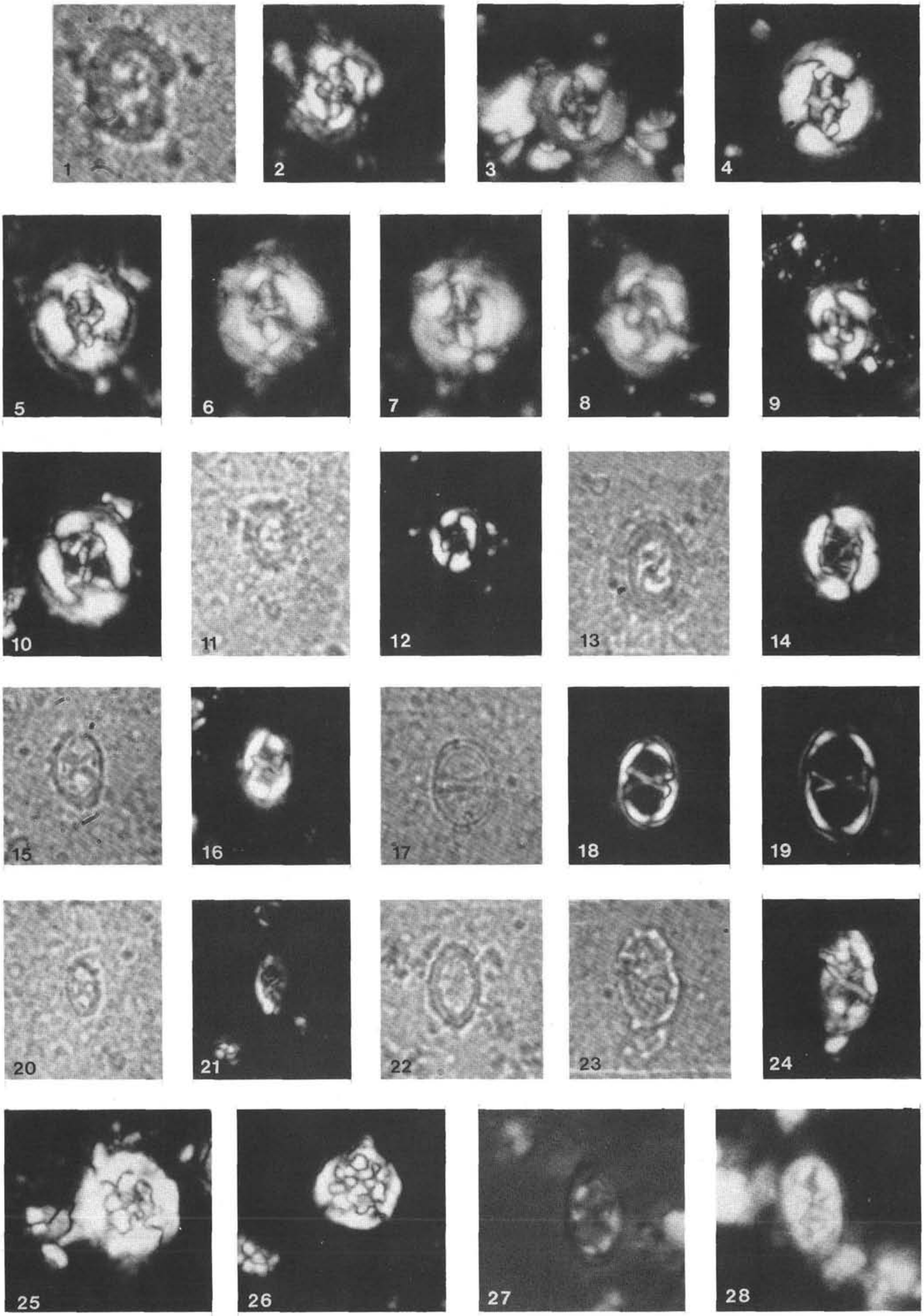
Figs. 20–21: *Neochiastozygus eosaepes.*
20: Distal view, DN A-2, 6048 ft, 4.5 μm. *N. modestus* Zone.
(EP/12, (o), 115.05/5.6).
21: Same specimen, ×nicols aligned with axes.

Figs. 22–24,27,28: *Neochiastozygus saepes.*
22: DN A-1, 5990.7 ft, 7 μm. *N. saepes* Zone.
(EP/12, 118.4/15.0).
23: Proximal view, DN A-2, 5990.7 ft, 8 μm. *N. saepes* Zone. Larger form.
(EP/12, 124.85/14.9).
24: Same specimen, ×nicols aligned with axes..
27: Distal view, DN N-3, 6724 ft, 8.5 μm. *N. saepes* Zone. Larger form.
(UEE/32, 22.0/95.9).
28: Same specimen, ×nicols aligned with axes.

Fig. 25: *Thoracosphaera crassa* n. sp.
DN A-2, 6092 ft, 9 μm. ×nicols. *N. modestus* Zone. Holotype.
(EP/12, 115.9/3.8).

Fig. 26: *Thoracosphaera operculata.*
DN A-2, 6052.9 ft, 7 μm. ×nicols. *N. modestus* Zone.
(EP/12, (o), 125.1/11.55).

All magnifications approximately 2500×.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